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Geomorphology Part II

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1. Volcanism

- A volcano is a vent or a fissure in the crust from which lava (molten rock), ash, gases, rock fragments erupt from a magma chamber below the surface.
- Volcanism is the phenomenon of eruption of molten rock, pyroclastics and volcanic gases to the surface through a vent.

1.1 Causes of Volcanism

- There is a **huge temperature difference** between the inner layers and the outer layers of the earth due to the differential amount of radioactivity.
- This temperature difference gives rise to **convectional currents** in the mantle.
- The convection currents in the mantle create convergent and divergent boundaries (weak zones).
- At the divergent boundary, molten, semi-molten and sometimes gaseous material appears on earth at the first available opportunity.
- The earthquakes here may expose fault zones through which magma may escape (**fissure type volcano**).
- At the convergent boundary, the subduction of denser plate creates magma at high pressure which will escape to the surface in the form of violent eruptions.

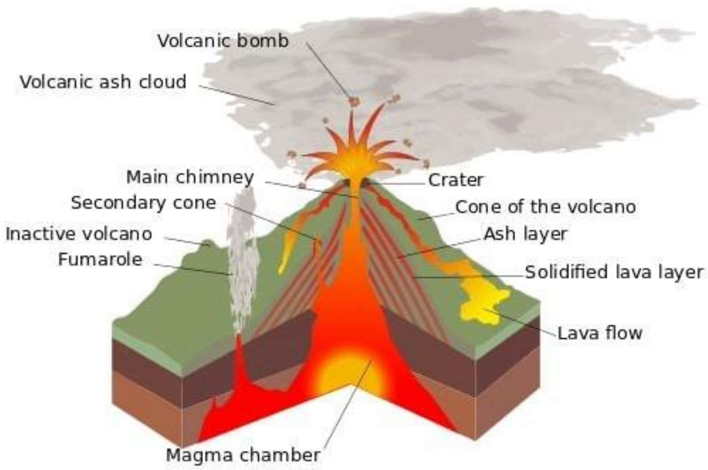
1.2 Lava types

- Magma is composed of molten rock and is stored in the Earth's crust. Lava is magma that reaches the surface through a volcano vent.

Andesitic or Acidic or Composite or Stratovolcanic lava

- These lavas are **highly viscous** with a high melting point.
- They are **light-coloured, of low density, and have a high percentage of silica**.
- They **flow slowly and seldom travel far** before solidifying.
- The resultant volcanic cone is therefore stratified (hence the name **stratovolcano**) and steep-sided.
- The **rapid solidifying of lava** in the vent obstructs the flow of the out-pouring lava, result-

ing in **loud explosions**, throwing out many volcanic **bombs or pyroclasts**.



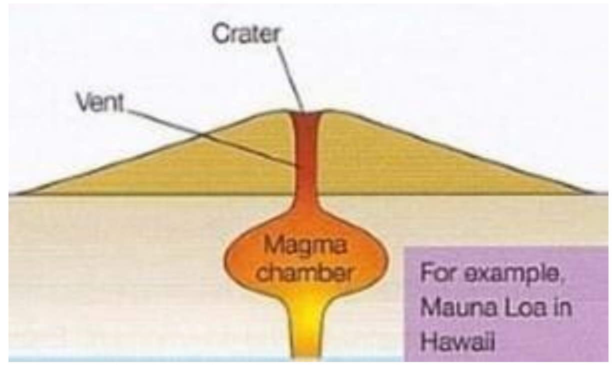
Volcano (Medium69.Cette William Crochot, via Wikimedia Commons)

- Sometimes the lavas are so viscous that they form a **lava plug** at the crater like that of **Mt. Pelée** in Martinique (an island in the Lesser Antilles, Caribbean Islands).
- Andesitic lava flow occurs mostly along the **destructive boundaries** (convergent boundaries).

Lava Plug at the crater

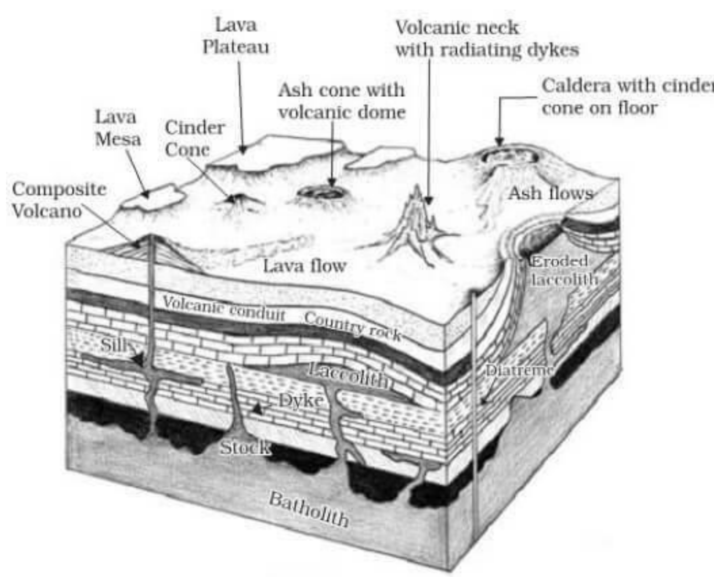
Basic or Basaltic or Shield lava

- These are the **hottest lavas**, about 1,000 °C and are **highly fluid**.
- They are **dark coloured basalt, rich in iron and magnesium but poor in silica**.
- They flow out of volcanic vent **quietly** and are **not very explosive**.
- Due to their **high fluidity**, they flow readily with a speed of 10 to 30 miles per hour.
- They affect extensive areas, spreading out as **thin sheets** over **great distances** before they solidify.
- The resultant volcano is **gently sloping** with a wide diameter and forms a flattened shield or dome.
- Shield type lava flow is common along the **constructive boundaries** (divergent boundary).



1.3 Volcanic Landforms

- Volcanic landforms are divided into **extrusive and intrusive landforms** based on whether magma cools within the crust or above the crust.
- Rocks formed by cooling of magma within the crust are called **Plutonic rocks.**
- Rocks formed by cooling of lava above the surface are called **Igneous rocks**.
- In general, the term 'Igneous rocks' is used to refer all rocks of volcanic origin.



Extrusive and Intrusive volcanic landforms

Extrusive Volcanic Landforms

- Extrusive landforms are formed from material thrown out to the surface during volcanic activity.
- The materials thrown out include lava flows, pyroclastic debris, volcanic bombs, ash, dust and gases such as **nitrogen compounds, sulphur compounds** and minor amounts of **chlorine, hydrogen** and **argon**.

Conical Vent and Fissure Vent

Fissure vent

- A fissure vent (volcanic fissure) is a narrow, linear volcanic vent through which lava erupts, **usually without any explosive activity**.
- The vent is often a few meters wide and may be many kilometres long.
- Fissure vents are common in **basaltic volcanism** (**shield type volcanoes**).

Conical vent

- A conical vent is a narrow cylindrical vent through which magma flows out violently.
- Conical vents are common in **andesitic volcanism** (**composite or stratovolcano**).

Mid-Ocean Ridges

- The system of mid-ocean ridges stretches for more than 70,000 km across all the ocean basins.
- The central portion of the mid-ocean ridges experiences frequent eruptions.
- The lava is **basaltic** (less silica and hence less viscous) and causes the **spreading of the seafloor**.

Composite Type Volcanic Landforms

- They are conical or central type volcanic landforms.
- Along with andesitic lava, large quantities of pyroclastic material and ashes find their way to the surface.
- **Andesitic lava** along with pyroclastic material accumulates in the vicinity of the vent openings leading to the formation of layers, and this makes the mounts appear as a **composite volcano or a stratovolcano** (divided into layers).

- The highest and most common volcanoes have composite cones.
- **Mount Stromboli (the Lighthouse of the Mediterranean)**, Mount Vesuvius, Mount Fuji are examples.

Shield Type Volcanic Landforms

- The **Hawaiian volcanoes** are the most familiar examples.
- These volcanoes are mostly made up of **basaltic lava** (very fluid).
- These volcanoes are not steep.
- They become explosive if somehow water gets into the vent; otherwise, they are less explosive.
- Example: Hawaiian volcanoes **Mauna Loa** (active shield volcano) and **Mauna Kea** (dormant shield volcano).

Fissure Type Flood Basalt Landforms (Lava Plateaus)

- Sometimes, a very thin magma escapes through cracks and fissures in the earth's surface and flows after intervals for a **long time**, **spreading over a vast area**, finally producing a **layered, undulating (wave-like), flat surface**.

- Example: **Siberian Traps**, **Deccan Traps**, **Snake Basin, Icelandic Shield, Canadian Shield**.

Crater

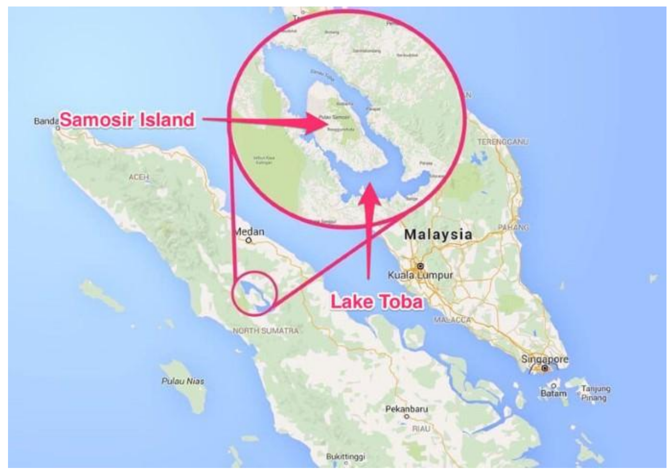
- A crater is an inverted cone-shaped vent through which the magma flows out. When the volcano is not active the crater appears as a bowl-shaped depression.

The crater of Mount Fuji, Japan

- When water from rain or melted snow gets accumulated in the crater, it becomes a **crater lake**.

Caldera

- In some volcanoes, the magma chamber below the surface may be emptied after volcanic eruptions.
- The volcanic material above the chamber **collapses** into the empty magma chamber, and the collapsed surface appears like a large cauldron-like hollow (tub shaped) called the caldera.
- When water from rain or melted snow gets accumulated in the caldera, it becomes a **caldera lake** (in general, the caldera lakes are also called crater lakes).
- Due to their unstable environments, some crater lakes exist only intermittently. Caldera lakes, in contrast, can be quite **large and long-lasting**.
- For example, **Lake Toba (Indonesia)** formed after its supervolcanic eruption around 75,000 years ago. It is the **largest crater lake in the world**.



- Mount Mazama (Cascade Volcanic Arc, USA) collapsed into a caldera, which was filled with water to form Crater Lake (the literal name of the lake formed by the collapse of Mount Mazama is 'Crater Lake'!).

Caldera lake of Mount Mazama

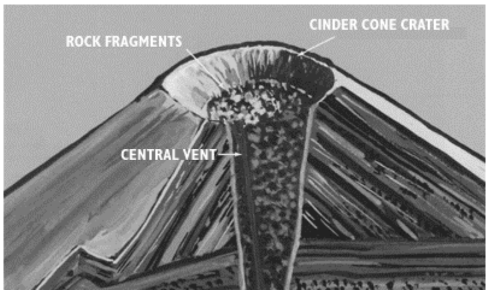
A crater lake, in general, could be of volcanic origin (volcanic crater lake, volcanic caldera lake) or due to a meteorite impact (meteor

crater or impact crater), or in the crater left by an artificial explosion caused by humans.

Lonar Lake, also known as Lonar crater (Lonar, Buldhana district, Maharashtra) was created by a meteor impact during the Pleistocene Epoch.

Cinder cone

- A cinder cone is a **steep circular or oval-shaped hill of loose pyroclastic fragments** that have been built around a volcanic vent.



Lava Dome

- A lava dome (volcanic dome) is a mound-shaped protrusion (a structure that extends outside the surface) resulting from the slow extrusion (coming out) of viscous lava from a volcano.
- In Lava domes, viscous **magma piles up** around the vent.
- The magma does not have enough gas or pressure to escape, although sometime later after sufficient pressure builds up, it may erupt explosively.

Lava dome protruding from a volcanic vent

Pseudo volcanic features

- Pseudo volcanic features are certain topographic features that resemble volcanic forms but are of non-volcanic origin. They include **meteorite crater, salt plugs, and mud-volcanoes**.

Meteorite Craters

- Meteorite craters are impact craters that are formed when a meteorite strikes the surface of the earth creating a huge depression.

Salt plug or salt dome

- A salt plug is formed when underground salt deposits at high pressure become ductile and pierce through the overlying sediments to create a diapir (a dome-like intrusion forced into brittle overlying rocks.
- Salt extrusions may take the form of salt hills which exhibit volcanic crater like features.
- Salt structures are impermeable and can lead to the formation of a **stratigraphic trap** (an impermeable layer capable of retaining hydrocarbons. **Structural traps**, in contrast, are cracks in faults and folds that can retain hydrocarbons).

Mud-volcanoes

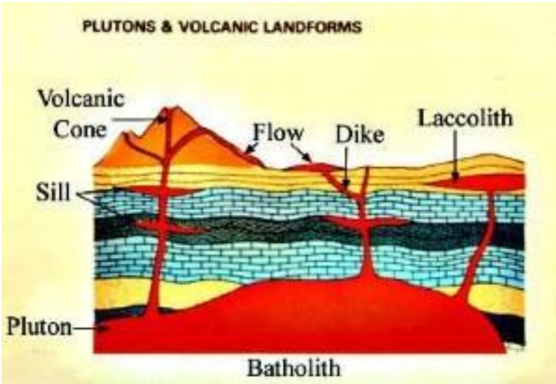
- A mud volcano or mud dome is a landform created by the eruption of mud, water and gases.
- Mud-volcanoes have a similar shape to other types of volcanoes and contains several cones.
- They are usually found near the subduction zones and hot springs.
- Other mud volcanoes, entirely of a **non-volcanic origin**, occur near oil-fields where **methane and other volatile hydrocarbon gases** mixed with mud force their way upward.

Intrusive Volcanic Landforms

- Intrusive landforms are formed when magma cools within the crust.

Batholiths

- These are large **granitic** rock bodies formed due to solidification of hot magma **inside the earth**.
- They appear on the surface only after the denudation processes remove the overlying materials.
- Batholiths **form the core of huge mountains** and may be exposed on the surface after erosion.



Laccoliths

- These are large dome-shaped intrusive bodies connected by a pipe-like conduit from below.
- These are intrusive counterparts of an exposed domelike batholith.
- The **Karnataka plateau** is spotted with dome hills of granite rocks. Most of these, now exfoliated, are examples of laccoliths or batholiths.

Lapolith

- As and when the lava moves upwards, a portion of the same may tend to move in a **horizontal** direction wherever it finds a weak plane. It may get rested in different forms.
- In case it develops into a saucer shape, concave to the sky body, it is called Lapolith.

Phacolith

- A wavy mass of intrusive rocks, at times, is found at the base of synclines or the top of the anticline in folded igneous strata.
- Such wavy materials have a definite conduit to source beneath in the form of magma chambers (subsequently developed as batholiths). These are called the Phacoliths.

Sills

- The near horizontal bodies of the intrusive igneous rocks are called sill. The thinner ones are called sheets.

Dykes

- When the lava makes its way through cracks and the fissures developed in the land, it solidifies almost **perpendicular** to the ground.
- It gets cooled in the same position to develop a **wall-like structure**. Such structures are called dykes.
- These are the most commonly found intrusive forms in the western Maharashtra area.
- These are considered the **feeders for the eruptions** that led to the development of the **Deccan traps**.

1.4 Volcanism Types

- Four types of volcanism can be identified.
  1. **Exhalative (vapour or fumes)**
  2. **Effusive (lava outpouring)**
  3. **Explosive (violent ejection solid material)**
  4. **Subaqueous Volcanism**

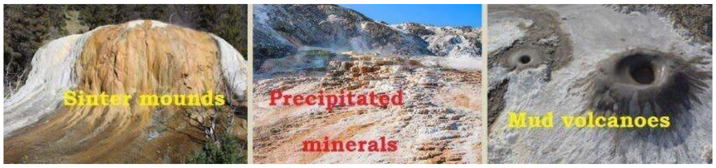
Exhalative (vapour or fumes)

This includes the discharge of material in **gaseous forms**, such as

- ✓ **steam, fumes and**
- ✓ **Hydrochloric acid**
- ✓ **Ammonium chloride**
- ✓ **Sulphur dioxide**
- ✓ **Carbon dioxide**
- ✓ **Carbon monoxide.**
- ✓ **Hydrogen sulphide**
- ✓ **Hydrogen**
- ✓ **Nitrogen**

- These gases may escape through vents which are in the form of **hot springs, geysers, fumaroles and solfataras.**
- This kind of volcanism indicates the volcano is reaching its **extinction**.

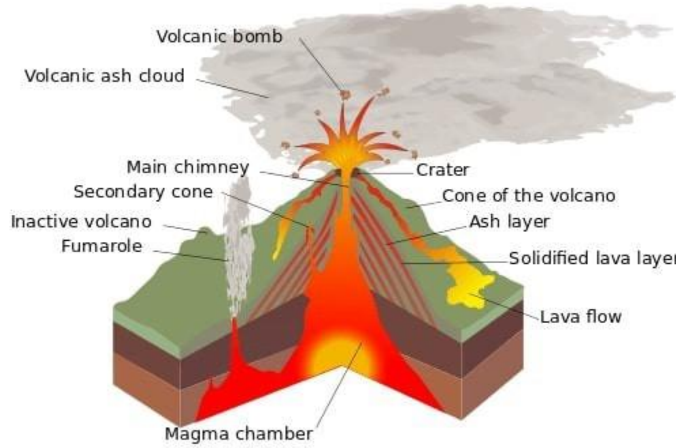
- Associated landforms are called sinter mounds, cones of precipitated minerals and mud volcanoes.



Effusive (Lava outpouring)

- Effusive: relating to or denoting igneous rocks poured out as lava and later solidified.
- This type of activity refers to **abundant outpourings of basaltic lava from a vent or fissure**.
- The **Deccan traps**, which are composed of such lavas today, cover an area of 5,00,000 square km. The original extent of the formation must have been at least 14 lakh square km.
- **Columnar structure** is sometimes developed in fine-grained plateau basalts (Deccan Traps near Mumbai).

Explosive (Violent ejection of solid material)



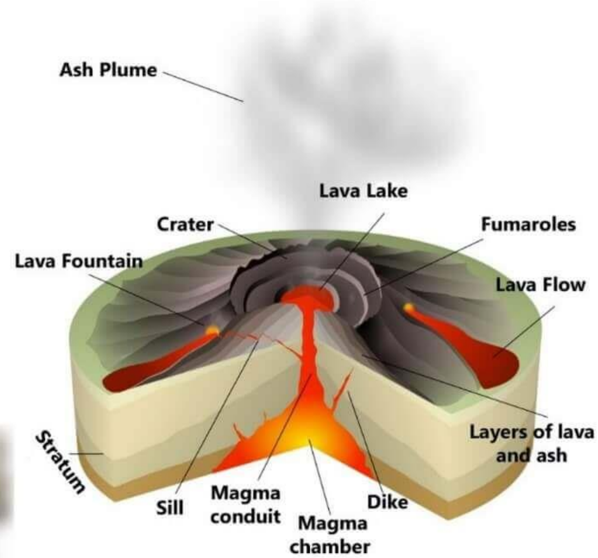
Volcano (William Crochot, via Wikimedia Commons)

- This type of activity results in fragmentation and ejection of solid material through vents.
- Volcanic eject that settles out of air or water is sometimes called pyroclastic sediments.
- **Tephra:** all fragmented ejects from the volcanoes.
- **Ash:** The finest sand-sized tephra
- **Lapilli:** These are gravel-sized particles either in the molten or solid state.
- **Blocks:** Cobble or boulder-sized solid ejecta.
- **Bombs:** a lump of lava thrown out by a volcano.
- **Tuff:** Layers of volcanic dust and ashes.
- Smaller particles like lapilli and ash travel through air for many kilometres.
- The heavier particles like bombs and blocks fall in the vicinity of the vent.

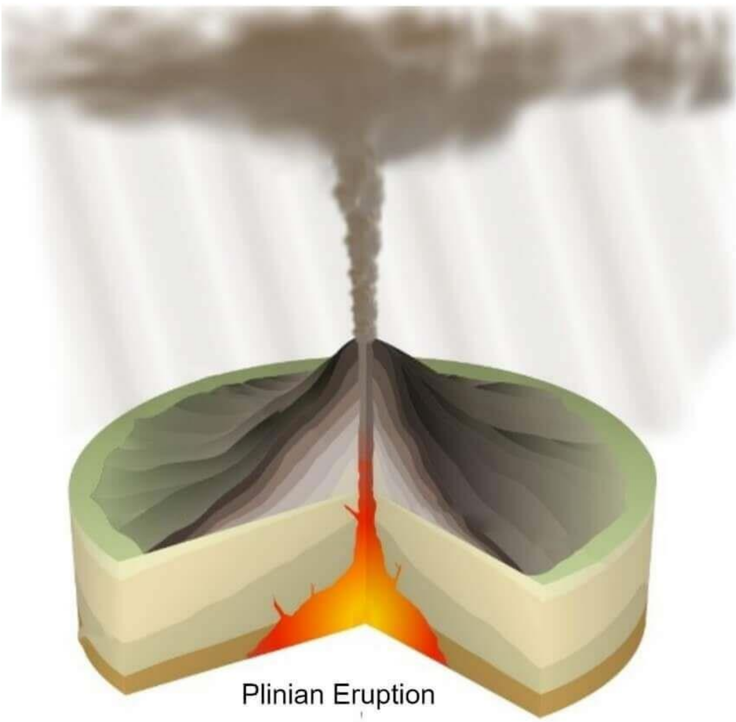
Subaqueous Volcanism

- This type of volcanic activity takes places **below the surface of the water**.
- When lava is in contact with water, it consolidates to produce a structure like that of a heap of pillows.

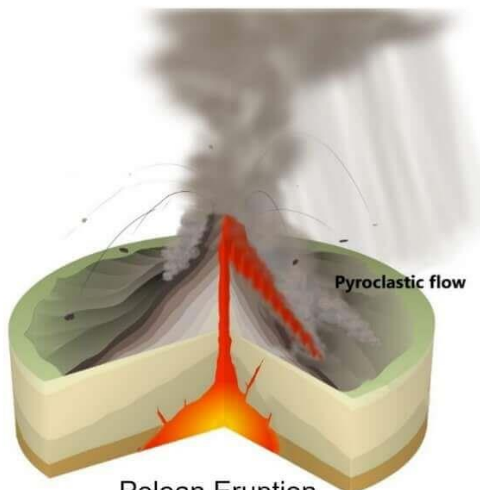
Icelandic Eruption



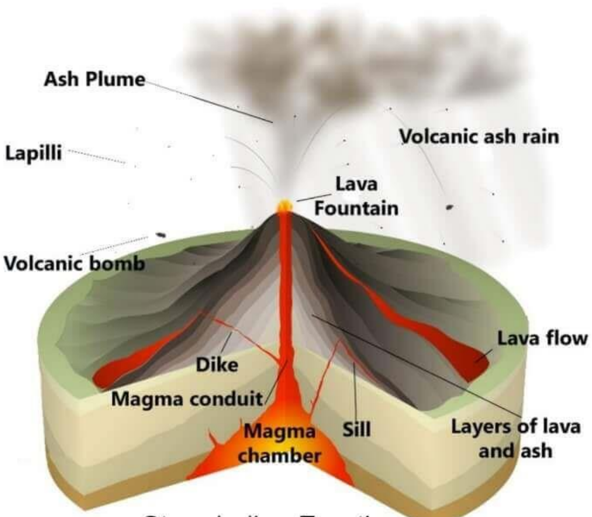
Hawaiian Eruption



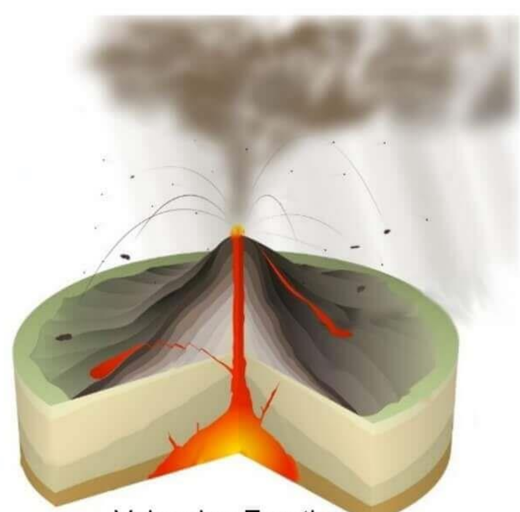
Plinian Eruption



Pelean Eruption



Strombolian Eruption



Vulcanian Eruption

- Highly viscous lavas erupted at lesser depths develop glassy margins on pillows. The related volcanic product is **hyaloclastite**. Most hyaloclastites identified are in Iceland.

1.5 Eruptive Volcanism Types

Hawaiian Eruption

- Hawaiian eruptions are a type of volcanic eruption, named after the Hawaiian volcanoes.
- They are the **calmest types** characterised by the **effusive eruption** of very fluid **basalt-type lavas** from craters, lava lakes, fissures with **little-ejected material** (**low gaseous content)**.
- A single flow spreads widely over open slopes or flows down the valleys as lava rivers.

- Steady production of small amounts of lava builds up the large, broad form of a **shield volcano**.

- Eruptions **are not centralised** at the main summit as with other volcanic types and often occur at vents around the summit and from fissure vents radiating out of the centre.

Icelandic Eruptions

- The Icelandic type is characterized by effusions of molten basaltic lava that flow from long, parallel fissures.
- Such outpourings often build lava plateaus. E.g. **Deccan Traps, Siberian Traps**.

Strombolian Eruption

- Strombolian eruptions are a type of volcanic eruption, named after Stromboli (Lipari Islands, Italy).
- Stromboli Volcano (**lighthouse of the Mediterranean**) has been erupting continuously for centuries.
- Strombolian eruptions are driven by the **continuous formation of large gas bubbles** within the magma.
- Upon reaching the surface, the bubbles burst with a loud pop, throwing magma in the air.
- Because of the high gas pressures associated with the magma, **episodic explosive eruptions** occur (erupts once in every few minutes – fountain like eruption).

Anak Krakatoa

- The greatest volcanic explosion known to humans is perhaps that of Krakatoa (**Plinian**) eruption in 1883.
- The explosion could be heard in Perth, Australia, almost 3,000 miles away.
- More than 36,000 people died, mostly from the tsunamis that followed the explosion.
- At present, Krakatoa (Krakatau or Krakatoa Archipelago) is a group of four small volcanic islands in the **Sunda Strait**, **between Java and Sumatra**.
- Three of the four islands are the remnants of the previous volcanic structure destroyed in 1883 eruption.

- The fourth island, **Anak Krakatau** (meaning Child of Krakatoa) emerged in the 1920s from the caldera formed in 1883. It is the current location of eruptive activity.
- In recent times, Anak Krakatau has become increasingly active with Strombolian type eruptions.

2018 Sunda Strait tsunami

- The eruption of Anak Krakatoa in December 2018 and subsequent collapse of the southwest sector of the volcano, including the summit, triggered the tsunami that has killed more than 400 people.
- While Indonesia possessed a tsunami warning system for tsunamis caused by earthquakes, there were none in place for volcanic tsunamis, and hence there were no early warnings.

Vulcanian Eruption

- In Vulcanian eruptions, intermediate viscous magma within the volcano makes it difficult for gases to escape.
- This leads to the **build-up of high gas pressure**, eventually resulting in an **explosive eruption**.
- They are also more explosive than their Strombolian counterparts, with eruptive columns often reaching between 5 and 10 km high.
- The molten lava is explosively ejected as a great cauliflower cloud of dark tephra. Bombs, blocks, lapilli and other ejecta fall in the surrounding area.
- After each eruption cycle, **the volcano is dormant for decades or centuries**.

Plinian Eruption

- Plinian eruptions (or **Vesuvian**) are a type of volcanic eruption, named after the historical eruption of **Mount Vesuvius** in 79 AD that buried the Roman town of Pompeii.
- In Plinian eruptions, dissolved volatile gases stored in the magma are channelled to the top through a narrow conduit (pipe-like structure).
- The gases erupt into a **massive column** of the gas plume that reaches up **2 to 45 km into the atmosphere**.
- As it reaches higher the plume expands and becomes less dense and convection and thermal expansion of volcanic ash drive it even further up into the stratosphere.
- At the top of the plume, powerful prevailing winds drive the plume in a direction away from the volcano.

Mount Vesuvius

- Mount Vesuvius is a stratovolcano in Bay of Naples, Italy.
- It is best known for its **Plinian type** eruption in AD 79 that led to the destruction of the Roman cities of Pompeii, Herculaneum and others. More than 1,000 people died in the eruption.
- The eruption ejected a cloud of stones, ashes and volcanic gases to a height of more than 30 km.
- Vesuvius has erupted many times since. Today, it is regarded as **one of the most dangerous volcanoes** in the world because of the population of 3,000,000 people living nearby.
- The eruptions alternated between Plinian and Peléan with most of them being Plinian type.

Mount St. Helens

- Mount St. Helens is an **active** volcano located in the Cascade Volcanic Arc.

- Mount St. Helens is most notorious for its major 1980 Plinian type eruption that killed more than 50 people.

Mount Tambora

- Mount Tambora is an active volcano located in Lesser Sunda Islands of Indonesia.

Mount Tambora (Google Maps)

- Tambora is known for its major Plinian type eruption in 1815.
- The 1815 eruption was one of the most powerful in recorded history, with a Volcanic Explosivity Index (VEI) of 7.
- The ash from the eruption column dispersed around the world and **lowered global temperatures**, in an event sometimes known as the **Year Without a Summer** in 1816.
- More than 71,000 people died due to **famines** caused in Europe and America.

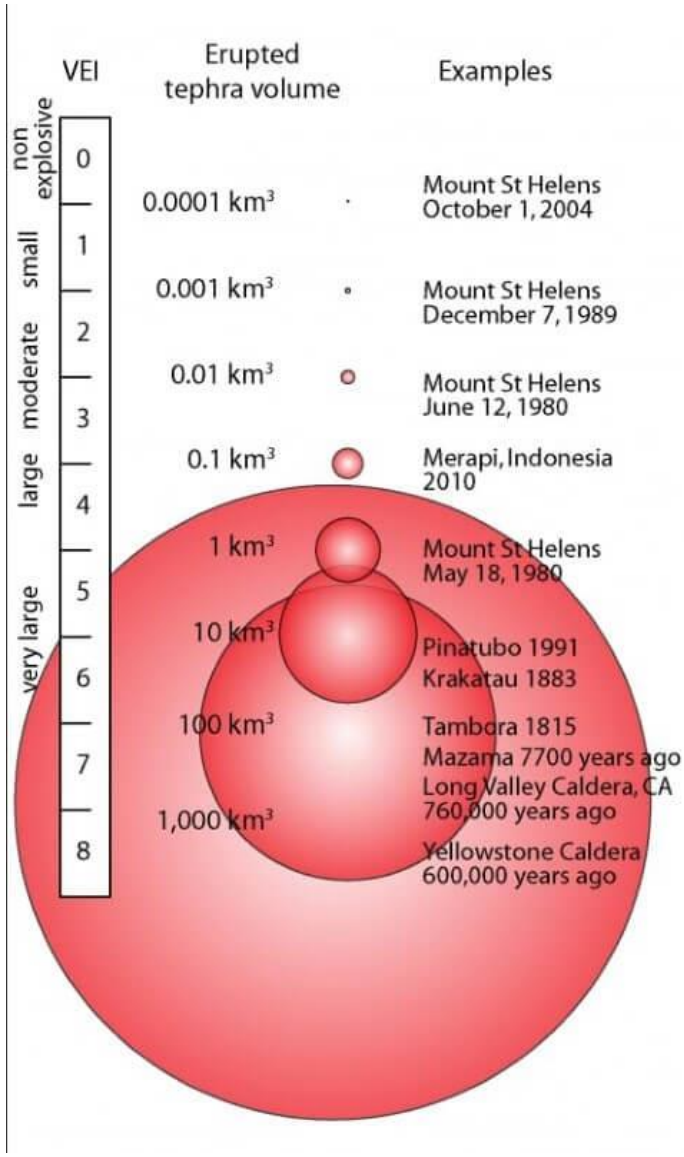
Nevado del Ruiz

- Nevado del Ruiz is a volcano located in Colombia.
- The volcano usually generates Vulcanian to Plinian eruptions, which produce **destructive lahars**.
- In 1985, a small eruption produced an enormous lahar that buried and destroyed the towns causing an estimated 25,000 deaths.

Lahar

- A lahar is a **violent type of mudflow or debris flow** composed of a slurry of pyroclastic material, rocky debris and water. The material flows down from a volcano, typically along a river valley.
- Lahars are extremely destructive as they flow fast and can engulf entire settlements in a matter of minutes.

Lahar



Volcanic Explosivity Index (USGS)

Mount Pinatubo

- Mount Pinatubo is an active volcano located in the Luzon island of the Philippines.

- Pinatubo Plinian type eruption in 1991 brought about **dramatic changes in the global environment**.
- The amount of sulfuric ash it sent into the **stratosphere** cooled global ground temperatures by 1°C for the next two years, and **ozone depletion** temporarily increased substantially.
- The eruption resulted in more than 700 deaths.

Pelean Eruption

- Peléan eruptions are a type of volcanic eruption, named after the volcano **Mount Pelée in Martinique**.
- In Peléan eruptions, a large amount of gas, dust, ash, and lava fragments are blown out **laterally** by the **collapse of the cinder cone**. The sudden burst of lava dome causes the collapse of the cinder cone.
- This type of eruption results in very viscous, gas-rich, acidic lava **breaking out laterally and flowing out violently** at high speed causing massive destruction on its path.
- Hot gas and lava mixture are not carried skyward to become cold tephra but spreads downslope as a **nuce ardente**, continuing to **cushion** the flowing fragments.

Pelean Eruption

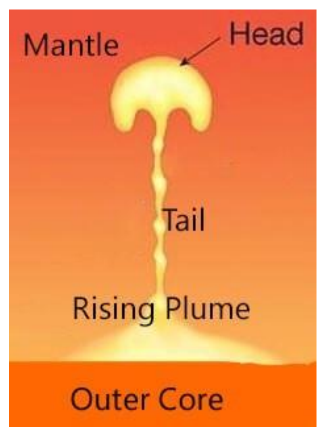
Mount Pelée

- Mount Pelée is a volcano at the northern end of Martinique Island (French overseas department in the Lesser Antilles island arc of the Caribbean).
- The volcano is famous for its Pelean type eruption in 1902 that killed about 30,000 people.
- Most deaths were caused by pyroclastic flows which destroyed the city of Saint-Pierre.

1.6 Hotspot Volcanism

- Hotspot volcanism is a type of volcanism that typically occurs at the **interior parts of the lithospheric plates** rather than at the zones of convergence and divergence (plate margins).
- The **Iceland Hotspot** and **Afar Hotspot** which are situated at the divergent boundary are exceptions.
- Hotspot volcanism explains the so-called **anomalous volcanism** — the type that occurs far from plate boundaries, like in Hawaii and Yellowstone, or in excessive amounts along mid-ocean ridges, as in Iceland.
- Well known hotspots include the **Hawaiian Hotspot, the Yellowstone Hotspot, the Reunion Hotspot**.
- Hotspot volcanism occurs due to abnormally hot centres in the mantle known as **mantle plumes**.
- Most of the mantle plumes lie far from tectonic plate boundaries (e.g. Hawaiian Hotspot), while others represent unusually large-volume volcanism near plate boundaries (e.g. Iceland Hotspot).

Mantle Plumes

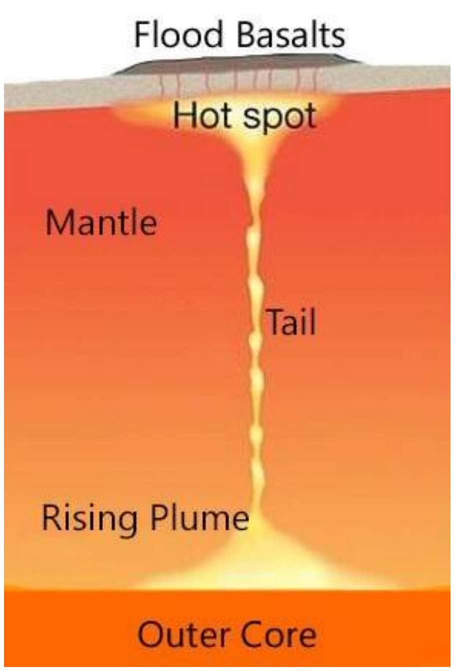


- A mantle plume is **convection of abnormally hot rock** (magma) within the Earth's mantle.
- Unlike the larger convection cells in the mantle which change their position over geological timescales, the position of the mantle plumes seems to be relatively **fixed**.

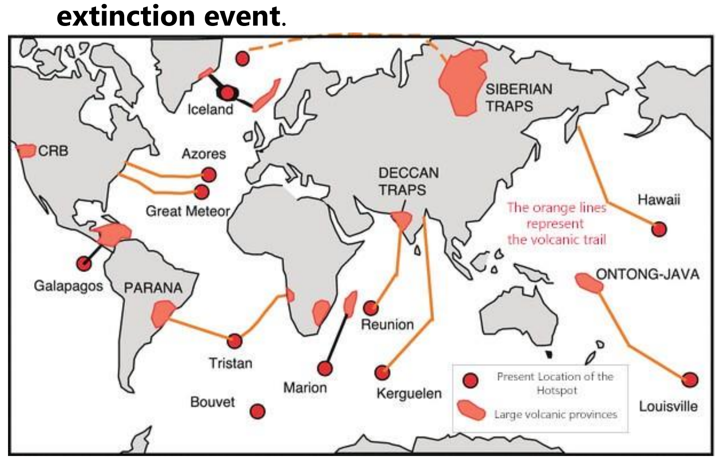
- Mantle plumes are theorised to form at the **core-mantle boundary** where an abnormally hot plume of rock accumulates.
- The mantle plume is shaped like a mushroom with a long conduit (tail) connecting the bulbous head to its base. The head expands in size as the plume rises.
- The plume rises through the Earth's mantle becoming a diapir (dome-like intrusion forced into brittle overlying rocks) in the upper mantle (lower parts of the lithosphere).

Mantle plumes and flood basalt volcanism (large igneous provinces)

- On the continents, mantle plumes have been responsible for **extensive accumulations of flood basalts**.
- Mantle plumes (few hundred kilometres in diameter) and rise slowly towards the upper mantle.
- When a plume head encounters the base of the lithosphere, it flattens out and undergoes widespread decompression melting to form **large volumes of basalt magma**.
- The basaltic magma may then erupt onto the surface through a series of fissures giving rise to **large igneous provinces**. When created, these regions often occupy several thousand square kilometres.



- Large igneous provinces, such as **Iceland, Siberian Traps, Deccan Traps, and Ontong Java Plateau**, are extensive regions of basalts on a continental scale resulting from flood basalt eruptions.
- Very large amounts of volcanic material in large igneous provinces can cover huge areas with lava and volcanic ash, causing **long-lasting climate change** (such as the triggering of a small ice age).
- The **Réunion hotspot** (produced the **Deccan Traps about 66 million years ago**) coincides with the Cretaceous–Paleogene extinction event (also known as Cretaceous-Tertiary (K-T) extinction or — fifth and the most recent mass extinction).
- Though a meteor impact (**Chicxulub Crater**) was the cause of the extinction event, the volcanic activity may have caused environmental stresses.
- Additionally, the largest flood basalt event (the **Siberian Traps**) occurred around 250 million years ago and was coincident with the largest mass extinction in history, the **Permian–Triassic extinction event**.

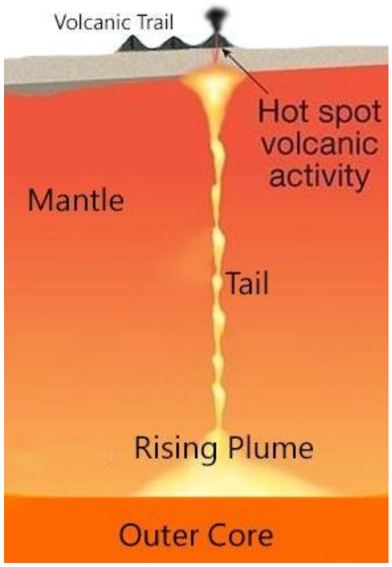


Large Igneous Provinces (Credits: [Gautam Sen](#))

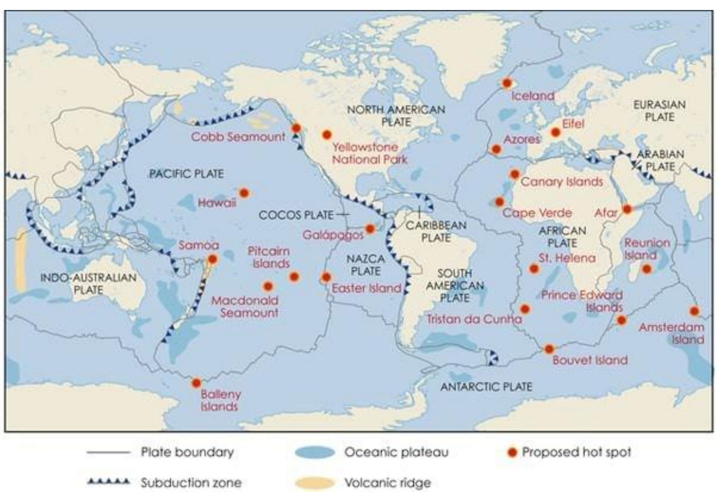
Mantle plumes and volcanic hotspots

- The mantle plume provides a continuous supply of **abnormally hot magma** to a **fixed location** in the mantle referred to as a **hotspot**.
- The abnormally high heat of the hotspot facilitates the **melting of rock at the base of the lithosphere**.
- The melted rock, known as magma, which is at high pressure, often pushes through cracks in

the crust to form hotspot volcanoes (e.g. Mount Mauna Kea).



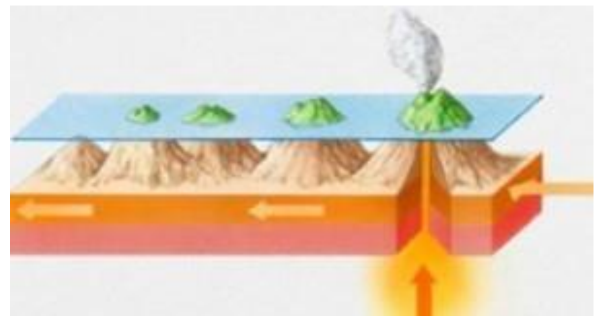
Distribution of hotspots

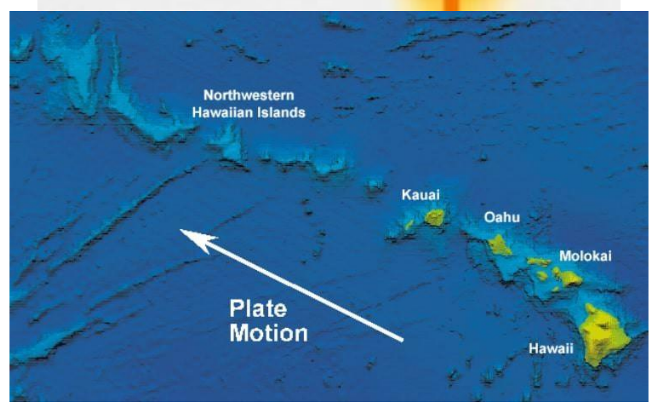


Distribution of hotspots (Credits: K. Cantner, Earth Magazine)

Hotspot volcano chain

- A volcano above a hotspot does not erupt forever. Attached to the tectonic plate below, the volcano moves and is eventually cut off from the hotspot (**plate moves overhead relative to the fixed plume source**).
- Without any source of heat, the volcano becomes extinct and cools. This cooling causes the rock of the volcano and the tectonic plate to become denser. Over time, the dense rock **sinks and erodes**.
- A new and active volcano develops over the hotspot creating a continuous cycle of volcanism, forming a **volcanic arc** that parallels plate motion.
- The Hawaiian Islands chain in the Pacific Ocean is the best example. The islands and seamounts (submarine mountains) exhibit **age progression**, with the youngest near present-day Hawaii and the oldest near the **Aleutian Trench**.



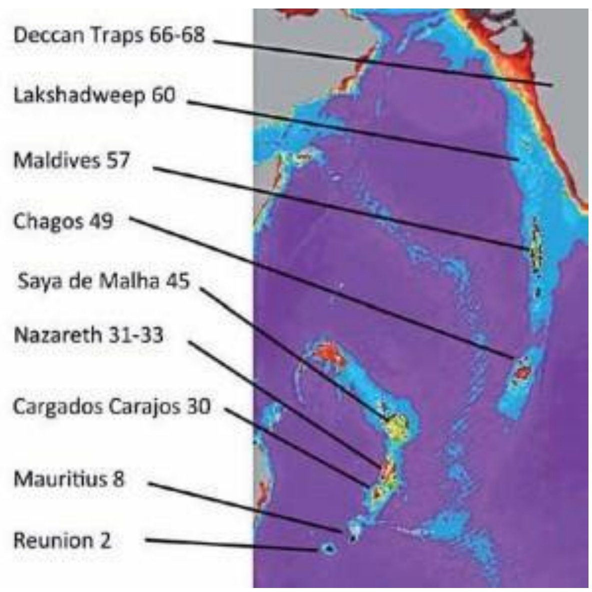


- Other hotspots with time-progressive volcanic chains behind them include **Réunion, the Chagos-Laccadive Ridge, the Louisville Ridge, the Yellowstone**.
- Some hotspots lack time-progressive volcanic trails, e.g., **Iceland, the Galapagos, the Azores, the Canaries**.

Reunion Hotspot

- The Reunion hotspot is a volcanic hotspot which currently lies under the **Island of Reunion in the Indian Ocean**. The hotspot is believed to have been active for over 66 million years.
- A huge eruption of this hotspot 66 million years ago is thought to have laid down the **Deccan Traps** and opened a rift which separated India from the Seychelles Plateau.
- As the Indian plate drifted north, the hotspot continued to punch through the plate, creating a string of volcanic islands and undersea plateaus.

- The **Chagos-Laccadive Ridge (Lakshadweep is a part of this ridge)** and the southern part of the **Mascarene Plateau** are volcanic traces of the Reunion hotspot.
- The **Laccadive Islands, the Maldives, and the Chagos Archipelago** are **atolls** resting on former volcanoes created 60-45 million years ago that subsequently submerged below sea level.
- About 45 million years ago the mid-ocean rift crossed over the hotspot, and the hotspot passed under the African Plate.
- The hotspot appears to have been relatively quiet from 45-10 million years ago, when activity resumed, creating the **Mascarene Islands, which include Mauritius, Reunion, and Rodrigues**.



Mantle plumes and divergence (plate tectonics)

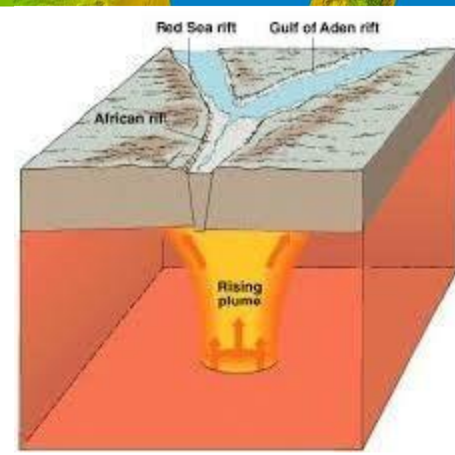
Mains 2018: What is a mantle plume and what role it plays in plate tectonics?

Backdrop: In early 2018, a large crack made a sudden appearance in south-western Kenya adding fuel to the debate on the breakup of Africa.

Also, the Yellowstone supervolcano has evoked a lot of interest in recent times (The Yellowstone supervolcano is a disaster waiting to happen).

- Mantle plumes are convection currents on a small scale (in comparison to major convection currents in the mantle).
- The plume rises through the centre and diverges in all directions just below the lithospheric plates.
- The divergence of the plume exerts extensional stress (tensile stress) on the lithospheric plate above and causes the plate to stretch and rupture and then diverge to form a **rift** in between.
- **Afar hotspot** in Africa got ruptured due to the mantle plume below. At the **Afar triple junction**, the Arabian, African, and Somali plates are moving away from the centre.

Afar Triple Junction: The Afar Triple Junction is located along a divergent plate boundary dividing the Nubian, Somalian, and Arabian plates. Here, the Red Sea Rift meets the Aden Ridge and the East African Rift.



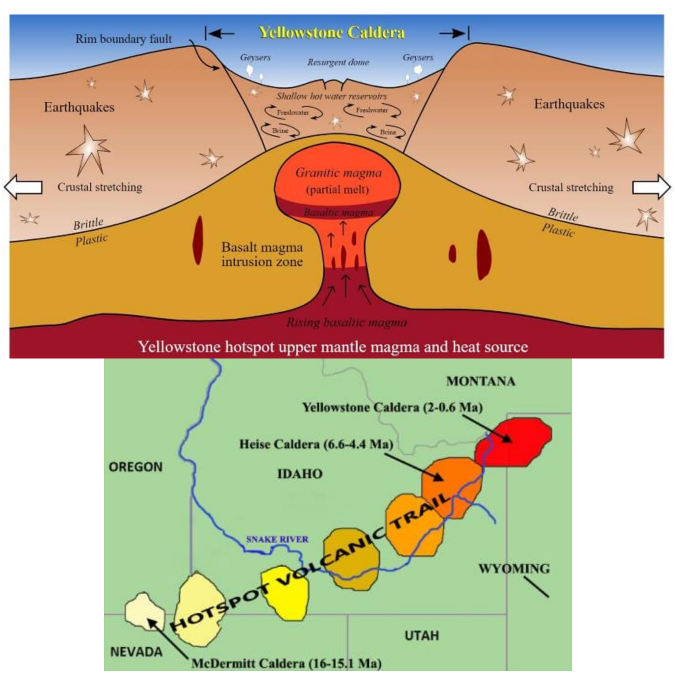
Mantle plumes and uplifted landforms (epeirogenic movements)

- As the plume reaches the lithosphere, it spreads out laterally doming zones of the Earth. E.g. The Ethiopian Highlands.
- The **Ethiopian Highlands** began before the beginning of the Tertiary Period (66 mya), as the mantle plume below uplifted a broad dome of the ancient rocks of the Arabian-Nubian Shield.
- Around 30 million years ago, a flood basalt plateau began to form, piling layers upon layers of voluminous fissure-fed basaltic lava flows.
- The opening of the Great Rift Valley split the dome of the Ethiopian Highlands into three parts — two parts to the east and west of the rift and the third part consist of the mountains of the southern Arabian Peninsula (geologically a part of the ancient Ethiopian Highlands, now separated by the rifting).

Mantle plumes and thinning of the continental crust

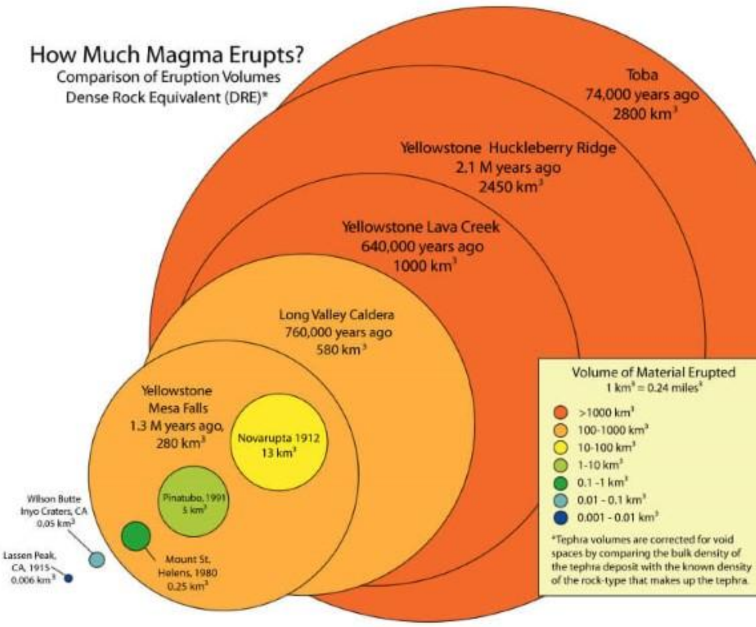
- The Yellowstone hotspot is an example for a **hotspot developed beneath a continent**.
- Here the mantle plume has been **thinning the part of America's crust** (divergence of the plume exerts extensional stress on the lithospheric plate) above and is likely to thin the whole of the surface opening the door for the underlying **supervolcano**.

Mantle plumes and Supervolcanoes



Yellowstone hotspot volcanic trail

- A supervolcano is a large volcano in which the volume of magma deposits that can erupt to the surface is greater than 1,000 cubic kilometres.
- Supervolcanoes occur when a large volume of magma accumulates under the lithospheric plate but is unable to break through it.
- Over time (thousands of years), the pressure keeps building up until the plate can no longer contain the pressure, resulting in an eruption.
- This can occur at **hotspots (for example, Yellowstone Caldera)** or **subduction zones (for example, Toba Caldera Lake**, Sumatra Island, Indonesia).



- A supervolcanic super-eruption can cause a **small-scale or regional extinction event**.
- The ash from such a volcano can engulf the entire counties and major portions of the continent in which they occur.
- The gas and dust ejected from the volcano can blanket the earth's troposphere for months or years to come causing **severe climate change**.
- There were more than 40 super-eruptions in earth's history, and the most recent occurred in New Zealand's **Lake Taupo** (Taupo supervolcano) some 26,000 years ago.
- The Oruanui eruption of the Taupo Volcano was the world's largest known eruption in the past

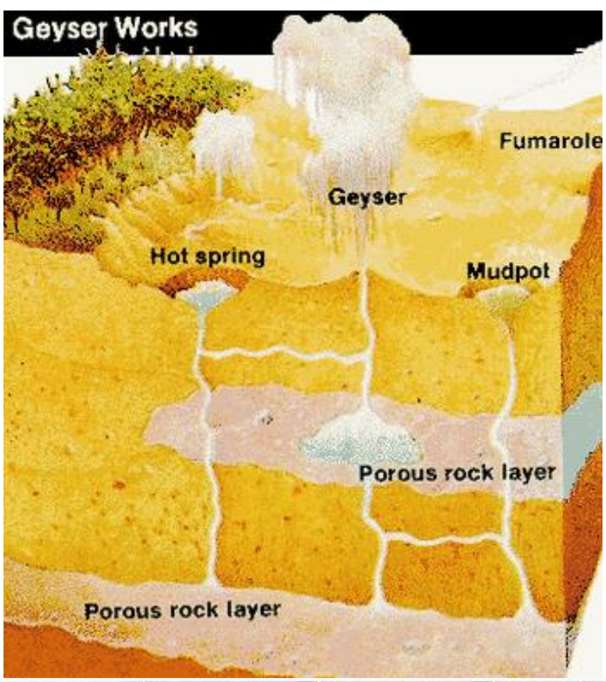
70,000 years, with a Volcanic Explosivity Index of 8.

- The Toba eruption (Indonesia) 74,000 years ago, caused by shifting tectonic plates triggered a dramatic global winter.

1.7 Geysers and Hot Springs

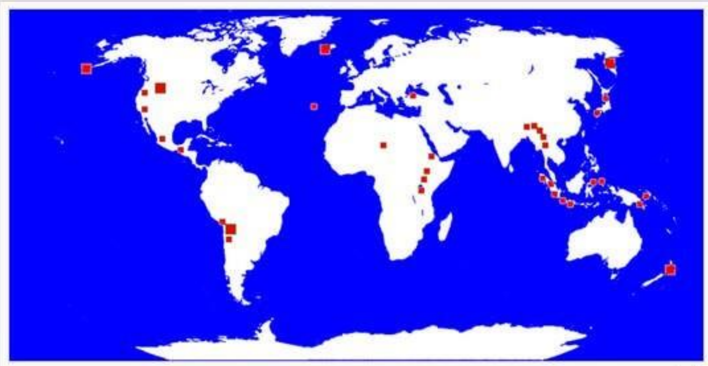
- Water that percolated into the porous rock is subjected to intense heat by the underlying hard rock which is in contact with hot magma in the mantle or the lower part of the crust.
- Under the influence of intense heat, the water in the capillaries and narrow roots in the porous rock undergoes intense expansion and gets converted to steam resulting in high pressure.
- When this steam or water at high pressure finds a path to the surface through narrow vents and weak zones, appear at the surface as geysers and hot water springs.

Geyser	Hot water spring
Steam or water at high pressure, along its path, gets accumulated in small reservoirs, fissures and fractures. Once the pressure exceeds the threshold limit, the steam bursts out to the surface disrupting the water at the mouth. Hence the name geyser.	Steam or water at high pressure smoothly flows to the top through the vent and condense at the surface giving rise to a spring.
Silicate deposits at mouth give them their distinct colours.	Some springs are very colourful because of the presence of **cyanobacteria** of different colours.
Generally, geysers are located near active volcanic areas. **Iceland** is famous for its geysers.	Found all across the world
Usually, a carter like structure is created at the mouth.	



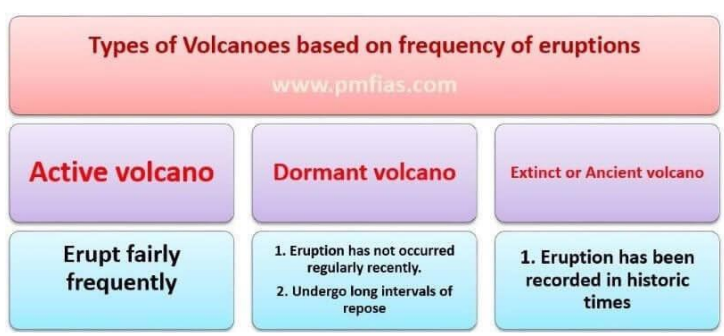
1. Steam rises from heated water | 2. Pulses of water swell upward | 3. Surface is broken | 4. Ejected water spouts upward and falls back down into the pipe

- Almost all the world's geysers are confined to three major areas: **Iceland, New Zealand and Yellowstone Park of U.S.A**.



Distribution of major geysers in the world.

1.8 Extinct, Dormant and Active volcanoes

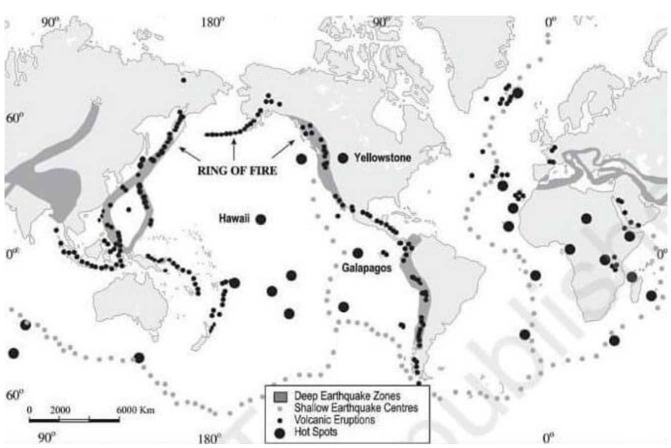


- **Barren Island in the Andaman and Nicobar Islands**, Anak Krakatoa are active volcanoes

- **Mount Kilimanjaro** (it has three volcanic cones), is a **dormant** stratovolcano in Tanzania.
- **Mount Kenya** is an extinct stratovolcano.
- The **Barren Island in the Andaman and Nicobar Islands** of India which was thought to be extinct erupted recently.
- Before a volcano becomes extinct, it passes through a **waning stage** during which steam and other hot gases and vapours are exhaled. These are known as **fumaroles or solfataras.**

1.9 Distribution of Earthquakes and Volcanoes across the World

- Most known volcanic activity and the earthquakes occur **along converging plate margins and mid-oceanic ridges**.
- It is said that nearly 70 per cent of earthquakes occur in the Circum-Pacific belt.
- Another 20 per cent of earthquakes take place in the Mediterranean-Himalayan belt including Asia Minor, the Himalayas and parts of northwest China.
- Since the 16th century, around 480 volcanoes have been reported to be active.
- Of these, nearly 400 are located in and around the Pacific Ocean, and 80 are in the mid-world belt across the Mediterranean Sea, Alpine-Himalayan belt and in the Atlantic and Indian Oceans.
- The belts of highest concentration are **Aleutian-Kurile islands** arc, **Melanesia** and **New Zealand-Tonga belt**.
- Only 10 per cent to 20 per cent of all volcanic activity is above the sea, and terrestrial volcanic mountains are small when compared to their submarine counterparts.



Pacific Ring of Fire

- Circum-Pacific region popularly termed the **'Pacific Ring of Fire'**, has the greatest concentration of active volcanoes. Volcanic belt and earthquake belt closely overlap along the 'Pacific Ring of Fire'.

Regions with active volcanism along 'Pacific Ring of Fire'

- The Aleutian Islands into Kamchatka, Japan,
- the Philippines, and Indonesia (Java and Sumatra in particular),
- Pacific islands of Solomon, New Hebrides, Tonga and North Island, New Zealand.
- Andes to Central America (particularly Guatemala, Costa Rica and Nicaragua), Mexico and right up to Alaska.

The 5 countries with the most volcanoes (Source)

1. United States – 173 (most of them are in Alaska)
2. Russia - 166
3. Indonesia - 139
4. Iceland - 130
5. Japan – 112

Other regions

Along the Atlantic coast

- In contrast, the Atlantic coasts have comparatively few active volcanoes but many dormant or extinct volcanoes, e.g. St. Helena, Cape Verde Islands and the Canary Islands etc.
- But the volcanoes of **Iceland** and the **Azores** are active.

Great Rift region

- In Africa, some volcanoes are found along the East African Rift Valley, e.g. **Mt. Kilimanjaro** and **Mt. Kenya**.

The West Indian islands

- The Lesser Antilles (Part of West Indies Islands) are made up mainly of volcanic islands, and some of them still bear signs of volcanic liveliness.

Mediterranean volcanism

- Volcanoes of the Mediterranean region are mainly associated with the Alpine folds, e.g. **Vesuvius**, **Stromboli (Light House of the Mediterranean)** and those of the Aegean islands.
- A few continue into Asia Minor (Mt. Ararat, Mt. Elbruz).
- The volcanism of this broad region is largely the result of convergence between the Eurasian Plate and the northward-moving African Plate.
- This type of volcanism is mainly due to **breaking up of the Mediterranean plate** into multiple plates due to the interaction of African and Eurasian plate

Volcanos in India

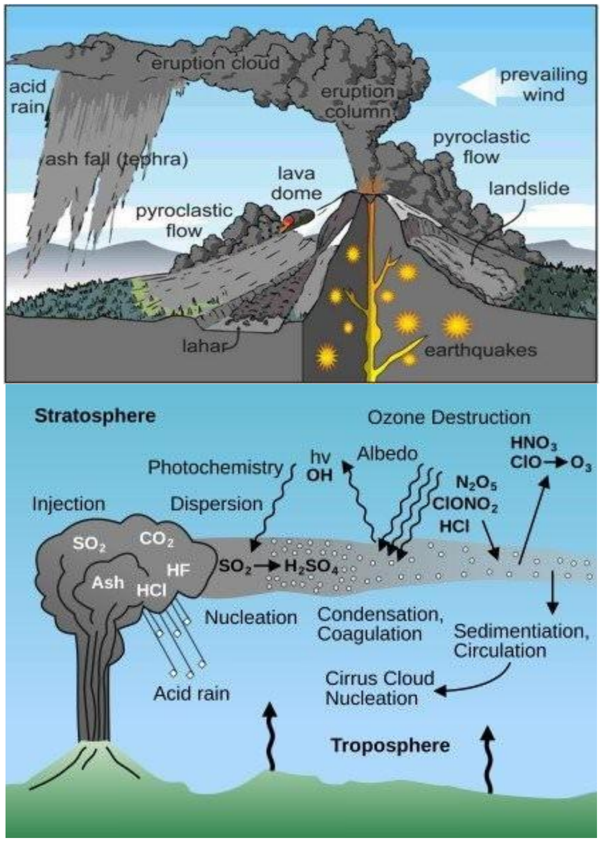
- There are **no volcanoes in the Himalayan region** or the Indian peninsula.
- **Barren Island** (**only active volcano in India**) in the Andaman and Nicobar Islands became active in the 1990s.
- It is now considered an active volcano after it spewed lava and ash in 2017.
- The other volcanic island in Indian territory is **Narcondam**, about 150 km north-east of Barren Island; it is **probably extinct**. Its crater wall has been destroyed.

1.10 Destructive Effects of Volcanoes

- Showers of cinders and bombs can cause damage to life. E.g. the eruption of **Mount Vesuvius** in 79 AD.
- Tsunamis can be generated in large water bodies due to violent eruptions. E.g. 1883 Krakatoa eruption.
- The collapse of the volcanic landforms in seas and oceans cause tsunamis. E.g. 2018 Sunda Strait tsunami.
- The ash from a larger eruption dispersing over a large area can lower temperatures at a regional or global scale. This could trigger famines on a large scale. E.g. 1815 eruption of Mount Tambora.
- In Hawaiian type eruption, a single flow spreads widely over open slopes or down the valleys as lava rivers engulfing entire cities.
- Lahars (a violent type of mudflow or debris flow) can bury entire cities in a matter of minutes causing a high number of causalities. E.g. 1985 eruption of Nevado del Ruiz volcano.
- The sudden collapse of lava domes can cause violent volcanic flows that destroy everything on their path. E.g. the 1902 eruption of Mount Pelée.
- Powerful winds drive the gas plume higher into the atmosphere and carry it to a greater distance disrupting air travel (this happened in 2010 when a stratovolcano in Iceland erupted and disrupted air travel over entire Europe for weeks).
- A supervolcanic super-eruption can cause a small-scale extinction event. E.g. The Toba eruption (Indonesia) triggered a dramatic global winter 74,000 years ago.

Volcanism – Acid Rain, Ozone Destruction

- The volcanic gases that pose the greatest potential hazard to people, animals, agriculture, and property are **sulphur dioxide, carbon dioxide, and hydrogen fluoride**.
- Locally, sulphur dioxide gas can lead to acid rain and air pollution downwind from a volcano.
- Globally, large explosive eruptions that inject a tremendous volume of sulphur aerosols into the stratosphere can lead to lower surface temperatures and **promote depletion of the Earth's ozone layer**.



1.11 Positive Effects of Volcanoes

- Volcanism creates new fertile landforms like islands, plateaus, volcanic mountains etc. E.g. Deccan traps.
- The volcanic ash and dust are **very fertile** for farms and orchards.
- Volcanic rocks yield very fertile soil upon weathering and decomposition.
- Although steep volcano slopes prevent extensive agriculture, forestry operations on them provide valuable timber resources.
- Mineral resources, particularly metallic ores are brought to the surface by volcanoes. Sometimes copper and other ores fill the gas-bubble cavities.
- The famed Kimberlite rock of South Africa, the source of diamonds, is the pipe of an ancient volcano.
- In the vicinity of active volcanoes, waters in depth are heated from contact with hot magma giving rise to **springs and geysers**.
- The heat from the earth's interior in areas of volcanic activity is used to generate **geothermal electricity**. Countries producing geothermal power include USA, Russia, Japan, Italy, New Zealand and Mexico.
- The **Puga valley in Ladakh** region and **Manikaran (Himachal Pradesh)** are promising spots in India for the generation of geothermal electricity.
- Geothermal potential can also be used for space heating.
- As scenic features of great beauty, attracting a heavy tourist trade, few landforms outrank volcanoes.
- At several places, national parks have been set up, centred around volcanoes. E.g. Yellowstone National Park.
- As a source of crushed rock for concrete aggregate or railroad ballast and other engineering purposes, lava rock is often extensively used.

1.12 Rocks

- Rock is an aggregate of one or more minerals held together by chemical bonds.
- **Feldspar** and **quartz** are the most common minerals found in rocks.
- The scientific study of rocks is called **petrology**.
- Based on the mode of formation three major groups of rocks are defined: igneous, sedimentary, and metamorphic.
- **Igneous Rocks** — solidified from magma and lava.
- **Sedimentary Rocks** — the result of deposition of fragments of rocks.
- **Metamorphic Rocks** — formed out of existing rocks undergoing recrystallisation.

Igneous Rocks or Primary rocks

- The solidification of magma formed the first rocks on earth.
- Rocks formed out of solidification of magma (molten rock below the surface) and lava (molten rock above the surface) and are known as **igneous or primary rocks**.
- Having their origin under conditions of high temperatures the igneous rocks are **unfossiliferous**.
- **Granite, gabbro, basalt,** are some of the examples of igneous rocks.

- There are three types of igneous rocks based on place and time taken in cooling of the molten matter, **plutonic rocks, volcanic rocks** and **intermediate rocks**.
- There are two types of rocks based on the presence of acid-forming radical, silicon, **acidic rocks** and **basic rocks.**

Intrusive igneous rocks (Plutonic rocks)

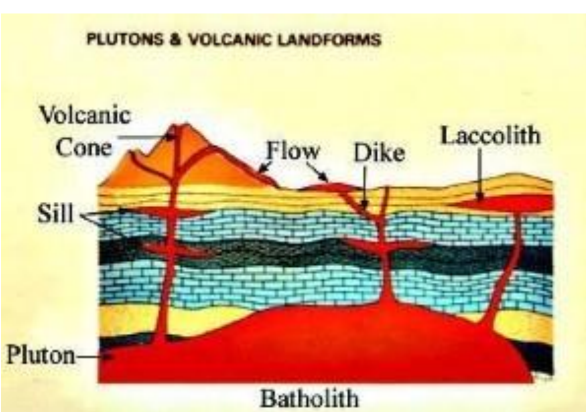
- If magma cools slowly at great depths, mineral grains formed in the rocks may be **very large**.
- Such rocks are called **intrusive rocks or plutonic rocks (e.g. Granite).**
- These rocks appear on the surface only after being uplifted and denuded.

Extrusive igneous rocks (Lava or Volcanic rocks

- Sudden cooling of magma just below the surface or lava above the surface results in small and smooth grains in rocks as rapid cooling prevents crystallisation, as a result, such rocks are fine-grained.
- Such rocks are called **extrusive rocks or volcanic rocks (e.g. Basalt)**.
- The Deccan traps in the Indian peninsular region is of basaltic origin.
- Basic rocks contain a greater proportion of **basic oxides**, e.g. of iron, aluminium or magnesium, and are thus **denser and darker in colour**.

Hypabyssal or Dyke Rocks or Intermediate rocks

- These rocks occupy an intermediate position between the deep-seated plutonic bodies and the surface lava flows.
- Dyke rocks are semi-crystalline in structure.



Acid Rocks

- Acidic rocks are characterised by high content of silica (quartz and feldspar) — up to 80 per cent.
- The rest is divided among aluminium, alkalis, magnesium, iron oxide, lime etc.
- These rocks have a lesser content of heavier minerals like iron and magnesium. Hence, they are less dense and are lighter in colour than basic rocks.
- These rocks constitute the sial portion of the crust.
- Due to the excess of silicon, **acidic magma cools fast,** and it does not flow and spread far away.
- **High mountains** are formed of this type of rock.
- Add rocks are hard, compact, massive and resistant to weathering.
- **Granite, quartz** and **feldspar** are typical examples.

Basic Rocks

- These rocks are poor in silica (about 40 per cent); magnesia content is up to 40 per cent, and the remaining is spread over iron oxide, lime, aluminium, alkalis, potassium etc.
- Due to low silica content, the parent material of such rocks **cools slowly and thus, flows and spreads far away**. This flow and cooling give rise to plateaus.
- Presence of heavy elements imparts to these rocks a dark colour. **Not being very hard, these rocks are weathered relatively easily**.
- **Basalt**, **gabbro** and **dolerite** are typical examples.

Economic Significance of Igneous Rocks

- Since magma is the chief source of metal ores, many of them are associated with igneous rocks.
- The minerals of great economic value found in igneous rocks are magnetic iron, nickel, copper, lead, zinc, chromite, manganese, gold, diamond and platinum.

- Amygdales are almond-shaped bubbles formed in basalt due to escape of gases and are filled with minerals.
- The old rocks of the great Indian peninsula are rich in these crystallised minerals or metals.
- Many igneous rocks like granite are used as building materials as they come in beautiful shades.

Sedimentary Rocks or detrital rocks

- Sedimentary rocks are formed by **lithification** — consolidation and compaction of sediments.
- Hence, they are layered or stratified of varying thickness. Example: **sandstone, shale** etc.
- Sediments are a result of denudation (weathering and erosion) of all types of rocks.
- These types of rocks cover 75 per cent of the earth's crust but volumetrically occupy only 5 per cent (because they are available only in the upper part of the crust).
- Ice deposited sedimentary rocks are called **till or tillite**. Wind-deposited sediments are called **loess**.

Depending upon the mode of formation, sedimentary rocks are classified into:

1. mechanically formed — **sandstone, conglomerate, limestone, shale, loess**.
2. organically formed — **geyserite, chalk, limestone, coal**.
3. chemically formed — **limestone, halite, potash**.

Mechanically Formed Sedimentary Rocks

- They are formed by mechanical agents like running water, wind, ocean currents, ice, etc.
- Arenaceous sedimentary rocks have more sand and bigger sized particles and are hard and **porous**. They form the **best reservoirs for liquids like groundwater and petroleum**. E.g. sandstone.
- Argillaceous rocks have more clay and are fine-grained, softer, **mostly impermeable** (mostly non-porous or have very tiny pores). E.g. claystone and shales are predominantly argillaceous.

Chemically Formed Sedimentary Rocks

- Water containing minerals evaporate at the mouth of springs or salt lakes and give rise to Stalactites and stalagmites (deposits of lime left over by the lime-mixed water as it evaporates in the underground caves).

Organically Formed Sedimentary Rocks

- The remains of plants and animals are buried under sediments, and due to heat and pressure from overlying layers, their composition changes. **Coal and limestone** are well-known examples.
- Depending on the predominance of calcium content or the carbon content, sedimentary rocks may be calcareous **(limestone, chalk, dolomite)** or **carbonaceous (coal)**.

Chief Characteristics of Sedimentary Rocks

- They are **stratified** — consist of many layers or strata.
- They hold the most informative geological records due to the marks left behind by various geophysical (weather patterns, wind and water flow) and biological activities (fossils).
- They are **fossiliferous** — have fossils of plants and animals.
- These rocks are **generally porous and allow water to percolate** through them.

The spread of Sedimentary Rocks in India

- Alluvial deposits in the Indo-Gangetic plain and coastal plains is of sedimentary accumulation. These deposits contain loam and clay.
- Different varieties of sandstone are spread over Madhya Pradesh, eastern Rajasthan, parts of Himalayas, Andhra Pradesh, Bihar and Orissa.
- The great Vindhyan highland in central India consists of sandstones, shales, limestones.

- Coal deposits occur in river basins of the Damodar, Mahanadi, the Godavari in the Gondwana sedimentary deposits.

Economic Significance of Sedimentary Rocks

- Sedimentary rocks are not as rich in minerals of economic value as the igneous rocks.
- But important minerals such as hematite iron ore, phosphates, building stones, coals, petroleum and material used in the cement industry are found.
- The decay of tiny marine organisms yields petroleum. Petroleum occurs in suitable structures only.
- Important minerals like bauxite, manganese, tin, are derived from other rocks but are found in gravels and sands carried by water.
- Sedimentary rocks also yield some of the richest soils.

Metamorphic Rocks

- The word metamorphic means '**change of form**'.
- Metamorphism is a process by which **recrystallisation and reorganisation of minerals** occur within a rock. This occurs due to pressure, volume and temperature changes.
- When rocks are forced down to lower levels by tectonic processes or when molten magma rising through the crust comes in contact with the crustal rocks, metamorphosis occurs.
- In the process of metamorphism in some rocks grains or **minerals get arranged in layers or lines**. Such an arrangement is called **foliation or lineation**.
- Sometimes minerals or materials of different groups are arranged into alternating thin to thick layers. Such a structure in is called **banding**.
- **Gneissoid, slate, schist, marble, quartzite** etc. are some examples of metamorphic rocks.

Causes of Metamorphism

- **Orogenic (Mountain Building) Movements:** Such movements often take place with an interplay of folding, warping and high temperatures. These processes give existing rocks a new appearance.
- **Lava Inflow:** The molten magmatic material inside the earth's crust brings the surrounding rocks under the influence of intense temperature pressure and causes changes in them.
- **Geodynamic Forces:** The omnipresent geodynamic forces such as plate tectonics also play an important role in metamorphism.

On the basis of the agency of metamorphism, metamorphic rocks can be of two types

Thermal Metamorphism

- The change of form or re-crystallisation of minerals of sedimentary and igneous rocks under the influence of high temperatures is known as thermal metamorphism.
- A magmatic intrusion causing thermal metamorphism is responsible for the **peak of Mount Everest** consisting of **metamorphosed limestone**.
- As a result of thermal metamorphism, **sandstone changes into quartzite and limestone into marble**.

Dynamic Metamorphism

- This refers to the formation of metamorphic rocks under high pressure.
- Sometimes high pressure is accompanied by high temperatures and the action of chemically charged water.
- The combination of directed pressure and heat is very powerful in producing metamorphism because it leads to more or less complete recrystallisation of rocks and the production of new structures. This is known as dynamo thermal metamorphism.
- Under high pressure, **granite is converted into gneiss; clay and shale are transformed into schist**.

Metamorphic Rocks in India

- The gneisses and schists are commonly found in the Himalayas, Assam, West Bengal, Bihar, Orissa, Madhya Pradesh and Rajasthan.

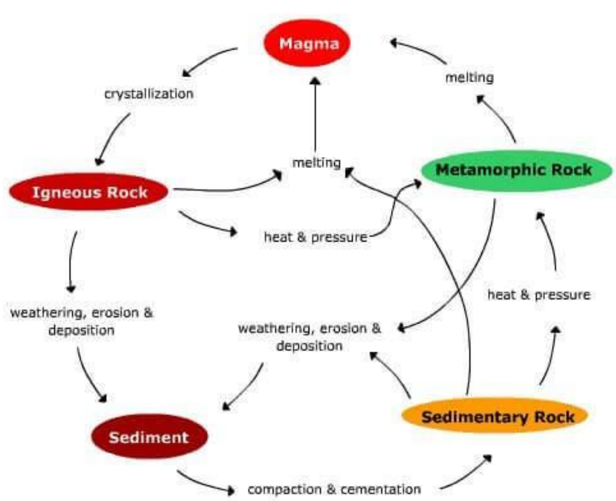
- Quartzite is a hard rock found over Rajasthan, Bihar, Madhya Pradesh, Tamil Nadu and areas surrounding Delhi.
- Marble occurs near Alwar, Ajmer, Jaipur, Jodhpur in Rajasthan and parts of Narmada Valley in Madhya Pradesh.
- Slate, which is used as a roofing material and for writing in schools, is found over Rewari (Haryana), Kangra (Himachal Pradesh) and parts of Bihar.
- Graphite is found in Orissa and Andhra Pradesh.

Some examples of Metamorphosis

Igneous or Sedimentary rock	Influence	Metamorphosed rock
Granite	Pressure	Gneiss
Clay, Shale	Pressure	Schist
Sandstone	Heat	Quartzite
Clay, Shale	Heat	Slate ➔ Phyllite
Coal	Heat	Anthracite ➔ Graphite
Limestone	Heat	Marble

Rock cycle

- Rock cycle is a continuous process through which old rocks are transformed into new ones.
- **Igneous rocks are primary rocks**, and other rocks form from these rocks.
- Igneous rocks can be changed into **sedimentary or metamorphic rocks**.
- The fragments derived out of igneous and metamorphic rocks form into sedimentary rocks.
- **Sedimentary and igneous rocks themselves can turn into metamorphic rocks**.
- The crustal rocks (igneous, metamorphic and sedimentary) may be carried down into the mantle (interior of the earth) through subduction process and the same meltdown and turn into molten magma, the source for igneous rocks



Some Rock-Forming Minerals

- **Feldspar:** Half the crust is composed of feldspar. It has a light colour, and its main constituents are silicon, oxygen, sodium, potassium, calcium, aluminium. It is used for **ceramics and gloss making**.
- **Quartz:** It has two elements, silicon and oxygen. It has a hexagonal crystalline structure. It is uncleaved, white or colourless. It cracks like glass and is present in sand and granite. It is used in the manufacture of **radio and radar**.
- **Bauxite:** A hydrous oxide of aluminium, it is the **ore of aluminium**. It is non-crystalline and occurs in small pellets.
- **Cinnabar (mercury sulphide):** Mercury is derived from it. It has a brownish colour.
- **Dolomite:** A double carbonate of calcium and magnesium. It is used in cement and iron and steel industries. It is white.
- **Gypsum:** It is hydrous calcium sulphate and is used in cement, fertiliser and chemical industries.
- **Haematite:** It is a red ore of iron.
- **Magnetite:** It is the black ore (or iron oxide) of iron.
- **Amphibole:** It forms about 7 per cent of the earth's crust and consists mainly of aluminium, calcium, silica, iron, magnesium, etc. It is used in the **asbestos industry**.
- **Mica:** It consists of potassium, aluminium, magnesium, iron, silica, etc., and forms 4 % of the earth's crust. It is generally found in igneous

and metamorphic rocks and is mainly used in **electrical instruments**.

- **Olivine:** The main elements of olivine are magnesium, iron and silica. It is normally a greenish crystal.
- **Pyroxene:** It consists of calcium, aluminium, magnesium, iron and silica. It is of green or black colour.
- Other minerals like chlorite, calcite, magnetite, hematite, bauxite, barite, etc., are also present in rocks.

Multiple choice questions.

1. Which one of the following are the two main constituents of granite? (a) Iron and nickel (c) Silica and aluminium (b) Iron and silver (d) Iron Oxide and potassium
2. Which one of the following is the salient feature of metamorphic rocks? (a) Changeable (c) Crystalline (b) Quite (d) Foliation
3. Which one of the following is not a single element mineral? (a) Gold (c) Mica (b) Silver (d) Graphite
4. Which one of the following is the hardest mineral? (a) Topaz (c) Quartz (b) Diamond (d) Feldspar
5. Which one of the following is not a sedimentary rock? (a) Tillite (c) Breccia (b) Borax (d) Marble

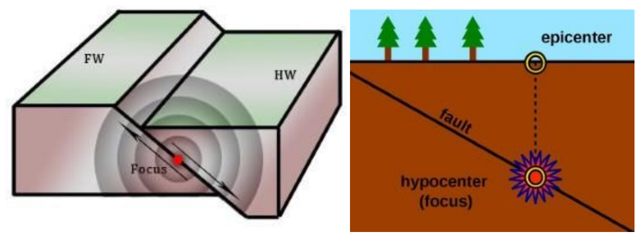
Answers:
1) C. Silica and aluminium (Granite is an acidic igneous rock).
2) D. Foliation (E.g. Marble)
3) C. Mica is a group of silicate minerals; Graphite is a naturally-occurring form of crystalline carbon
4) B. Diamond is the hardest
5) D. Marble is a metamorphic rock

2. Earthquakes

- An earthquake is shaking or trembling of the earth's surface, caused by the seismic waves or earthquake waves that are generated due to a sudden movement (sudden release of energy) in the earth's crust (shallow-focus earthquakes) or upper mantle (some shallow-focus and all intermediate and deep-focus earthquakes).
- A seismograph, or seismometer, is an instrument used to detect and record earthquakes.

Focus and epicentre

- The point where the energy is released is called the **focus** or the **hypocentre** of an earthquake.
- The point on the surface directly above the focus is called **epicentre** (first surface point to experience the earthquake waves).
- A line connecting all points on the surface where the intensity is the same is called an **isoseismic line**.



The focus of an Earthquake

Foreshocks and aftershocks

- Usually, a major or even moderate earthquake of shallow focus is followed by many lesser-size earthquakes known as aftershocks.
- A mild earthquake preceding the violent shaking movement of an earthquake is known as a foreshock.

Swarms

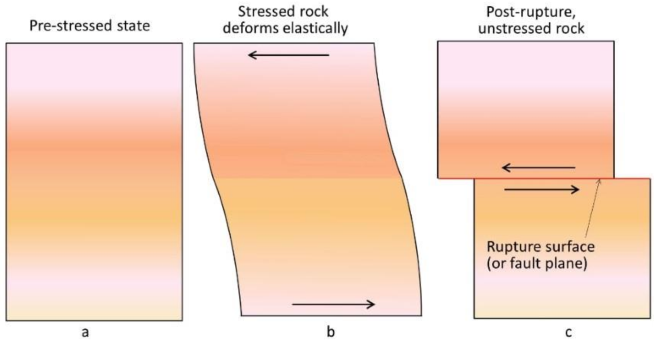
- Large numbers of small earthquakes may occur in a region for months without a major earthquake.
- Such series of earthquakes are called earthquake swarms.
- Earthquakes associated with volcanic activity often occur in swarms.
- Earthquake swarms can serve as markers for the location of the flowing magma throughout the volcanoes.

2.2 Causes of Earthquakes

Fault Zones

- The immediate cause of most shallow earthquakes is the sudden release of stress along a fault rupture (crack) in the earth's crust.

- Sudden slipping of rock formations along fault rupture in the earth's crust happens due to the constant change in volume and density of rocks due to intense temperature and pressure in the earth's interior.



Deformation and Rupturing (Steven Earle)

- The longer the length and the wider the width of the faulted area, the larger the resulting magnitude.
- The **longest earthquake ruptures along thrust faults (convergent boundary)** are approximately 1,000 km.
- The longest earthquake ruptures on strike-slip faults (transform fault) are about half to one third as long as the lengths along the thrust fault.
- The fault ruptures along normal faults (divergent boundary) are **shorter**.

Plate tectonics

- Slipping of land along the faultline along convergent, divergent and transform boundaries cause earthquakes.
- **Reverse faults (convergent boundary) are associated with the most powerful earthquakes**, **megathrust earthquakes**, including almost **all of those of magnitude 8 or more**.
- **Megathrust earthquakes** occur at subduction zones, where one tectonic plate is forced underneath another. E.g. 2004 Indian Ocean earthquake.
- Strike-slip faults, particularly **continental transforms**, can produce major earthquakes **up to about magnitude 8**.
- **San Andreas Fault** is a transform fault where Pacific plate and North American plate move horizontally relative to each other causing earthquakes along the fault lines.
- Earthquakes associated with normal faults (divergent boundary) are generally less than magnitude 7.

Volcanic activity

- Volcanic activity also can cause an earthquake, but **the earthquakes of volcanic origin are generally less severe and more limited in extent** than those caused by fracturing of the earth's crust.
- Earthquakes in volcanic regions are caused by the consequent release of elastic strain energy both by tectonic faults and the movement of magma in volcanoes.
- Such earthquakes can serve as an **early warning of volcanic eruptions**, as during the 1980 eruption of Mount St. Helens
- There is a clear correspondence between the geographic distribution of volcanoes and major earthquakes, particularly in the Circum-Pacific Belt and along oceanic ridges.
- Volcanic vents, however, are generally several hundred kilometres from the epicentres of most major shallow earthquakes, and many earthquake sources occur nowhere near active volcanoes.

Human Induced Earthquakes

- Human Induced Earthquakes refers to typically minor earthquakes and tremors that are caused by human activity like mining, large scale petroleum extraction, artificial lakes (reservoirs), nuclear tests etc.

Reservoir-induced seismicity

- The pressure offered by a column of water in a large and **deep** artificial lake alter stresses along an existing fault or fracture. Also, the percolation of water weakens the soil structure and lubricates the faults.
- Loading and unloading of water can significantly change the stress. This significant change in stress can lead to a sudden movement along the fault or fracture, resulting in an earthquake.
- The 6.3 magnitude 1967 **Koynanagar earthquake** occurred near the Koyna Dam reservoir in Maharashtra and claimed more than 150

lives. There have been several earthquakes of smaller magnitude since then.

- Some geologists believe that the earthquake was due to reservoir-triggered seismic activity.
- The **2008 Sichuan earthquake**, which caused approximately 68,000 deaths, is another possible example. It is believed that the construction and filling of the Zipingpu Dam may have triggered the earthquake.

2.3 Earthquakes based on the depth of focus

- Earthquakes can occur anywhere between the Earth's surface and about 700 kilometres below the surface.
- For scientific purposes, this earthquake depth range of 0 – 700 km is divided into three zones: **shallow, intermediate, and deep**.
- Shallow focus earthquakes are found within the earth's outer crustal layer, while deep focus earthquakes occur within the deeper subduction zones of the earth.
- **Shallow earthquakes are 0 – 70 km deep.**
- **Intermediate earthquakes are 70 – 300 km deep.**
- **Deep earthquakes are 300 – 700 km deep**.
- Of the total energy released in earthquakes, about **12-15 per cent comes from intermediate earthquakes**, about **3-5 per cent from deeper earthquakes** and about **70-85 per cent from the shallow earthquakes**.
- A quake's destructive force depends not only on the energy released but also on location, distance from the epicentre and depth.
- On 24 August 2016, a 6.2 earthquake rocked Central Italy killing about 300 people. An even bigger 6.8 hit Myanmar the same day killing just a few people.
- Italy's quake was very shallow, originating within 10 kilometres underground. By contrast, the quake in Myanmar was deeper — 84 kilometres.

Shallow-focus earthquake

- The great majority of earthquakes have shallow-focus. Hence, they are also called as '**crustal earthquakes**.'
- Majority of the shallow focus earthquakes are of smaller magnitudes (usual range of 1 to 5). But a few can be of a higher magnitude and can cause a great deal of destruction.
- They occur quite frequently and at random. However, as most of them are either of smaller magnitudes or occur along submarine ridges, they are often not felt.
- **Though comparatively of low magnitude, shallow focus earthquakes can cause relatively greater damage at the surface (as the whole energy is directed towards a small area) compared to their deep-focus counterparts**.

Deep-focus earthquake

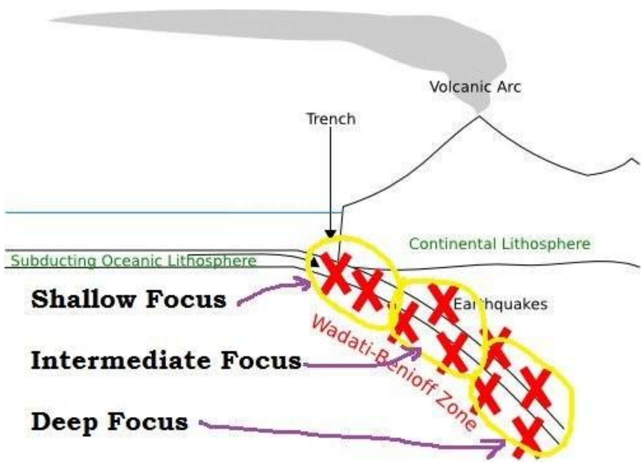
- In general, the term "deep-focus earthquakes" is applied to earthquakes deeper than 70 km.
- The deeper-focus earthquakes commonly occur in patterns called **Benioff zones** that dip into the Earth, indicating the presence of a **subducting slab (zone of subduction)**.
- Hence, they are also are known as **intraplate earthquakes** (triggered by the collision between plates).
- They happen as **huge quakes with larger magnitudes** (usual range of 6 to 8), as a great deal of energy is released with the forceful collision of the plates.
- **But the earthquakes alone may not cause much destruction as the foci of the quakes lie at great depths and the energy of the quakes dissipates over a wide area**.
- The strongest deep-focus earthquake in seismic record was the magnitude 8.3 Okhotsk Sea earthquake that occurred at a depth of 609 km in 2013.
- The deepest earthquake ever recorded was a 4.2 earthquake in Vanuatu at a depth of 735.8 km in 2004.

Wadati–Benioff zone: Earthquakes along the Convergent boundary

- Wadati Benioff zone is a zone of subduction along which earthquakes are common. **The most powerful earthquakes occur along this**

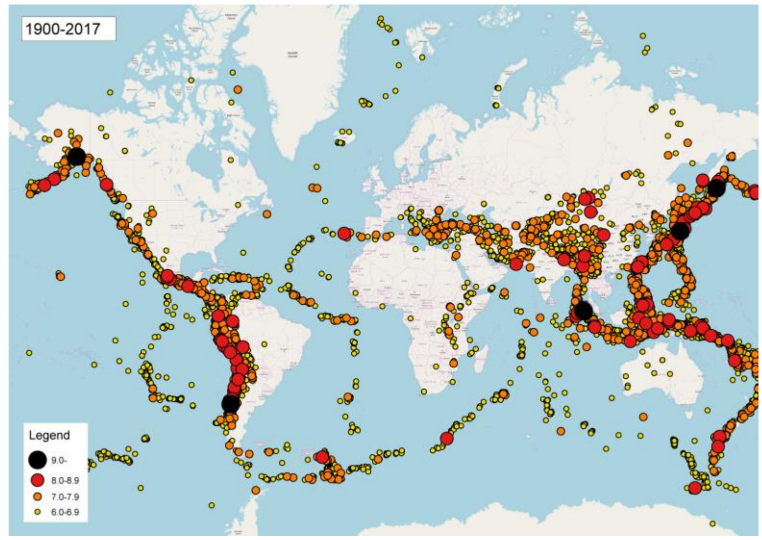
zone (most powerful earthquakes occur along the convergent boundary).

- Differential motion along the zone produces numerous earthquakes, the foci of which may be as deep as about 700 kilometres.
- **Wadati–Benioff zones** can be produced by slip along the **subduction thrust fault (Himalayan Region – C-C convergent boundary)** or **slip on faults within the downgoing plate (O-O and C-O convergent boundary)**.



2.4 Distribution of Earthquakes

- Earth's major earthquakes occur mainly in belts coinciding with the margins of tectonic plates.
- The most important earthquake belt is the **Circum-Pacific Belt**, which affects many populated coastal regions around the Pacific Ocean—for example, those of New Zealand, New Guinea, Japan, the Aleutian Islands, Alaska, and the western coasts of North and South America.
- The seismic activity is by no means uniform throughout the belt, and there are many branches at various points.
- Because at many places the Circum-Pacific Belt is associated with volcanic activity, it has been popularly dubbed the "Pacific Ring of Fire."
- **The Pacific Ring of Fire accounts for about 68 per cent of all earthquakes**.
- A second belt, known as the **Alpine Belt (Himalayas and Alps)**. The energy released in earthquakes from this belt is about 15 per cent of the world total.
- The mid-world mountain belt (Alpine Belt) extends parallel to the equator from Mexico across the Atlantic Ocean, the Mediterranean Sea from Alpine-Caucasus ranges to the Caspian, Himalayan mountains and the adjoining lands.
- There also are striking connected belts of seismic activity, mainly along oceanic ridges—including those in the Arctic Ocean, the Atlantic Ocean, and the western Indian Ocean—and along the **rift valleys of East Africa**.



Distribution of Earthquakes

2.5 Richter magnitude scale

- Charles F. Richter developed the Richter magnitude scale (M_L) for measuring the strength (amount of energy released) of earthquakes in 1930s.
- Because of the various shortcomings of the M_L scale, seismologists now use moment magnitude scale (M_w).
- Both the scales are logarithmic and are scaled to have **roughly comparable numeric values**.
- Moment magnitude scale M_w scale is now generally referred to as the Richter scale.
- Under the Richter magnitude scale, an **increase of one step corresponds to about 32 times increase in the amount of energy released**, and **an increase of two steps corresponds to 1,000 times increase in energy**.
- Thus, **an earthquake of M_w of 7.0 releases about 32 times as much energy as one of 6.0 and nearly 1,000 times (~ 32 X 32) one of 5.0**.

- Richter scale is only effective for regional earthquakes no greater than M_5. Moment magnitude scale is more effective for large earthquakes.

Magnitude	Description	Average earthquake effects	Frequency of occurrence
1.0–1.9	Micro	• Microearthquakes, not felt, or felt rarely. • They are recorded by seismographs.	Several million per year
2.0–2.9	Minor	• Felt slightly by some people. • No damage to buildings.	Over one million per year
3.0–3.9		• Often felt by people, but very rarely causes damage. • Shaking of indoor objects can be noticeable.	Over 100,000 per year
4.0–4.9	Light	• Noticeable shaking of indoor objects. • They are felt by most people in the affected area. • Slightly felt outside. • Generally, causes none to minimal damage. • Some objects may fall off shelves or be knocked over.	10,000 to 15,000 per year
5.0–5.9	Moderate	• Can cause damage of varying severity to poorly constructed buildings. • At most, none to slight damage to all other buildings. • Felt by everyone.	1,000 to 1,500 per year
6.0–6.9	**Strong**	• Damage to a moderate number of well-built structures in populated areas. • Earthquake-resistant structures survive with slight to moderate damage. • Poorly designed structures receive moderate to severe damage. • Felt in wider areas; up to hundreds of kilometres from the epicentre. • Strong to violent shaking in the epicentral area.	100 to 150 per year • 2011 Christchurch earthquake (6.2)
7.0–7.9	**Major**	• Causes damage to most buildings, some to partially or completely collapse or receive severe damage. Well-designed structures are likely to receive damage. Felt across great distances with major damage mostly limited to 250 km from epicentre.	10 to 20 per year • **1819 Rann of Kutch earthquake (7.7–8.2)** • **2001 Gujarat earthquake (7.7)**
8.0–8.9	**Great**	• Major damage to buildings, structures likely to be destroyed. • Will cause moderate to heavy damage to sturdy or earthquake-resistant buildings. • Damaging in large areas. • Felt in extremely large regions.	One per year • 1556 Shaanxi earthquake (8.0) • 1950 Assam–Tibet earthquake (8.6) • 2008 Sichuan earthquake (8.0) • 2010 Chile earthquake (8.8)
9.0 and		• At or near total destruction – severe	One per 10 to 50 years

greater		damage or collapse to all buildings. • Heavy damage and shaking extends to distant locations. • Permanent changes in ground topography.	• **1960 Valdivia earthquake, Chile (9.4–9.6)** • **1964 Alaska earthquake (9.2)** • **2004 Indian Ocean earthquake (9.1–9.3)** • **2011 Tōhoku earthquake, Japan (9.1)**

Based on U.S. Geological Survey documents

Most powerful earthquakes ever recorded

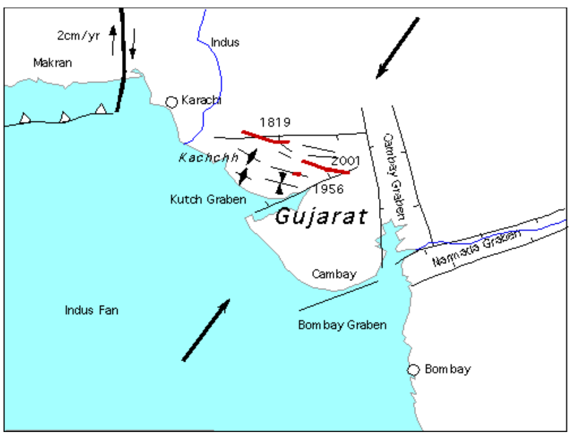
	Event	M_w	Focus	
1	1960 Valdivia earthquake	9.4–9.6	33 km	• Undersea megathrust earthquake • **Most powerful earthquake ever recorded** • The resulting tsunami affected the entire Pacific Rim killing 1,000–7,000 people.
2	1964 Alaska earthquake	9.2	25 km	• Collapsing structures and tsunamis resulted in 100+ deaths.
3	2004 Indian Ocean earthquake	9.1–9.3	30 km	• Undersea megathrust earthquake • Caused by a rupture along the fault between the **Burma Plate** and **the Indian Plate**. • A series of large tsunamis up to 30 metres high were created. • The earthquake and the resulting tsunami caused the 6^{th} deadliest natural disaster in recorded history with more than 227,000 causalities in 14 countries. • The shift of mass and the massive release of energy slightly altered the Earth's rotation.
4	2011 Tōhoku earthquake	9.1	30 km	• Undersea megathrust earthquake • Most powerful earthquake ever recorded in Japan • The earthquake triggered powerful tsunami waves • 15,896 causalities • Caused **Fukushima Daiichi nuclear disaster**

Notable earthquakes

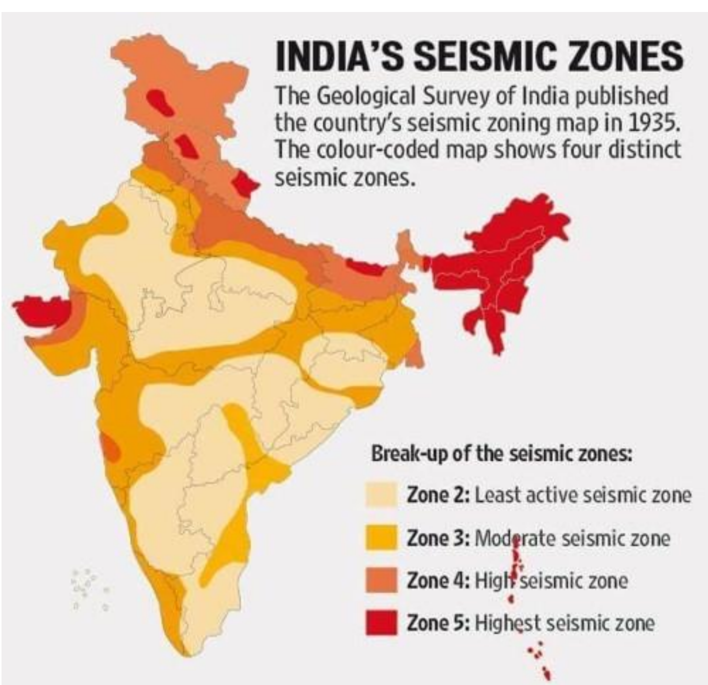
Event	Magnitude	Notes
1556 Shaanxi earthquake	8.0	**Deadliest earthquake** with 8,00,000+ fatalities Most of the deaths were caused due to the collapse of artificial caves carved into the loess cliffs
2011 Tōhoku earthquake and tsunami	9.1	**Costliest earthquake** that caused damage to property worth $250 billion
1819 Rann of Kutch earthquake	7.7 to 8.2	It triggered a tsunami and caused more than 1000 deaths The earthquake caused an area of subsidence that formed the **Sindri Lake** and a local zone of uplift to the north about 80 km long, 6 km wide and 6 m high that dammed the several rivers. This natural dam was known as the **Al-**

		lah Bund (Dam of God).
2001 Gujarat earthquake (Focus: 24 km)	7.7	The earthquake killed between 13000 and 20000 people

- The Gujarat quake occurred 400 km to the south-east of the tectonic boundary separating Indian Plate and the Eurasian Plate.
- The current tectonics is governed by the effects of the continuing continental collision along this boundary.
- The collision has reactivated the original rift faults and development of new thrust faults in the region.
- The pattern of uplift and subsidence associated with the 1819 Rann of Kutch earthquake is consistent with reactivation of such faults.
- The area saw many minor earthquakes in the 20th Century including the 2001 earthquake.



Earthquake zones of India



Earthquake zones of India (Source)

- The latest seismic zone map prepared by the National Disaster Management Authority reveals that **nearly 59% of India's land area is prone to moderate or severe earthquakes**.
- This earthquake zoning map divides India into five different zones of earthquake intensity and highlights the location that falls under them.

2.6 Effects of Earthquakes

Shaking and ground rupture

- Shaking and ground rupture result in severe damage to buildings and other rigid structures.
- Ground rupture (crack along the fault) is a major risk for large engineering structures such as dams, bridges and nuclear power stations.

Landslides and avalanches

- Earthquakes, along with severe storms, volcanic activity, coastal wave attack, and wildfires, can produce slope instability leading to landslides, a major geological hazard.

Fires

- Earthquakes can cause fires by damaging electrical power or gas lines.
- More deaths in the 1906 San Francisco earthquake were caused by fire than by the earthquake itself.

Soil liquefaction

- Soil liquefaction occurs when water-saturated soil temporarily loses its strength and transforms from a solid to a liquid. Soil liquefaction may cause rigid structures, like buildings and bridges, to tilt or sink.

Tsunami

- Megathrust earthquakes can produce long-wavelength, long-period sea waves due to abrupt movement of large volumes of water.

Floods

- Floods may be secondary effects of earthquakes if dams are damaged.
- Earthquakes may cause landslips to dam rivers, which collapse and cause floods.

3. Tsunami

- Tsunami is a Japanese word for "**Harbour wave**". A tsunami is a series of **very long-wavelength** waves in large water bodies like seas or large lakes caused by a major disturbance above or below the water surface or due to the displacement of a large volume of water.
- They are sometimes referred to as tidal waves because of **long wavelengths**, although the attractions of the Moon and Sun play no role in their formation.
- Earthquakes (e.g. 2004 Indian Ocean Tsunami), volcanic eruptions (e.g. tsunami caused by the violent eruption of Krakatoa in 1883), landslides (tsunami caused by the collapse of a section of Anak Krakatoa in 2018), underwater explosions, meteorite impacts, etc. have the potential to generate a tsunami.
- Subduction zones off Chile, Nicaragua, Mexico and Indonesia have created killer tsunamis.
- The Pacific among the oceans has witnessed the most number of tsunamis (over 790 since 1990).

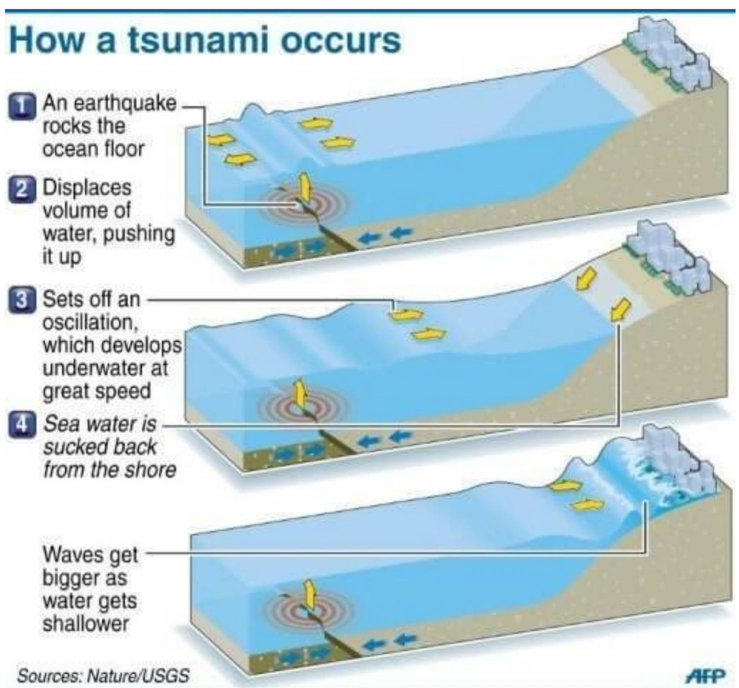
3.1 Mechanism of tsunami waves

Disturbance

- Megathrust earthquakes cause a sudden displacement in a seabed sufficient to cause the sudden raising of a large body of water.
- As the subducting plate plunges beneath the less dense plate, stresses build up, the locked zone between the plates give way abruptly, and the parts of the oceanic crust is then upthrust resulting in the displacement of a large column of water vertically.
- The tsunami on December 26, 2004, was caused after an earthquake displaced the seabed off the coast of Sumatra, Indonesia.
- A marine volcanic eruption can generate an impulsive force that displaces the water column and gives birth to a tsunami.
- During a submarine landslide, the equilibrium sea-level is altered by sediment moving along the floor of the sea. Gravitational forces then propagate a tsunami.
- Most destructive tsunamis can be caused due to the fall of extra-terrestrial objects on to the earth.

Propagation of the waves

- Gravity acts to return the sea surface to its original shape.
- The ripples then race outward, and a tsunami is caused.
- As a tsunami leaves deep waters and propagates into the shallow waters, it transforms. This is because as the depth of the water decreases, the speed of the tsunami reduces. But the change of total energy of the tsunami remains constant.
- With the decrease in speed, the height of the tsunami wave grows. A tsunami which was imperceptible in deep water may grow to many metres high, and this is called the **'shoaling' effect**.



- Sometimes, the sea seems to at first draw a breath, but then this withdrawal is followed by the arrival of the crest of a tsunami wave. Tsunamis have been known to occur suddenly without warning.

- In some cases, there are several great waves separated by intervals of several minutes or more.
- The first of these waves is often preceded by an extraordinary recession of water from the shore, which may commence several minutes or even half an hour beforehand.

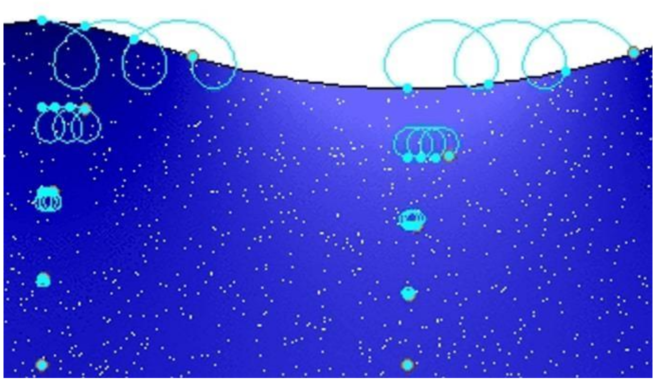
3.2 Properties of Tsunami Waves

Basics

- Wave crest and trough: The highest and lowest points of a wave are called the crest and trough respectively.
- Wave height: It is the vertical distance from the bottom of a trough to the top of a crest of a wave.
- Wave amplitude: It is one-half of the wave height.
- Wave period: It is the time interval between two successive wave crests or troughs.
- Wavelength: It is the horizontal distance between two successive crests.
- Wave frequency: It is the number of waves passing a given point during a one second time interval.

Normal waves

- The horizontal and vertical motions are common in ocean water bodies.
- The **horizontal motion** refers to the **ocean currents and waves**. The **vertical motion** refers to **tides**.



Wind generated wave motion

- Water moves ahead from one place to another through ocean currents while the water in the normal wind-generated waves do not move, but the **wave trains move ahead**.
- The motion of normal waves seldom affects the stagnant deep bottom water of the oceans.
- The actual motion of the water beneath the waves is **circular**. It indicates that things are carried up and forward as the wave approaches, and down and back as it passes.
- As a wave approaches the beach, it slows down. And, when the depth of water is less than half the wavelength of the wave, the wave breaks (dies).

Normal waves vs Tsunami waves

Typical Tsunami Wave vs. Typical Wave

WAVE FEATURE	WIND-GENERATED WAVE	TSUNAMI WAVE
Wave Speed	5-60 miles per hour (8-100 kilometers per hour)	500-600 miles per hour (800-965 kilometers per hour)
Wave Period	5 to 20 seconds apart	10 minutes to 2 hours apart
Wavelength	300-600 feet apart (100-200 meters apart)	60-300 miles apart (100-500 kilometers apart)

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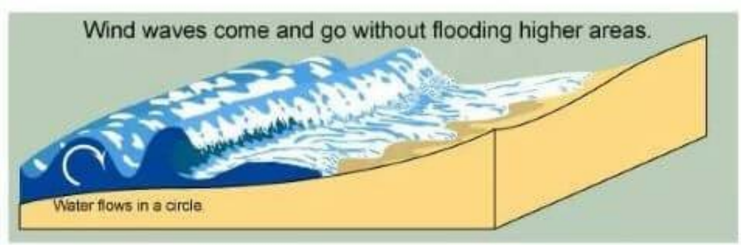
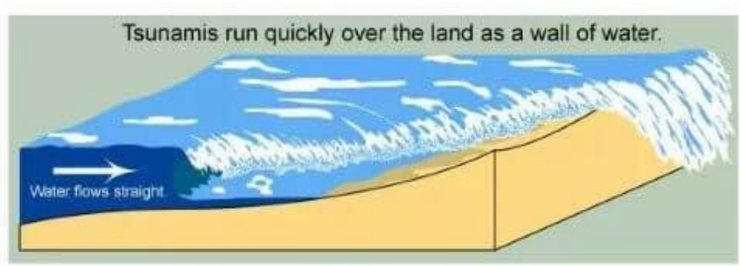
Tsunamis are often no taller than normal wind waves, but they are much more dangerous.





Even a tsunami that looks small can be dangerous!

Any time you feel a large earthquake, or see a disturbance in the ocean that might be a tsunami, head to high ground or inland.

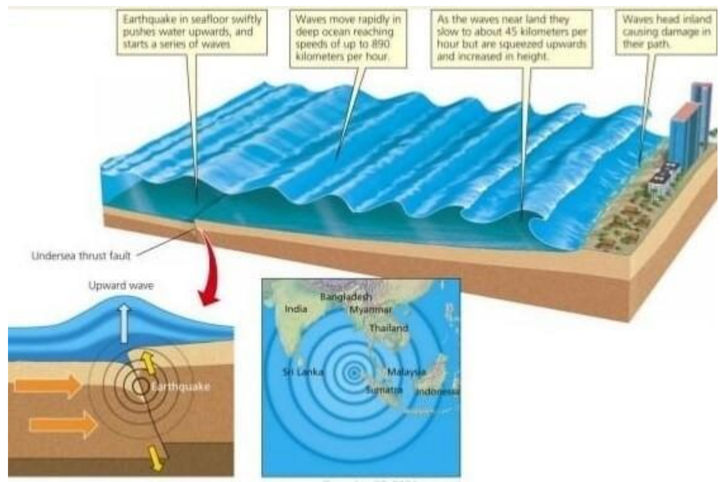
- Tsunamis are a series of waves of very, very long wavelengths and period.
- Tsunamis are different from the wind-generated waves (period of five to twenty seconds).
- Tsunamis behave as **shallow-water waves** because of their long wavelengths. They have a period in the range of ten minutes to two hours and a wavelength exceeding 500 km.
- The rate of energy loss of a wave is inversely related to its wavelength. So, tsunamis lose little energy as they propagate because of their very large wavelength.
- **They travel at high speeds in deep waters, and their speed falls when they hit shallow waters**.
- A tsunami that occurs 1000 metres deep in water has a speed of more about 350 km per hour. At 6000 m, it can travel at speeds about 850 km per hour.
- **Tsunami waves are not noticed by ships far out at sea**.
- Their amplitude is negligible when compared with their wavelength, and hence the waves go unnoticed in deep oceans.
- **When tsunamis approach shallow water, however, the wave amplitude increases (conservation of energy)**.
- The waves may occasionally reach a height of 20 to 30 metres above mean sea level in closed harbours and inlets (funnelling effect).

3.3 2004 Indian Ocean Tsunami

- Tsunami or the Harbour wave struck havoc in the Indian Ocean on the 26th of December 2004.
- The wave was the result of an earthquake that had its epicentre near the western boundary of Sumatra.
- The magnitude of the earthquake was 9.0 on the Richter scale.

Plate tectonics

- **Indian plate** went under the **Burma plate**, there was a sudden movement of the sea floor, causing the earthquake.
- The ocean floor was displaced by about 10 – 20m and tilted in a downward direction.
- A huge mass of ocean water flowed to fill in the gap that was being created by the displacement.
- This marked the withdrawal of the water mass from the coastlines of the landmasses in the south and Southeast Asia.
- After thrusting of the Indian plate below the Burma plate, the water mass rushed back towards the coastline as a tsunami.



Tsunami waves

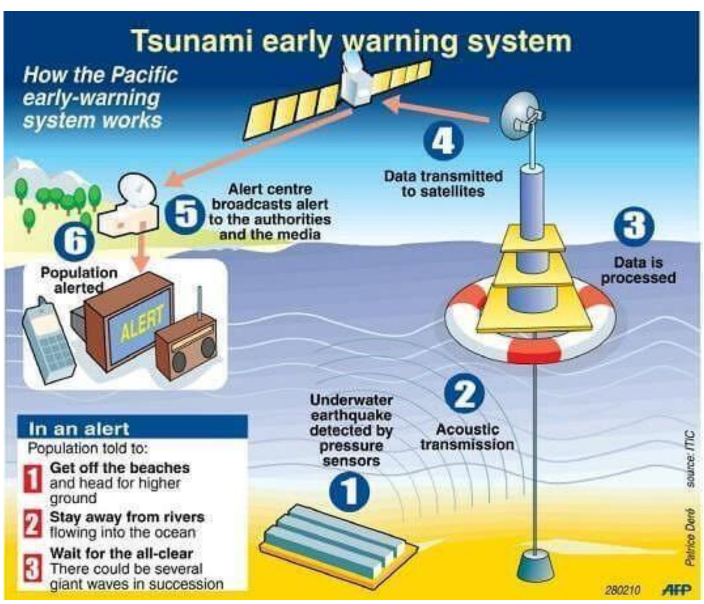
- Tsunami travelled at a speed of about 800 km. per hour, comparable to speed of commercial aircraft and completely washed away some of the islands in the Indian ocean.
- The Indira point in the Andaman and Nicobar Islands that marked the southernmost point of India got completely submerged.
- As the wave moved from earthquake epicentre from Sumatra towards the Andaman Islands and Sri Lanka, the **wavelength decreased with decreasing depth of water**.
- The travel speed also declined from 700-900 km per hour to less than 70 km per hour.
- Tsunami waves travelled up to a depth of 3 km from the coast killing more than 10,000 people and affected more than lakh of houses.
- In India, the worst affected were the coastal areas of Andhra Pradesh, Tamil Nadu, Kerala, Pondicherry and the Andaman and Nicobar Islands.

Shifts in Geography

- Tsunamis and earthquakes can cause changes in geography.
- The December 26 earthquake and tsunami shifted the North Pole by 2.5 cm in the direction of 145 degrees East longitude and reduced the length of the day by 2.68 microseconds.
- This, in turn, affected the velocity of earth's rotation and the Coriolis force which plays a strong role in weather patterns.
- The Andaman and Nicobar Islands may have (moved by about 1.25 m owing to the impact of the colossal earthquake and the tsunami.

3.4 Warning Systems

- While the earthquake cannot be predicted in advance, it is possible to give a three-hour notice of a potential tsunami.
- Such early warning systems are in place across the Pacific Ocean. Post-2004, they were installed in the Indian Ocean as well.
- In 1965, early warning system was started by the National Oceanic and Atmospheric Administration (NOAA). The member states of the NOAA include the major Pacific Rim countries.
- NOAA has developed the **'Deep Ocean Assessment and Reporting of Tsunamis' (DART) gauge.**



- Each gauge has a very sensitive pressure recorder on the sea floor. Data is generated whenever changes in water pressure occur.
- The data is transmitted to a surface **buoy** which then relays it over satellite.
- Computer systems at the **Pacific Tsunami Warning Centre (PTWC) in Hawaii** monitor data.
- Based on the data, warnings are issued.

India's preparedness

- The Deep Ocean Assessment and Reporting System (DOARS) was set up in the Indian Ocean post-2004.
- The Indian government plans to set up a network with Indonesia, Myanmar and Thailand etc.
- A **National Tsunami Early Warning Centre**, which can detect earthquakes of more than 6 magnitude in the Indian Ocean, was inaugurated in 2007 in India.
- Set up by the **Ministry of Earth Sciences** in the **Indian National Centre for Ocean Information Services (INCOIS), Hyderabad**, the tsunami warning system would take 10-30 minutes to analyse the seismic data following an earthquake.

4. Soil erosion and Landforms

- Soil erosion is the loosening and displacement of topsoil from the land due to the action of agents like wind and water.
- Soil erosion in nature may be a slow process (geological erosion) or a fast process promoted by human activities like overgrazing, deforestation.
- Weathering and erosion lead to the simultaneous process of 'degradation' and 'aggradation'.
- Erosion is a mobile process while weathering is a static process (there is no motion of disintegrated material except the falling down under the force of gravity).

4.1 Water Erosion

- Running water is one of the main agents, which carries away soil particles.

- Soil erosion by water occurs by means of raindrops, waves or ice.
- Erosion by water is termed differently according to the intensity and nature of erosion: **raindrop erosion, sheet erosion, rill and gully erosion, stream bank erosion, landslides, coastal erosion, glacial erosion**.

Raindrop erosion or splash erosion

- A raindrop is approximately 5 mm in diameter and hits the soil at a velocity of 32 km/hr. Larger raindrops and gusts of wind hit the soil surface even at higher velocities.
- Raindrops behave like tiny bombs when falling on exposed soil, displace soil particles and destroy soil structure.
- Presence of vegetation on land prevents raindrops from falling directly on the soil thus erosion of soil in areas covered by vegetation is prevented.

Sheet erosion

- With continued rainfall the displaced soil particles fill in the spaces between soil particles and prevent water from seeping into the soil. This results in surface runoff and even more erosion.
- The detachment and transportation of soil particles by flowing rainwater is called sheet or wash off erosion.

- Weathering and erosion tend to level down the irregularities of landforms and create a **peneplane**.

Rill and gully erosion

- In rill erosion finger like rills appear on the cultivated land after it has undergone sheet erosion.
- These rills are usually smoothened out every year while forming.
- Each year the rills slowly increase in number become wider and deeper.

- Gully erosion is the removal of soil along drainage lines by surface water runoff.
- When rills increase in size, they become gullies. Once started, gullies will continue to move by headward erosion or by slumping of the side walls.
- Gullies formed over a large area gives rise to **badland topography (Chambal Ravines)**.
- When a gully bed is eroded further due to headward erosion, the bed gradually deepens and flattens out, and a **ravine** is formed. The depth of a ravine may extend to 30 metres or more.
- Further erosion of ravine beds gives rise to **canyons.** Canyons are few hundred meters deep and wide. (Grand Canyon on Colorado River).

Streambank erosion

- The erosion of soil from the banks (shores) of the streams or rivers due to the flowing water is called bank erosion.

- In certain areas where the river changes its course, the river banks get eroded at a rapid rate.
- Streambank erosion damages the adjoining agricultural lands, highways and bridges.

Landslide

- The sudden mass movement of soil is called a landslide.
- Landslides occur due to instability or loss of balance of land mass with respect to gravity.
- The loss in balance occurred mainly due to excessive water or moisture in the earth mass.
- Gravity acts on such an unstable landmass and causes the large chunks of surface materials such as soil and rocks to slide down rapidly.

Coastal erosion

- In the coastal areas, waves dash along the coast and cause heavy damage to the soil.
- During the landfall of cyclones, storm surges destroy beaches and wash away the top layer.
- In estuaries, tidal bores cause extensive damage to the surrounding banks.

Glacial erosion

- In the polar regions and high mountainous regions like the Himalayas, soil erosion is caused by sowing moving glaciers. This is called glacial erosion.

4.2 Wind Erosion

- Wind erosion or **aeolian erosion** is quite significant in arid and semi-arid regions.
- Winds usually blow at high speeds in deserts due to the absence of physical obstruction.
- These winds remove the fertile, arable, loose soils leaving behind a depression devoid of topsoil.
- The depression formation in deserts is the first step in Oasis formation. Oasis forms in depressions when there is underground water that gets accumulated above rocks.
- Very fine and medium sands are moved by wind in a succession of bounds and leaps, known as **saltation**.
- Small sand and dust particles are transported over long distances through the air by a process known as **suspension**.
- Coarse sand is not usually airborne but rather is rolled along the soil surface. This type of erosion is called **surface creep.**
- Very coarse sand and gravels are too large to be rolled by wind, so wind-eroded soils have surfaces covered with coarse fragments. This kind of arid soil surface is known as **desert pavement**.

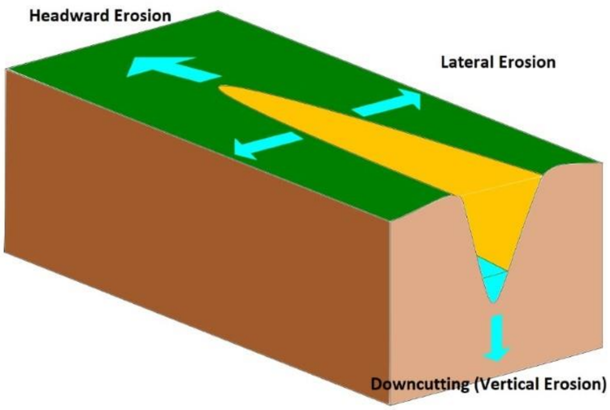
4.3 Fluvial Landforms and Cycle of Erosion

- The landforms created as a result of **degradational action (erosion and transportation)** or **aggradational work (deposition)** of running water are called fluvial landforms.

Fluvial Erosional Landforms

- Fluvial Erosional Landforms are landforms created by the erosional activity of rivers.
- Various aspects of fluvial erosive action include:
- ✓ **Hydration:** the force of running water wearing down rocks.
- ✓ **Corrosion:** chemical action that leads to weathering.
- ✓ **Attrition:** river load particles striking, colliding against each other and breaking down in the process.
- ✓ **Corrasion or abrasion:** solid river load striking against rocks and wearing them down.
- ✓ **Downcutting (vertical erosion):** the erosion of the base of a stream (downcutting leads to valley deepening).

- ✓ **Lateral erosion:** the erosion of the walls of a stream (leads to valley widening).
- ✓ **Headward erosion:** erosion at the origin of a stream channel, which causes the origin to move back away from the direction of the stream flow, and so causes the stream channel to lengthen.

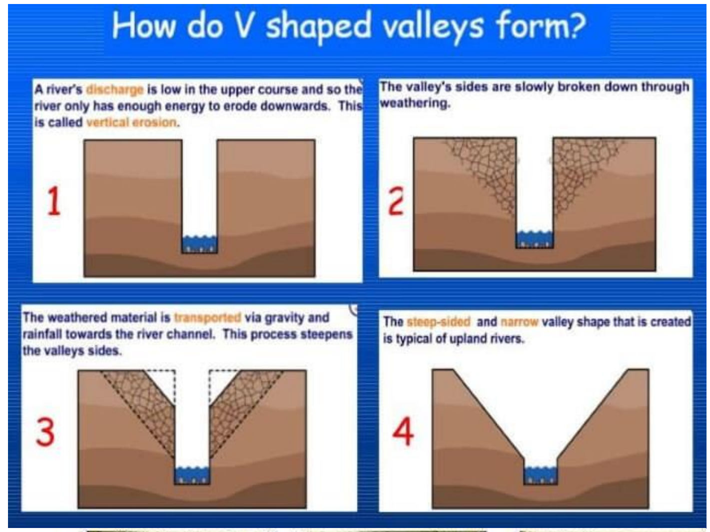


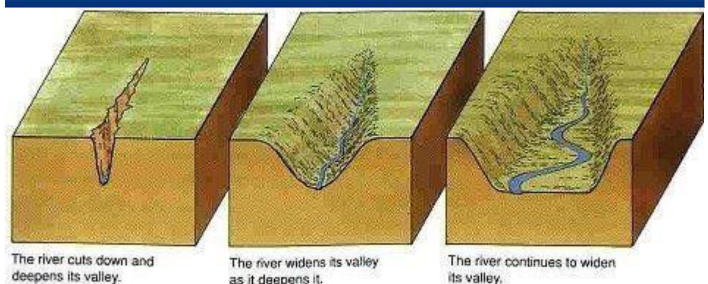
Vertical, Lateral and Headward Erosion (Kayau, from Wikimedia Commons)

- ✓ **Braiding:** the main water channel splitting into multiple, narrower channel. A braided river, or braided channel, consists of a network of river channels separated by small, and often temporary, islands called braid bars. Braided streams occur in rivers with low slope and/or large sediment load.

River Valley Formation

- The extended depression on the ground through which a stream flows is called a river valley.
- At different stages of the erosional cycle, the valley acquires different profiles.
- At a young stage, the valley is deep, narrow with steep wall-like sides and a convex slope.
- The erosional action here is characterized by predominantly **vertical downcutting** nature.



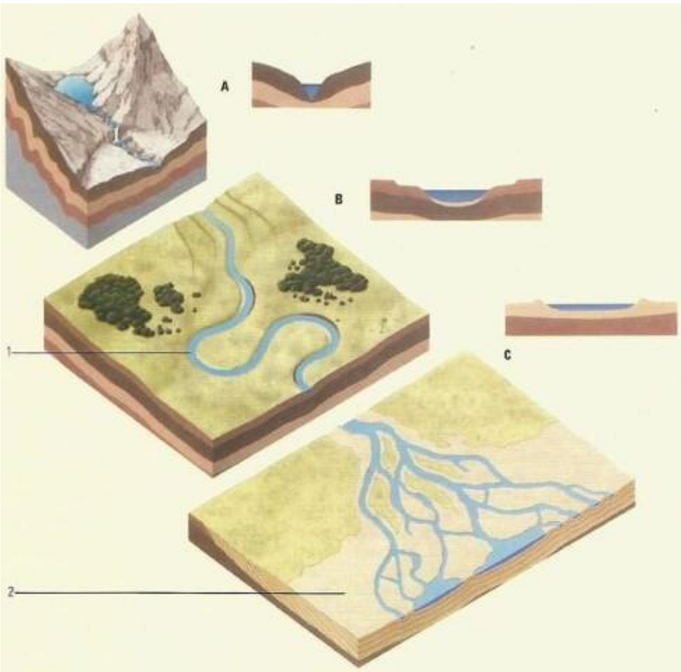


- The profile of valley here is typically 'V' shaped.
- A deep and narrow 'V' shaped valley is also referred to as **gorge** and may result due to downcutting erosion or because of the recession of a waterfall (the position of the waterfall receding due to erosive action).
- Most Himalayan rivers pass through deep gorges (at times more than 500 metres deep) before they descend to the plains.
- An extended form of the gorge is called a **canyon.** The Grand Canyon of the Colorado River in Arizona (USA) runs for 483 km and has a depth of 2.88 km.
- A tributary valley lies above the main valley and is separated from it by a steep slope down which the stream may flow as a waterfall or a series of rapids.
- As the cycle attains maturity, the **lateral erosion** (erosion of the walls of a stream) becomes

prominent and the valley floor flattens out (attains a 'V' to 'U' shape).

- The valley profile now becomes typically 'U' shaped with a broad base and a concave slope.

River course



Youth

- Young rivers (A) close to their source tend to be fast-flowing, high-energy environments with rapid headward erosion, despite the hardness of the rock over which they may flow.
- Steep-sided **"V-shaped' valleys, waterfalls, and rapids** are characteristic features.
- E.g. Rivers flowing in the Himalayas.

Maturity

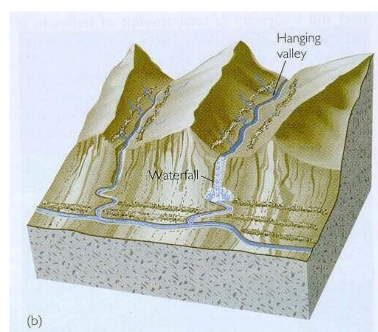
- Mature rivers (B) are lower-energy systems.
- Erosion takes place on the outside of bends, creating looping meanders in the soft alluvium of the river plain.
- Deposition occurs on the inside of bends and on the river bed.
- E.g. Rivers flowing in the Indo-Gangetic-Brahmaputra plain.

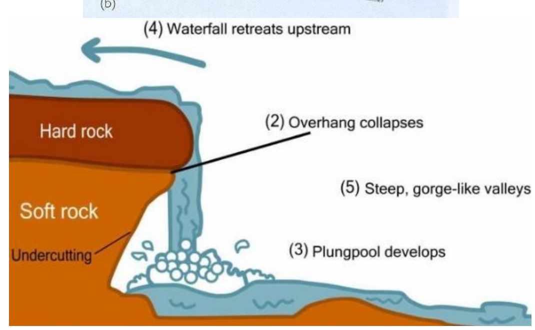
Old Age

- At a river's mouth (C), sediment is deposited as the velocity of the river slows.
- As the river becomes shallower more deposition occurs, forming **temporary islands (Majuli, a river island in the Brahmaputra River, Assam is currently the world's largest river island)** and **braiding** (e.g. braided channels of Brahmaputra river flood plain in Assam) the main channel into multiple, narrower channels.
- As the sediment is laid down, the actual mouth of the river moves away from the source into the sea or lake, forming a **delta**.
- E.g. Ganga-Brahmaputra delta.

Waterfalls

- A waterfall is simply the fall of an enormous volume of water from a great height.
- They are **mostly seen in** the **youth stage** of the river.
- Relative resistance of rocks, the relative difference in topographic reliefs, fall in the sea level and related rejuvenation, earth movements etc. are responsible for the formation of waterfalls.





- **Kunchikal Falls** (it is a cascade falls — falls with many steps) formed by Varahi river in Shimoga district, Karnataka is the highest waterfall in India (455 m).
- **Nohkalikai Falls (340 m)** is the tallest plunge waterfall in India. The waterfall is located near Cherrapunji.
- **Jog or Gersoppa falls (253 m)** on Sharavati river (a tributary of Cauvery), Karnataka is the second-highest plunge waterfall in India.
- **Angel Falls** in Venezuela is the world's highest waterfall, with a height of 979 metres and a plunge of 807 metres.
- **Tugela Falls** (948 m) in the Drakensberg mountains, South Africa is the world's second highest waterfall.

Potholes

- The small cylindrical depressions in the rocky beds of the river valleys are called potholes.
- Potholing or pothole-drilling is the mechanism through which the fragments of rocks when caught in the water eddies or swirling water start dancing circularly and grind and drill the rock beds.
- They thus form small holes which are gradually enlarged by the repetition of the said mechanism.

Terraces

- Stepped benches along the river course in a flood plain are called terraces.
- Terraces represent the level of former valley floors and remnants of former (older) floodplains.

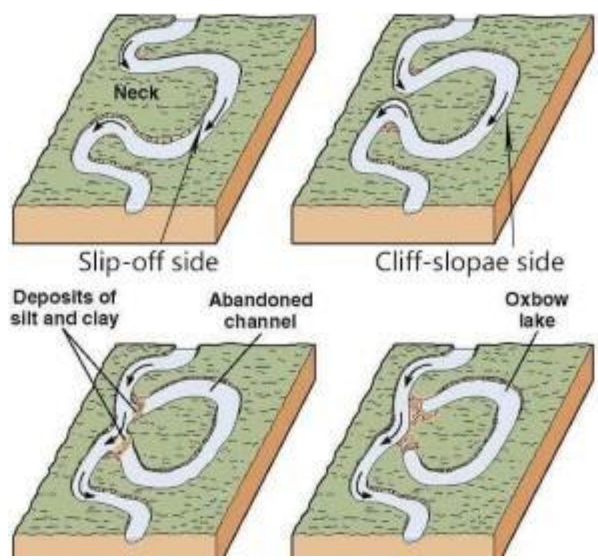
Gulleys/Rills

- Gulley is a water-worn channel, which is particularly common in semi-arid areas.
- It is formed when water from overland-flows down a slope, especially following heavy rainfall, is concentrated into rills, which merge and enlarge into a gulley.
- The **ravines of Chambal Valley** in Central India and the **Chos of Hoshiarpur** in Punjab are examples of gulleys.

Ravines of Chambal Valley in Madhya Pradesh

Meanders

- A meander is defined as a pronounced curve or loop in the course of a river channel.
- The outer bend of the loop in a meander is characterized by intensive erosion and vertical cliffs and is called the **cliff-slope side**. This side has a concave slope.
- The inner side of the loop is characterized by deposition, a gentle convex slope, and is called the **slip-off side.**
- The meanders may be wavy, horse-shoe type or oxbow type.



Oxbow Lake

- Sometimes, because of intensive erosion action, the outer curve of a meander gets accentuated to such an extent that the inner ends of the loop come close enough to get disconnected from the main channel and exist as independent water bodies called as oxbow lakes.
- These water bodies are converted into swamps in due course of time.

- In the Indo-Gangetic plains, southwards shifting of Ganga has left many oxbow lakes to the north of the present course of the Ganga.

Peneplane (Or peneplain)

- This refers to an undulating featureless plain punctuated with low-lying residual hills of resistant rocks. It is considered to be an **end product of an erosional cycle**.

Uluru or Ayers Rock in central Australia standing on a peneplane

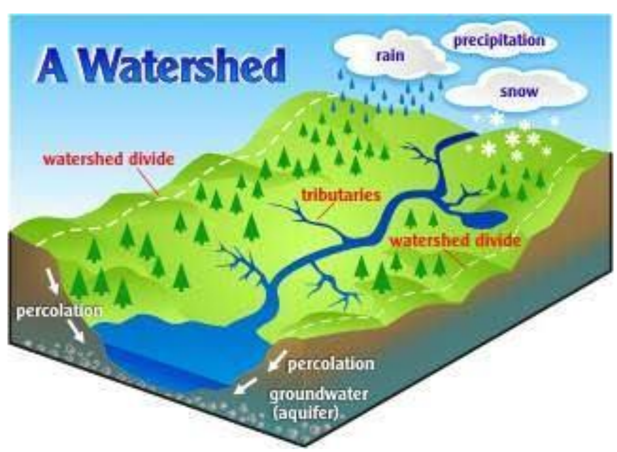
- Fluvial erosion, in the course of geologic time, reduces the land almost to base level (sea level), leaving so little gradient that essentially **no more erosion could occur**.

Drainage basin

- Other terms that are used to describe drainage basins are **catchment, catchment area, catchment basin, drainage area, river basin, and water basin.**
- The drainage basin includes both the streams and rivers and the land surface.
- The drainage basin acts as a funnel by collecting all the water within the area covered by the basin and channelling it to a single point.
- In **closed (endorheic) drainage** basins the water converges to a single point inside the basin, known as a **sink**, which may be a permanent lake (e.g. Lake Aral, also known Aral Sea, Dead Sea), dry lake (some desert lakes like Lake Chad, Africa), or a point where surface water is lost underground (sinkholes in Karst landforms).

Drainage Divide

- Adjacent drainage basins are separated from one another by a drainage divide.
- Drainage divide is usually a ridge or a high platform.
- Drainage divide is conspicuous in case of youthful topography (Himalayas), and it is not well marked in plains and senile topography (old featureless landforms — rolling plateaus of Peninsular region).



Difference between a River Basin and a Watershed

- Both river basins and watersheds are areas of land that drain to a particular water body, such as a lake, stream, river or estuary.
- In a river basin, all the water drains to a large river. The term watershed is used to describe a smaller area of land that drains to a smaller stream, lake or wetland.
- There are many smaller watersheds within a river basin.
- Example: watershed of Yamuna + watershed of Chambal + watershed of Gandak + ... = Drainage basin of Ganga.

Some important drainage basins across the world

Basin	Continent	Drains to	Basin Area km^2
Amazon River	**South America**	**Atlantic Ocean**	**6,144,727**
Hudson Bay	North America	Atlantic Ocean	3,861,400
Congo River	Africa	Atlantic Ocean	3,730,474
Caspian Sea	Asia/Europe	**Endorheic basin**	3,626,000
Nile River	Africa	Mediterranean Sea	3,254,555
Mississippi-Missouri River	North America	Gulf of Mexico	3,202,230
Lake Chad	Africa	**Endorheic basin**	2,497,918
Black Sea	multiple	Mediterranean Sea	2,400,000
Niger River	Africa	Atlantic Ocean	2,261,763
Yangtze River (Chang Jiang)	Asia	Pacific Ocean	1,722,155
Baltic Sea	Europe	Atlantic Ocean	1,700,000
Ganges–Brahmaputra	**Asia**	**Bay of Bengal**	**1,621,000**
Indus River	**Asia**	**Arabian Sea**	**1,081,733**

Drainage systems (drainage patterns)

- Drainage systems, also known as river systems, are the patterns formed by the streams, rivers, and lakes in a particular drainage basin.
- They are governed by tectonic irregularity, nature of underlying rock strata, and the gradient of the land.
- Based on the correlation between the topology and the direction of flow, drainage patterns are classified into concordant drainage and discordant or insequent drainage.

Concordant drainage

- A drainage pattern is described as concordant if it **correlates to the topology** and **geology** of the area.
- In simple words, in a concordant drainage pattern, the path of the river is highly dependent on the slope of the river and topography.
- Concordant drainage patterns are the most commonly found drainage patterns and are classified into many consequent, subsequent, obsequent and resequent.

Consequent Rivers

- The rivers which follow the **general direction of the slope** are known as the consequent rivers.
- Most of the rivers of peninsular India are consequent rivers.
- For example, rivers like the **Godavari, Krishna and Cauvery,** descending from the Western Ghats and flowing into the Bay of Bengal, are some of the consequent rivers of Peninsular India.

Subsequent Rivers

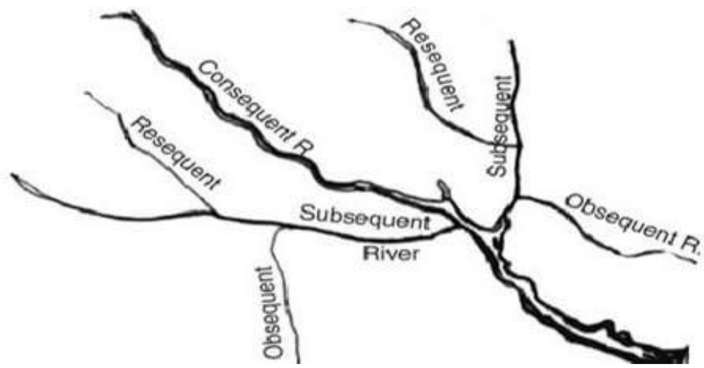
- A tributary stream that is formed by headward erosion **along** an underlying rock after the main drainage pattern (consequent river) has been established is known as a subsequent river.
- The **Chambal, Sind, Ken, Betwa, Tons and Son** meet the Yamuna and the Ganga at right angles. They are the subsequent drainage of the Ganga drainage system.

Obsequent Rivers

- After the valley development of consequent and subsequent rivers, obsequent rivers may form at right angles to the subsequent rivers and flow **opposite** to the direction of flow of the original consequent river.

Resequent Rivers

- A resequent river flows in the same direction as that of the initial consequent drainage.
- Resequent rivers originate at a much later stage (hence they are called resequent) in comparison to the master consequent rivers.



Discordant or Insequent drainage patterns

- A drainage pattern is described as discordant if it **does not correlate to the topology (surface relief features)** and **geology** of the area.
- In simple words, in a discordant drainage pattern, the river follows its initial path irrespective of the changes in topography.
- Discordant drainage patterns are classified into two main types: **antecedent** and **superimposed**.
- Usually, rivers in both these drainage types flow through a **highly sloping surface**.

Antecedent Drainage or Inconsequent Drainage

- A part of a river slope and the surrounding area gets uplifted, and the river **sticks to its original slope**, cutting through the uplifted portion like a saw (vertical erosion) and forming deep gorges. This type of drainage is called **antecedent drainage.**
- Example: **Indus, Sutlej, Brahmaputra and other Himalayan rivers that are older than the Himalayas themselves**. There are usually called **antecedent rivers (rivers older than the existing land itself)**.

Superimposed or Epigenetic (Discordant) or Superinduced Drainage

- When a river flowing over a softer rock stratum reaches the harder basal rocks but continues to follow the initial slope, it seems to have no relation with the harder rock bed. This type of drainage is called superimposed drainage.

Explanation

- Usually, the drainage patterns (dendritic, trellis, etc.) are strongly influenced by the hardness and softness of the rock and patterns of faults or fractures.
- Sometimes, however, the land rises rapidly relative to the base level of the stream. This increases the gradient of the stream and therefore, gives the stream more erosive power.
- The stream has enough erosive power that it cuts its way through any bedrock, **maintaining its former drainage pattern**.
- You get a situation, then, where the drainage pattern does not correspond to the hardness or softness of the bedrock or the locations of faults and fractures.
- In other words, it is a drainage pattern which exhibits discordance with the underlying rock structure because it originally developed on a cover of rocks that has now disappeared due to denudation.
- Consequently, river directions relate to the former cover rocks and, as the latter was being eroded, the rivers have been able to retain their courses unaffected by the newly exposed structures.
- The stream pattern is thus superposed on or placed on structural features that were previously buried.
- The **Damodar**, the **Subarnarekha**, the **Chambal**, the **Banas** and the rivers flowing at the **Rewa Plateau** present some good examples of superimposed drainage.
- [In simple words, the river flow becomes independent of present Topography. It flows in its initial paths without being influenced by changing topography].

Antecedent Drainage: *cuts through the newly formed landform and maintains the same path. E.g. Himalayan Rivers.*

Superimposed Drainage: *cuts deeper through the existing landform and maintains the same path. E.g. some medium scale rivers of the Northern and Eastern peninsular India.*

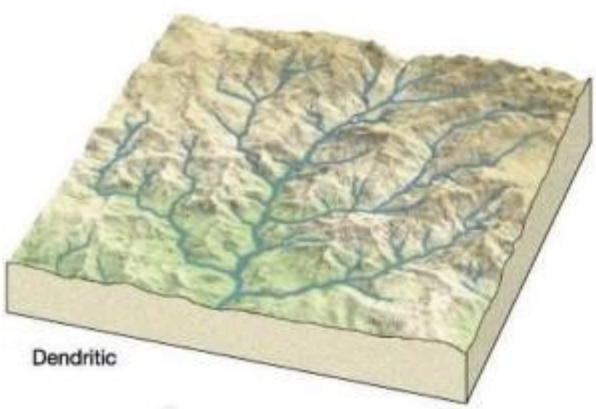
Antecedent Drainage: *The soil formed is weak (mostly weak sediments), and the rivers easily erode it.*

Superimposed Drainage: *The rivers have high erosive power so that they can cut through the underlying strata.*

Other Drainage Patterns

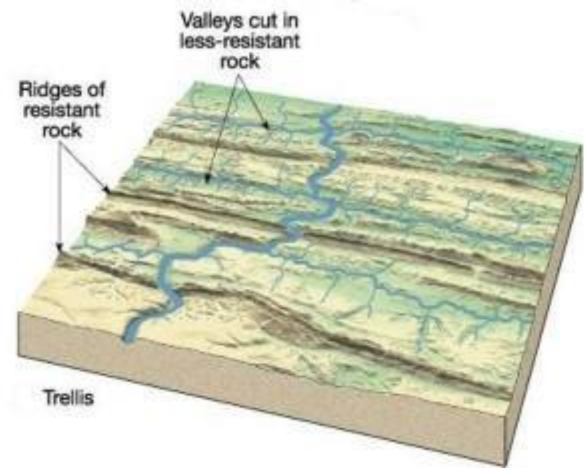
Dendritic or Pinnate Drainage Pattern

- This is an irregular tree branch shaped pattern that develops in a terrain which has uniform lithology (uniform rock structure), and where faulting and jointing are insignificant.
- Examples**: Indus, Godavari, Mahanadi, Cauvery, Krishna.**



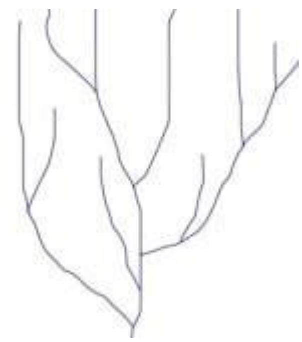
Trellis Drainage Pattern

- In this type of pattern, the short subsequent streams meet the main stream at **right angles**, and differential erosion through soft rocks paves the way for tributaries.
- Examples: The old folded mountains of the **Singhbhum (Chotanagpur Plateau)** and **Seine and its tributaries in Paris basin (France)** have drainage of trellis pattern.



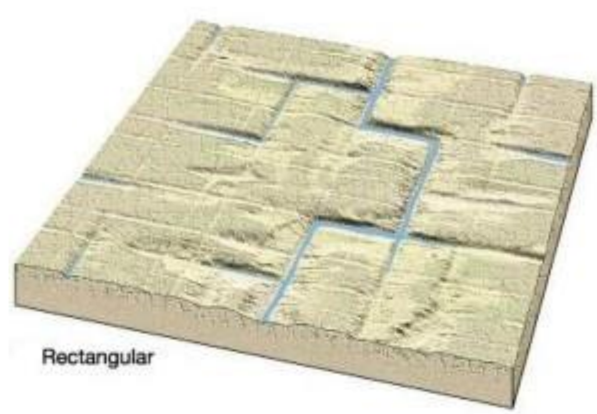
Angular Drainage Pattern

- The tributaries join the main stream at acute angles.
- This pattern is common in **Himalayan foothill regions.**



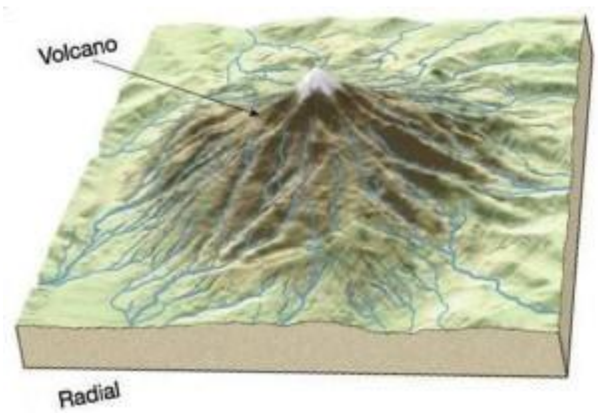
Rectangular Drainage Pattern

- The main stream bends at right angles and the tributaries join at **right angles** creating rectangular patterns.
- This pattern has a subsequent origin. Example: Colorado River (USA), streams found is the Vindhyan Mountains of India.



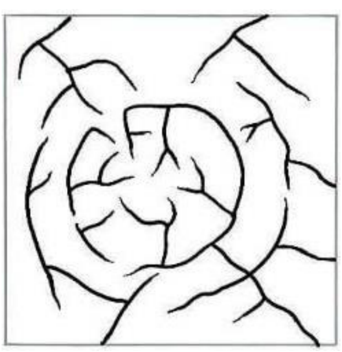
Radial Drainage Pattern

- The tributaries from a summit follow the slope downwards and drain down in all directions.
- Examples: **Streams of Saurashtra region,** the **rivers originating from the Amarkantak Mountain, Central French Plateau, Mt. Kilimanjaro**.
- The Narmada, Son and Mahanadi originate from Amarkantak Hills and flow in different directions.



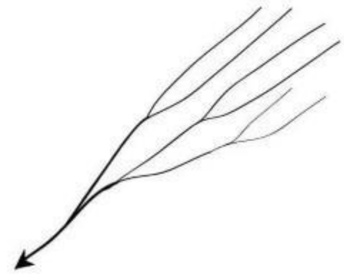
Annular Drainage Pattern

- When the upland has a soft outer stratum, the radial streams develop subsequent tributaries which try to follow circular drainage around the summit.
- Example: Black Hill streams of South Dakota.
- This is not a very common drainage pattern in India. Some examples of this are however found in **Pithoragarh (Uttarakhand), Nilgiri Hills in Tamil Nadu and Kerala**.



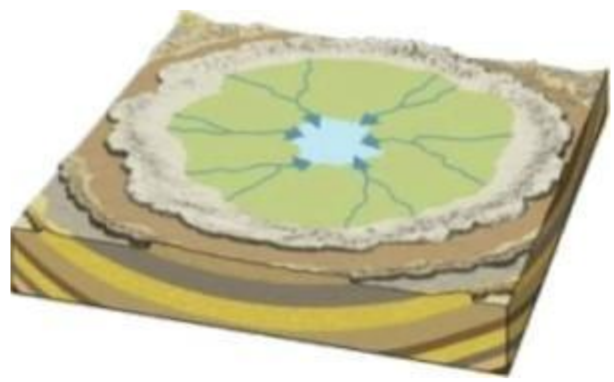
Parallel Drainage Pattern

- The tributaries seem to be running parallel to each other in a uniformly sloping region.
- Example: **Rivers of lesser Himalayas** and The **small and swift rivers originating in the Western Ghats** that flow into Arabian Sea.



Centripetal Drainage Pattern

- In a low-lying basin, the streams converge from all sides.
- Examples: **streams of Ladakh, Tibet**, and the **Baghmati** and its tributaries in Nepal.



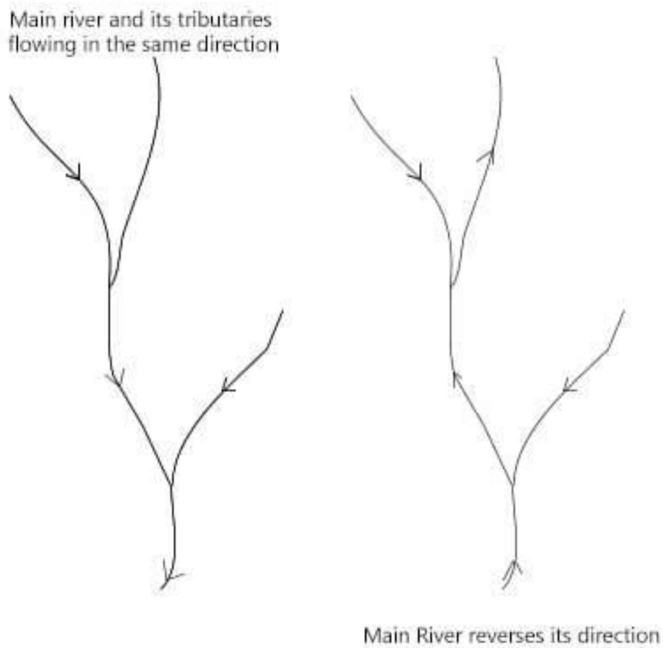
Deranged Drainage Pattern

- This is an uncoordinated pattern of drainage characteristic of a region recently vacated by an ice-sheet.
- The picture is one of the numerous watercourses, lakes and marshes; some inter-connected and some in local drainage basins of their own.
- This type of drainage is found in the glaciated valleys of Karakoram.

Barbed Drainage Pattern

- A pattern of drainage in which the confluence of a tributary with the main river is characterized by a discordant junction — as if the tributary intends to flow upstream and not downstream.

- This pattern is the result of the capture of the main river which completely reverses its direction of flow, while the tributaries continue to point in the direction of former flow.
- The Arun River (Nepal), a tributary of the Kosi is an interesting example of barbed drainage pattern.



Fluvial Depositional Landforms

- Fluvial Depositional Landforms are landforms created by the depositional activity of rivers.
- The depositional action of a stream is influenced by stream velocity and the volume of river load.
- The decrease in stream velocity reduces the transporting power of the streams which are forced to leave some load to settle down.
- Various landforms resulting from fluvial deposition are as follows:

Alluvial Fans and Cones

- When a stream leaves the mountains and comes down to the plains, its velocity decreases due to a lower gradient.
- As a result, it sheds a lot of material, which it had been carrying from the mountains, at the foothills.
- This deposited material acquires a conical shape and appears as a series of continuous fans. These are called alluvial fans.
- Such fans appear throughout the **Himalayan foothills** in the north Indian plains.

Natural Levees

- These are narrow ridges of low height on both sides of a river, formed due to deposition action of the stream, appearing as natural embankments.
- These act as natural protection against floods but a breach in a levee causes sudden floods in adjoining areas, as it happens in the case of the **Hwang Ho river of China**.

Delta

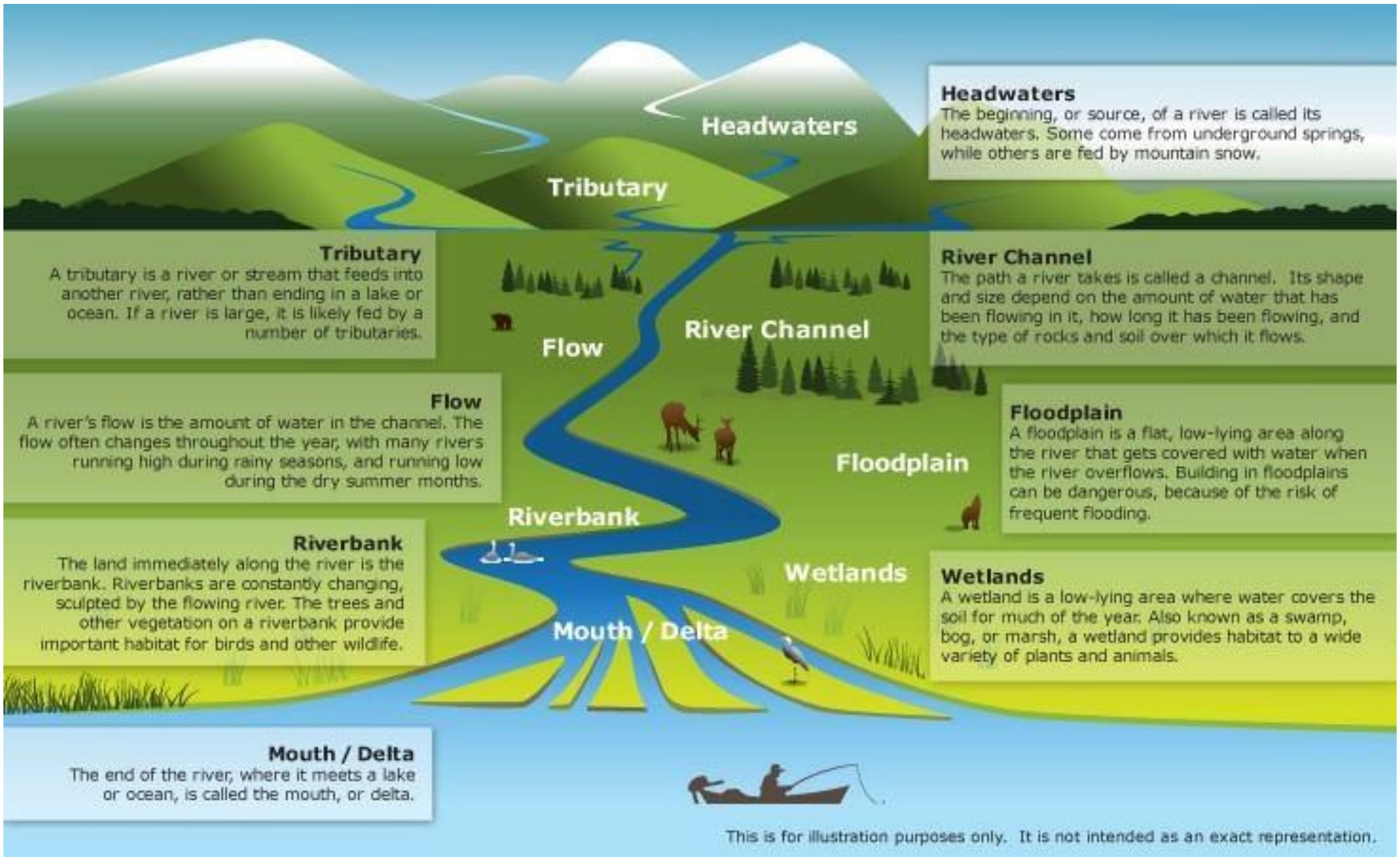
- A delta is a tract of alluvium at the mouth of a river where it deposits more material than that can be carried away.
- The river gets divided into distributaries which may further divide and rejoin to form a network of channels.

A combination of two processes forms a delta:

1. the load-bearing capacity of a river is reduced as a result of the check to its speed as it enters a sea or lake, and

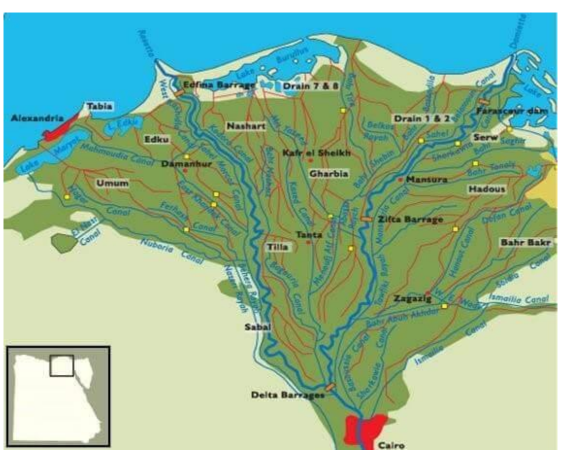
2. clay particles carried in suspension in the river **coagulate** in the presence of salt water and are deposited.

- The finest particles are carried farthest to accumulate as bottom-set beds. Depending on the conditions under which they are formed, deltas can be of many types.



Arcuate or Fan-shaped (Curved)

- This type of delta results when light depositions give rise to shallow, shifting distributaries and a general fan-shaped profile. Examples: **Nile, Ganga, Indus.**



Bird's Foot Delta (Elongated)

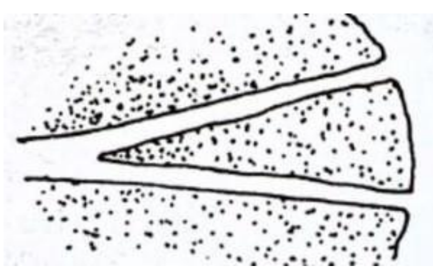
- This type of delta emerges when limestone sediment deposits do not allow downward seepage of water.
- The distributaries seem to be flowing over projections of these deposits which appear as a bird's foot.
- The currents and tides are weak in such areas and the number of distributaries lesser as compared to an arcuate delta. Example: **Mississippi River**.

Estuaries

- Sometimes the mouth of the river appears to be submerged. This may be due to a drowned valley because of a rise in sea level.
- Here fresh water and the saline water get mixed. When the river starts ‘filling its mouth’ with sediments, mud bars, marshes and plains seem to be developing in it.
- These are **ideal sites for fisheries, ports and industries** because estuaries provide access to deep water, especially if protected from currents and tides. Example: **Hudson estuary**.

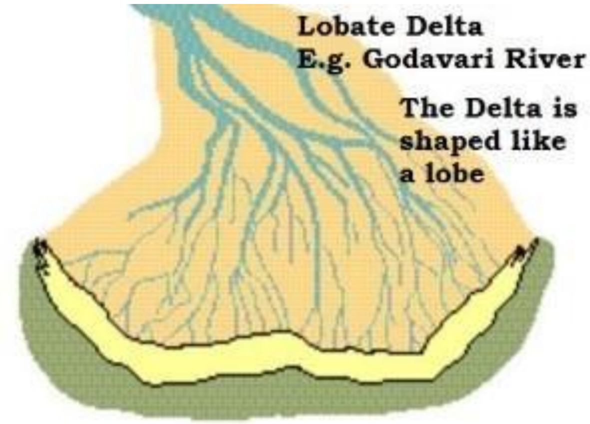
Cuspate Delta

- This is a pointed delta generally formed along strong coasts and is subjected to strong wave action. There are very few or no distributaries in a cuspate delta.
- Example: Tiber river on the west coast of Italy.



High-constructive deltas – Elongate and Lobate Delta

- Develops when fluvial action and depositional process dominate the system.
- Elongate delta is represented by the **bird-foot delta of the Mississippi River**.
- The Godavari River represents lobate delta.



Lobate: Shaped like a lobe

Godavari – Lobate
Krishna – Arcuate
Kaveri – Quadrilateral
Nile, Indus, Ganga-Brahmaputra – Arcuate
All the above are more or less the same kind (arcuate) of deltas

- Both of these types have a large sediment supply that tends to disperse sediment along the shoreline.
- A lobate delta (a subtype of fan-shaped delta) is formed if the river water is as dense as the seawater (precipitation or coagulation of river sediments occur immediately, and hence the delta is not elongated).
- A bird-boot delta (elongated delta) is formed when the river water is lighter than seawater (precipitation or coagulation of river sediments can occur at a distance from shore, and hence the delta is elongated).

High-destructive deltas

- Shoreline energy is high and much of the sediment delivered by the river is reworked by wave action or currents before it is finally deposited. .
- Deltas formed by rivers such as the Nile and the Rhône have been classified as wave-dominated.
- In this class of high-destructive delta, sediment is finally deposited as arcuate sand barriers near the mouth of the river.

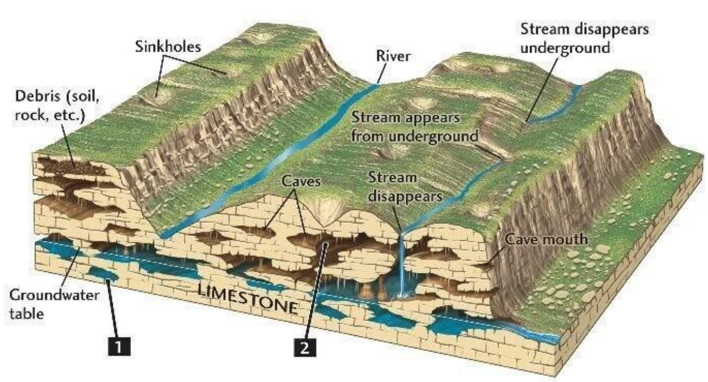
4.4 Karst Landforms and Cycle of Erosion

- Karst landforms are characterized by **underground** drainage systems with sinkholes, fissures, caves formed from the dissolution (chemical weathering) and erosion of soluble rocks such as limestone, dolomite.

- There is the general absence of surface drainage as the water flow is mostly subsurface (underground).
- In its pure state, limestone is made up of calcium carbonate, but where magnesium is also present, it is termed as dolomite.
- Limestone is an organically formed sedimentary rock (formed by the decomposition of calcareous shells) and is soluble in rainwater.
- The carbonic acid that causes karstic features is formed as rain passes through the atmosphere picking up carbon dioxide (CO_2).
- Once the rain reaches the ground, it may pass through soil that can provide much more CO_2 to form a weak carbonic acid solution, which dissolves calcium carbonate (limestone).
- Karsts are so named after a province of **Yugoslavia** (in Balkans) **on the Adriatic Sea** coast where such formations are most noticeable.

Conditions for the formation of karst topography

- Surface or subsurface strata made up of porous water-soluble rocks such as limestone.
- Thinly bedded and highly jointed and cracked rock strata that make it easy for the water to seep in.
- Moderate to abundant rainfall for chemical weathering of limestone.
- A perennial source of water and a low water table to erode the weathered rock.



Sinkhole/Swallow Hole

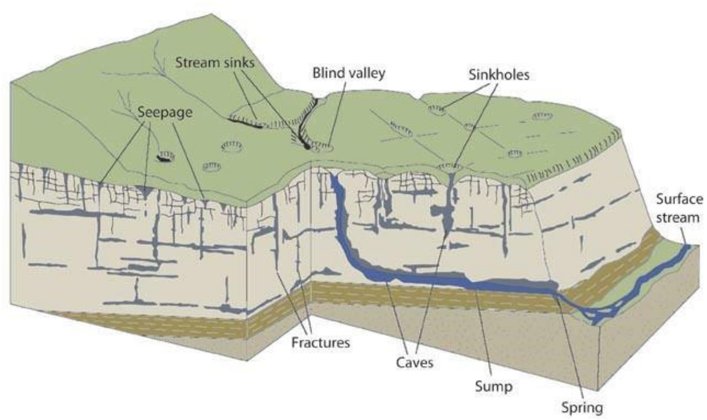
- Sinkholes are funnel-shaped depressions developed by enlargement of the cracks found in porous water-soluble rocks, as a result of continuous solvent action (chemical weathering) of the rainwater.
- The surface streams disappear underground through swallow holes.
- There is a great variation in size and depth of sinkholes.


Karst Window

- When some adjoining sinkholes collapse, they form an open, broad area called a karst window.

Polje/Blind Valley

- Dolines are small depressions dotting a karst landscape. They are less common than sinkholes
- Some adjoining dolines may come together to form a long, narrow trench called uvala.
- Some uvalas may coalesce to create a 'U' shaped valley called polje.
- If the streams lose themselves in these valleys, then these are called blind valleys.



Cavern

- This is an underground cave formed by water action by various methods in a limestone stratum.
- Mechanical action by rock debris and pebbles and solution action of water may be responsible for cavern formation.
- In India, such caves can be seen in Bastar, Dehradun, Shillong plateau.

Arch/Natural Bridge

- When a part of the cavern collapses the portion, which keeps standing forms an arch.

Sinking Creeks/Bogas

- In a karst valley, the water often gets lost through cracks and fissures in the bed. These are called sinking creeks, and if their tops are open, they are called bogas.

Stalactite and Stalagmite

- When water containing limestone seeps through the roof in the form of a continuous chain of drops a small deposit of limestone is left behind due to evaporation of water contributing to the formation of a lean inverted cone-like structure growing downwards from the roof called stalactite.
- The remaining portion of the drop falls to the floor. This also evaporates, leaving behind a small deposit of limestone aiding the formation of a stalagmite, thicker and flatter, rising upwards from the floor.
- Sometimes, stalactite and stalagmite join together to form a complete pillar known as the column.

Dry Valley/Hanging Valley/Bourne

- Sometimes, a stream erodes so much that it goes very deep. The water table is also lowered. Now the tributaries start serving the subterranean drainage and get dried up. These are dry valleys or bournes.
- Lack of adequate quantities of water and reduced erosion leaves them hanging at a height from the main valley. Thus, they are also referred to as hanging valleys.

The Karst Cycle of Erosion

Youth

- Youth begins with the surface drainage on an initial limestone surface.
- Gradually, the upper impervious layer is eroded.
- Dolines, sinkholes and swallow holes are formed.

- No large caverns exist, and underground drainage has not yet completed its course.

Maturity

- There is maximum underground drainage.
- Surface drainage is limited to short-sinking cracks ending in swallow holes or blind valleys.
- Cavern networks are characteristic of this stage.
- Late maturity marks the beginning of the decline of karst features.
- The portions of cavern streams are exposed through karst windows. These expand to form large uvalas, and detached areas of original limestone upland begin to stand out as hums.

Old Age

- Large-scale removal of limestone mass leaves behind a karst plain.
- There is a reappearance of surface drainage with only a few isolated hums as remnants of the original limestone terrain.

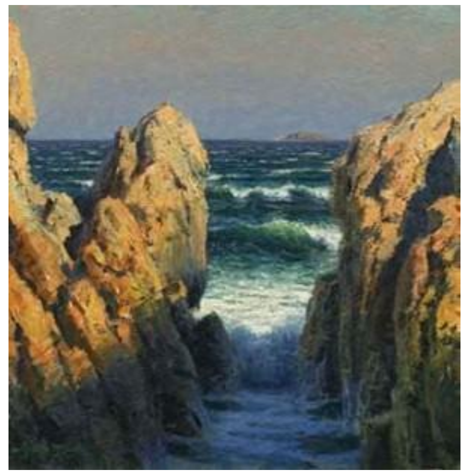
4.5 Marine Landforms and Cycle of Erosion

- Sea waves, aided by winds, currents, tides and storms carry on the erosional and depositional processes.
- The erosive work of the sea depends upon size and strength of waves, slope, the height of the shore between low and high tides, the shape of the coast, the composition of rocks, depth of water, human activity etc.
- The wave pressure compresses the air trapped inside rock fissures, joints, faults, etc. forcing it to expand and rupture the rocks along weak points. This is how rocks undergo weathering under wave action.
- Waves also use rock debris as instruments of erosion (glaciers are quite good at this). These rock fragments carried by waves themselves get worn down by striking against the coast or one another.
- The solvent or chemical action of waves is another mode of erosion, but it is pronounced only in case of soluble rocks like limestone and chalk.

Marine Erosional Landforms

Chasms

- These are narrow, deep indentations (a deep recess or notch on the edge or surface of something) carved due to headward erosion (downcutting) through vertical planes of weakness in the rocks by wave action.
- With time, further headward erosion is hindered by lateral erosion of chasm mouth, which itself keeps widening till a bay is formed.



Wave-Cut Platform

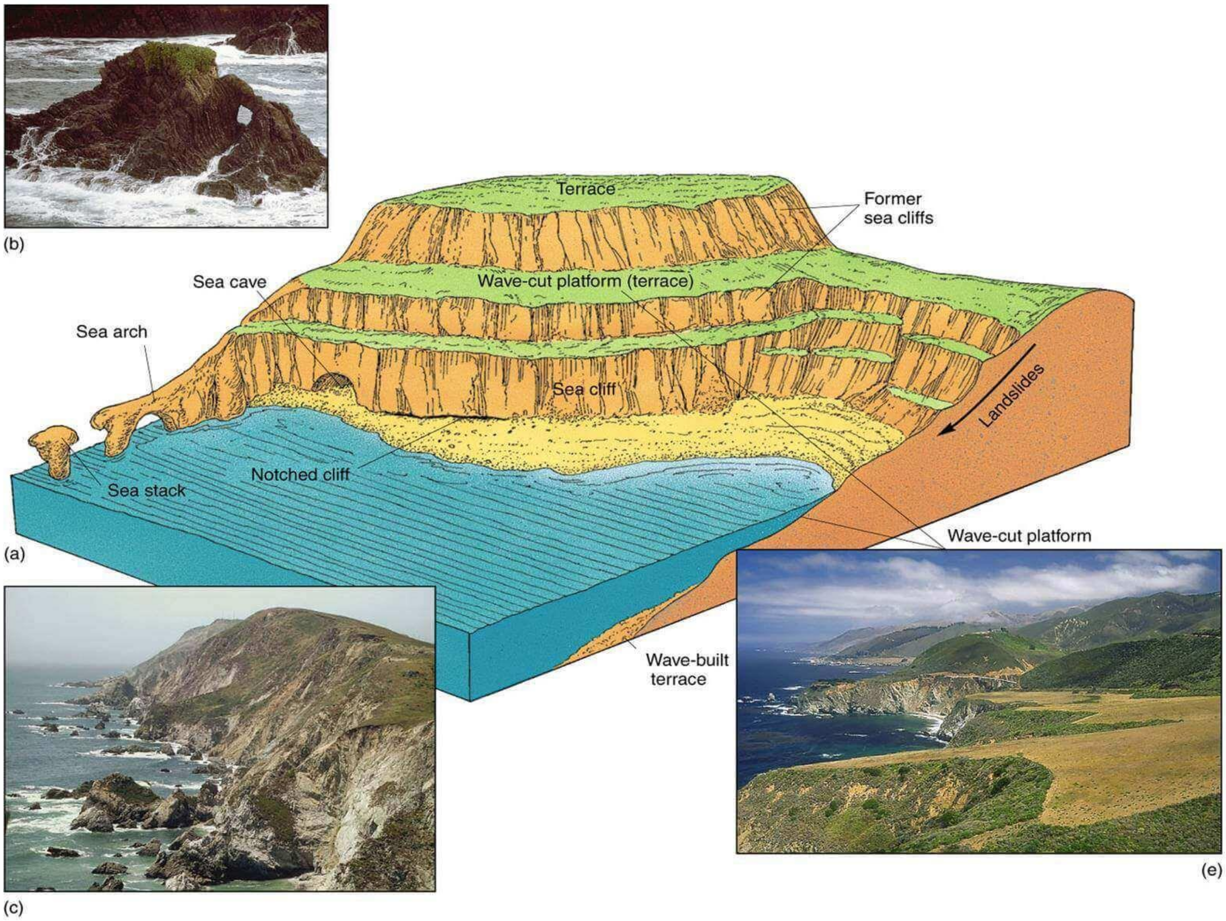
- When the sea waves strike against a cliff, the cliff gets eroded (lateral erosion) gradually and retreats.
- The waves level out the shore region to carve out a horizontal plane or a wave-cut platform.
- The bottom of the cliff suffers the maximum intensive erosion by waves and, as a result, a notch appears at this position.

Sea Cliff

- Shoreline marked by a steep bank (escarpment, scarp).

Sea Caves

- Differential erosion by sea waves through rock with varying resistance across its structure produces arched caves in rocks called sea caves.



Sea Arches

- When waves from opposite directions strike a narrow wall of rock, differential erosion of the rock leaves a **bridge like structure** called Sea arch.

Stacks/Skarries/Chimney Rock

- When a portion of the sea arch collapses, the remaining column-like structure is called a stack, skarry or chimney rock.

Hanging Valleys

- If the fluvial erosion of a stream at the shore doesn't match the retreat of the sea, the rivers appear to be hanging over the sea. These river valleys are called hanging valleys.

Blow Holes or Spouting Horns

- The burst of water through a small hole on a sea cave due to the compression of air in the cave by strong waves. They make a peculiar noise.

Plain of Marine Erosion/Peneplain

- The eroded plain left behind by marine action is called a plain of marine erosion. If the level difference between this plain and the sea level is not much, the agents of weathering convert it into a peneplain.

Marine Depositional Landforms

Beach

- This is the temporary covering of rock debris on or along a wave-cut platform.

Bar

- Currents and tidal currents deposit rock debris and sand along the coast at a distance from the shoreline.
- The resultant landforms which remain submerged are called bars.
- The enclosed water body so created is called a **lagoon.**

Barrier

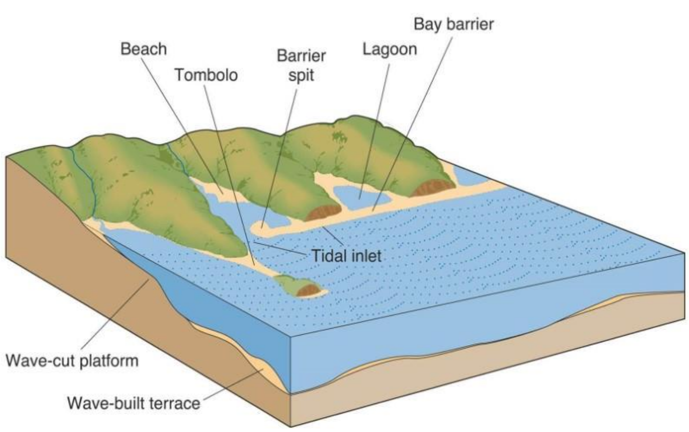
- It is the overwater counterpart of a bar.

Spit and Hook

- A spit is a projected deposition joined at one end to the headland, with the other end free in the sea.
- The mode of formation is similar to a bar or barrier.
- A shorter spit with one end curved towards the land is called a **hook.**

Tombolos

- Sometimes, islands are connected to each other by a bar called tombolo.



Coastlines

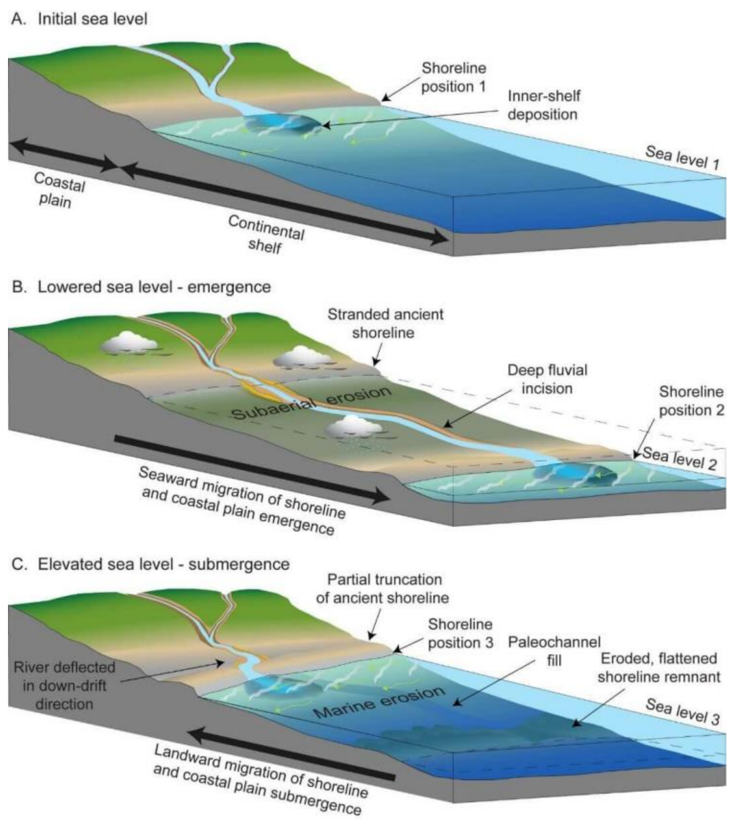
- The boundary between the coast (the part of the land adjoining or near the sea) and the shore (the land along the edge of a sea) is known as the coastline.

Coastlines can be divided into the following classes:

1. Coastline of Emergence
2. Coastline of Submergence
3. Neutral coastline
4. Compound coastline
5. Fault coastline

- Coastline is modified either due to rise or fall in sea levels or upliftment or subsidence of land, or both.

Coastlines of Emergence



- These are formed either by an uplift of the land or by the lowering of the sea level.
- Bars, spits, lagoons, salt marshes, beaches, sea cliffs and arches are the typical features.
- The **east coast of India**, especially its south-eastern part **(Tamil Nadu coast)**, appears to be a **coast of emergence**.
- The **west coast of India**, on the other hand, is **both emergent and submergent**. The **northern portion of the coast is submerged** as a result of faulting and the southern portion, that is the **Kerala coast, is an example of an emergent coast**.

- **Coramandal coast ➔ Tamil Nadu Coast ➔ Coastline of emergence**
- **Malabar coast ➔ Kerala Coast ➔ Coastline of emergence**
- **Konkan coast ➔ Maharashtra and Goa Coast ➔ Coastline of submergence**

Coastlines of Submergence

- A submerged coast is produced either by subsidence of land or by a rise in sea level.
- Ria, fjord, Dalmatian and drowned lowlands are its typical features.

Ria

- When streams dissect a region into a system of valleys and divides, submergence produces a highly irregular shoreline called ria coastline.
- The coast of south-west Ireland is a typical example of ria coastline.

Fjord

- Some coastal regions have been heavily eroded by glacial action, and the valley glacier troughs have been excavated below sea level.
- After the glaciers have disappeared, a fjord coastline emerges.
- These coasts have long and narrow inlets with very steep sides.
- The fjord coasts of Norway are a typical example.

Dalmatian

- The Dalmatian coasts result by submergence of mountain ridges with alternating crests and troughs which run parallel to the sea coast.
- The Dalmatian coast of Yugoslavia is a typical example.

Drowned lowland

- A drowned lowland coast is low and free from indentations, as the submergence of a low-lying area forms it.
- It is characterized by a series of bars running parallel to the coast, enclosing lagoons.
- The Baltic coast of eastern Germany is an example of this type of coastline.

Neutral Coastlines

- These are coastlines formed as a result of new materials being built out into the water.
- The word 'neutral' implies that there need be no relative change between the level of the sea and the coastal region of the continent.
- Neutral coastlines include the alluvial fan-shaped coastline, delta coastline, volcano coastline and the coral reef coastline.

Compound Coastlines

- Such coastlines show the forms of two of the previous classes combined, for example, submergence followed by emergence or vice versa.
- The coastlines of Norway and Sweden are examples of compound coastlines.

Fault Coastlines

- Such coastlines are unusual features and result from the submergence of a downthrown block along a fault, such that the uplifted block has its steep side (or the faultline) standing against the sea forming a fault coastline.

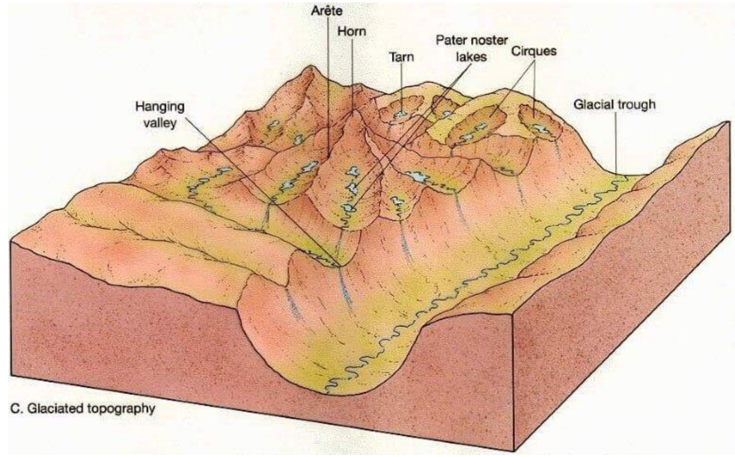
4.6 Glacial Landforms and Cycle of Erosion

- A glacier is a moving mass of ice at speeds averaging a few meters a day.
- Types of Glaciers: **continental glaciers, ice caps, piedmont glaciers and valley glaciers**.
- The continental glaciers are found in Antarctica and Greenland. The biggest continental ice sheet in **Iceland.**
- Ice caps are the covers of snow and ice on mountains from which the valley or mountain glaciers originate.
- The piedmont glaciers form a continuous ice sheet at the base of mountains as in southern Alaska.
- The valley glaciers, also known as Alpine glaciers, are found in higher regions of the Himalayas in our country and all such high mountain ranges of the world.
- The largest of Indian glaciers occur in the Karakoram range, viz. **Siachen (72 km),** while Gangotri in Uttar Pradesh (Himalayas) is 25.5 km long.
- A glacier is charged with rock debris which are used for erosional activity by moving ice.
- A glacier during its lifetime creates various landforms which may be classified into erosional and depositional landforms.

Glacial Erosional Landforms

Cirque/Corrie

- Hollow basin cut into a mountain ridge.
- It has a steep sided slope on three sides, an open end on one side and a flat bottom.
- When the ice melts, the cirque may develop into a **tarn lake.**



Glacial Trough

- Original stream-cut valley further modified by glacial action.
- It is a 'U' Shaped Valley. It is at a mature stage of valley formation.
- Since glacial mass is heavy and slow-moving, erosional activity is uniform – horizontally as well as vertically.
- A steep-sided and flat bottomed valley results, which has a 'U' shaped profile.

Hanging Valley

- Formed when smaller tributaries are unable to cut as deeply as bigger ones and remain 'hanging' at higher levels than the main valley as **discordant tributaries**.
- A valley carved out by a small tributary glacier that joins with a valley carved out by a much larger glacier.

Arete

- Steep-sided, sharp-tipped summit with the glacial activity cutting into it from **two** sides.

Horn

- The ridge that acquires a 'horn' shape when the glacial activity cuts it from **more than two sides.**

D-Fjord

- Steep-sided narrow entrance-like feature at the coast where the stream meets the coast.
- Fjords are common in **Norway, Greenland and New Zealand**.

Why are the world's highest mountains at the equator?

- Ice and glacier coverage at lower altitudes in cold climates is more important than the collision of tectonic plates. (Glacial erosion is very strong because of the huge boulders of rocks carried by the glacial ice that graze the surface. Though ice moves only a few meters a day, it can take along it huge rocks that can peel the outer layers.)
- Scientists have solved the mystery of why the world's highest mountains sit near the equator.
- Colder climates are better at eroding peaks. In colder climates, the snowline on mountains starts lower down, and erosion takes place at lower altitudes.
- In general, mountains only rise to around 1,500m above their snow lines, so it is the altitude of these lines — which depends on climate and latitude — which ultimately decides their height.
- At low latitudes, the atmosphere is warm, and the snowline is high. Around the equator, the snowline is about 5,500m at its highest, so mountains get up to 7,000m.
- There are a few exceptions (that are higher), such as Everest, but extremely few.
- When you then go to Canada or Chile, the snowline altitude is around 1,000 m, so the mountains are around 2.5km.

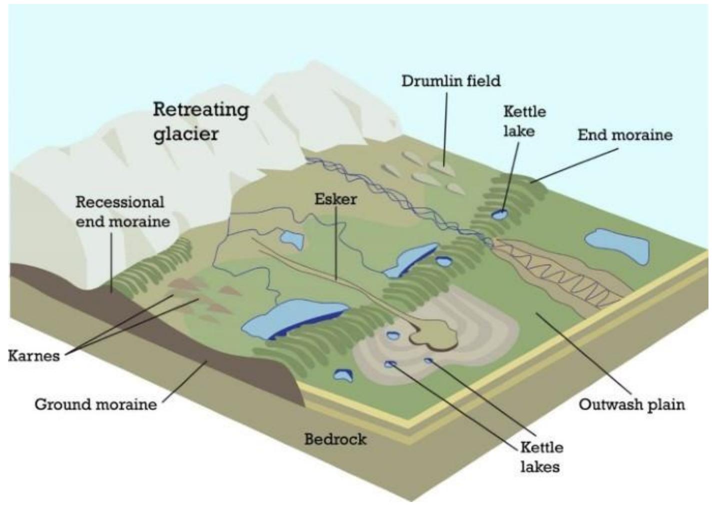
Glacial Depositional Landforms

Outwash Plain

- When the glacier reaches its lowest point and melts, it leaves behind a stratified deposition material, consisting of rock debris, clay, sand, gravel etc. This layered surface is called till plain or an outwash plain.

Esker

- Winding ridge of un-assorted depositions of rock, gravel, clay etc. running along a glacier in a till plain.
- The eskers resemble the features of an embankment and are often used for making roads.



Kame Terraces

- Kame terraces form when sediment accumulates in ponds and lakes trapped between lobes of glacier ice or between a glacier and the valley side.

Drumlin

- Inverted boat-shaped deposition in a till plain caused by deposition.

Kettle Holes

- Formed when the deposited material in a till plain gets depressed locally and forms a basin.

Moraine

- The general term applied to rock fragments, gravel, sand, etc. carried by a glacier.
- Depending on its position, the moraine can be ground moraine and end moraine.

Glacial Cycle of Erosion

Youth

- The stage is marked by the inward cutting activity of ice in a cirque.
- Aretes and horns are emerging. The hanging valleys are not prominent at this stage.

Maturity

- Hanging valleys start emerging. The opposite cirques come closer, and the glacial trough acquires a stepped profile which is regular and graded.

Old Age

- The emergence of a 'U'-shaped valley marks the beginning of old age.
- An outwash plain with features such as eskers, kame terraces, drumlins, kettle holes etc. is a prominent development.

4.7 Arid Landforms and Cycle of Erosion

- Arid regions are regions with scanty rainfall. Deserts and Semi-arid regions fall under arid landforms.

Erosional Arid Landforms

Water Eroded Arid Landforms

Rill

- A rill is a narrow and shallow channel cut into the soil by the erosive action of flowing water.

Gully

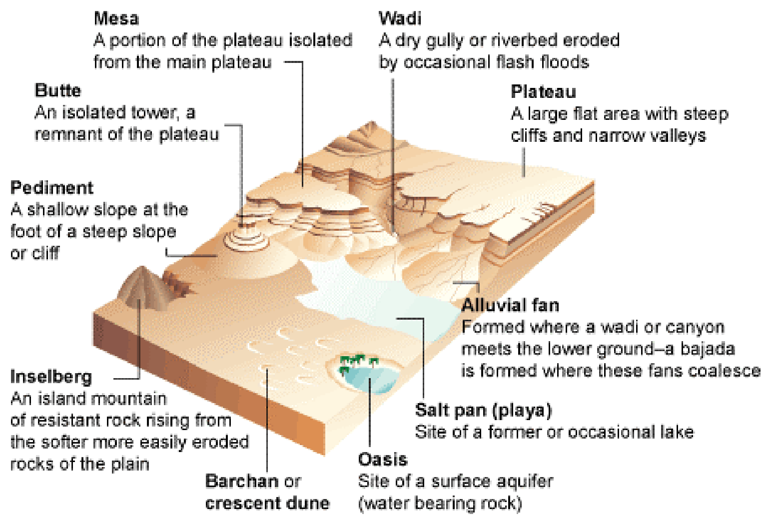
- A gully is a landform created by running water. Gullies resemble large ditches or small valleys but are metres to tens of metres in depth and width.

Ravine

- A ravine is a landform narrower than a canyon and is often the product of stream cutting erosion. Ravines are typically classified as larger in scale than gullies, although smaller than valleys.

Badland Topography

- In arid regions, occasional rainstorms produce numerous rills and channels which extensively erode weak sedimentary formations.
- Ravines and gullies are developed by linear fluvial erosion leading to the formation of badland topography.
- Example: **Chambal Ravines.**



Bolsons

- The intermontane basins in dry regions are generally known as bolsons.

Playas

- Three unique landforms viz. pediments, bajadas and playas are typically found in bolsons.
- Small streams flow into bolsons, where water is accumulated. These **temporary lakes are called playas.**
- After the evaporation of water, salt-covered playas are called **salinas**.

Pediments

- In form and function there is no difference between a pediment and an alluvial fan; however,

pediment is an erosional landform while a fan is a constructional one.
- A true pediment is a rock cut surface at the foot of mountains.

Bajada

- Bajadas are **moderately sloping depositional plains** located between pediments and playa.
- Several alluvial fans coalesce to form a bajada.

Wind Eroded Arid Landforms

- The wind or **Aeolian erosion** takes place in the following ways, viz. deflation, abrasion, and attrition.
- Deflation == removing, lifting and carrying away dry, unsorted dust particles by winds. It causes depressions known as blowouts.
- Abrasion == When wind loaded with sand grains erodes the rock by grinding against its walls is called abrasion or sandblasting.
- Attrition == Attrition refers to wear and tear of the sand particles while they are being transported.

Following are the major landforms produced by wind erosion.

Deflation basins

- Deflation basins, called blowouts, are hollows formed by the removal of particles by wind. Blowouts are generally small but may be up to several kilometres in diameter.

Mushroom rocks

- A mushroom rock also called **rock pedestal or a pedestal rock**, is a naturally occurring rock whose shape, as its name implies, resembles a mushroom.
- The rocks are deformed in many different ways: by erosion and weathering, glacial action, or from a sudden disturbance. Mushroom rocks are related to, but different from, yardang.

Inselbergs

- A **monadnock or inselberg** is an isolated hill, knob, ridge, outcrop, or small mountain that rises abruptly from a gently sloping or virtually level surrounding plain.

Demoiselles

- These are rock pillars which stand as resistant rocks above soft rocks as a result of differential erosion of hard and soft rocks.

Zeugen

- A table-shaped area of rock found in arid and semi-arid areas formed when the more resistant rock is reduced at a slower rate than softer rocks around it.

Yardangs

- Ridge of rock, formed by the action of the wind, usually parallel to the prevailing wind direction.

Wind bridges and windows

- Powerful wind continuously abrades stone lattices, creating holes. Sometimes the holes are gradually widened to reach the other end of the rocks to create the effect of a window—thus forming a wind window. Window bridges are formed when the holes are further widened to form an arch-like feature.

Arid Depositional Landforms

- The depositional force of wind also creates landforms. These are as follows.

Ripple Marks

- These are depositional features on a small scale formed by saltation (the transport of hard particles over an uneven surface in a turbulent flow of air or water).

Sand Dunes

- Sand dunes are heaps or mounds of sand found in deserts. Generally, their heights vary from a few metres to 20 metres, but in some cases, dunes are several hundred metres high and 5 to 6 km long.

Some of the forms are discussed below:

Longitudinal dunes

- Formed parallel to the wind movement. The windward slope of the dune is gentle whereas the leeward side is steep. These dunes are commonly found at the heart of trade-wind deserts like the Sahara, Australian, Libyan, South African and Thar deserts.

Transverse dunes

- Dunes deposited perpendicular (transverse) to the prevailing wind direction.

Barchans

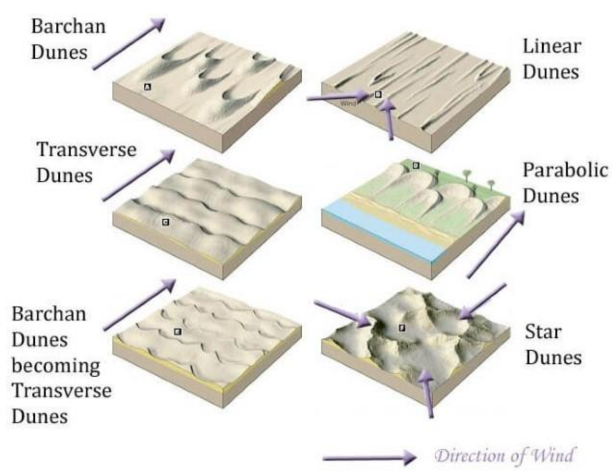
- Crescent-shaped dunes. The windward side is convex whereas the leeward side is concave and steep.

Parabolic dunes

- They are U-shaped and are much longer and narrower than barchans.

Star dunes

- Have a high central peak, radically extending three or more arms.

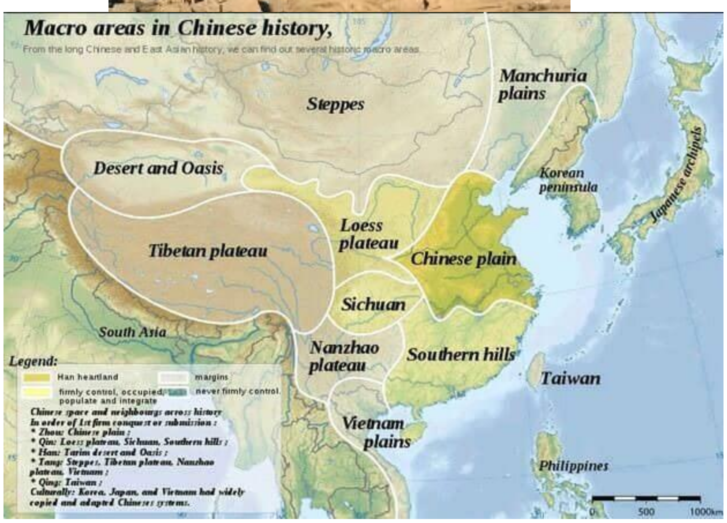


Loess

- In some parts of the world, windblown dust and silt blanket the land. This layer of fine, **mineral-rich** material is called loess.
- Extensive loess deposits are found in **northern China, the Great Plains of North America, central Europe, and parts of Russia and Kazakhstan**.
- The thickest loess deposits are near the **Missouri River** in the U.S. state of Iowa and along the **Yellow River in China**.
- Loess accumulates, or builds up, at the edges of deserts. For example, as the wind blows across the Gobi, a desert in Asia, it picks up and carries fine particles. These particles include sand crys-

tals made of quartz or mica. It may also contain organic material, such as the dusty remains of skeletons from desert animals.

- Loess often develops into **extremely fertile agricultural soil**. It is full of minerals and drains water very well. It is easily tilled, or broken up, for planting seeds.
- Loess usually erodes very slowly – Chinese farmers have been working the loess around the Yellow River for more than a thousand years.



5. Lakes

- A lake is a body of water of considerable size, localised in a basin, that is surrounded by land apart from a river or other outlet that serves to feed or drain the lake.
- Lakes lie on land and are not part of the ocean, and therefore are distinct from lagoons, and are also larger and deeper than ponds.
- Natural lakes are generally found in mountainous areas, rift zones, and areas with ongoing glaciation.
- Most lakes have at least one natural outflow (**exorheic lake**) in the form of a river or stream, which maintain a lake's average level by allowing the drainage of excess water
- Other lakes are found in **endorheic basins**. Some lakes do not have a natural outflow and lose water solely by evaporation or underground seepage or both. They are termed **endorheic lakes**.
- The majority of lakes on Earth are fresh water, and most lie in the Northern Hemisphere at higher latitudes.
- Canada, Finland and Siberia contain most of the freshwater lakes.
- Lakes are temporary features of the earth's crust; they will eventually be eliminated by the double process of draining and silting up.

5.1 Classification of Lakes

Temporary lakes

- Lakes may exist temporarily filling up the small depressions of undulating ground after a heavy shower.
- In this kind of lakes, evaporation is greater than precipitation.
- Example: Small lakes of deserts.

Permanent lakes

- In this kind of lakes, Evaporation is lesser than Precipitation.
- These lakes are deep and carry more water than could ever be evaporated.
- Example: **Great Lakes of North America, East African Rift Lakes**.

Freshwater lakes

- Most of the lakes in the world are fresh-water lakes fed by rivers and without-flowing streams e.g. Great Lakes of North America.

Saline lakes

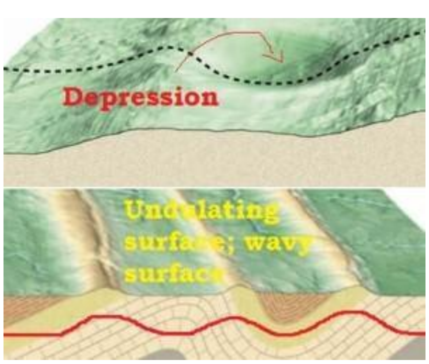
- Salt lakes (saline lakes) can form where there is **no natural outlet** or where the water evaporates rapidly, and the drainage surface of the water table has a higher-than-normal salt content.

- Because of the intense evaporation (negative freshwater balance, i.e., more water is lost in evaporation than gained from rivers) these lakes are saline.
- For example, the **Dead Sea** has a salinity (salt content) of 250 parts per thousand, and the **Great Salt Lake of Utah, U.S.A**. has a salinity of 220 parts per thousand.
- Examples of salt lakes include the **Great Salt Lake**, the **Aral Sea** and the **Dead Sea**.
- **Playas or salt lakes** are a common feature of deserts (arid landforms).

Lakes Formed by Earth Movement:

Tectonic lakes

- Due to the warping (simple deformation), subsidence (sliding downwards), bending and fracturing (splitting) of the earth's crust, tectonic depressions occur.
- Such depressions give rise to **lakes of immense sizes and depths**.
- They include **Lake Titicaca** and the **Caspian Sea.**



Rift valley lakes

- A rift valley is formed when two blocks of earth move apart letting the 'in-between' block slide downwards. Or, it's a sunken land between two parallel faults.
- Rift valleys are deep, narrow and elongated. Hence the lakes formed along rift valleys are also deep, narrow and very long.
- Water collects in troughs (valley in the rift), and their floors are often below sea level.
- The best-known example is the **East African Rift Valley** which runs through Zambia, Malawi, Tanzania, Kenya and Ethiopia, and extends along the Red Sea to Israel and Jordan over a total distance of 3,000 miles.
- It includes such lakes as **Lakes Tanganyika**, **Malawi, Rudolf, Edward, Albert**, as well as the **Dead Sea** 1,286 feet below mean sea level, the **world's lowest lake**.

Lakes Formed by Glaciation:

Cirque lakes or tarns

- Cirque is a hollow basin cut into a mountain ridge.
- It has a steep-sided slope on three sides, an open end on one side and a flat bottom.
- When the ice melts, the cirque may develop into a tarn lake.

Rock-hollow lakes

- The advance and retreat of glaciers can scrape depressions in the surface where water accumulates; such lakes are common in Scandinavia, Patagonia, Siberia and Canada.
- These are formed by ice-scouring (eroding) when ice sheets scoop out (dig) hollows on the surface.
- Such lakes of glacial origin are abundant in **Finland (Land of Lakes)**. It is said that there are over 35,000 glacial lakes in Finland.

Lakes due to morainic damming of valleys

- Valley glaciers often deposit morainic debris across a valley so that lakes are formed when water accumulates behind the barrier.

Lakes Formed by Volcanic Activity:

Crater and caldera lakes

- During a volcanic explosion, the top of the cone may be blown off leaving behind a natural hollow called a crater. This may be enlarged by subsidence into a caldera.
- In dormant or extinct volcanoes, rain falls straight into the crater or caldera which has no superficial outlet and forms a crater or caldera lake. E.g. **Lake Toba (Indonesia)**.
- When water accumulates in an **impact crater** a crater lake is formed. Example: **Lonar in Maharashtra**.

Lakes Formed by Erosion:

Karst lakes

- The solvent action of rain-water on limestone carves out solution hollows. When these become clogged with debris lakes may form in them.
- The collapse of limestone roofs of underground caverns may result in the exposure of long, narrow- lakes that were once underground.

Wind-deflated lakes

- The winds in deserts create hollows. These may reach groundwater which seeps out forming small, shallow lakes. Excessive evaporation causes these to become **salt lakes and playas**.
- Example: **Great Basin of Utah, U.S.A.**

Lakes Formed by Deposition:

Lakes due to river deposits

- Ox-bow lake, e.g. those that occur on the flood-plains of Lower Mississippi, Lower Ganges etc.

Lakes due to Marine deposits

- Also called as Lagoons. Example: Lake Chilka.

Lakes due to damming of water

- Lakes formed by these processes are also known as barrier lakes. Landslides, avalanches may block valleys so that rivers are dammed. Such lakes are short-lived.
- Example: Lakes that are formed in Shiwaliks (Outer Himalayas). Dehradun (all Duns) were lakes few centuries ago.

Man-made lakes

- Besides the natural lakes, man has now created artificial lakes by erecting a concrete dam across a river valley so that the river water can be kept back to form reservoirs.
- Example: Lake Mead above the Hoover Dam on the Colorado River, U.S.A.
- Man's mining activities, e.g. tin mining in West Malaysia, have created numerous lakes. Inland fish culture has necessitated the creation of many fishing lakes.

5.2 Lakes and Man

- In countries where they are found in abundance, such as Finland, Canada, U.S.A., Sweden and the East African states, lakes are used as inland waterways.

Means of communication

- Large lakes like the Great Lakes of North America provide a cheap and convenient form of transport for heavy and bulky goods such as coal, iron, machinery, grains and timber.
- **The Great Lakes-St. Lawrence waterways** penetrate more than 1,700 miles into the interior. They are thus used as the chief arteries of commerce.

Economic and industrial development

- The Great Lakes-St. Lawrence waterways were responsible for the development of the interior wheat farms and lakeside industries.

Water storage

- E.g. Kolleru lake in Andhra Pradesh.

Hydro-electric power generation

- E.g. Artificial lakes like Hirakud.

Agricultural purposes

- Many dams are built across artificial lakes. E.g. Bhakra Nangal Dam (Himachal Pradesh; its reservoir is known as the **Gobind Sagar Lake**) and Hirakud Dam (Odisha) on the Mahanadi in India.

Regulating river flows

- E.g. **Hoover Dam on the River Colorado** and the **Bhakra and Nangal Dams on the Sutlej** in India.
- The Hirakud dam was originally conceived as a flood control measure. But the project is criticised for doing more damage than good.

Moderation of climate

- Land and sea breeze.

Source of food

- Many large lakes have important supplies of protein food in the form of freshwater fish. Sturgeon is commercially caught in the Caspian Sea, salmon and sea trout in the Great Lakes.

Source of minerals

- Salt lakes provide valuable rock salts. In the Dead Sea, the highly saline water is being evaporated and produces common salt. **Borax** is mined in the salt lakes of the Mojave Desert.

Tourist attraction and health resorts

- E.g. Lake Chilka, Leh, Dead Sea etc.

5.3 Important Lakes on Earth

- **Note 1:** ***Black Sea is not a lake*** *since* ***Bosporus*** *and* ***Dardanelles Straits*** *connect it to the Mediterranean Sea. Many big rivers fall into the Black Sea, making the salinity of its surface water half that of the ocean: 17 per cent.*
- **Note 2:** *the* ***Caspian Sea and the Dead Sea are lakes****.* ***The surface and shores of the Dead Sea are 423 metres below sea level, making it Earth's lowest elevation on land.***
- **Note 3:** *While writing facts about lakes, people ignore the Caspian Sea because for them it is too big to be considered a lake. But it is still a lake (closed body).*

World's Highest and Lowest Lakes

- The world's highest lake, if size is not a criterion, maybe the **crater lake of Ojos del Salado**, at 6,390 metres. It is in the Andes.

- The **highest large lake** in the world is the **Pumoyong Tso (Pumuoyong Tso**; 5018 metres above sea level) in the Tibet Autonomous Region of China.
- The **world's highest commercially navigable lake** is **Lake Titicaca** in Peru and Bolivia border at 3,812 m. It is also the **largest lake in South America**.
- The world's **lowest lake is the Dead Sea**, bordering Israel and Jordan at 418 metres below sea level. It is also one of the lakes with the highest salt concentration.

The largest lakes (surface area) by continent

- **Australia – Lake Eyre** (salt lake)
- **Africa – Lake Victoria**, also the third-largest freshwater lake on Earth. It is one of the Great Lakes of Africa.
- **Antarctica – Lake Vostok** (subglacial)
- **Asia – Lake Baikal** (if the Caspian Sea is considered a lake, it is the largest in Eurasia, but is divided between the two geographic continents)
- **Europe – Lake Ladoga**, followed by Lake Onega, both located in northwestern Russia.
- **North America – Lake Superior**.
- **South America – Lake Titicaca**, which is also the highest navigable body of water on Earth at 3,812 metres above sea level. The much larger Lake Maracaibo is a contiguous body of water with the sea, so it is ignored.

Largest Lakes by Surface Area

1. **Caspian Sea (saline lake) – Asia**
2. **Lake Superior (freshwater lake) – North America**
3. **Lake Victoria (freshwater lake) – Africa**
4. **Lake Huron (freshwater lake) – North America**
5. **Lake Michigan (freshwater lake) – North America**

Largest Lakes by Volume

1. **Caspian Sea (saline lake)**
1. **Lake Baikal (fresh water lake)**
2. **Lake Tanganyika (freshwater lake)**
3. **Lake Superior (freshwater lake)**

Deepest Lakes in the World

1. **Lake Baikal**
2. **Lake Tanganyika**
3. **Caspian Sea**

Lake Baikal (Deepest)

- Located in Siberia, Russia.
- It is the **deepest lake in the world** (1,600+ metres deep).
- It is the world's second largest lake by volume (the Caspian Sea is the largest lake) and the world's largest freshwater lake by volume.
- It is the second longest freshwater lake.

Lake Tanganyika (Longest)

- The **longest freshwater lake in the world**.
- It is also the second largest freshwater lake by volume.
- It is the second deepest lake in the world, after Lake Baikal.

Great Lakes

- Great Lakes of North America are a series of interconnected freshwater lakes which connect to the Atlantic Ocean through the **Saint Lawrence Seaway**.
- **Lake Michigan is the largest lake that is entirely within one country**.

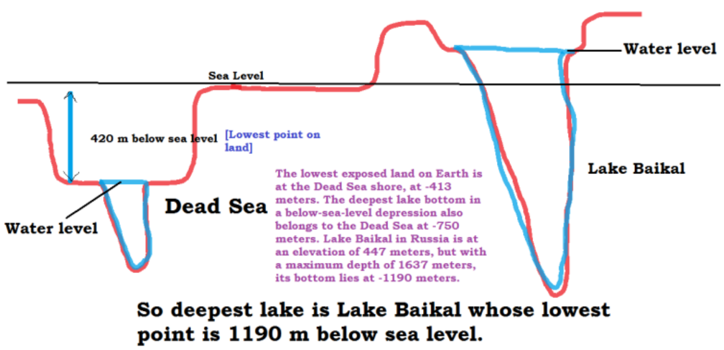
Superior, Michigan, Huron, Erie, and Ontario (in the order of west to east)
Superior, Huron, Michigan, Erie, and Ontario (In the order of largest to smallest)

Dead Sea

- Also called the Salt Sea.

- Lake bordering Jordan to the east, and Palestine and Israel to the west.
- It Earth's lowest elevation on land.

- Lake Baikal is the deepest lake. Its depth is 1,642 m. Considering that the lake surface is at 455.5 m above sea level, the deepest point of Lake Baikal is at 1186.5 m below sea level.
- The lowest point on land is the Dead Sea. It's **420 meters below sea level**. Its depth is 306 m. The lowest point of dead sea is 420+306 = 726 meters below sea level.
- There is a fundamental difference between the lowest point on land and the deepest lake.



Aral Sea

- It was a lake lying between Kazakhstan in the north and Uzbekistan, in the south.
- The Aral Sea has been steadily shrinking since the 1960s after the rivers that fed the lake were diverted to feed Soviet irrigation projects.
- The Aral Sea in 1989 (left) and 2008 (right).

6. Plateau

- A plateau is a flat-topped tableland.
- Plateaus occur in every continent and take up a **third of the Earths land**.
- They are one of the four major landforms, along with mountains, plains, and hills.
- Plateaus, like mountains, may be young or old. The Deccan plateau in India is one of the oldest plateaus.
- Valleys form when river water cuts through the plateau. The Columbia Plateau, between the Cascade and the Rocky Mountains in the north-western United States, is cut through by the Columbia River.
- Sometimes, a plateau is so eroded that it is broken up into smaller raised sections called **outliers.**
- Many outlier plateaus are composed of very old, dense rock formations.
- Iron ore and coal often are found in plateau outliers.
- Plateaus are very useful because they are rich in mineral deposits. As a result, many of the mining areas in the world are located in the plateau areas.

6.1 Economic significance of plateaus

Plateaus are of great economic significance. Comment with reference to India And World.

- The plateau of France (Massif Central), the Deccan plateau of India, Katanga plateau of Congo (Copper mines), Western Australian plateau or Kimberly Plateau (diamond mines) and Brazilian plateau or Brazilian Highlands are very good sources of minerals.
- Iron, copper, gold, diamonds, Manganese, coal, etc., are found in these plateaus.

- East African plateau is famous for gold and diamond mining.
- In India, huge reserves of iron, coal and manganese are found in the Chotanagpur plateau.
- In the plateau areas, there may be several waterfalls as the river falls from a great height. In India, the **Hundru Falls** in the **Chotanagpur plateau** on the river **Subarnarekha** and the **Jog Falls in Karnataka** are examples of such waterfalls.
- These sites are ideal for hydro-electric power generation.
- **Angel falls** in Venezuela is also a waterfall that descends a plateau.
- Plateaus are not as useful as plains from agriculture perspective.
- It is difficult to dig wells and canals in plateaus due to the presence of hard rocks. This hampers irrigation.
- The hard rocks on plateaus cannot form fertile soil, but agricultural activities are promoted where lava soils have developed.
- The lava plateaus like **Deccan traps** are rich in **black soil** that is fertile and good for cultivation. Example: Maharashtra has good **cotton growing soils** called **regurs**.
- **Loess Plateau** in China has very fertile soils that are good for many kinds of crops.
- Many plateaus have scenic spots and are of great attraction to tourists (e.g. Jog Falls in Karnataka, Grand Canyon, USA, many waterfalls)

6.2 Plateau Formation

- Tectonic plateaus are formed from processes that create mountain ranges, **volcanism (Deccan Plateau),** crustal shortening (**Tibetan Plateau —** thrusting of one block of crust over another, and folding occurs. Example:), and thermal expansion **(Ethiopian Highlands)**.

Thermal expansion

- Plateaus caused by thermal expansion of the lithosphere are usually associated with hot spots.
- Thermal expansion of the lithosphere means the replacement of cold mantle lithosphere by hot asthenosphere (magma).
- When the lithosphere underlying a broad area is heated rapidly by an upwelling of hot material (mantle plume) in the underlying asthenosphere, the consequent warming and thermal expansion of the uppermost mantle causes uplift of the overlying surface.
- The **Yellowstone Plateau in the United States**, the **Massif Central in France**, and the **Ethiopian Plateau in Africa** are prominent examples.

Crustal shortening

- The great heights of some plateaus, such as the Plateau of Tibet is due to **crustal shortening.**
- Crustal shortening, which thickens the crust as described above, has created high mountains along what are now the margins of such plateaus.
- Plateaus that were formed by crustal shortening and internal drainage lie within major mountain belts and generally in arid climates.
- They can be found in North Africa, Turkey, Iran, and Tibet, where the African, Arabian, and Indian continental masses have collided with the Eurasian continent.

Volcanic flood basalts

- Plateaus can form where extensive lava flows and volcanic ash bury pre-existing terrain giving rise to **flood basalts or traps**.
- The volcanism involved in such situations is commonly associated with **hot spots**.
- For example, the basalts of the Deccan Traps, which cover the Deccan plateau in India, were erupted 60–65 million years ago over the same hot spot that presently underlies the volcanic island of **Reunion**.
- In North America, the Columbia River basalts may have been ejected over the same hot spot that underlies the **Yellowstone** area today.
- The lavas and ash are generally carried long distances from their sources and the **topography is not dominated by volcanoes or volcanic centres**.
- The thickness of the volcanic rock can be tens to even hundreds of metres, and the top surface of flood basalts is typically very flat but often with sharply incised canyons and valleys.

- Volcanic plateaus are commonly associated with massive eruptions that occurred during the Cenozoic or Mesozoic eras. Eruptions of that scale are rare, and none seems to have taken place in recent time.
- Volcanic plateaus include the **Columbia Plateau** in the north-western USA, **Deccan Traps** of peninsular India, **Laurentian plateau or The Canadian Shield** and the **Siberian Traps of Russia**.

Others

- Some plateaus, like the Colorado Plateau, the Ordos Plateau in northern China, or the East African Highlands (e.g. Kenya Dome), do not seem to be related to hot spots or to vigorous upwelling in the asthenosphere but appear to be underlain by unusually hot material.
- The reason for localised heating beneath such areas is poorly understood, and thus an explanation for the distribution of plateaus of that type is not known.
- There are some plateaus whose origin is not known. Those of the Iberian Peninsula and north-central Mexico exhibit a topography that is largely high and relatively flat.

6.3 Plateau Types

- There are two kinds of plateaus: **dissected plateaus** and **volcanic plateaus**.

Dissected plateau

- A dissected plateau forms as a result of upward movement in the Earth's crust.
- The slow collision of tectonic plates causes the uplift.
- The **Colorado Plateau**, in the western United States, Tibetan plateau etc. are examples.

Volcanic plateau

- A volcanic plateau is formed by numerous small volcanic eruptions that slowly build up over time, forming a plateau from the resulting lava flows.
- The **Columbia Plateau** in the north-western United States of America and **Deccan Traps** are two such plateaus.

Others

- **Intermontane plateaus** are the highest in the world, bordered by mountains. The **Tibetan Plateau** is one such plateau.
- **Continental plateaus** are bordered on all sides by the plains or seas, forming away from mountains.

6.4 Major plateaus of the World

Tibetan Plateau

- It is the **Highest and largest plateau** in the world and hence called the **'roof of the world'.**
- It is formed due to the collision of the Indo-Australian and Eurasian tectonic plates.
- The plateau is sufficiently high enough to reverse the Hadley cell convection cycles and to drive the monsoons of India towards the south.
- It covers most of the Autonomous Tibetan Region, Qinghai Province of Western China, and a part of Ladakh in Jammu and Kashmir.
- It is surrounded by mountains to the south by the Himalayan Range, to the northeast by the **Kunlun Range**, and to the west by the **Karakoram Range**.

Columbia – Snake Plateau

- River Columbia and its tributary Snake meet in this plateau.
- It is bordered by the **Cascade Range** and the **Rocky Mountains** and divided by the **Columbia River.**
- This plateau has been formed as the result of volcanic eruptions with a consequent coating of **basalt lava (flood basalt plateau).**

Colorado Plateau

- It lies in the western part of U.S.A. It is the largest plateau in America.
- It is divided by the **Colorado River** and the **Grand Canyon**.
- This plateau is an example of the intermontane plateau. Mesas and buttes are found here at many places (arid Landforms).
- The plateau is known for the groundwater which is under positive pressure and causes the emergence of springs called **Artesian wells**.

Deccan Plateau

- Deccan Plateau is a large plateau which forms most of the southern part of India.
- It is bordered by two mountain ranges, the Western Ghats and the Eastern Ghats.
- The plateau includes the Deccan Traps which is one of the largest volcanic features on Earth.
- Made of multiple basalt layers or lava flows, the Deccan Traps covers 500,000 square kilometres in area.
- The Deccan Traps are known for containing some unique fossils.
- The Deccan is rich in minerals. Primary mineral ores found in this region are **mica and iron** ore in the **Chotanagpur region**, and **diamonds, gold** and other metals in the **Golconda region**.

Kimberley Plateau

- It lies in the northern part of Australia.
- This plateau is made of volcanic eruption.
- Many minerals like iron, gold, lead, zinc, silver and **diamonds** are found here.

Katanga Plateau

- It lies in the Congo.
- It is famous for **copper production**.
- Other minerals like Cobalt, Uranium, Zinc, Silver, Gold and Tin are also mined here.

Mascarene Plateau

- Plateaus also form in the ocean, such as the Mascarene Plateau in the Indian Ocean.
- It extends between the Seychelles and Mauritius Islands.

Laurentian Plateau

- Lying in the eastern part of Canada, it is a part of Canadian Shield.
- Fine quality of iron-ore is found here.

Mexican Plateau

- It is called as ‘Mineral Store’. Different types of metallic minerals like silver, copper etc. are obtained from here.
- World’s biggest silver mine Chihuahua is situated in the plateau.

Patagonian Plateau

- It is a Piedmont plateau (arid landforms) lying in southern part of Argentina.
- It is a **rain shadow desert plateau**.
- It is an important region for sheep rearing.

Altiplano Plateau or Bolivian Plateau

- It is an intermontane plateau which is located between two ranges of Andes Mountain.
- It is a major area of Tin reserves.

Massif Central

- This plateau lies in central France.
- It is famous for Grape cultivation.

Anatolian Plateau

- Also known as **Asia Minor**, most of Turkey lies on this plateau.
- It is an intermontane plateau lying between **Pontiac** and **Taurus Mountain ranges**.

- **Tigris – Euphrates Rivers** flow through this plateau.
- Precious wool producing **Angora goats** are found here.

Others

- **Piedmont Plateau:** it is located in the Eastern United States. It sits between the Atlantic coastal plain and the main Appalachian Mountains
- **Spanish Plateau or Iberian Plateau:** It is situated in the middle of Spain. It is a lava plateau. It is rich in minerals like Iron.
- **Loess Plateau**: It is in China. The soil here is made of fine particles brought by the wind. This fine loamy soil is extremely productive. Crops grown in this soil along the **Yellow River** give great yields.
- **Potwar Plateau:** It is situated in the northern plateau (Punjab) region of Pakistan. The **Salt Range** is located to the south-west of the plateau.
- **Bavarian Plateau:** Southern part of Germany.
- **Ahaggar Plateau:** A small plateau located in Algeria, Sahara.
-