Chapter 6

Plate Tectonics

6.1 Consequences of Tectonic Activity

The movement and interaction of tectonic plates lead to several major geological events.

Volcano an opening (vent) where molten rock reaches the Earth's surface. Volcanoes can also form mountains built from the products of repeated eruptions.

Earthquake episodes of ground shaking caused by the sudden release of energy as plates slip along faults.

Mountain building the formation of mountain belts. This involves uplift (the crust rising) and deformation (rocks bending, breaking, or flowing) due to stress as compression, tension, or shearing.

6.2 Volcanoes

- Beneath a volcano, magma rises through cracks in the crust and collects in a **magma chamber**.
- When pressure builds up, some of this magma erupts at the surface–either through the central vent or along the volcano's flanks.
- The style of eruption depends largely on the viscosity of the magma.
  - High-viscosity magma
  - Low-viscosity magma
- Because of this variation, volcanoes come in many different forms.

6.3 Products of Volcanic Eruptions

- Volcanic eruption transfers materials from inside the Earth to our planet's surface.

- Products of an eruption come in different forms:

  Lava flows molten rock that moves over the ground.

  Pyroclastic debris fragments blown out of a volcano.

  Volcanic gases expelled vapor and aerosols

6.3.1 Lava Flows

- Outpouring of molten rock, or magma, during eruption.
- Lava can be thin and runny or thick and sticky depending on viscosity, which is due to composition (especially silica content), temperature, and gas content.
- Higher silica → higher viscosity → less ability to flow.

  Basaltic (mafic) lavas low silica, low viscosity → runny, travel long distance

  Ryolitic (felsic) lavas high silica, high viscosity → thick, pile up near the vent

  Andesite lavas intermediate properties

6.3.2 Pyroclastic Debris

Fragmented igneous materials forcefully ejected from a volcano.

- Basaltic eruptions produce relatively little pyroclastic debris.
- Andesitic and Rhyolitic eruptions are much richer in silica and often generate immense quantities of pyroclastic debris, much more than basaltic eruptions.

6.3.3 Volcanic Gases

- Most magma contains dissolved gases (volatiles):
  - Water vapor (H_2O), Carbon Dioxide (CO_2), sulfur dioxide (SO_2), and hydrogen sulfide (H_2S).
- As magma rises toward the surface, dissolved gases escape because:
  - Lower pressure near the surface reduce the ability of magma to hold gas.
  - Crystallization excludes gases (they don't fit into crystals), so gas concentration in the melt increases until bubbles form.
- Eruption style:
  - Low-viscosity basaltic magma: gases escape easily → eruptions are typically gentle
  - High-viscosity rhyolitic magma: gases are trapped, pressure builds up → eruptions are often explosive and violent.

6.3.4 Other Volcanic Deposits

Pyroclastic deposits fragments ejected during an eruption that accumulate directly from ash clouds in the atmosphere or from hot avalanches of debris rushing down the volcano's flank.

Volcanic-sedimentary deposits volcanic material that has been reworked and redeposited after the eruption–for example, by debris flows or lahars carrying volcanic ash and rock downslope.

Fragmented lava deposits angular debris produced when lava breaks apart while flowing on the surface, without being ejected into the air.

6.4 Geological Settings of Volcanism

- Different styles of volcanism occur at different locations on Earth.

6.4.1 Mid-Ocean Ridge Submarine Eruptions

- Mid-ocean ridge volcanoes develop along fissures parallel to the ridge axis.
- Products of mid-ocean ridge volcanism cover 70% of Earth's surface.
- Mid-ocean ridge volcanoes are not all continuously active.
- We don't generally see this volcanic activity, because the ocean hides most of it beneath a blanket of water.

6.5 Volcanism of Continental Rifts

- Igneous activity of rift zones occurs because the thinning and stretching of the continental lithosphere reduces the pressure on the underlying asthenosphere.
- As the asthenosphere rises to shallower depths, it partially melts, producing magma.
- Some of this magma rises directly to the surface, erupting as lava flows or volcanic cones.
- A portion of the magma, however, stalls and crystallizes at the base of the crust or within crustal fractures, forming intrusive igneous bodies.

6.6 Volcanic Arcs at Convergent Boundaries

- Most subaerial volcanoes on the Earth lies along convergent boundaries (subduction zones).
- Island arc: magma rises from the mantle through the oceanic crust.

- Continental arc: volcanoes grow on continental crust.
- The **Ring of Fire** defines the location of most subduction-related volcanoes.

6.7 Hot-Spot Volcanism

- Host spots are volcanic regions fed by mantle plumes. Unlike plate boundary volcanism, hot spot volcanism occurs in the middle of tectonic plates.
- Oceanic host spots are created when rising mantle plumes undergo decompression melting beneath oceanic lithosphere (e.g., Hawaiian Islands).
- Continental hot spots occur when mantle plumes rise beneath continents, causing partial melting of both mantle and continental crust (e.g., Yellowstone).

6.8 Volcanic Hazards Due to Eruptive Materials

- Threat from lava flows
  - Basaltic lava from effusive eruptions is the greatest thread because it can spread over a broad area.
- Pyroclastic debris flows
  - Pyroclastic flows can move extremely fast (100-300 km/h) and are so hot (500-1,000°C) that they represent a profound hazard to humans and the environment.
- Volcanic Ash and Lapilli
  - During a large explosive eruption, ash and lapilli erupt into the air, later fall back to the ground. Ashfalls can completely bury landscapes, killing plants and crops.

6.9 Other Hazards Related to Eruptions

6.9.1 Threat of blast

- When explosions are eject sideways, they can create severe blast hazards.

6.9.2 Threat of landslide

- Eruptions commonly trigger large landslides along a volcano's flanks.
- Volcanic debris, composed of ash and solidified lava that erupt earlier, can move downslope fast (250 km/h) and far.

6.9.3 Threat of lahars

- Mixing volcanic ash and other debris with water produces a lahar, an ash slurry that resembles wet concrete, very thick and dense.
- Lahars may develop when heavy rains happen during an eruption, or in regions where snow and ice cover an erupting volcano, for the eruption melts the snow and ice, thereby generating a supply of water.

6.9.4 Threat of earthquakes

- Earthquakes accompany almost all major volcanic eruptions because the movement of magma break rocks underground.

6.9.5 Threat of tsunamis

- Where explosive eruptions occur at an island arc; the blast and the underwater collapse of a caldera can generate huge sea waves or tsunamis, tens of meters high.

6.9.6 Threat of gas

- Volcanoes erupt not only solid material, but also large quantities of gas such as water vapor (H_2O), carbon dioxide (CO_2), sulfur dioxide (SO_2), and hydrogen sulfide (H_2S).
- Usually, eruption of gases accompanies the eruption of lava and ash.

6.10 Active, Dormant and Extinct Volcanoes

- The threat from a volcano depends on the likelihood of eruption.
- Tectonic processes will eventually shut off volcanoes' magma source, then erosion takes over.

  Active erupting, recently erupted, or likely to erupt

  Dormant hasn't erupted in hundreds to thousands of years

  Extinct no longer capable of erupting

- How to determine?
  - Examine the historical record
  - Determine the age of erupted rocks
  - Search for evidence that the volcano sill lies within a tectonically active area
  - Examine the landscape character of the volcano (shape)

6.11 Predicting Eruption

- Long-term prediction comes from:
  - Recurrence interval - the average time between eruptions
  - Age of erupted layers making up the volcano
- Indicators for volcanic unrest:

  Earthquake activity movement of magma generates vibrations in the Earth.

  Changes in heat flow the presence of hot magma increases the local heat flow, the amount of heat passing upward through rock.

  Changes in shape As magma fills the magma chamber inside a volcano, it pushes outward and cna cause the surface of the volcano to bulge.

  Increase in gas and steam emission Gases bubbling out of the magma and steam formed as the magma heats groundwater percolate upward through cracks in the Earth and rise from the volcanic vent.

6.12 Earthquake

The shaking of the Earth's surface resulting from a sudden release of **energy**, most of which is a consequence of **plate movement**.

- Before an earthquake, rock bends elastically, like a stick arch in your hands.
- Eventually, the rock break, and sliding suddenly occurs a fault. This break generates vibrations.
- When the vibrations produced, the land surface lurched back and forth and bounced up and down - the ground shaking is called an earthquake.
- Almost 1 million detectable earthquakes happen every year.
- Most cause no damage or causalities, either because they are too small or because they occur in unpopulated areas.
- A few hundred earthquakes per year rattle the ground sufficiently to crack buildings and injure their occupants.
- Every 5 to 20 years, on average, a great earthquake triggers a horrific calamity.

6.12.1 Causes of the Earthquakes

- Seismic activity can result from a variety of geologic and human-induced processing including:
  - Sudden formation of a new fault
  - Sudden slip on an existing fault
  - Phase change in minerals
  - Volcanic activity
  - Giant landslides
  - Meteorite impacts
  - Underground nuclear explosions

6.13 Location of an Earthquake

- Hypocenter (focus):
  - Actual point inside the Earth where an earthquake begins.
  - The spot along the fault where rocks first rupture and start slipping, releasing seismic energy.
- Epicenter:
  - The point directly above the hypocenter, projected up to the Earth's surface.

6.14 Faults and Related Features

- Fault: a fracture or break in the Earth's crust along which rocks or sediments have moved relative to each other.
  - Blind faults: Some faults do not extend to the Earth's surface while they are active.
  - When a fault does intersect the surface, it can offset the ground. This offset creates a fault scarp.
  - Fault line (fault trace): visible line where the fault plane meets the Earth's surface.
- Movement along faults:
  - Miners described fault motion observing the relative movement of the hanging wall compared to the footwall.

6.14.1 Basic Types of Faults

Normal Fault

- Hanging wall moves down relative to footwall.
- Faults form during extension (stretching) of the crust.

Reverse fault (steep) or a thrust fault (shallow)

- Hanging wall moves up relative to footwall.
- Faults form during compression (squeezing or shortening) of the crust.

Strike-slip fault

- Blocks slide past each other horizontally.
- No vertical displacement takes place.

6.14.2 Development of New Faults

- Faults form when tectonic forces add stress (push, pull, or shear) to rock. Think of a block of rock held by clamps:
  - When force is applied, the rock bends slightly at first without breaking.
  - With continued stress, small cracks begin to form inside the rock. These cracks slowly grow and start to connect with each other.
  - Eventually, the connected cracks create a continuous fracture that cut across the entire block of rock.

6.14.3 Foreshocks, Mainshock, Aftershocks

Foreshocks

- Sometimes, smaller earthquakes occur before the mainshock.
- They happen as minor cracks develop.

Mainshock

The largest and most powerful earthquake in a sequence. It usually releases the bulk of accumulated stress along a fault.

Aftershocks

- After the mainshock, a series of small quakes called aftershocks often follow.
- These occur because the fault system doesn't settle into a stable configuration immediately after the main rupture.
- Aftershocks may continue for weeks, months, or even years.

6.14.4 Seismic Waves

- Earthquake energy moves through rock and sediment in the form of vibration, and this movement is called seismic waves, or earthquake waves.
- Different types of seismic waves travel at different velocities.

  P-waves travel by compressing and expanding the material parallel to the wave-travel direction. P-waves are the fastest seismic waves, and they travel through solids, liquids, and gases.

  S-waves travel by moving material back and forth, perpendicular to the wave-travel direction. S-waves are slower than P-waves, and they travel only through solids, never liquids or gases.

  Surface waves travel along Earth's exterior. Surface waves are the slowest and most destructive.

6.14.5 Record of Earthquakes

Sesimographs – instruments that record ground motion.

- A weighted pen on a spring traces movement of the frame.
- Vertical motion is recorded as up-and-down movement; horizontal motion is recorded as back-and-forth motion.

Seismogram – the data record from a seismograph.

- Seismogram depicts earthquake wave behavior, particularly the arrival times of the different waves, which are used to determine the distance to the epicenter.
- Seismic waves arrive at a station in sequence.
  - P-waves are first (fastest).
  - S-waves are second (slower).
  - Surface waves are last.
- Measure the time difference between the arrival of P-waves and S-waves.

- Because P-waves and S-waves travel at different velocities through the Earth, this time gap increases with distance from the epicenter.
- Locating an Earthquake epicenter:
  - Use travel-time curves for P- and S-waves to find out how far away an earthquake occurred.
  - The S–P interval gives the distance from the seismograph station to the epicenter.
  - On a map, draw a circle around each seismograph station with a radius equal to that calculated distance.
  - The point where the circles overlap marks the earthquake's epicenter.

6.14.6 Size of Earthquake

- Seismologists have developed two scales to define size:

Mercalli intensity scale depends on human perception of ground shaking and the damage resulting from it at given locality.

Magnitude scale focuses on the measured amount of ground motion, as recorded by a seismograph at a specified distance from the epicenter.

- Richter scale
- *Moment magnitude scale* – provide the most accuracte representation of an earthquake size (most common).

6.14.7 Where Do Earthquakes Occur?

- Shallow earthquakes happen in the top 60 km of the Earth.
- Intermediate earthquakes take place between 60 and 330 km.
- Deep earthquakes occur down to a depth of $\sim$ 660 km.
- Shallow earthquakes occur at divergent and transform boundaries.
- Intermediate and deep earthquakes occur at convergent boundaries.

6.14.8 Earthquakes at Plate Boundaries

- Divergent boundary (mid-ocean ridges)
  - Two oceanic plates form and move apart.
  - Divergent boundary consists of spreading segments linked by transform faults.
- Two types of faults develop at divergent boundaries:
  - *Normal faults* at the spreading ridge axis;

  - *Strike-slip faults* along the transforms.

- Earthquakes along mid-ocean ridges have foci at depths of less than 25 km, and classified as shallow earthquakes.

- Mid-ocean ridge earthquakes don't cause damage.

Transform-Plate Boundary

- Most are strike-slip faults.

- All transform-fault earthquakes have a shallow focus, so the larger earthquakes on land cause immense damage.

- The San Andreas fault cuts through western California where the Pacific plate shears north and the North American plate south.

- The San Francisco earthquake of 1906 (M_W of 7.9) serves an example of a continental transform-fault earthquake.

Convergent Boundary

- One plate subducts under another, and several different kinds of earthquakes take place (shallow, intermediate, and deep earthquakes):

  Normal faults form where the downgoing slab bends, seaward of trench.

  Large thrust faults occur at the contact between downgoing and overriding plates. Shear on the faults can produce disastrous, shallow earthquakes.

- Convergent boundaries host shallow, intermediate and deep earthquakes.

- The earthquakes occur in downgoing slab as it sinks into the mantle, and a sloping band of seismicity called a *Wadati Benioff zone*.

- Earthquakes are rare below 660 km as the mantle becomes too ductile.

6.14.9 Earthquakes Due to Continental Rifting

- The stretching of continental crust at continental rifts generates normal faults.

- Shallow earthquakes rattle the landscape.

- In contrast to mid-ocean ridge earthquakes, earthquakes in rifts occur on land and can be located under or near populated areas.

- Earthquakes in Africa occur mostly along the East African rift.

6.14.10 Earthquakes Due to Collision

- Two continents collide when the oceanic lithosphere that once separated them has been completely subducted.
- Such collision produce great mountains.
- Earthquakes in Southern Asia occur primarily in crust deforming due to the collision of Eurasia and India.

6.14.11 Intraplate Earthquakes

- Some earthquakes (about 5%) affect the interiors of plates and are not associated with late boundaries, active rifts, or collision zones.
- Intraplate earthquakes are caused by the stress applied to continental lithosphere triggers lip on pre-existing faults in the crust – long-lived weak "scars" in the crust.

6.14.12 Earthquake Waves

Earthquake Waves arrive in a distinct sequence with different motions.

P-waves are first to arrive. They produce a rapid, bucking, up-and-down motion.

S-waves arrive next (second). They produce a pronounced back-and-forth motion. This motion is much stronger than that from P-waves. S-waves cause extensive damage.

Surface waves are delayed traveling along the exterior.

L-waves follow quickly behind the S-waves. They cause the ground to writhe like a snake.

R-waves are the last to arrive. The land surface undulates like ripples across a pond. These waves usually last longer than the other kinds. R-waves cause extensive damage.

6.14.13 Earthquake Damages Due to Vibration

- Building floors "pancake".
- Bridges and roadways topple.
- Bridge support crush.
- Masonry walls break apart.

6.14.14 Earthquake Hazards

Landslides

- A landslide is the downslope tumbling, sliding, or flow of soil, rock or debris under the influence of gravity.
- Strong shaking can destabilize steep slopes or ground made up of loose or weak sediment, causing them to suddenly give way.
- Landslides frequently accompany earthquakes in places with topographic relief (hills, mountains, or steep valleys).

Liquefaction

- During strong shaking, seismic waves increase the pressure of water in the pore spaces of saturated sediments. As pore-water pressure rises, friction between grains is reduced.
- The sediment temporarily loses its strength and behave like a fluid (slurry).
  - Sandy soil can behave like quicksand.
  - Clay-rich soils can transform into quickclay.
- Liquefaction causes soil to lose strength. Land, and the structures on it, will slump and flow. Buildings may founder and topple over intact.

Fire

- Fire is a common result of earthquakes.
- The shaking during an earthquake can tip over lamps, stoves, or candles with open flames, and it may break wires or topple power lines, generating sparks.
- Firefighters are often powerless to combat fire without road access, no water, and too many hot spots.
- Fire may greatly magnify the destruction and tool in human lives.

Tsunamis

- Tsunami means harbor wave in Japanese.
- Tsunamis result from displacement of the sea floor by an earthquake, submarine landslide, or volcanic explosion that displaces the entire volume of overlying water.

6.14.15 Earthquake Prediction

- Can we predict earthquakes? Yes and no.
- We *can* predict in the long term (tens to thousands of years).
- We *cannot* predict in the short term (hours and weeks).
- Hazards can be mapped to assess risk and develop building codes, implement land-use planning, and disaster response.
- Earthquakes have precursors:
  - Clustered foreshocks
  - Crustal strain
  - Level changes in wells
  - Gases (Rn, He) in wells
  - Unusual animal behavior

6.14.16 Preparedness

- Map active faults and areas likely to liquefy from shaking.
- Develop construction codes to reduce building failures.
- Regulate land use to control development in hazard areas.