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Geomorphology Part I

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Geography is the study of

1. the **physical features** of the earth and its atmosphere,
2. **human activity which affects and is affected by the physical features** of the earth and its atmosphere. (Definition from Oxford Dictionary)

- Human activity which affects and is affected by the physical features include the distribution of populations, distribution of resources and economic activities, and changes in the environment.

Geography, the natural science, is divided into two main branches:

1. **Physical geography:** deals with the study of processes and patterns in the natural environment like the atmosphere, hydrosphere, biosphere, and geosphere.
2. **Human geography:** deals with the environment shaped by human activity.

Physical Geography can be divided into several sub-fields, as follows:

- **Geomorphology** ('geo' meaning earth, 'morphe' meaning form and 'logos' meaning discourse) is the field concerned with understanding the surface of the Earth and the processes by which it is shaped.

- **Climatology** is the study of the climate (weather conditions averaged over a long period).
- **Meteorology** focuses on weather processes and short-term forecasting (in contrast with climatology).
- **Oceanography** is the branch of physical geography that studies the Earth's oceans and seas.
- **Hydrology** is concerned with the amounts and quality of water moving and accumulating on the land surface and in the soils and rocks near the surface and is typified by the hydrological cycle.
- **Biogeography** deals with geographic patterns of species distribution and the processes that determine these patterns.
- **Environmental geography** analyses the spatial aspects of interactions between humans and the natural environment. The branch bridges the divide between human and physical geography.
- **Geomatics** is the field of gathering, storing, processing, and delivering geographic information.

There are many other sub-branches in physical geography.

1. Interior of The Earth

- Understanding the structure of the earth's interior (crust, mantle, core) and various forces (heat, seismic waves) emanating from it is essential to understand the evolution of the earth's surface, its current shape and its future.

1.1 The study of the earth's interior is essential

- to understand the earth's surface
- to understand the geophysical phenomenon like volcanism, earthquakes, etc.
- to understand the earth's magnetic field
- to understand the internal structure of various solar system objects
- to understand the evolution and present composition of the atmosphere
- for mineral exploration

Earth's surface

- Many different geological processes shape the Earth's surface.
- The forces that cause these processes come from both above and beneath the Earth's surface.
- Processes that are caused by forces from within the Earth are **endogenous processes** (Endo meaning "in").
- By contrast, **exogenous processes** (Exo meaning "out") come from forces on or above the Earth's surface.
- The major geological features of the earth's surface like mountains, plateaus, lakes are mostly a result of endogenous processes like folding, faulting that are driven by forces from inside the earth.

Geophysical phenomenon like volcanism, earthquakes

- The forces that cause catastrophic events like earthquakes, volcanic eruptions come from deep below the earth's surface.
- For example, earthquakes occur due to the movement of the tectonic plates and the energy required for this movement is supplied by the **conventional currents in the mantle**.
- Similarly, volcanism occurs through the vents and fissures created by the tectonic movements.

Earth's magnetic field

- Earth's magnetic field is a result of **convection currents in the outer core** of the earth.
- Life on earth would not have been possible if not for the earth's magnetic field which protects the earth's atmosphere from the harmful **solar wind**.

The internal structure of various solar system objects

- The entire solar system was formed from a single nebular cloud, and the process of the formation of every solar system object is believed to be similar to that of the earth.

Evolution and present composition of the atmosphere

- For life to flourish on the surface of the earth, the atmosphere needs to have essential components like oxygen for respiration, CO_2 and other greenhouse gases to maintain the temperature on the surface, ozone to protect life from ultraviolet radiation and the right atmospheric pressure.
- All these components of the earth's atmosphere owe their existence to the **volcanic eruptions** that unlock them from the earth's interior.

Mineral exploration

- Understanding volcanic activity and the nature of rocks is essential for mineral exploration.
- Most of the minerals like **diamonds (form at a depth of 150-800 km in the mantle)** that occur on the earth's surface are formed deep below the earth's surface. They are brought to the surface by **volcanic activity**.

1.2 Direct Sources of information about the interior

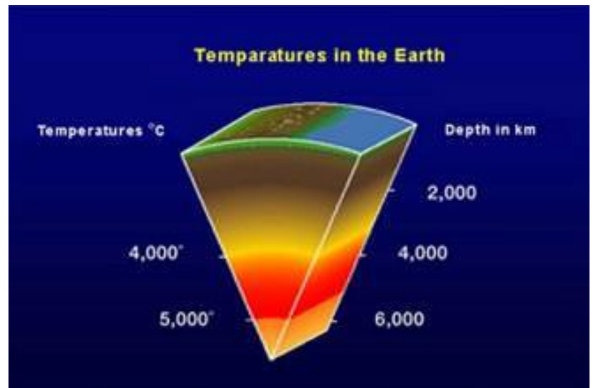
- Deep earth mining and drilling reveal the nature of rocks deep down the surface.
- But as mining and drilling are not practically possible beyond a certain depth, they don't reveal much information about the earth's interior.
- **Mponeng gold mine** (deepest mine in the world) and **TauTona gold mine** (second deepest mine in the world) in South Africa are deepest mines reaching to a depth of only 3.9 km.
- And the deepest drilling is only about 12 km deep hole bored by the Soviet Union in the 1970s over the **Kola Peninsula**.

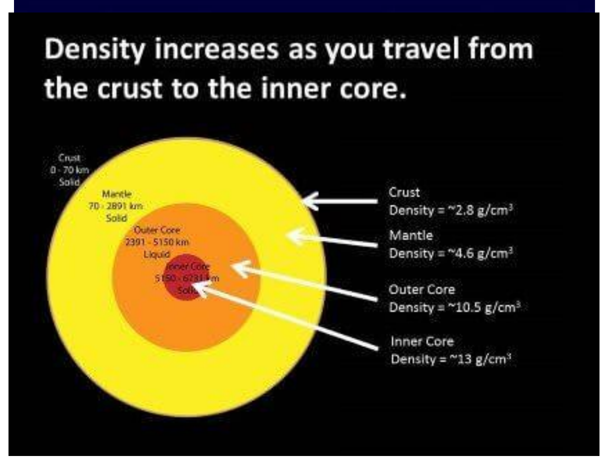
The Kola Peninsula in north-west Russia. ([TUBS, from Wikimedia Commons]())

- Volcanic eruption forms another source of obtaining direct information.

1.3 Indirect Sources of information about the interior

- Gravitation and the diameter of the earth help in estimating pressure deep inside.
- Volcanic eruptions and existence of hot springs, geysers etc. point to an interior which is very hot.





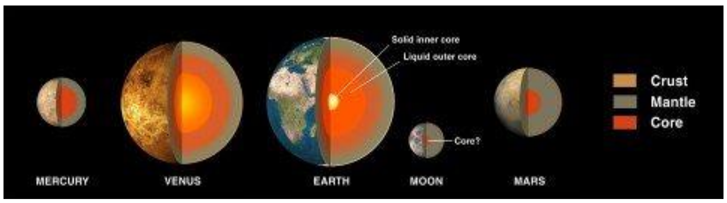
Seismic waves

- They are the most important source available to understand the layered structure of the earth.
- The velocity of seismic waves changes as they travel through materials with different **elasticity** and **density**.
- The **more elastic and denser the material is, the higher is the velocity**.
- They also undergo **refection or refraction** when they come across materials with different densities.
- Earth's internal structure can be understood by analysing the patterns of reflection, refraction

and change in velocity of the seismic waves when they travel through it.

Meteorites

- Meteorites and Earth are born from the same nebular cloud. Thus, they are likely to have a similar internal structure.
- When meteoroids they fall to earth, their outer layer is burnt during their fall due to extreme friction and the inner core is exposed.
- The heavy material composition of their cores confirms the similar composition of the inner core of the earth.



Gravitation

- The gravitation force differs according to the mass of material. The uneven distribution of mass of material within the earth influences this value. Such a difference is called **gravity anomaly**.
- Gravity anomalies give us information about the **distribution of mass** in the crust of the earth.

Magnetic field

- The geodynamo effect helps scientists understand what's happening inside the Earth's core. Shifts in the magnetic field also provide clues to the inaccessible iron core.

Sources of earth's heat

Radioactive decay

- The high temperature below the crust is attributed to the **disintegration of the radioactive substances**.
- **The nuclear decay happens primarily in the crust and the mantle**.
- Scientists believe that uranium could become sufficiently concentrated **at the base of Earth's mantle** to ignite self-sustained **nuclear fission**, as in a human-made reactor.
- The new measurements suggest **radioactive decay provides more than half of Earth's total heat**.

Nuclear fusion doesn't occur inside the earth*. For nuclear fusion to occur there must be far more pressure and temperature inside the earth. The earth is not massive enough to cause such conditions.*

Primordial heat

- The rest is the heat left over from Earth's formation known as the **primordial heat**.
- Primordial heat is the kinetic energy transferred to Earth by external impacts of comets and meteorites and the subsequent effects (**friction** caused by sinking of heavy elements like Fe, rising light elements like Si) and **latent heat of crystallisation released as the core solidified**.

Tidal friction

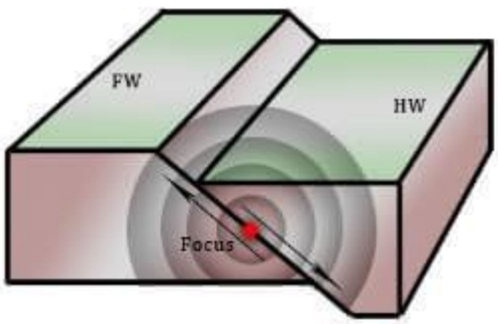
- The ocean tides are not the only effect of tidal forces (gravitational influence of the moon and the sun on earth; tides are explained in oceanography). The solid body of the Earth also bulges slightly in this way.
- The daily flexing of the Earth (both solid body and the oceans) cause loss of energy of the Earth's rotation, due to friction.
- This energy goes into heat, leading to miniscule increase in the Earth's internal temperature.
- The loss of rotational energy means that the **Earth is slowing down in its rotation rate**, currently by about 0.002 seconds per century.

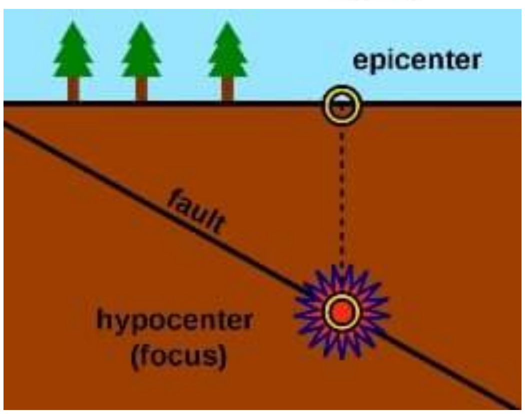
1.4 Seismic waves

- Seismic: relating to earthquakes or other vibrations of the earth and its crust.
- Seismic waves are waves of energy that travel through the Earth's layers and are a result of earthquakes, volcanic eruptions, magma movement, large landslides and large human-made explosions.
- The refraction or reflection of seismic waves is used for research into the structure of the Earth's interior.
- The terms seismic waves and earthquake waves are often used interchangeably.

How are earthquake waves produced?

- The abrupt release of energy along a fault (sharp break in the crustal layer) causes earthquake waves.
- Rock layers along a fault tend to move in opposite directions due to the force excreted on them but are held in place by counteracting frictional force exerted by the overlying rock strata.



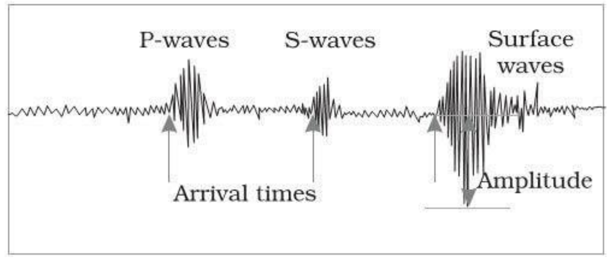


The Focus of an Earthquake ([Eround1]); Epicentre (AnsateSam, via [Wikimedia Commons])

- The pressure on the rock layers builds up over a period and overcomes the frictional force resulting in a sudden movement generating shockwaves (seismic waves) that travel in all directions.
- 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**.
- An instrument called 'seismograph' records the waves reaching the surface.

1.5 Types of Seismic waves or earthquake waves

- The seismic waves or earthquake waves are basically of two types — **body waves** and **surface waves**.

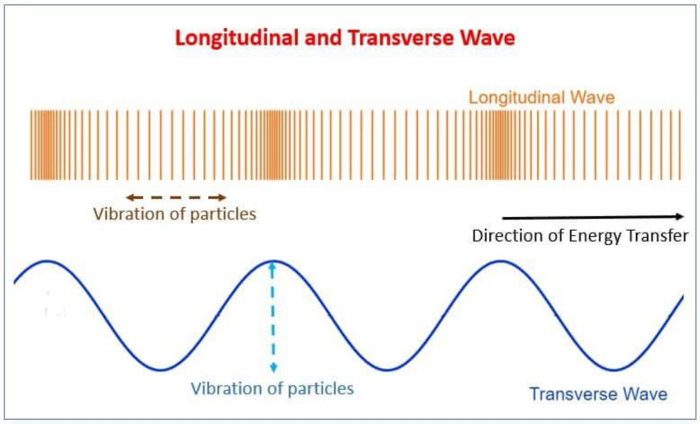


Body waves

- Body waves are generated due to the release of energy at the focus and **move in all directions** travelling through the interior of the earth. Hence, the name body waves.
- There are two types of body waves:
  1) the **P-waves or primary waves** (**longitudinal** in nature — wave propagation is similar to sound waves), and
  2) the **S-waves or secondary waves** (**transverse** in nature — wave propagation is similar to ripples on the surface of the water).

Primary Waves (P-waves)

- Primary waves are called so because they are the **fastest** among the seismic waves and hence are **recorded first on the seismograph**.
- P-waves are also called as the
  - **longitudinal waves** because the displacement of the medium is in the same direction as, or the opposite direction to, (parallel to) the direction of propagation of the wave; or
  - **compressional waves** because they produce compression and rarefaction when travelling through a medium; or
  - **pressure waves** because they produce increases and decreases in pressure in the medium.
- P-waves creates density differences in the material leading to stretching (rarefaction) and squeezing (compression) of the material.



The vibration of particles in Longitudinal wave and Transverse wave (Source)

- These waves are of relatively high frequency and are the **least destructive** among the earthquake waves.
- The trembling on the earth's surface caused due to these waves is in the **up-down direction (vertical)**.
- **They can travel in all mediums,** and their velocity depends on **shear strength (elasticity)** of the medium.
- Hence, the velocity of the P-waves in **Solids > Liquids > Gases**.
- These waves take the form of **sound waves** when they enter the atmosphere.
- P-wave velocity in earthquakes is in the range 5 to 8 km/s.
- The precise speed varies according to the region of the Earth's interior, from less than 6 km/s in the Earth's crust to 13.5 km/s in the lower mantle, and 11 km/s through the inner core.

*We usually say that the speed of sound waves depends on density. But there are few exceptions — **mercury is denser than iron**, but it is less elastic; hence the **speed of sound in iron is greater than that in mercury***

Why do P-waves travel faster than S-waves?

- **P-waves are about 1.7 times faster than the S-waves**.
- P-waves are compression waves that apply a force in the direction of propagation and hence transmit their energy quite easily through the medium and thus travel quickly.
- On the other hand, S-waves are **transverse waves** or **shear waves** (motion of the medium is perpendicular to the direction of propagation of the wave) and are hence less easily transmitted through the medium.

P-waves as an earthquake warning

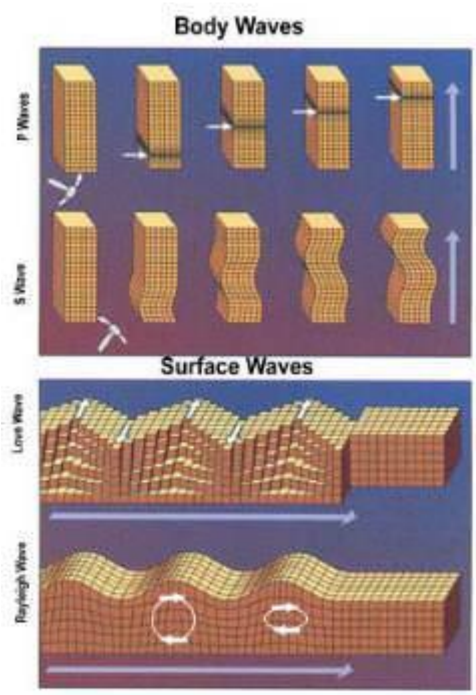
- Advance earthquake warning is possible by detecting the non-destructive primary waves that travel more quickly through the Earth's crust than do the destructive secondary and surface waves.
- Depending on the depth of focus of the earthquake, the delay between the arrival of the P-wave and other destructive waves could be up to about 60 to 90 seconds (depends of the depth of the focus).

Secondary Waves (S-waves)

- Secondary waves (secondary ➔ they are recorded second on the seismograph) or S-waves are also called as **transverse waves or shear waves or distortional waves**.
- They are analogous to water ripples or light waves.
- **Transverse waves or shear waves** mean that the direction of vibrations of the particles in the medium is perpendicular to the direction of propagation of the wave. Hence, they create **troughs** and **crests** in the material through which they pass (they distort the medium).
- S-waves arrive at the surface after the P-waves.
- These waves are of high frequency and possess **slightly higher destructive power** compared to P-waves.
- The trembling on the earth's surface caused due to these waves is from **side to side (horizontal)**.
- S-waves **cannot pass through fluids (liquids and gases)** as fluids do not support **shear stresses**.
- They travel at varying velocities (proportional to shear strength) through the solid part of the Earth.

Surface waves (L-Waves)

- The body waves **interact with the surface rocks and generate new set of waves called surface waves** (long or L-waves). **These waves move only along the surface**.
- Surface Waves are also called long period waves because of their **long wavelength**.
- They are **low-frequency transverse waves (shear waves)**.
- They develop in the **immediate neighbourhood of the epicentre** and affect only the surface of the earth and die out at smaller depth.
- **They lose energy more slowly with distance than the body waves** because they travel only across the surface unlike the body waves which travel in all directions.
- **Particle motion of surface waves (amplitude) is larger than that of body waves**, so surface waves are the **most destructive** among the earthquake waves.
- They are **slowest** among the earthquake waves and are recorded last on the seismograph.



Types of earthquake waves
https://www.youtube.com/watch?v=wDfIgoXaXis

Love waves

- It's the fastest surface wave and moves the ground from side-to-side.

Rayleigh waves

- A Rayleigh wave rolls along the ground just like a wave rolls across a lake or an ocean.
- Because it rolls, it moves the ground **up and down and side-to-side** in the same direction that the wave is moving.
- **Most of the shaking and damage** from an earthquake is due to the **Rayleigh wave**.

How do seismic waves help in understanding the earth's interior?

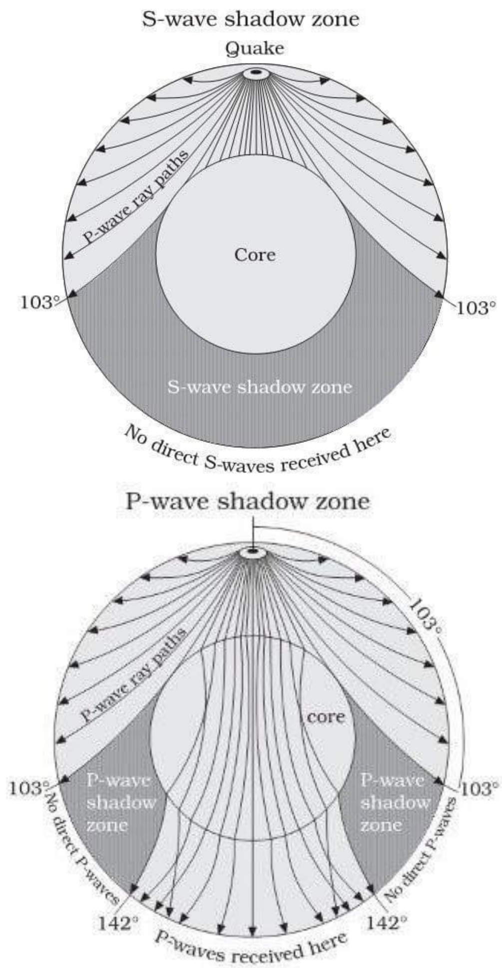
- Seismic waves get recorded in seismographs located at far off locations.
- Differences in arrival times, waves taking different paths than expected (due to refraction) and absence of the seismic waves in certain regions called as shadow zones, allow mapping of the Earth's interior.
- Discontinuities in velocity as a function of depth are indicative of changes in composition and density.
- That's is, by observing the changes in velocity, the density and composition of the earth's interior can be estimated (change in densities greatly varies the wave velocity).
- Discontinuities in wave motion as a function of depth are indicative of changes in phase.
- That is, by observing the changes in the direction of the waves, the emergence of shadow zones, different layers can be identified.

The emergence of Shadow Zone of P-waves and S-waves

- S-waves do not travel through liquids (they are **attenuated**).
- The entire zone beyond 103° does not receive S-waves, and hence this zone is identified as the shadow zone of S-waves. This observation led to the discovery of the **liquid outer core**.
- The shadow zone of P-waves appears as a band around the earth between 103° and 142° away from the epicentre.
- This is because P-waves are refracted when they pass through the transition between the semi-solid mantle and the liquid outer core.
- However, the seismographs located beyond 142° from the epicentre, record the arrival of P-

waves, but not that of S-waves. This gives clues about the **solid inner core**.

- Thus, a zone between **103° and 142°** from epicentre was identified as the **shadow zone for both the types of waves**.



Shadow Zone of P-waves and S-waves

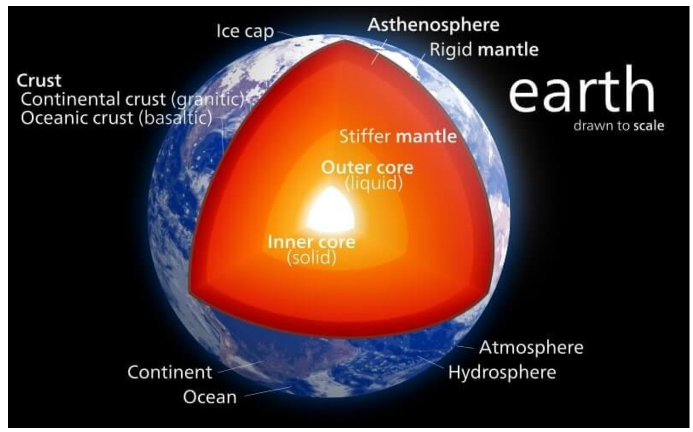
- The seismographs located at any distance within 103° from the epicentre, recorded the arrival of both P and S-waves.

Why do sound waves travel faster in a denser medium whereas light travels slower?

- The sound is a mechanical wave and travels by compression and rarefaction of the medium.
- A higher density leads to more elasticity in the medium and hence the ease by which compression and rarefaction can take place. This way the velocity of sound increases with an increase in density.
- Light, on the other hand, is a transverse electromagnetic wave.
- An increase in the density increases effective path length, and hence it leads to higher refractive index and lower velocity.

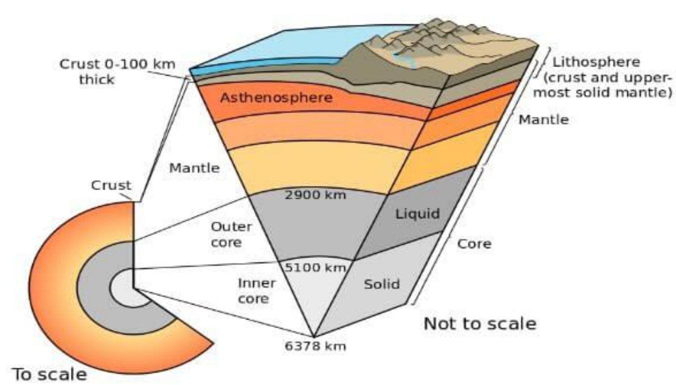
- The span of the shadow zone of the P-Waves = 78° [2 x (142° - 103°)]
- The span of the shadow zone of the S-Waves = 154° [360° – (103° + 103°)]
- The span of the shadow zone common for both the waves = 78°

1.6 The internal structure of the Earth



Earth's Layers ([Kelvinsong](), from Wikimedia Commons)

- The interior of the earth is made up of several concentric layers of which the crust, the mantle, the outer core and the inner core are significant because of their unique physical and chemical properties.
- The crust is a silicate solid, the mantle is a viscous molten rock, the outer core is a viscous liquid, and the inner core is a dense solid.



- Mechanically, the earth's layers can be divided into **lithosphere, asthenosphere, mesospheric mantle** (part of the Earth's mantle below the lithosphere and the asthenosphere), **outer core**, and **inner core**.
- Chemically, Earth can be divided into the **crust, upper mantle, lower mantle, outer core, and inner core**.

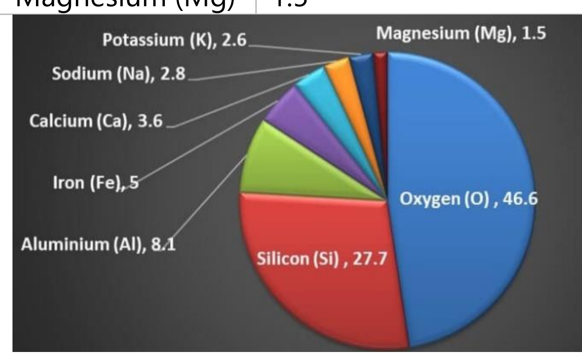
The Crust

- The crust is the outermost layer of the earth making up **0.5-1.0 per cent of the earth's volume** and **less than 1 per cent of Earth's mass**.
- Density increases with depth, and the average density is about **2.7 g/cm^3** (average density of the earth is 5.51 g/cm^3).
- The thickness of the crust varies in the range of range of **5-30 km in case of the oceanic crust** and as **50-70 km in case of the continental crust**.
- The continental crust can be thicker than 70 km in the areas of major mountain systems. It is as much as 70-100 km thick in the Himalayan region.
- The temperature of the crust increases with depth, reaching values typically in the range from about 200 °C to 400 °C at the boundary with the underlying mantle.
- The temperature increases by as much as 30 °C for every kilometre in the upper part of the crust.
- The outer covering of the crust is of **sedimentary material** and below that lie crystalline, igneous and metamorphic rocks which are acidic in nature.
- The lower layer of the crust consists of basaltic and ultra-basic rocks.
- The continents are composed of lighter silicates — **silica + aluminium** (also called **sial**) while the oceans have the heavier silicates — **silica + magnesium** (also called **sima**) [Suess,1831–1914 — this classification is now obsolete (out of date)].
- The continental crust is composed of lighter (**felsic**) **sodium potassium aluminium silicate** rocks, like **granite**.
- The oceanic crust, on the other hand, is composed of dense (**mafic**) **iron magnesium silicate** igneous rocks, like **basalt**.

In geology, felsic refers to igneous rocks that are relatively rich in elements that form feldspar and quartz.
It is contrasted with mafic rocks, which are relatively richer in magnesium and iron.
Felsic refers to rocks which are enriched in the lighter elements such as silicon, oxygen, aluminium, sodium, and potassium.

Most Abundant Elements of the Earth's Crust

Element	Approximate % by weight
1. Oxygen (O)	**46.6**
2. Silicon (Si)	**27.7**
3. Aluminium (Al)	**8.1**
4. Iron (Fe)	**5.0**
5. Calcium (Ca)	**3.6**
6. Sodium (Na)	2.8
7. Potassium (K)	2.6
8. Magnesium (Mg)	1.5



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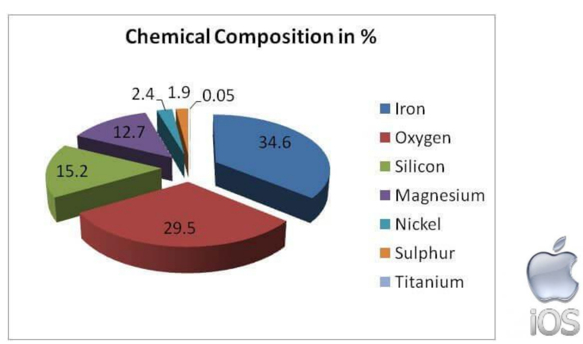
Most Abundant Elements of the Earth



Most Abundant Elements of the Earth's Crust ➔ ***OS CIA***
Most Abundant Elements of the Earth ➔ ***iOS***

The Mohorovicic (Moho) discontinuity

- Mohorovicic (Moho) discontinuity forms the boundary between the **crust** and the **asthenosphere** (upper reaches of the mantle) where there is a discontinuity in the seismic velocity.
- It occurs at an average depth of about 8 kilometres beneath the ocean basins and 30 kilometres beneath continental surfaces.
- The cause of the Moho is thought to be a change in rock composition from rocks containing **feldspar** (above) to rocks that contain no feldspars (below).

Lithosphere

- The lithosphere is the rigid outer part of the earth with thickness varying between 10-200 km.
- It is includes the **crust and the upper part of the mantle**.
- The lithosphere is broken into **tectonic plates (lithospheric plates),** and the movement of these tectonic plates cause large-scale changes in the earth's geological structure (folding, faulting).
- The source of heat that drives plate tectonics is the **primordial heat** left over from the planet's formation as well as the **radioactive decay of uranium, thorium, and potassium in Earth's crust and mantle**.

The Mantle

- It forms about **83 per cent of the earth's volume and holds 67% of the earth's mass**.
- It extends from Moho's discontinuity to a depth of 2,900 km.
- The density of the upper mantle varies between **2.9 g/cm^3 and 3.3 g/cm^3**.
- The lower mantle extends beyond the **asthenosphere**. It is in a solid state.
- The density ranges from **3.3 g/cm^3** to **5.7 g/cm^3** in the lower mantle.
- The mantle is composed of **silicate rocks that are rich in iron and magnesium** relative to the overlying crust.
- Regarding its constituent elements, the mantle is made up of **45% oxygen, 21% silicon,** and **23% magnesium (OSM)**.
- In the mantle, temperatures range from approximately 200 °C at the upper boundary with the crust to approximately 4,000 °C at the core-mantle boundary.
- Because of the temperature difference, there is a **convective material circulation** in the mantle (although solid, the high temperatures within the mantle cause the silicate material to be sufficiently ductile).
- Convection of the mantle is expressed at the surface through the motions of tectonic plates.
- High-pressure conditions ought to inhibit seismicity in the mantle. However, in subduction zones, earthquakes are observed down to 670 km (420 mi).

Asthenosphere

- The upper portion of the mantle is called as asthenosphere (astheno means weak).
- It lies **just below the lithosphere** extending up to **80-200 km**.
- It is **highly viscous, mechanically weak and ductile** and its density is higher than that of the crust.
- These properties of the asthenosphere **aid in plate tectonic movement and isostatic adjustments** (the elevated part at one part of the crust area is counterbalanced by a depressed part at another).
- It is the **main source of magma** that finds its way to the surface during volcanic eruptions.

The Outer Core

- The outer core, surrounding the inner core, lies between 2900 km and 5100 km below the earth's surface.
- The outer core is composed of **iron mixed with nickel** (**nife**) and trace amounts of lighter elements.
- The outer core is **not under enough pressure to be solid**, so it is liquid even though it has a composition similar to the inner core.
- The density of the outer core ranges from **9.9 g/cm^3** to **12.2 g/cm^3**.

- The temperature of the outer core ranges from 4400 °C in the outer regions to 6000 °C near the inner core.
- Dynamo theory suggests that **convection in the outer core, combined with the Coriolis effect**, gives rise to **Earth's magnetic field**.

The Inner Core

- The inner core extends from the centre of the earth to 5100 km below the earth's surface.
- The inner core is generally believed to be composed primarily of **iron (80%) and some nickel** (**nife**).
- Since this layer can transmit shear waves (transverse seismic waves), it is solid. (When P-waves strike the outer core – inner core boundary, they give rise to S-waves)
- Earth's inner **core rotates slightly faster** relative to the rotation of the surface.
- The solid inner core is too hot to hold a permanent magnetic field.
- The density of the inner core ranges from **12.6 g/cm^3** to **13 g/cm^3**.
- The core (inner core and the outer core) accounts for just about **16 per cent of the earth's volume but 33% of earth's mass**.
- Scientists have determined the temperature near the Earth's centre to be 6000° C, 1000° C hotter than previously thought.
- At 6000°C, this iron core is as hot as the Sun's surface, but the **crushing pressure caused by gravity prevents it from becoming liquid**.

Remember: when ambient pressure increases the melting point of solid increases, and vice versa. One exception is Ice. In the case of ice increase in ambient pressure will lower its melting point.

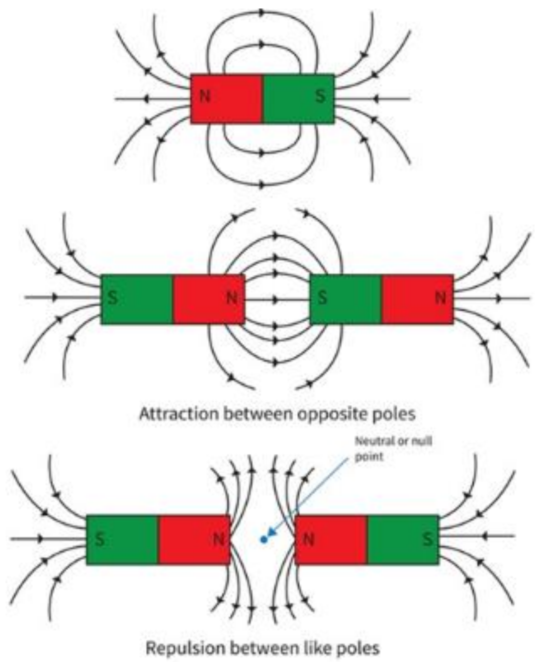
Seismic Discontinuities

- Seismic discontinuities are the regions in the earth where seismic waves behave a lot different compared to the surrounding regions due to a marked change in physical or chemical properties.

1. **Mohorovicic Discontinuity (Moho): separates the crust from the mantle.**
2. **Asthenosphere: highly viscous, mechanically weak and ductile part of mantle.**
3. **Gutenberg Discontinuity: lies between the mantle and the outer core.**

2. Earth's Magnetic Field

- A 'field' is a region in which a body experiences a force owing to the presence of other bodies.
- Gravitational fields determine how bodies with mass are attracted to each other.
- In electric fields, objects that have an electric charge are attracted or repelled from each other.
- Magnetic fields determine how electric currents that contain **moving electric charges** exert a force on other electric currents.



Field lines or magnetic flux in a simple bar magnet

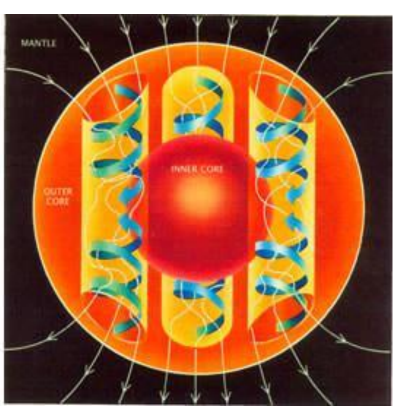
2.1 Dynamo theory: Generation of Earth's Magnetic Field and Sustaining it

- **Dynamo theory** proposes a mechanism by which a celestial body such as Earth or a star generates a magnetic field and sustains it over astronomical time scales (millions of years).
- Dynamo theory suggests that **convection in the outer core, combined with the Coriolis**

effect (caused due to the rotation of the earth), gives rise to **self-sustaining (geodynamo)** Earth's magnetic field.

Mechanism

- Earth’s magnetic field is generated in the **earth’s outer core**.
- Lower pressure than the inner core means the metal in the outer core is **fluid**.
- The temperature of the outer core ranges from 4400 °C in the outer regions to 6000 °C near the inner core.
- Heat sources include energy released by the compression of the core, energy released at the inner core boundary as it grows (latent heat of crystallisation), and radioactivity of potassium, uranium and thorium.
- The differences in temperature, pressure and composition within the outer core cause **convection currents** in the molten iron of the outer core as cool, dense matter sinks while warm, less dense matter rises.
- This **flow of liquid iron** generates **electric currents**, which in turn produce **magnetic fields**.
- Charged metals passing through these fields go on to create electric currents of their own, and so the cycle continues. This **self-sustaining loop** is known as the **geodynamo**.
- The **spiral movement** of the charged particles caused by the **Coriolis force** means that separate magnetic fields created are roughly aligned in the same direction, their combined effect adding up to produce one vast magnetic field of the planet.



Convection currents in the outer core. Spiral motion is caused due to the Coriolis Effect. (Wikipedia)

2.2 Magnetic poles

- A magnet's North pole is thought as the pole that is attracted by the Earth's North Magnetic Pole when the magnet is suspended so it can turn freely.
- Since opposite poles attract, **the North Magnetic Pole of the Earth is the south pole of its magnetic field**.
- Magnetic dipole field (simple north-south field like that of a simple bar magnet) is usually aligned fairly closely with the Earth's rotation axis; in other words, the magnetic poles are usually **fairly close to the geographic poles, which is why a compass works**.
- However, the dipole part of the field **reverses** after a few thousand years **causing the locations of the north and south magnetic poles to switch**.

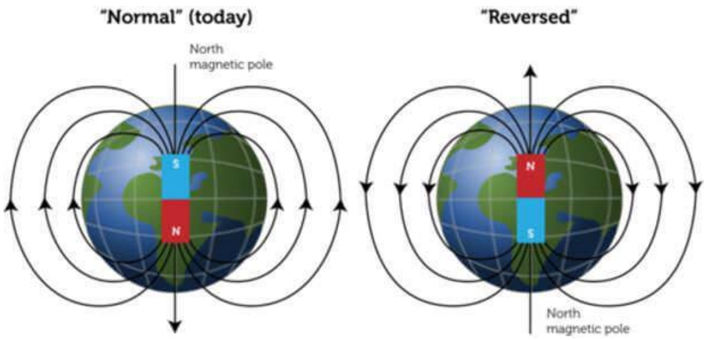
The terms magnetic north and magnetic south are not to be confused with geographic north and geographic south, and geomagnetic north and geomagnetic south.

2.3 Geomagnetic reversal

- A geomagnetic reversal or a reversal in earth’s magnetic field is a change in a planet's magnetic field such that the **positions of magnetic north and magnetic south are interchanged**.
- Based on **palaeomagnetism** (magnetism in rocks that was induced by the earth's magnetic field at the time of their formation), it is observed that over the last 20 million years, magnetic north and south have flipped roughly every 200,000 to 300,000 years.
- **The reversal is not literally 'periodic' as it is on the sun, whose magnetic field reverses every 11 years**.
- The time between magnetic reversals on the Earth is sometimes as short as 10,000 years and sometimes as long as 25 million years.
- And the time it takes to reverse could be about a few hundred or a few thousand years.
- The magnetic poles emerge at odd latitudes throughout the process of the reversal.

Normal and Reversed field

- The Earth's field has alternated between periods of **normal polarity, in which the predominant direction of the field was the same as the present direction**, and reverse polarity, in which it was the opposite.



Normal and Reversed field (The bar magnet at the centre represents earth's magnetic field)

- ***In Normal Polarity, Earth's North Magnetic Pole is the South Pole of its Magnetic Field.***
- ***In Reverse Polarity, Earth's North Magnetic Pole is the North Pole of its Magnetic Field.***

The current location of the Magnetic Poles

- The North and South Magnetic Poles wander (Polar Shift Theory) due to changes in Earth's magnetic field.
- The North Magnetic Pole (86° N, 172° W) lie to the north of Ellesmere Island in northern Canada and is rapidly drifting towards Siberia.
- The location of the South Magnetic Pole is currently off the coast of Antarctica and even outside the Antarctic Circle.
- Scientists suggest that the north magnetic pole migrates about 10 kilometres per year.
- Lately, the speed has accelerated to about 40 kilometres per year and could reach Siberia in a few decades.
- Since the Earth's magnetic field is not exactly symmetrical, the North and South Magnetic Poles are **not antipodal** (a straight line drawn from one to the other does not pass through the centre of the Earth).
- The Earth's North and South Magnetic Poles are also known as **Magnetic Dip Poles** because of the vertical "dip" of the magnetic field lines at those points.
- That is, if a magnetic compass needle is suspended freely at the magnetic poles then it will point **straight down** at the north magnetic pole (south pole of earth's magnetic field) and **straight up** at the south magnetic pole (north pole of earth's magnetic field).

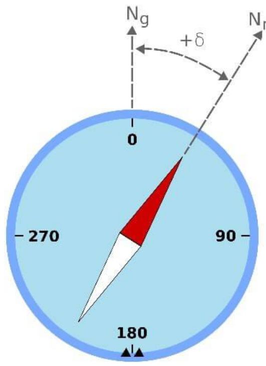
2.4 Compass

- A compass point north because all magnets have two poles, a north pole and a south pole, and the north pole of one magnet is attracted to the south pole of another magnet.
- The Earth is a magnet that can interact with other magnets in this way, so the north end of a compass magnet is drawn to align with the Earth's magnetic field.
- Because the Earth's Magnetic North Pole attracts the "north" ends of other magnets, **it is technically the "South Pole" of our planet's magnetic field**.
- While a compass is a great tool for navigation, it doesn't always point exactly north. This is because the Earth's magnetic North Pole is not the same as "true north (Earth's Geographic North Pole)."
- Although the **magnetic declination** (deviation from true north) does shift with time, this wandering is slow enough that a simple compass remains useful for navigation.

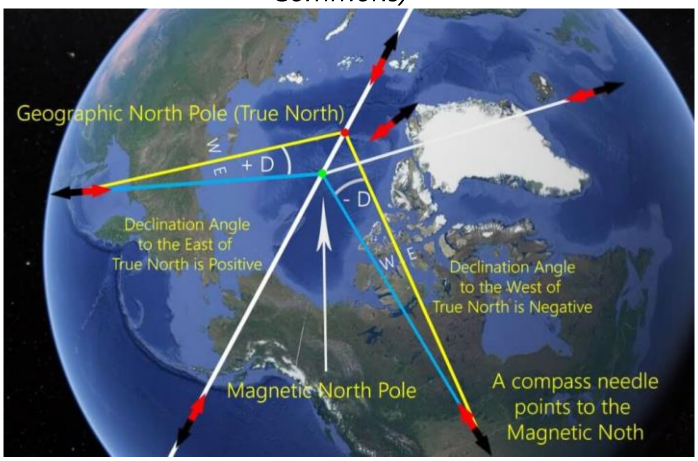
Using magnetoreception various organisms, ranging from some types of bacteria, sea turtles, some migratory birds, pigeons, etc. use the Earth's magnetic field for orientation and navigation.

Magnetic declination

- **Magnetic declination is the angle between magnetic north and true north**.
- It is positive when the angle derived is east of the true north, and it is considered negative when the angle measured is west of the true north.
- In which direction would a compass needle point if you were standing on the true North Pole?



[Magnetic Declination](#) (Odder or GPL, via Wikimedia Commons)



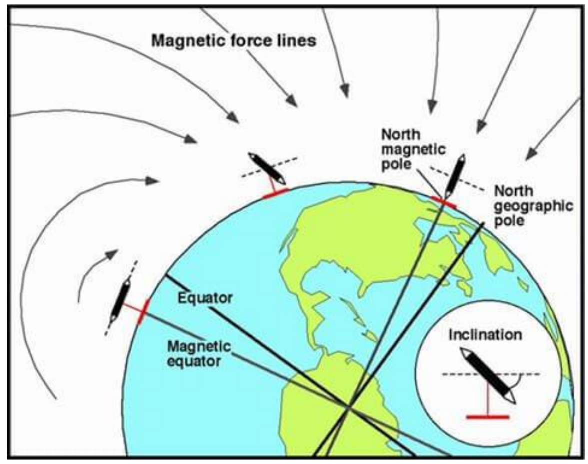
Magnetic Declination

- Importance: Ships and other long-distance means of transport that rely on the compass for navigation should do necessary corrections to account for magnetic declination at different latitudes and longitudes to stay in the right course.

***Magnetic deviation** is the error of a compass needle due to the influence of nearby metallic objects.*

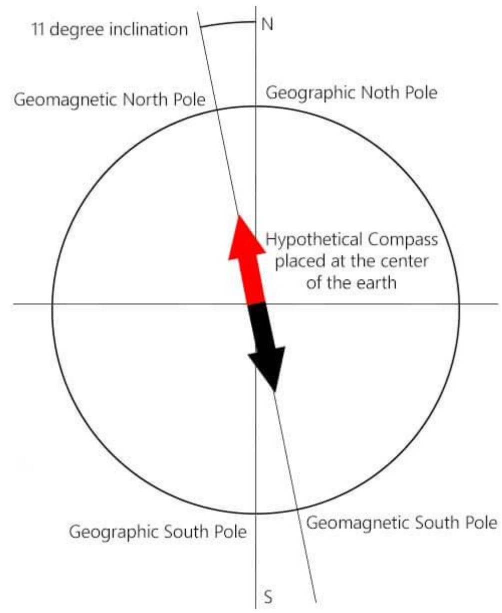
Magnetic Inclination or Magnetic Dip

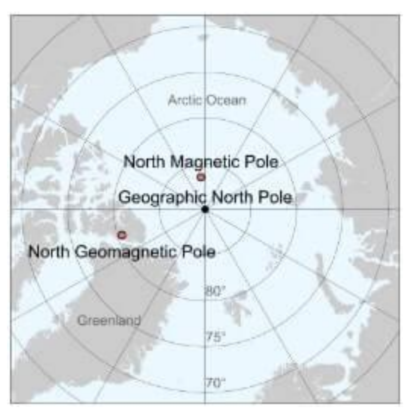
- Magnetic dip, dip angle, or magnetic inclination is the **angle made with the horizontal by the Earth's magnetic field lines**.
- In simple terms, magnetic inclination is the angle made by a compass needle when the compass is held in a **vertical** orientation.
- The magnetic equator is the irregular imaginary line, passing round the earth near the equator, on which a **magnetic needle has no dip** (because magnetic field lines are parallel to the horizontal at the equator).
- Again, the magnetic equator, like the magnetic field and poles, is **not fixed**.



From Marshak, S., 2001, Earth: Portrait of a Planet: New York, W.W. Norton. via [Rutgers.edu](#)

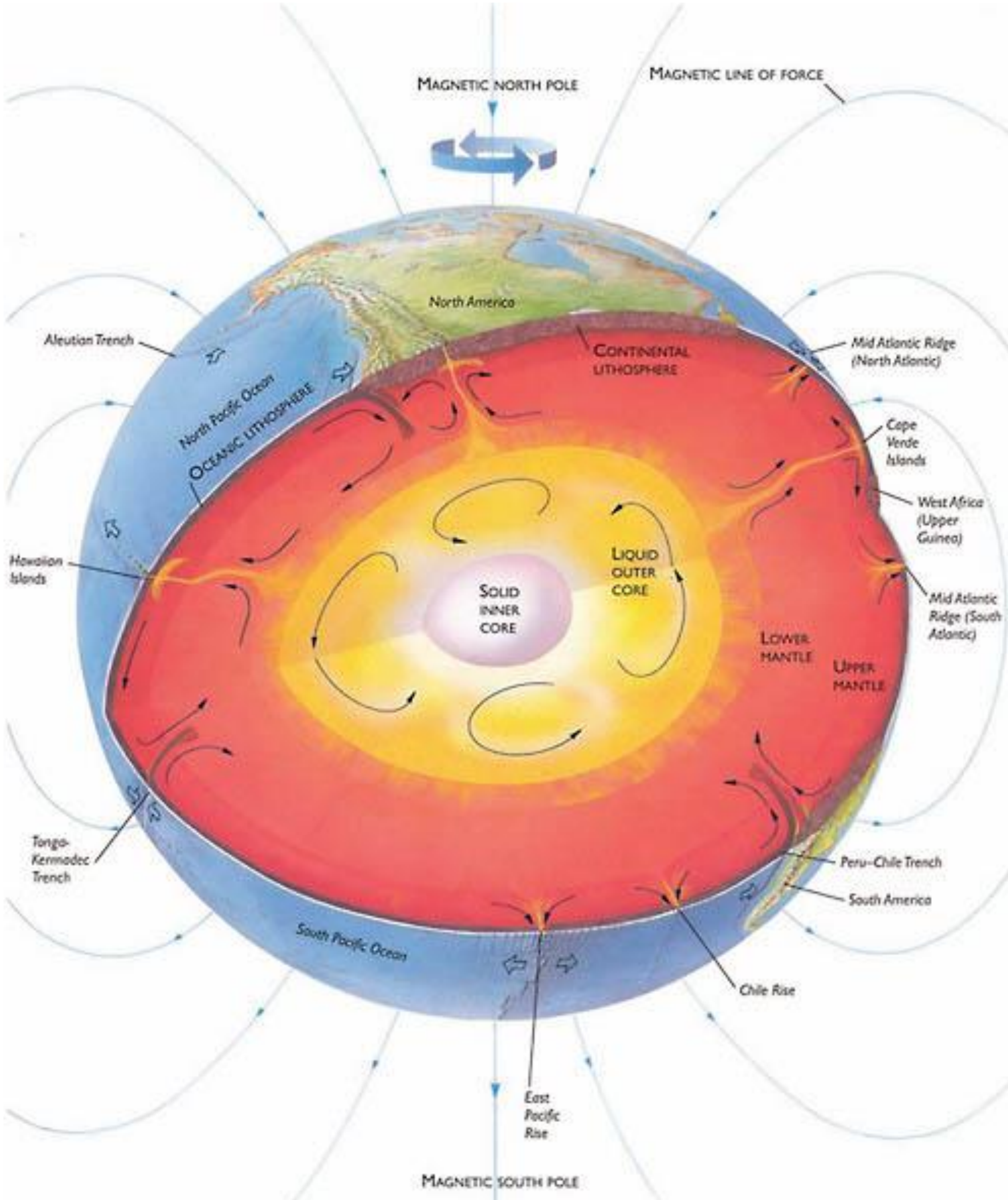
- **Magnetic dip at the magnetic equator is 0°, and at the magnetic poles, it is 90°**.
- Importance: The phenomenon of magnetic dip is important in aviation, as it causes the aeroplane's compass to give erroneous readings during banked turns and airspeed changes. Necessary corrections need to be made to the compass reading to stay in the right course.





2.5 Geomagnetic poles

- The Geomagnetic poles (dipole poles) are the **intersections of the Earth's surface and the axis of a bar magnet hypothetically placed at the centre the Earth**.
- There is such a pole in each hemisphere, and the poles are called as "the geomagnetic north pole" and "the geomagnetic south pole", respectively.
- Approximately, geomagnetic dipole is currently tilted at an angle of about **11 degrees** to Earth's rotational axis.
- On the other hand, the magnetic poles (the magnetic north pole and the magnetic south pole) are the points at which **magnetic needles become vertical**.
- The difference in the position of magnetic poles and geomagnetic poles is due to the uneven and complex distribution of the earth's magnetic field.



Earth's Magnetic field (Credits: universe-review.ca)

2.6 Magnetosphere

- The magnetosphere is the region above the ionosphere that is **defined by the extent of the Earth's magnetic field in space**.
- It extends several tens of thousands of kilometres into space, **protecting the Earth from the charged particles of the solar wind and cosmic rays** that would otherwise strip away the upper atmosphere, **including the ozone layer** that protects the Earth from harmful ultraviolet radiation.
- Many cosmic rays are kept out of the Solar system by the **Sun's magnetosphere called heliosphere**.

Magnetopause

- Earth's magnetic field, predominantly dipolar at its surface, is distorted further out by the **solar wind**.
- The solar wind exerts a pressure. However, it is kept away by the pressure of the Earth's magnetic field.
- The **magnetopause**, the **area where the pressures balance**, is the boundary of the magnetosphere.
- Despite its name, the magnetosphere is asymmetric, with the sunward side being about 10 Earth radii out but the other side stretching out in a magnetotail that extends beyond 200 Earth radii.

Magnetosheath

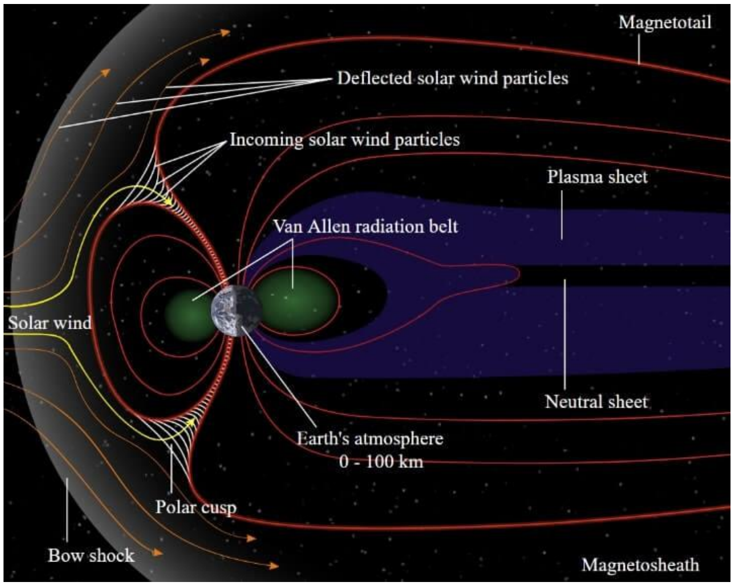
- The turbulent magnetic region just outside the magnetopause is known as the magnetosheath.

Plasmasphere

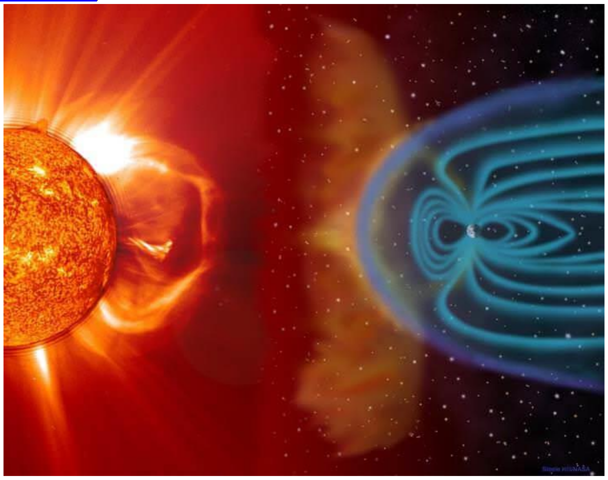
- Inside the magnetosphere is the plasmasphere, a region containing **low-energy charged particles**.
- This region begins at the height of 60 km, extends up to 3 or 4 Earth radii, and includes the **ionosphere**.
- This region rotates with the Earth.

Bow shock

- Sunward of the magnetopause is the **bow shock**, the area where the **solar wind slows abruptly**.



Earth's magnetosphere (Original bitmap from NASA. SVG rendering by Aaron Kaase, via Wikimedia Commons)



Earth's magnetosphere (Credits: losangeles.af.mil)

Auroras

- Aurora is the name given to the luminous glow in the upper atmosphere of the Earth which is produced by charged particles (solar wind) descending from the planet's magnetosphere.
- Positive ions slowly drift westward, and negative ions drift eastward, giving rise to a **ring current**. This current **reduces the magnetic field at the Earth's surface**.
- Some of these particles penetrate the ionosphere and collide with the atoms there.

- This results in an **excitation of the oxygen and nitrogen molecular electrons**. The molecules get back to their original state by emitting photons of light which are the aurorae.
- The charged particles follow magnetic field lines which are oriented in and out of our planet and its atmosphere near the magnetic poles. Therefore, aurorae mostly are seen to occur at **high latitudes**.

Geomagnetic storms

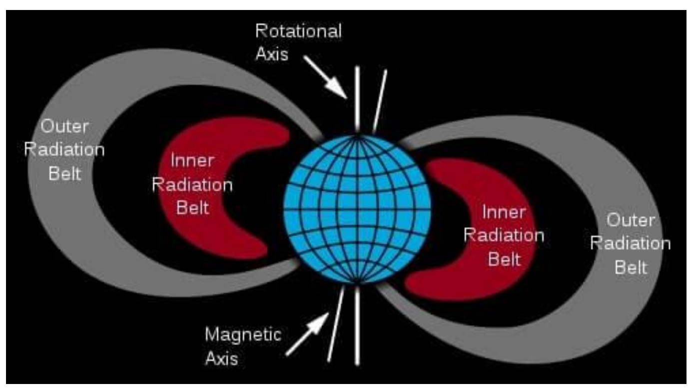
- The varying conditions in the magnetosphere, known as space weather, are largely driven by **solar activity**.
- If the solar wind is weak, the magnetosphere expands; while if it is strong, it compresses the magnetosphere and more of it gets in.
- Periods of intense activity, called geomagnetic storms, can occur when a **coronal mass ejection erupts** above the Sun and sends a shock wave through the Solar System. It takes just two days to reach the Earth.
- At the Earth's surface, a magnetic storm is seen as a **rapid drop in the Earth's magnetic field strength**.
- **Ring Current**: Ring current is the name given to the large electric current that circles the Earth above its equator during magnetic storms.

Effects

- The **ionosphere gets heated and distorted**, which means that **long-range radio communication that is dependent upon sub-ionospheric reflection can be difficult**.
- Ionospheric expansion can increase **satellite drag,** and it may become difficult to control their orbits.
- Geomagnetic storms disrupt satellite communication systems like GPS.
- Astronauts and high-altitude pilots would face high radiation levels.
- Electric power grids would see a high increase in voltage that would cause blackouts.
- Geomagnetic storms disrupt satellite communication systems like GPS.

2.7 Van Allen radiation belt

- A Van Allen radiation belt is a **zone of energetic charged particles**, most of which originate from the solar wind, that are **captured by and held around a planet by that planet's magnetic field**.
- There are two such concentric tire-shaped regions. The inner belt is 1–2 Earth radii out while the outer belt is at 4–7 Earth radii.
- By trapping the solar wind, the belts deflect the energetic particles and **protect the atmosphere**.
- The **belts endanger satellites**, which must have their sensitive components protected with adequate shielding if they spend significant time near that zone.
- Spacecraft travelling beyond low Earth orbit enter the zone of radiation of the Van Allen belts. Beyond the belts, they face additional hazards from cosmic rays and solar particle events.



Van Allen Belts (Booyabazooka, via Wikimedia Commons)

2.8 Magnetic field of other solar system objects

Moon

- The magnetic field of the Moon is very weak in comparison to that of the Earth and doesn't have a magnetic dipole. It is not strong enough to prevent atmospheric stripping by the solar wind.

Mercury

- Mercury's magnetic field is approximately a magnetic dipole (meaning the field has two poles) and is just 1.1% that of Earth's magnetic field.
- It's proximity to the sun makes it next to impossible to sustain an atmosphere.

Mars

- Mars does not have an intrinsic global magnetic field, but the solar wind directly interacts with the atmosphere of Mars, leading to the formation of a magnetosphere.
- The **lack of a significant magnetosphere** is thought to be one reason for Mars's thin atmosphere.

Venus

- Venus **lacks a magnetic field**.
- Its ionosphere separates the atmosphere from outer space and the solar wind.
- In spite of the absence of a magnetic field, **Venus's atmosphere is one of the densest among the terrestrial planets**.

Jupiter

- Jupiter has the **largest magnetic field and a thick atmosphere**.

Saturn

- Saturn's magnetosphere is the second largest of any planet in the Solar System after Jupiter.

Uranus and Neptune too have a significant and similar magnetic field.

3. Geomorphic Movements

- Earth's crust and its surface are constantly evolving (changing) due to various forces emanating from below (**endogenic forces**) as well as above the surface of the earth (**exogenic forces**).
- These forces cause physical and chemical changes to the geomorphic structure (earth's surface).
- Some of these changes are imperceptibly slow (e.g. weathering, folding), some others are gradual (e.g. erosion) while the remaining are quite sudden (earthquakes, volcanic eruptions).
- **Geomorphic:** relating to the form of the landscape and other natural features of the earth's surface.
- **Geomorphic agents:** mobile medium (like running water, moving ice masses or glaciers, wind, waves, currents etc.) which removes, transports and deposits earth materials.
- **Geomorphic processes:** physical and chemical processes that take place on the earth's surface (folding, faulting, weathering, erosion, etc.) due to endogenic and exogenic forces.
- **Geomorphic movements:** large scale physical and chemical changes that take place on the earth's surface due to geomorphic processes.

3.1 Endogenic Geomorphic Movements

- The large-scale movements on the earth's crust or its surface brought down by the forces emanating from deep below the earth's surface are called as endogenic geomorphic movements or simply endogenic movements (endo: internal; genic: origin; geo: earth; morphic: form).
- The geomorphic processes that are driven by the forces emanating from deep below the earth's surface are called endogenic geomorphic processes (folding, faulting, etc.).

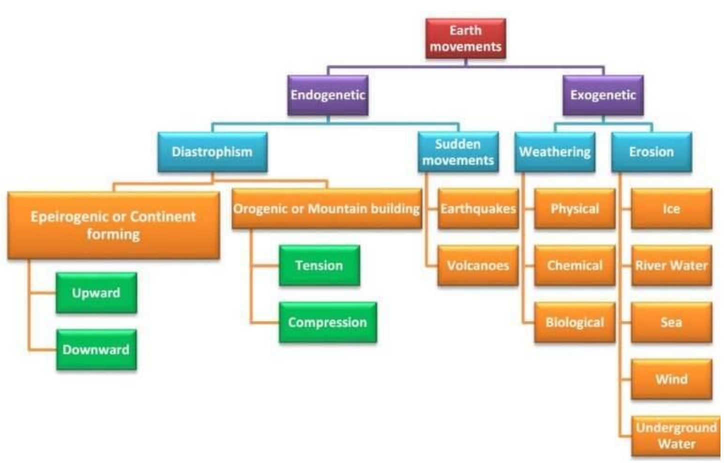
The force behind Endogenic Movements

- The ultimate source of energy behind forces that drive endogenic movements is **earth's internal heat**.
- Earth's internal heat is a result of mainly radioactive decay (50% of the earth's internal heat) and gravitation (causes pressure gradients).

- Differences in temperature and pressure (temperature gradients or geothermal gradients and pressure gradients) among various layers of the earth give rise to **density differences** and these density differences give rise to **conventional currents**.
- Convectional currents in the mantle drive the **lithospheric plates** (crust and upper mantle) and the **movement of the lithospheric plates** (**tectonics**) is the cause behind endogenic movements.
- The Earth's rotation (**Coriolis effect**) can influence where convection currents travel.
- The destination of convection currents determines the nature and location of the endogenic movements.

Classification of Endogenic movements

- Endogenic movements are divided into **diastrophic movements** and **sudden movements**.
- Diastrophism refers to **deformation** of the Earth's crust.
- Diastrophic movements are gradual and might stretch for thousands of years.
- On the other hand, sudden movements like earthquakes and volcanic eruptions occur in a very short period.
- Diastrophic movements are further classified into **epeirogenic movements (continent forming — subsidence, upliftment)** and **orogenic movements (mountain building — folding, faulting)**.



Diastrophism

- Diastrophism refers to deformation of the Earth's crust due to diastrophic movements (deforming movements) such as **folding, faulting, warping (bending or twisting of a large area) and fracturing**.
- All processes that move, elevate or build up portions of the earth's crust come under diastrophism. They include:
  1. **orogenic processes** involving mountain building through severe folding (crust is severely deformed into folds) and affecting long and narrow belts of the earth's crust;
  2. **epeirogenic processes** involving uplift or warping of large parts of the earth's crust (simple deformation);
  3. **earthquakes and volcanism** involving local relatively minor movements;
  4. **plate tectonics** involving horizontal movements of crustal plates.
- The most obvious evidence of diastrophic movement can be seen where sedimentary rocks have been bent, broken or tilted.

Epeirogenic or continent forming movements

- Epeirogenic or **continent forming** movements are **radial** movements (act **along the radius of the earth)**.
- Their direction may be **towards (subsidence)** or **away (uplift)** from the centre.
- They cause upheavals or depressions of land exhibiting **undulations** (wavy surface) of **long wavelengths** and little folding.
- The broad central parts of continents are called **cratons** and are subject to epeirogeny, hence the name continent forming movements.

Uplift

- Raised beaches, elevated wave-cut terraces, sea caves and fossiliferous beds above sea level are evidence of upliftment.

Uplifted landforms

- In India, raised beaches occur at several places along the **Kathiawar, Nellore, and Tirunelveli coasts**.
- Several places which were on the sea some centuries ago are now a few miles inland due to upliftment.
- For example, **Coringa near the mouth of the Godavari, Kaveripattinam in the Kaveri delta** and **Korkai on the coast of Tirunelveli**, were all flourishing seaports about 1,000 to 2,000 years ago.

Subsidence

- Submerged forests and valleys, as well as buildings, are evidence of subsidence.
- In 1819, a part of the **Rann of Kachchh** was submerged as a result of an earthquake.
- Presence of peat and lignite beds below the sea level in **Tirunelveli** and the **Sundarbans** is an example of subsidence.
- The **Andamans and Nicobars** have been isolated from the **Arakan coast** by **submergence** of the intervening land.

Arakan coast (Highlighted part)

- On the east side of **Bombay island**, trees have been found embedded in the mud about 4 m below low water mark. A similar submerged forest has also been noticed on the Tirunelveli coast in Tamil Nadu.
- A large part of the **Gulf of Mannar** and **Palk Strait** is very shallow and has been submerged in geologically recent times. A part of the former town of **Mahabalipuram** near Chennai is submerged in the sea.

Orogenic or the mountain-forming movements

- In contrast to epeirogenic movement, the orogenic movement is a **more complicated deformation** of the Earth's crust, associated with **crustal thickening** (due to the convergence of tectonic plates).
- Such plate convergence forms orogenic belts that are characterised by "the folding and faulting of layers of rock, by the intrusion of magma, and by volcanism.
- Orogenic or the mountain-forming movements **act tangentially to the earth surface,** as in plate tectonics.
- **Tension** produces **fissures** (since this type of force acts away from a point in two directions), and **compression** produces **folds** (because this type of force acts towards a point from two or more directions).

Fissure and Fold

Sudden Movements

- Sudden geomorphic movements occur mostly at the **lithospheric plate margins** (tectonic plate margins).
- The plate margins are highly unstable regions due to pressure created by pushing and pulling of magma in the mantle (**convectional currents**).

- These movements cause considerable deformation over a short period.

Earthquakes

- Earthquakes occur when the surplus accumulated stress in rocks in the earth's interior due to folding, faulting or other physical changes is relieved through the weak zones over the earth's surface in the form of **kinetic energy** (seismic waves).
- Such movements may result in uplift or subsidence in coastal areas.
- An earthquake in Chile (1822) caused a one-metre uplift in coastal areas.
- An earthquake in New Zealand (1885) caused an uplift of up to 3 metres.
- An earthquake in Japan (1891) caused subsidence of up to 6 metres.
- Earthquakes may cause a change in contours, change in river courses, shoreline changes, glacial surges (as in Alaska), landslides, soil creeps, mass wasting etc.

Volcanoes

- Volcanism includes the movement of molten rock (magma) onto or towards the earth's surface through narrow volcanic vents or fissures.
- A volcano is formed when the molten magma in the earth's interior escapes through the crust by vents and fissures in the crust, accompanied by steam, gases **(hydrogen sulphide, sulphur dioxide, hydrogen chloride, carbon dioxide** etc.) and pyroclastic material (cloud of ash, lava fragments carried through the air, and vapour).
- Depending on the chemical composition and viscosity of the lava, a volcano may take various forms.

3.2 Exogenic Geomorphic Movements

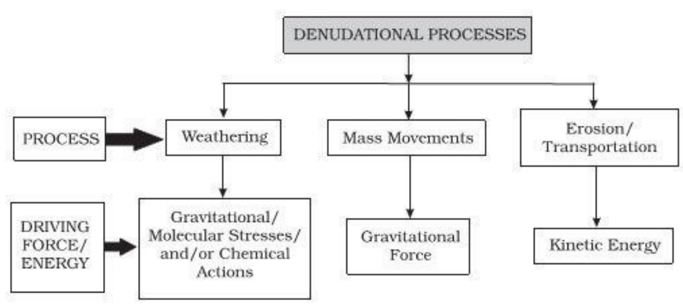
- The geomorphic processes on the earth's crust or its surface brought down by the **forces emanating from above the earth's surface** (wind, water) are called exogenic geomorphic process.
- Exogenic geomorphic process gives rise to exogenic geomorphic movements or simply exogenic movements such as **weathering** and **erosion**.
- The effects of most of the exogenic geomorphic processes are small and slow but will, in the long run, affect the rocks severely due to continued fatigue.

The force behind Exogenic Movements

- Exogenic processes are a direct result of the sun's heat.
- Sun's energy dictates the weather patterns like winds, precipitation, etc.
- Sun's heat along with weather patterns are responsible for stress induced in earth materials giving rise to exogenic movements (weathering and erosion).
- Earth materials become subjected to **molecular stresses** caused due to temperature changes.
- Chemical processes normally lead to **loosening of bonds** between grains.
- Stress is produced in a solid by pushing or pulling (**shear stresses** — separating forces) forces.

Denudation

- All the exogenic processes (weathering and erosion) are covered under a general term, denudation.
- The word 'denude' means to strip off or to uncover.
- Denudation depends on physical (folds, faults, orientation and inclination of beds, presence or absence of joints, bedding planes, hardness or softness of constituent minerals, permeability) and chemical (chemical susceptibility of mineral constituents to corrosion) properties of the rocks.



Weathering

- Weathering is the **disintegration** of rocks, soil, and minerals under the influence of physical (heat, pressure) and chemical (leaching, oxidation and reduction, hydration) agents.
- As very little or no motion of materials takes place in weathering, it is an **in-situ or on-site process**.
- The weathered material is carried farther away by **erosion**.
- There are three major groups of weathering processes: **1) chemical; 2) physical or mechanical; 3) biological weathering processes.** All the types of weathering often go hand in hand.

Physical Weathering Processes

- Physical weathering involves **mechanical disintegration** of rocks due to temperature changes, freeze-thaw cycles, wet-dry cycles, crystallisation of salts, animal and plant activity, etc.
- Various mechanisms of physical weathering are explained below.

Exfoliation due to pressure release or unloading

- Intrusive igneous rocks formed deep beneath the Earth's surface are under tremendous pressure due to overlying load.
- Removal of the overlying load because of continued erosion causes vertical pressure release with the result that the upper layers of the rock expand and fracture parallel to the surface.
- Over time, sheets of rock break away from the exposed rocks along the fractures, a process known as **exfoliation**.
- Exfoliation due to pressure release is also known as "**sheeting**".

Exfoliation due to thermal stress weathering

- Thermal stress weathering results from the subsequent expansion and contraction of rocks caused by diurnal and seasonal variations in the temperatures.
- The surface layers of the rocks tend to expand more than the rock at depth, and this leads to peeling off of the surface layers (exfoliation).
- This process is most effective in **dry climates** and **high elevations** where **diurnal temperature changes are drastic**.
- Although temperature changes are the principal driver, moisture can enhance thermal expansion in rock.

Granular Disintegration

- Granular disintegration happens in rocks composed of different types of coarse-grained minerals.
- Dark-coloured minerals absorb more heat than the light-coloured minerals.
- This leads to differential expansion and contraction of mineral grains resulting in grain by grain separation from the rock.

Frost weathering

- During the warm season, the water penetrates the pore spaces or fractures in rocks.
- During the cold season, the water freezes into ice, and its volume expands as a result.
- This exerts tremendous pressure on rock walls to tear apart even where the rocks are massive.
- Frost weathering occurs due to the growth of ice within pores and cracks of rocks during repeated cycles of freezing and melting.
- Frost weathering is the collective name for several processes where ice is present.
- These processes include **frost shattering, frost-wedging** and **freeze-thaw weathering**.

Frost wedging

- Freeze wedging is caused by the repeated freeze-thaw cycle.
- Cracks filled with water are forced further apart with subsequent freezing and thawing.

Shattering

- Severe frost can disintegrate rocks along weak zones to produce **highly angular pieces** with sharp corners and edges through the process of shattering.
- Shattering piles up rock fragments called **scree** at the foot of mountain areas or along slopes.

Block Separation (freeze-thaw weathering)

- Repeated freeze-thaw cycles weaken the rocks which, over time, break up along the joints into angular pieces. The splitting of rocks along the joints into blocks is called block disintegration.

Salt Weathering

- Salt weathering occurs when saline solutions seep into cracks and joints in the rocks and evaporate, leaving salt crystals behind.
- Salt crystals expand during the crystallization process and also when they are subjected to above normal temperatures.
- The expansion in near-surface pores causes splitting of individual grains within rocks, which eventually fall off (granular disintegration or granular foliation).
- Salt weathering is normally associated with **arid climates** where strong heating causes strong evaporation and crystallisation.

Mass Wasting

- Mass wasting is the mass movement of unconsolidated soil, sand, rocks, regolith (the layer of unconsolidated solid material covering the bedrock of a planet), etc. along a slope under the influence of gravity.
- Mass wasting occurs when the gravitational force acting on a slope exceeds its resisting force leading to **slope failure** (mass wasting).
- Timescales of the mass wasting process may be a few seconds (debris flows and mudflows) or hundreds of years (mass wasting along the slopes of stable mountains leaving behind alluvial fan like structures).

Chemical Weathering

- Chemical weathering involves **chemical decomposition** of rocks and soil.
- Chemical weathering processes include **dissolution, solution, carbonation, hydration, oxidation and reduction** that act on the rocks to decompose, dissolve or reduce them to a fine state.
- These weathering processes are interrelated and go hand in hand and hasten the weathering process.

- Acids produced by microbial and plant-root metabolism, water and air (oxygen and carbon dioxide) along with heat speed up all chemical reactions.

Natural dissolution

- Dissolution: a process where a solute in gaseous, liquid, or solid phase dissolves in a solvent to form a solution.
- Some minerals, due to their natural solubility (like nitrates, sulphates, and potassium), oxidation potential (iron-rich minerals) will weather through dissolution naturally (rains).
- These minerals are easily **leached** out without leaving any residue and accumulate in dry regions.

Solution weathering

- Solution weathering occurs **when the solvent is an acidic solution** rather than simple water.
- A solution is a liquid mixture in which the minor component (the solute) is uniformly distributed within the major component (the solvent).
- **Acidic solutions** are any solution that has a higher concentration of hydrogen ions than water; solutions that have a lower concentration of hydrogen ions than water is called **basic or alkaline solutions**.

Carbonation – Natural solution weathering

- Carbonation refers to reactions of carbon dioxide to give **carbonates, bicarbonates, and carbonic acid**.
- Carbonation weathering is a process in which atmospheric carbon dioxide leads to **solution weathering**.
- As rain falls, it dissolves small amounts of carbon dioxide from the air, forming a weak acid that can dissolve some minerals like **limestone (calcium carbonate)** (solution weathering).
- When carbonic acid reacts with limestone, it produces calcium bicarbonate, which is partially soluble in water (dissolution weathering).
- Caves are formed when underground water containing carbonic acid travels through blocks of limestone, dissolves out the limestone, and leaves empty pockets (caves) behind (E.g. **Karst topography**).
- Carbonation process speeds up with a decrease in temperature because **colder water holds more dissolved carbon dioxide gas**. Carbonation is, therefore, a large feature of **glacial weathering**.

Anthropogenic solution weathering

- **Rainfall is naturally acidic** — pH of ~5.6 (CO_2 dissolves in the rainwater producing **weak carbonic acid**).
- Acid rain occurs when gases such as **sulphur dioxide** and **nitrogen oxides** are present in the atmosphere.
- These oxides react in the rainwater to produce stronger acids and can lower the pH to less than 4.
- These acids are capable of attacking certain kinds of rocks in much the way that carbonic acid does.

*Sulphur dioxide, SO2, comes from **volcanic eruptions or fossil fuels**.*
The conversion of metallic ores to the pure metals often results in the formation of sulphur dioxide.

Hydration

- Hydration is the **chemical addition of water** that involves the rigid attachment of H+ and OH- ions to the atoms and molecules of a mineral.
- When rock minerals take up water, the increased volume creates physical stresses within the rock. For example, iron oxides are converted to iron hydroxides which are larger in volume.
- Hydration is reversible, and continued repetition of this process causes fatigue in the rocks and may lead to their disintegration.
- The volume changes in minerals due to hydration will also help in physical weathering through **exfoliation** and **granular disintegration**.

Hydrolysis

- In biological hydrolysis, a **water molecule is consumed** to affect the **separation of a larger molecule into component parts**.

- In biological hydrolysis pure water reacts with **silicate** or **carbonate minerals** resulting in the complete dissolution of the original mineral (dissolution weathering).
- Biological hydrolysis is an important reaction in **controlling the amount of CO_2 in the atmosphere** and can affect climate.

Oxidation and Reduction

- In weathering, oxidation means **a combination of a mineral with oxygen to form oxides** (rusting in case of iron) or hydroxides. **Red soils** appear red due to the presence of iron oxides.
- Oxidation occurs where there is ready access to the atmosphere and water.
- The minerals most commonly involved in this process are iron, manganese, sulphur etc.
- When oxidised minerals are placed in an environment where oxygen is absent, **reduction** takes place.
- Such conditions usually exist below the water table, in areas of stagnant water and waterlogged ground.
- The red colour of iron upon reduction turns to greenish or bluish grey.

Biological activity and weathering

- Biological weathering is the removal of minerals from the environment due to growth or movement of organisms.
- Living organisms contribute to both mechanical and chemical weathering.
- Lichens and mosses grow on essentially bare rock surfaces and create a more humid chemical microenvironment.
- On a larger scale, seedlings sprouting in a crevice and plant roots exert physical pressure as well as providing a pathway for water and chemical infiltration.
- Burrowing and wedging by organisms like earthworms, rodents etc., help in exposing the new surfaces to chemical attack and assists in the penetration of moisture and air.
- Decaying plant and animal matter help in the production of **humic, carbonic and other acids** which enhance decay and solubility of some elements.
- Algae utilise mineral nutrients for growth and help in the concentration of iron and manganese oxides.

Significance of weathering

- Weathering is the **first step in the formation of soil** from rocks.
- Weathering weakens soil and rocks and makes it easy to exploit natural resources.
- Weathering leads to **natural soil enrichment**.
- Weathering leads to **mineral enrichment** of certain ores by leaching unwanted minerals leaving behind the valuable ones.

Soil Erosion, another exogenic movement, is covered in the subsequent chapters.

4. Tectonics

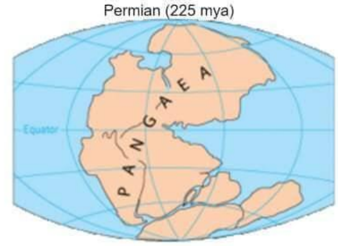
- During WW II, it was discovered that the ocean floor had some unique relief features like ridges, trenches, seamounts, shoals etc.
- Ridges and trenches gave insights into natural boundaries between various lithospheric plates (tectonic plates). These important discoveries led to the field of tectonics in geology.
- Tectonics is the scientific study of forces (convection currents in the mantle) and processes (collisions of the lithospheric plates, folding, faulting, volcanism) that control the structure of the Earth's crust and its evolution through time.
- It is basically about understanding the large-scale deformation of the lithosphere (crust and upper mantle above asthenosphere) and the forces that produce such deformation.
- It deals with the folding and faulting associated with mountain building; the large-scale, gradual upward and downward movements of the crust (epeirogenic movements); the growth and behaviour of old cores of continents known as cratons; and sudden horizontal displacements along faults.

4.1 Important concepts that tried to explain the tectonic processes

Geologic Time Scale
Tectonics (By Pmfias.com)

- Prechambrian Supereon (4.5 bya – 541 mya)
  - Hadean Eon (4.5 bya – 4.0 bya)
  - Archean Eon (4.0 bya – 2.5 bya)
  - Proterozoic Eon (2.5 bya – 541 mya)
- Unnamed Supereon (541 mya – present)
  - Phanerozoic Eon (541 mya – present)
    - Paleozoic Era (541 mya – 250 mya)
      - Cambrian Period (541 – 485 mya)
      - Ordovician Period (485 – 440 mya)
      - Silurian Period (440 – 415 mya)
      - Devonian Period (415 – 360 mya)
      - Carboniferous Period (360 – 300 mya)
      - Permian Period (300 – 250 mya)
    - Mesozoic Era (250 mya – 66 mya)
      - Triassic Period (250 – 200 mya)
        - Early Triassic Epoch (250 – 247 mya)
        - Middle Triassic Epoch (247 – 237 mya)
        - Late Triassic Epoch (237 – 200 mya)
      - Jurassic Period (200 – 145 mya)
        - Early Jurassic Epoch (200 – 175 mya)
        - Middle Jurassic Epoch (175 – 163 mya)
        - Late Jurassic Epoch (163 – 145 mya)
      - Cretaceous Period (145 – 66 mya)
        - Early Cretaceous Epoch (145 – 100 mya)
        - Late Cretaceous Epoch (100 – 65 mya)
    - Cenozoic Era (66 mya – present)
      - Paleogene Period (65 – 23 mya)
        - Paleocene Epoch (65 – 56 mya)
        - Eocene Epoch (56 – 33 mya)
        - Oligocene Epoch (33 mya – 23 mya)
      - Neogene Period (23 – 2.58 mya)
        - Miocene Epoch (23 mya – 5.3 mya)
        - Pliocene Epoch (5.3 mya – 2.58 mya)
      - Quaternary Period (2.58 mya – present)
        - Pleistocene Epoch (2.58 mya – 11,700 ya)
        - Halocene Epoch (11,700 ya – present)

Permian (225 mya)

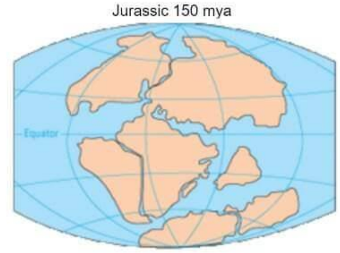


Permian Period:
- Pangea Intact
- Pangea was covered by a mighty ocean called as Panthalassa

Late Triassic Epoch:
- Pangaea broke up into Laurentia (Laurasia) to the north and Gondwanaland to the south
- The Tethys sea seperated Laurentia and Gondwanaland
- Rifts formed splitting West Gondwana from east Gondwana.
- India separated from Antarctica.
- Laurasia split from South America and Africa.

Triassic 200 mya

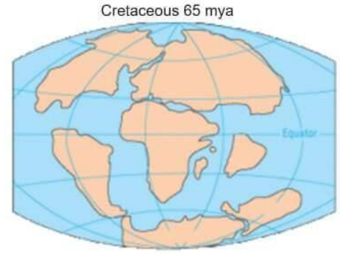
Jurassic 150 mya

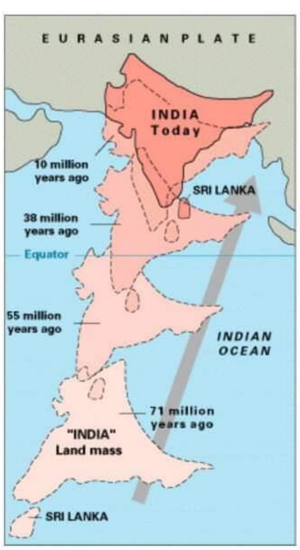


Late Jurassic Epoch:
- Seafloor spreading further opened the central North Atlantic and Indian oceans.
- At the end of the period, a new rift split South America from Africa.

Late Cretaceous Epoch:
- Madagascar drifted away from Africa, which continued its move north.
- The northward drift of India continued, and Australia split from Antarctica.
- Zealandia, a microcontinent nearly half the size of Australia, broke away from the Gondwanan supercontinent about 83 million years ago.

Cretaceous 65 mya





Tertiary is the former term for the geologic period from 66 million to 2.58million years ago. The term is now obsolete.

Continental Drift Theory (CDT)

- Continental drift refers to the movement of the continents relative to each other.

Polar wandering (similar to Continental Drift Theory)

- Polar wandering is the relative movement of the earth's crust and upper mantle with respect to the rotational poles of the earth.

Seafloor Spreading Theory (SFST)

- Seafloor spreading describes the movement of oceanic plates relative to one another.

Plate Tectonics (PT)

- Plate tectonics is the movement of lithospheric plates relative to each other.

Convection Current Theory (CCT)

- Convection current theory forms the basis of SFST and PT. It explains the force behind plate movements.

4.2 Continental Drift Theory (Alfred Wegener, 1922)

- Alfred Wegener suggested continental Drift Theory in the 1920's.
- According to Continental Drift Theory there existed one big landmass which he called **Pangaea** which was covered by one big ocean called **Panthalassa**.
- A sea called **Tethys** divided the Pangaea into two huge landmasses: **Laurentia (Laurasia)** to the north and **Gondwanaland** to the south of Tethys.
- Drift started around 200 million years ago (Mesozoic Era, Triassic Period, Late Triassic Epoch), and the continents began to break up and drift away from one another.

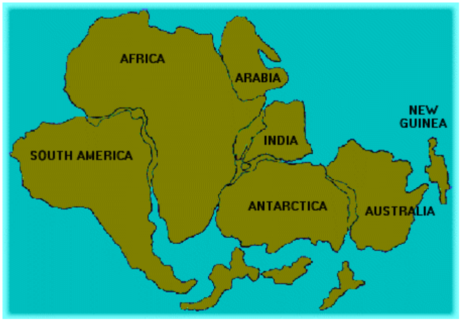
Forces behind the drifting of continents, according to Wegener

- According to Wegener, the drift was in two directions:
  - equator wards due to the interaction of forces of gravity, pole-fleeing force (due to centrifugal force caused by earth's rotation) and buoyancy (*ship floats in water due to buoyant force offered by water*), and
  - westwards due to tidal currents because of the earth's motion (earth rotates from west to east, so tidal currents act from east to west, according to Wegener).
  - Wegener suggested that tidal force (gravitational pull of the moon and to a lesser extent, the sun) also played a major role.
- The polar-fleeing force relates to the rotation of the earth. Earth is not a perfect sphere; it has a bulge at the equator. This bulge is due to the rotation of the earth (greater centrifugal force at the equator).
- Centrifugal force increases as we move from poles towards the equator. This increase in centrifugal force has led to pole fleeing, according to Wegener.
- Tidal force is due to the attraction of the moon and the sun that develops tides in oceanic waters (tides explained in detail in oceanography).
- According to Wegener, these forces would become effective when applied over many million years, and the drift is continuing.

Evidence in support of Continental Drift

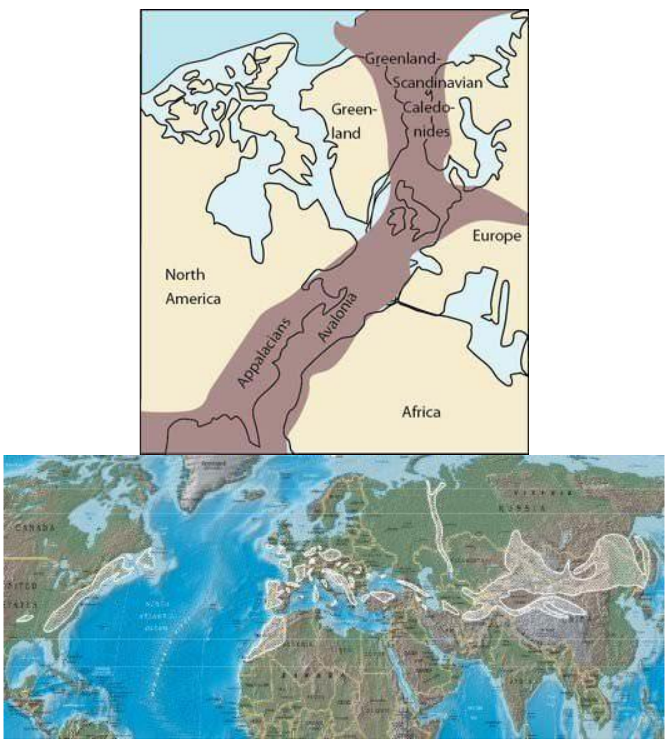
Evidence for CDT

Apparent Affinity of Physical Features



Apparent Affinity of Physical Features

- The bulge of Brazil (South America) seems to fit into the Gulf of Guinea (Africa).
- Greenland seems to fit in well with Ellesmere and Baffin islands of Canada.
- The west coast of India, Madagascar and Africa seem to have been joined.
- North and South America on one side and Africa and Europe on the other fit along the mid-Atlantic ridge.
- The Caledonian and Hercynian mountains of Europe and the Appalachians of USA seem to be one continuous series.



Continuous Very Old Fold Mountain Chain

Criticism

- Coastlines are a temporary feature and are liable to change.
- Several other combinations of fitting in of unrelated landforms could be attempted.
- Continental Drift Theory shifts India's position too much to the south, distorting its relationship with the Mediterranean Sea and the Alps.
- The mountains do not always exhibit geological affinity.

Causes of Drift

- The gravity of the earth, the buoyancy of the seas and the tidal currents were given as the main factors causing the drift, by Wegener.

Criticism

- This is illogical because for these factors to be able to cause a drift of such a magnitude, they will have to be millions of times stronger.

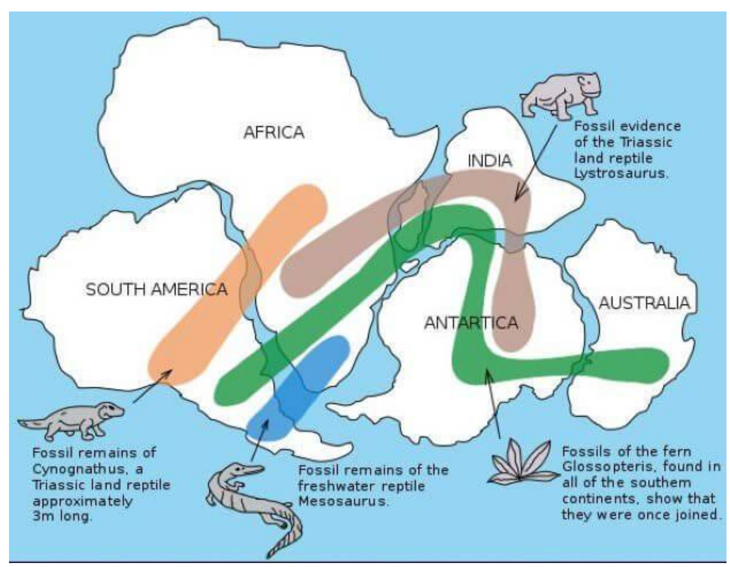
Polar wandering (Shifting of Poles)

- The position of the poles constantly drifted (due to plate tectonics).

Criticism

- Poles may have shifted, not necessarily the continents.

Botanical Evidence



Distribution of Fossils across the Gondwanaland

- Presence of glossopteris vegetation in Carboniferous rocks of India, Australia, South Africa, Falkland Islands (Overseas territory of UK), Antarctica, etc. (all split from the same landmass called Gondwana) can be explained from the fact that parts were linked in the past.

Criticism

- Similar vegetation is found in unrelated parts of the world like Afghanistan, Iran and Siberia.

Distribution of Fossils

- The observations that Lemurs occur in India, Madagascar and Africa led some to consider a contiguous landmass "Lemuria" linking these three landmasses.
- Mesosaurus was a small reptile adapted to shallow brackish water. The skeletons of these are found only in South Africa and Brazil. The two localities presently are 4,800 km apart with an ocean in between them.

Rocks of Same Age Across the Oceans

- The belt of ancient rocks of 2,000 million years from Brazil coast matches with those from western Africa.

Criticism

- Rocks of the same age and similar characteristics are found in other parts of the world too.

Tillite deposits

- **Tillite deposits** are **sedimentary rocks formed out of deposits of glaciers**.
- The Gondwana system of sediments are found in India, Africa, Falkland Island, Madagascar, Antarctica and Australia (all were previously part of Gondwana).
- Overall resemblance demonstrates that these landmasses had remarkably similar histories.

Placer Deposits

- Rich **placer deposits of gold** are found on the Ghana coast (West Africa) but the source (gold-bearing veins) are in Brazil, and it is obvious that the gold deposits of Ghana are derived from the Brazil plateau when the two continents lay side by side.

Drawbacks of Continental Drift Theory

- Wegener failed to explain why the drift began only in Mesozoic era and not before.
- The theory doesn't consider oceans.
- Proofs heavily depend on assumptions that are generalistic.
- Forces like buoyancy, tidal currents and gravity are too weak to be able to move continents.
- Modern theories (Plate Tectonics) accept the existence of Pangaea and related landmasses but give a very different explanation to the causes of drift.

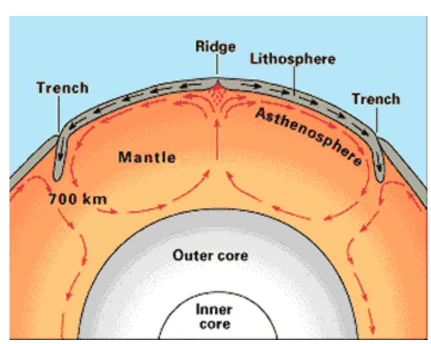
Though scientifically unsound on various grounds, Wegener's theory is a significant milestone in the study of tectonics, and it laid a strong foundation for future the theories like seafloor spreading and plate tectonics.

4.3 Seafloor Spreading

- To understand the concept of Seafloor Spreading, we must first understand some basic concepts that form the cornerstones for the concept of Seafloor Spreading.
- These cornerstones are **Convectional Current Theory** and **Paleomagnetism**.

Convection Current Theory

- Convection Current Theory is the soul of Seafloor Spreading Theory.
- **Arthur Holmes** in 1930s discussed the possibility of **convection currents in the mantle**.
- These currents are generated due to **radioactive elements causing thermal differences** in the mantle.



Convection currents in the mantle

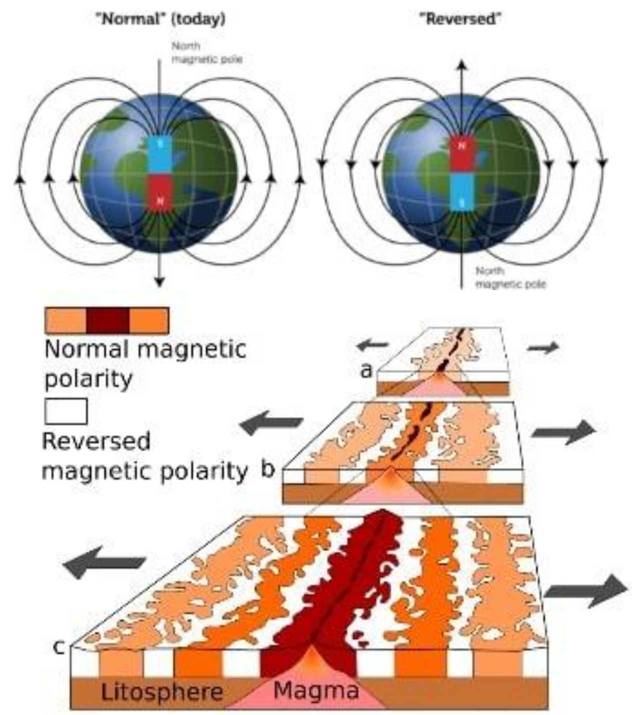
- According to this theory, the intense heat generated by radioactive substances in the mantle (100-2900 km below the earth surface) seeks a path to escape and gives rise to the formation of convection currents in the mantle.
- Wherever **rising limbs of these currents meet, oceanic ridges are formed** on the seafloor due to the **divergence** of the lithospheric plates (tectonic plates), and wherever the **failing limbs meet, trenches are formed** due to the **convergence** of the lithospheric plates (tectonic plates).
- **The movement of the lithospheric plates is caused by the movement of the magma in the mantle**.

Paleomagnetism

- Paleomagnetism is the study of the **record of earth's magnetic field** with the help of **magnetic fields recorded in rocks, sediment**, or archaeological materials.
- Rocks formed from underwater volcanic activity are mainly **basaltic** (low silica, iron-rich) that makes up most of the ocean floor.
- Basalt contains magnetic minerals, and as the rock is solidifying, these minerals **align themselves in the direction of the magnetic field.**
- This locks in a record of which way the magnetic field was positioned at the time.
- Paleomagnetic studies of rocks have demonstrated that the orientation of the earth's magnetic field has **frequently alternated (geomagnetic reversal)** over geologic time.
- The polarity of the Earth's magnetic field and magnetic field reversals are thus detectable by studying the rocks of different ages.

Paleomagnetism: Strong evidence of Seafloor Spreading and Plate Tectonics

- **Paleomagnetism** led the revival of the continental drift hypothesis and its transformation into theories of Sea Floor Spreading and Plate Tectonics.
- The regions that hold the unique record of earth's magnetic field lie along the **mid-ocean ridges** where the sea floor is spreading.
- On studying the **paleomagnetic rocks** on either side of the oceanic ridges, it is found that **alternate magnetic rock stripes were flipped** so that one stripe would be of normal polarity and the next, reversed.
- Hence, paleomagnetic rocks (paleo: denoting rocks) on either side of the mid-ocean or submarine ridges provide the **most important evidence to the concept of Sea Floor Spreading**.
- Magnetic field records also provide information on the **past location of tectonic plates**.



The alternating pattern of magnetic striping on the seafloor

Explanation

- These oceanic ridges are boundaries where tectonic plates are **diverging** (moving apart).
- The fissure or vent (in between the ridge) between the plates allowed the magma to rise and harden into a long narrow band of rock on either side of the vent.
- Rising magma **assumes the polarity of Earth's geomagnetic field at the time** before it solidifies on the oceanic crust.
- As the conventional currents pull the oceanic plates apart, the solidified band of rock moves away from the vent (or ridge), and a new band

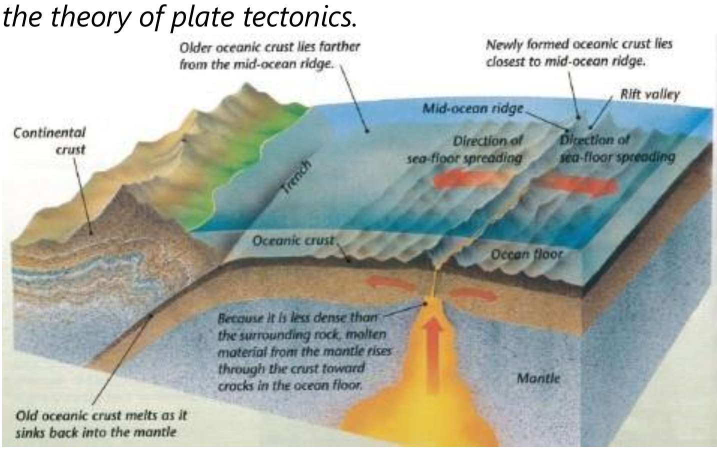
of rock takes its place a few million years later when the magnetic field was reversed. This results in this **magnetic striping** where the **adjacent rock bands have opposite polarities**.

- This process repeats over and over giving rise to a series of narrow parallel rock bands on either side of the ridge and **alternating pattern of magnetic striping on the seafloor.**

The concept of Sea Floor Spreading

- Harry Hess proposed the idea of See Floor Spreading**.**
- When oceanic plates diverge, tensional stress causes fractures to occur in the lithosphere.
- **Basaltic magma** rises from the fractures and cools on the ocean floor to form **new seafloor**.
- The newly formed seafloor (oceanic crust) then **gradually moves away** from the ridge, and its place is taken by an even newer seafloor and the cycle repeats.
- With time, **older rocks are spread farther away from the spreading zone** while **younger rocks will be found nearer to the spreading zone**.

Seafloor spreading helps explain continental drift in the theory of plate tectonics.



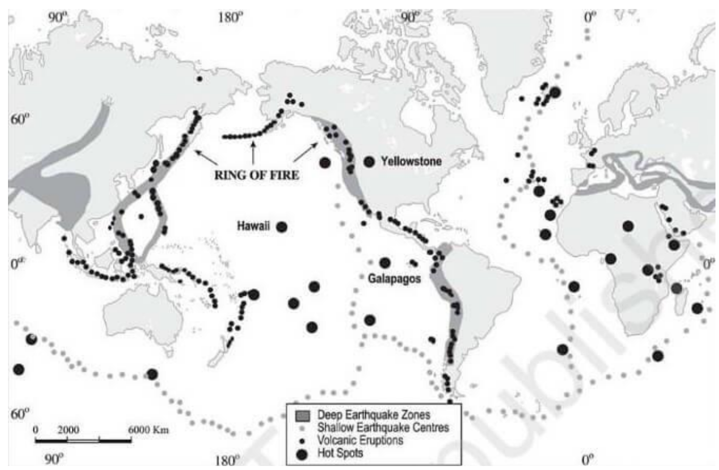
Seafloor Spreading

Evidence for Seafloor Spreading

Nature of oceanic rocks around mid-ocean ridges

- Rocks on either side of the crest of oceanic ridges having equidistant locations from the crest were found to have similarities both in terms of their constituents, their age and magnetic orientation.
- Rocks closer to the mid-oceanic ridges have normal polarity and are the youngest and the age of the rocks increases as one moves away from the crest (ridge).
- The **rocks of the oceanic crust near the oceanic ridges are much younger than the rocks of the continental crust**.

Distribution of Earthquakes and Volcanoes along the mid-ocean ridges

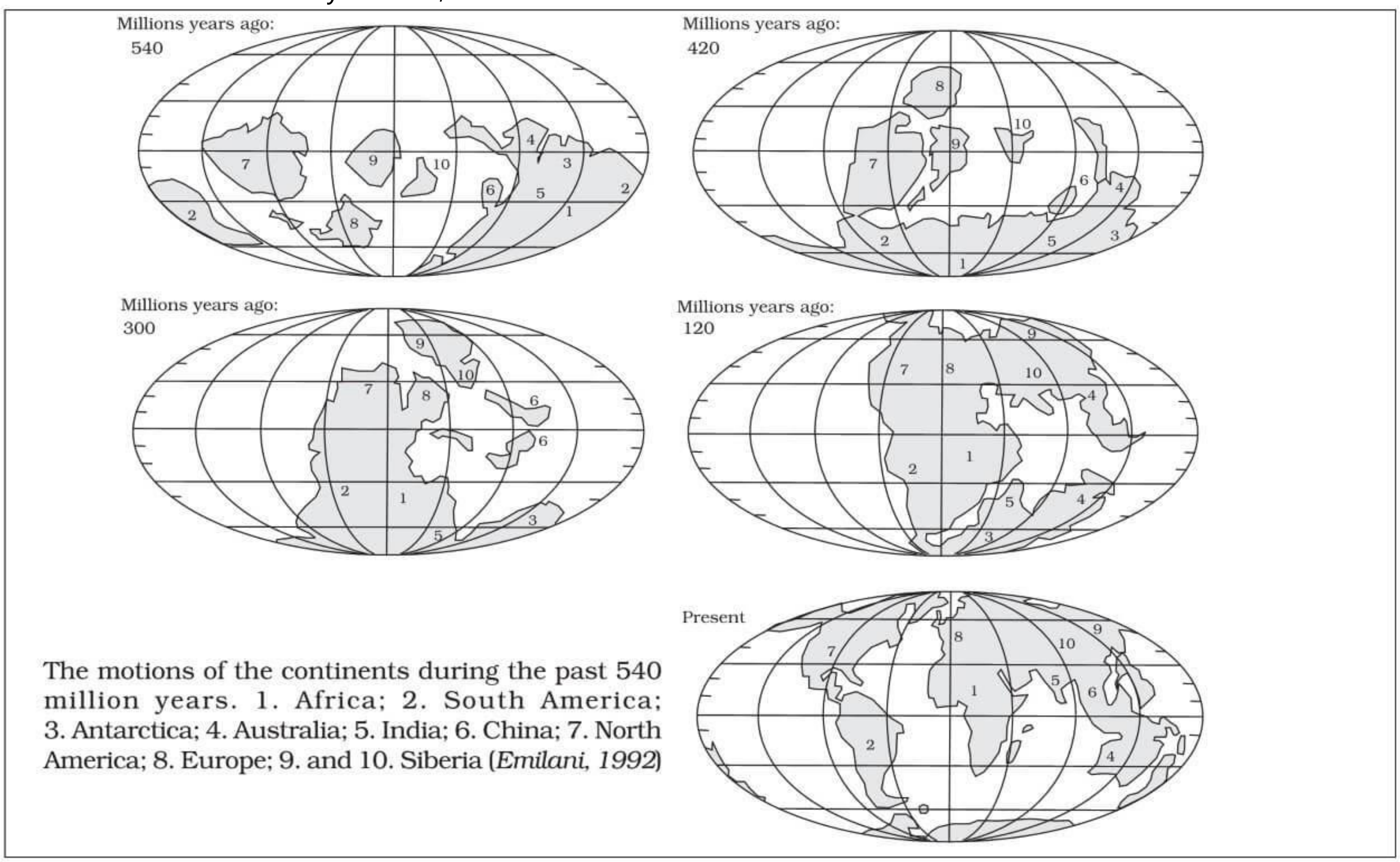


- The normal temperature gradient on the sea floor is 9.4° C/300 m, but near the ridges it becomes higher, indicating an upwelling of magmatic material from the mantle.
- Dots in the central parts of the Atlantic Ocean and other oceans are almost parallel to the coastlines. This indicates that the seafloor has widened with time.
- In general, the foci of the earthquake in the areas of mid-oceanic ridges are at shallow depths whereas, along the Alpine-Himalayan belt as well as the rim of the Pacific, the earthquakes are deep-seated ones.

4.4 Plate Tectonics

- It was from the continental drift theory, convection current theory and the theory of seafloor spreading, the theory of **Plate Tectonics** was formulated.
- In 1967, **McKenzie and Parker** suggested the theory of plate tectonics. Morgan later outlined the theory in 1968.

- According to the theory of plate tectonics, the **earth's lithosphere is broken into distinct plates** which are floating on a **ductile layer called asthenosphere** (upper part of the mantle).
- Plates move horizontally over the **asthenosphere** as rigid units.
- The lithosphere includes the **crust** and **top mantle** with its thickness range varying between **5-100 km in oceanic parts and about 200 km in the continental areas**.
- The oceanic plates contain mainly the **Simatic crust** and are relatively thinner, while the continental plates contain **Sialic material** and are relatively thicker.
- Lithospheric plates (**tectonic plates**) vary from **minor plates** to **major plates**, **continental plates** (Arabian plate) to **oceanic plates** (Pacific plate), sometimes a **combination** of both continental and oceanic plates (Indo-Australian plate).
- The movement of these crustal plates (due to convection currents in the mantle) causes the formation of various landforms and is the principal cause of all earth movements.



The motions of the continents during the past 540 million years. 1. Africa; 2. South America; 3. Antarctica; 4. Australia; 5. India; 6. China; 7. North America; 8. Europe; 9. and 10. Siberia (*Emilani, 1992*)

The position of the continents through geologic past

Force for plate movement

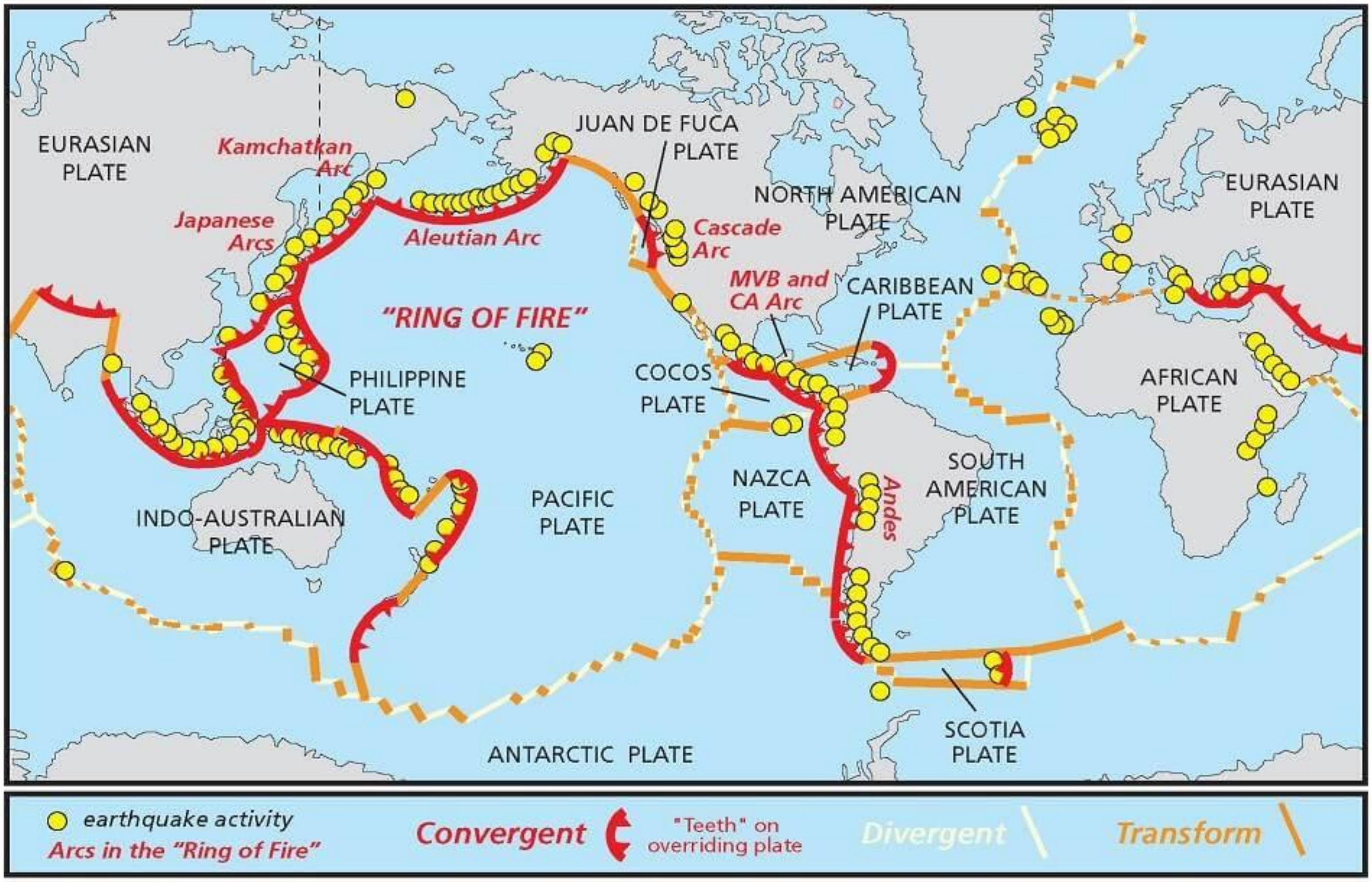
- Convection currents in the mantle that are generated due to thermal gradients.

Rates of Plate Movement

- The Arctic Ridge has the slowest rate (less than 2.5 cm/year), and the East Pacific Rise in the South Pacific (about 3,400 km west of Chile), has the fastest rate (more than 15 cm/year).

Major tectonic plates

1. Antarctica and the surrounding oceanic plate
2. North American plate
3. South American plate
4. Pacific plate
5. India-Australia-New Zealand plate
6. Africa with the eastern Atlantic floor plate
7. Eurasia and the adjacent oceanic plate



Divergent, Convergent and Transform Boundaries ([nps.gov](nps.gov) R.J. Lillie. 2005. Parks and Plates)

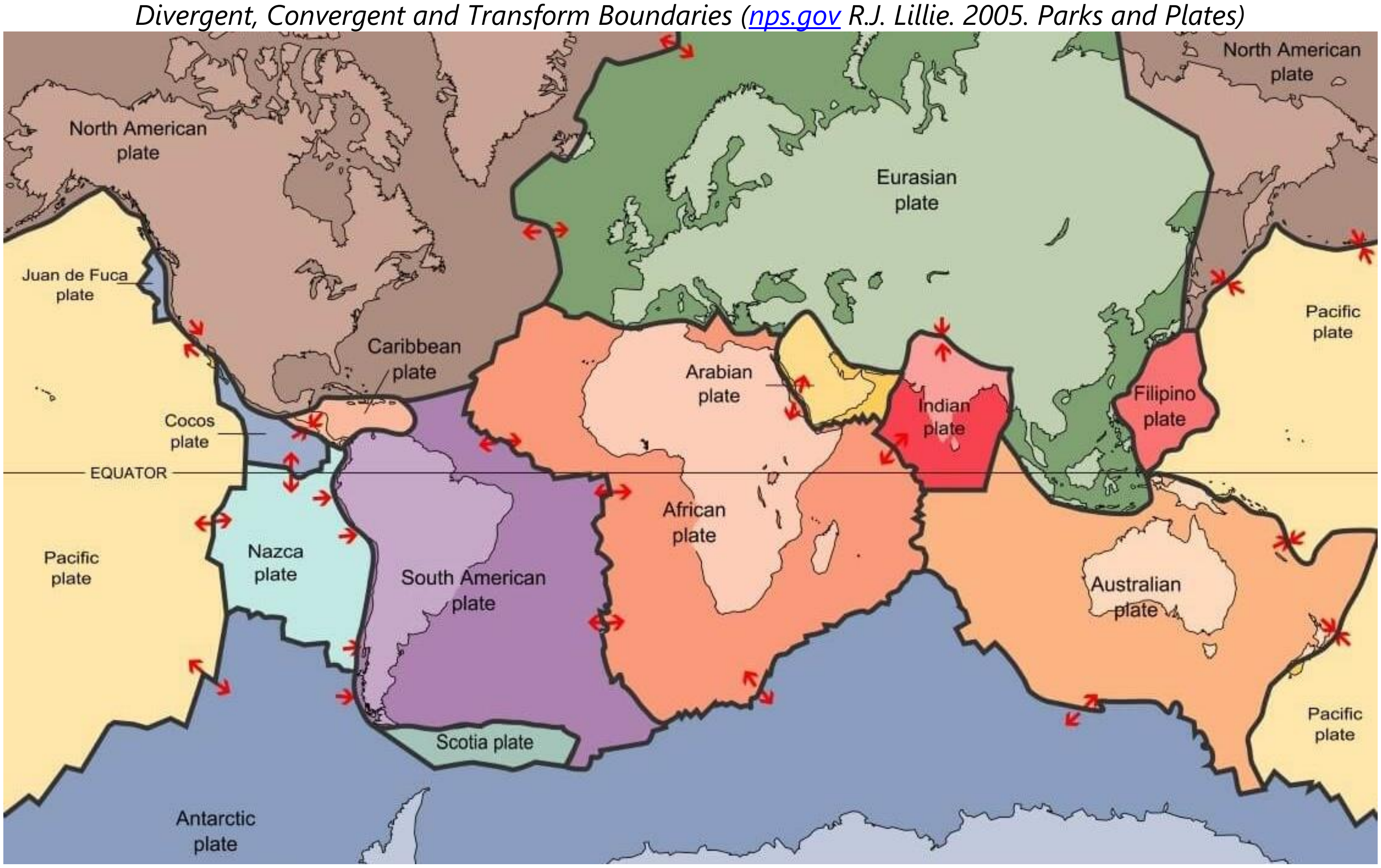


Plate Boundaries

Minor tectonic plates

1. Cocos plate: Between Central America and Pacific plate
2. Nazca plate: Between South America and Pacific plate
3. Arabian plate: Mostly the Saudi Arabian landmass
4. Philippine plate: Between the Asiatic and Pacific plate
5. Caroline plate: Between the Philippine and Indian plate (North of New Guinea)
6. Fuji plate: North-east of Australia
7. Turkish plate
8. Aegean plate (Mediterranean region)
9. Caribbean plate
10. Juan de Fuca plate (between Pacific and North American plates)
11. Iranian plate.

- There are many more minor plates other than the ones mentioned above.
- Most of these minor plates were formed due to **stress created by converging major plates**.
- Example: the Mediterranean Sea is divided into numerous minor plates due to the compressive force exerted by Eurasian and African plates.

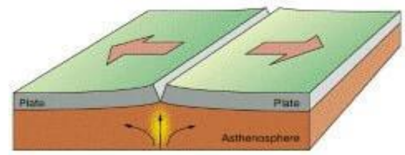
The figure below shows the changes in landform with time due to the interaction of various plates.

Interaction of Plates

- Major geomorphological features such as fold and block mountains, mid-oceanic ridges, trenches, volcanism, earthquakes etc. are a direct consequence of the interaction between various lithospheric plates.
- There are three ways in which the plates interact with each other.

Divergence forming Divergent Edge or the Constructive Edge

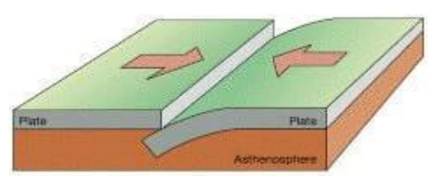
- In this kind of interaction, the plates diverge (**move away** from each other).
- **Mid-ocean ridges** (e.g. Mid-Atlantic Ridge) are formed due to this kind of interaction.
- Here, the basaltic magma erupts and moves apart (seafloor spreading).
- On continents, **East African Rift Valley** is the most important geomorphological feature formed due to the divergence of **African and Somali plates**.
- Divergent edges are sites of earth **crust formation** (hence the name **constructive edge**), and volcanic earth forms are common along such edges.
- Earthquakes (shallow focus) are common along divergent edges.



Divergent Boundary

Convergence forming Convergent Edge or Destructive Edge

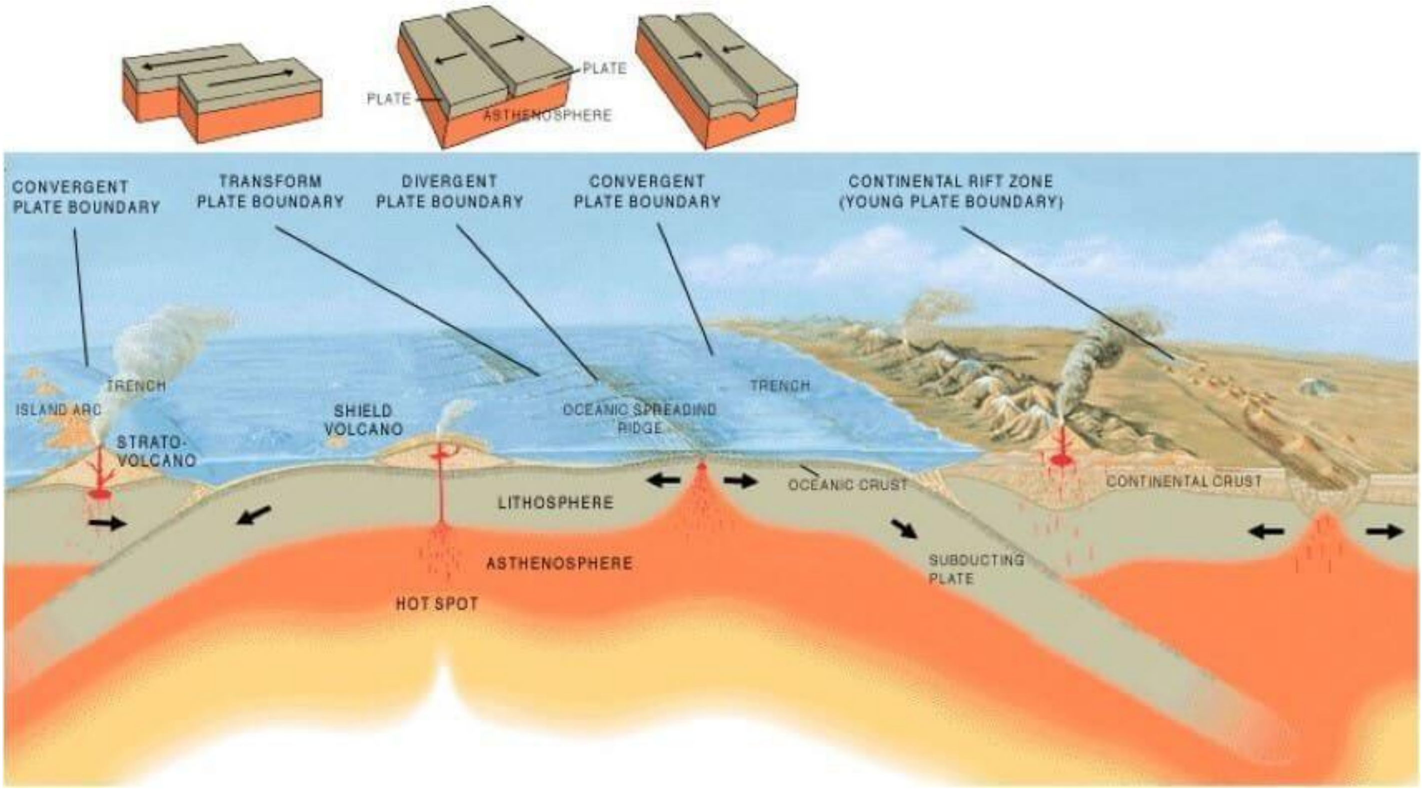
- In this kind of interaction, two lithospheric plates **collide** against each other.
- The zone of collision may undergo crumpling and folding, and folded mountains may emerge (**orogenic collision**). **Himalayan Boundary Fault** is one such example.
- When one of the plates is an oceanic plate, it gets embedded in the **softer asthenosphere** of the continental plate, and as a result, **trenches** are formed at the **zone of subduction.**
- Near the convergent edge a part of the crust is destroyed, hence the name **Destructive Edge**.
- The subducted material gets heated, up and is thrown out forming **volcanic island arc and continental arc systems** and a dynamic equilibrium is achieved.



Convergent Boundary

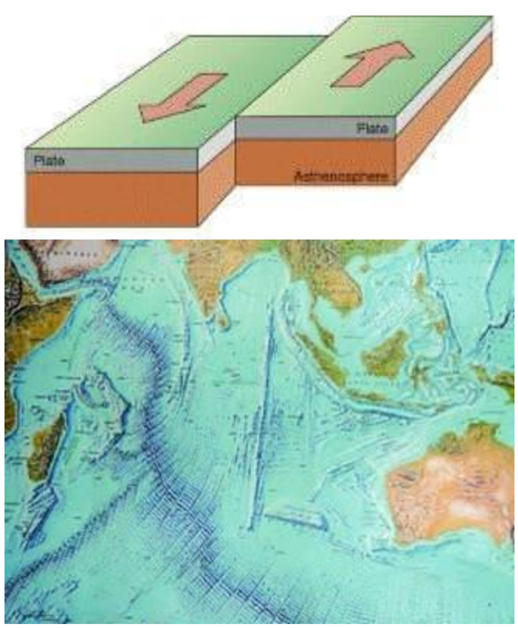
Transcurrent Edge or Conservative Edge or Transform Edge

- In this kind of interaction, two plates slide past against each other, and there is **no creation or destruction of landform** but **only deformation** of the existing landform.



Types of Plate Boundaries (Jose F. Vigil. USGS, via Wikimedia Commons)

- In oceans, **transform faults** are the planes of separation generally perpendicular to the mid-oceanic ridges.
- **San Andreas Fault** (Silicon Valley lies dangerously close to the faultline) along the western coast of USA is the best example for a transcurrent edge on continents.



Transform Edge

Evidence in Support of Plate Tectonics

- Evidence for both See Floor Spreading and Plate tectonics are **complimentary** (almost same evidences).

Paleomagnetism

- **Paleomagnetic rocks** are the most important evidence. The orientation of iron grains on older rocks shows an orientation which points to the existence of the South Pole, once upon a time, somewhere between present-day Africa and Antarctica (polar wandering).

Older rocks form the continents while younger rocks are present on the ocean floor

- On continents, rocks of up to 3.5 billion years old can be found while the oldest rock found on the ocean floor is not more than 75 million years old (western part of Pacific floor).
- As we move, towards ridges, still younger rocks appear. This points to an effective spread of seafloor (See floor spreading is almost similar to plate tectonics except that it examines the interaction between oceanic plates only) along oceanic ridges which are also the plate margins.

Gravitational anomalies

- In trenches, where subduction has taken place (convergent edge), the value of gravitational constant 'g' is less. This indicates a loss of material.
- For instance, gravity measurements around the Indonesian islands have indicated that large gravity anomalies are associated with the oceanic trench bordering Indonesia.

Earthquakes and Volcanoes

- The fact that all plate boundary regions are areas of earthquake and volcanic disturbances goes to prove the theory of plate tectonics.

The significance of Plate Tectonics

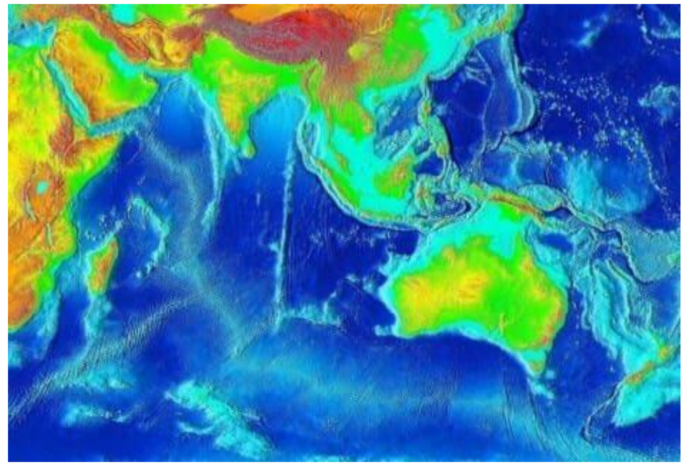
- Almost all major landforms formed are due to plate tectonics.
- New minerals are thrown up from the core with the magmatic eruptions.
- Economically valuable minerals like copper and uranium are found near the plate boundaries.
- From present knowledge of crustal plate movement, the shape of landmasses in future can be predicted.
- For instance, if the present trends continue, North and South America will separate. A piece of land will separate from the east coast of Africa. Australia will move closer to Asia.

Movement of The Indian Plate

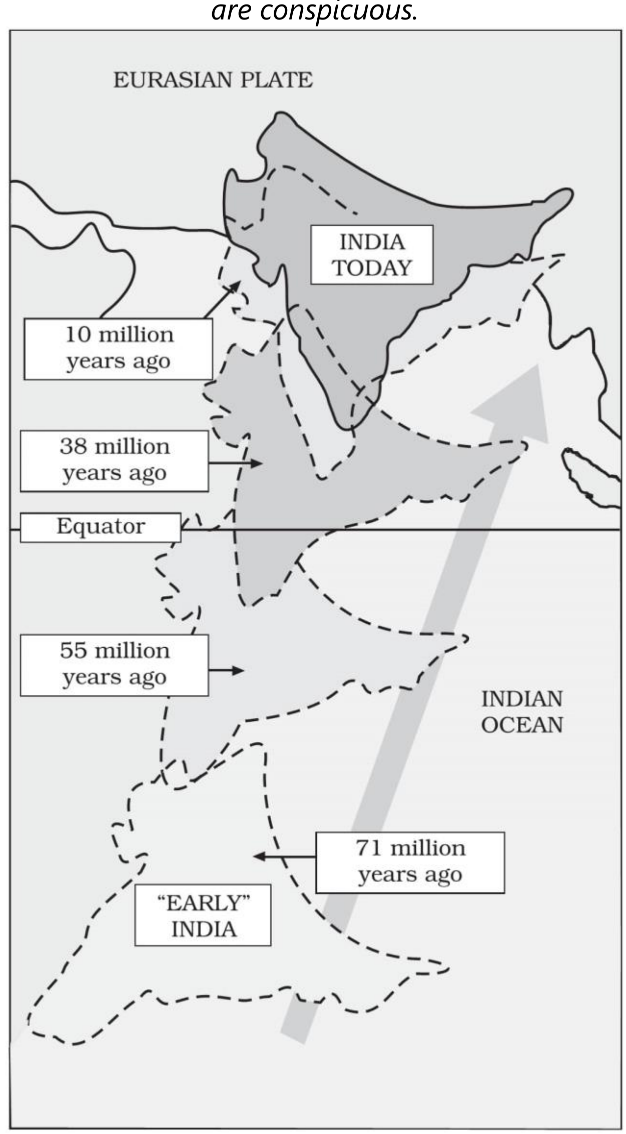
- The Indian plate includes Peninsular India and the Australian continental portions.

Indian Plate Boundaries

- The subduction zone along the **Himalayas** forms the northern plate boundary in the form of continent-continent convergence.
- In the east, it extends through Rakinyoma Mountains (Arakan Yoma) of Myanmar towards the island arc along the Java Trench.
- The eastern margin is a spreading site lying to the east of Australia in the form of an oceanic ridge in SW Pacific.
- The Western margin follows **Kirthar Mountain** of Pakistan. It further extends along the **Makrana coast** (Pakistan and Iranian coasts) and joins the spreading site from the **Red Sea rift (Red Sea rift is formed due to the divergence of Somali plate and Arabian plate)** south-eastward along the **Chagos Archipelago (Formed due to hotspot volcanism)**.



Topography of Indo-Australian Plate. The boundaries are conspicuous.



- The boundary between India and the Antarctic plate is also marked by an oceanic ridge (divergent boundary) running in roughly W-E direction and merging into the spreading site, a little south of New Zealand.

Movement

- India was a large island situated off the Australian coast. The **Tethys Sea** separated it from the Asian continent till about 225 million years ago.
- India is supposed to have started her northward journey about 200 million years (**Pangaea** broke).
- About 140 million years ago, the subcontinent was located as south as 50° S latitude.
- The Tethys Sea separated the Indian plate and the Eurasian plate.
- The Tibetan block was a part of the Asiatic landmass.
- India collided with Asia about **40-50 million years ago** causing rapid uplift of the Himalayas (the Indian plate and the Eurasian plate were close to the equator back then).
- It's thought that India's coastline was denser and more firmly attached to the seabed, which is why Asia's softer soil was pushed up rather than the other way around.
- The process is continuing, and the **height of the Himalayas is rising** even to this date.
- The northward movement of the Indian tectonic plate pushing slowly against the Asiatic plate is evident by the **frequent earthquakes** in the region.
- During the movement of the Indian plate towards the Asiatic plate, a major event that occurred was the outpouring of lava and formation of the **Deccan Traps (shield volcano)**.
- The shield volcanism started somewhere around **60 million years ago** and continued for a long period.

4.5 Comparison: Continental Drift – See Floor Spreading – Plate Tectonics

	Continental Drift	See Floor Spreading	Plate Tectonics
Explained by	Put forward by **Alfred Wegener** in 1920s	**Arthur Holmes** explained Convectional Current Theory in the 1930s. Based on convection current theory, **Harry Hess** explained See Floor Spreading in the 1940s	In 1967, McKenzie and Parker suggested the theory of plate tectonics. Morgan later outlined the theory in 1968
Theory	Explains the Movement of Continents only	Explains the Movement of Oceanic Plates only	Explains the Movement of Lithospheric plates that include both continents and oceans.
Forces for movement	Buoyancy, gravity, pole-fleeing force, tidal currents, tides,	Convection currents in the mantle drag crustal plates	Convection currents in the mantle drag crustal plates
Evidence	Apparent affinity of physical features, botanical evidence, fossil evidence, Tillite deposits, placer deposits, rocks of same age across different continents etc.	Ocean bottom relief, Paleomagnetic rocks, distribution of earthquakes and volcanoes etc.	Ocean bottom relief, Paleomagnetic rocks, distribution of earthquakes and volcanoes, gravitational anomalies at trenches, etc.
Drawbacks	Too general with silly and sometimes illogical evidence.	Doesn't explain the movement of continental plates	---------------------
Acceptance	Discarded	Not complete	Most widely accepted
Usefulness	Helped in the evolution of	Helped in the evolution of	Helped us understand various

	convection current theory and seafloor spreading theory	plate tectonics theory	geographical features.

Multiple choice questions

1. Polar fleeing force relates to:
    a) Revolution of the Earth
    b) Rotation of the earth
    c) Gravitation
    d) Tides
2. Which one of the following is not a minor plate?
    a) Nazca
    b) Philippines
    c) Arabia
    d) Antarctica
3. Which one of the following facts was not considered by those while discussing the concept of sea floor spreading?
    a) Volcanic activity along the mid-oceanic ridges.
    b) Stripes of normal and reverse magnetic field observed in rocks of ocean floor.
    c) Distribution of fossils in different continents.
    d) Age of rocks from the ocean floor.
4. Which one of the following is the type of plate boundary of the Indian plate along the Himalayan mountains?
    a) Ocean-continent convergence
    b) Divergent boundary
    c) Transform boundary
    d) Continent-continent convergence

Answers: 1: b); 2: d); 3: c) & 4: d)

Answer in about 30 words.

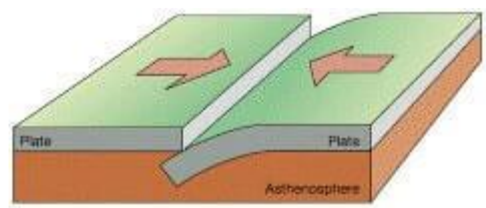
1. What were the forces suggested by Wegener for the movement of the continents?
2. How are the convectional currents in the mantle initiated and maintained?
3. What is the major difference between the transform boundary and the convergent or divergent boundaries of plates?
4. What was the location of the Indian landmass during the formation of the Deccan Traps?

Answer in about 150 words

1. What are the evidences in support of the continental drift theory?
2. Bring about the basic difference between the drift theory and Plate tectonics.
3. What were the major post-drift discoveries that rejuvenated the interest of scientists in the study of distribution of oceans and continents?

5. Convergent Boundary

- Along a convergent boundary two lithospheric plates **collide** against each other.
- When one of the plates is an oceanic plate, it gets embedded in the **softer asthenosphere** of the continental plate, and as a result, **trenches** are formed at the **zone of subduction.**



Convergent Boundary

In convergence there are subtypes namely:

1. **Collision of oceanic plates or ocean-ocean convergence** (formation of **volcanic island arcs**).
2. **Collision of continental and oceanic plates or ocean-continent convergence** (formation of **continental arcs and fold mountains**).
3. **Collision of continental plates or continent-continent convergence** (formation of **fold mountains**)
4. **Collision of continent and arc, or continent-arc convergence.**

The above concepts are explained in the next chapters.

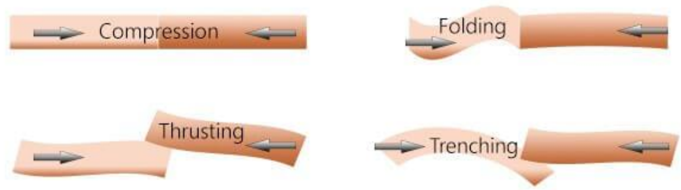
5.1 Ocean-Ocean Convergence or The Island-Arc Convergence

- The concept of Ocean-Ocean Convergence helps us understand the **formation of Japa-**

nese Island Arc, Indonesian Archipelago, Philippine Island Arc and Caribbean Islands.

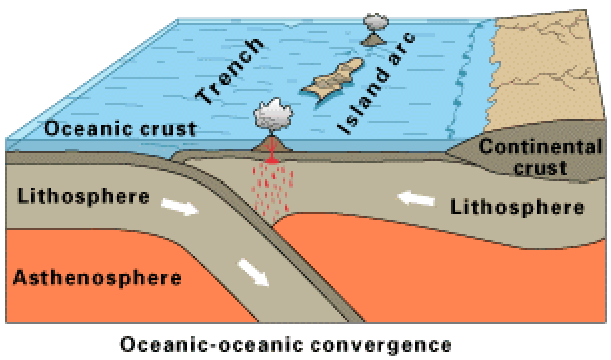
- **Archipelago:** an extensive group of islands.
- **Island arc:** narrow chain of islands which are volcanic in origin. An island arc is usually curved.

Basics



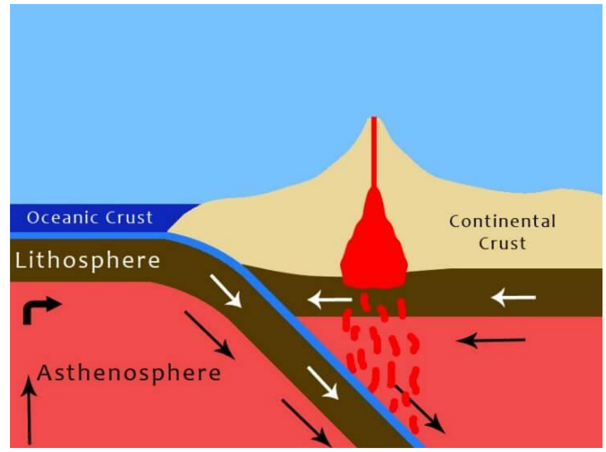
*In all types of convergence, the **denser plate subducts,** and the less dense plate is either **up thrust or folded or both** (upthrust and folded).*

- In Ocean-Ocean Convergence, a **denser oceanic plate** subducts below a **less dense oceanic plate** forming a **trench** along the boundary.



Ocean – Ocean Convergence (via Wikimedia Commons)

- As the ocean floor crust (oceanic plate) loaded with sediments **subducts** into the softer **asthenosphere**, the rocks in the subduction zone become **metamorphosed (alteration of the composition or structure of a rock)** under high pressure and temperature.
- After reaching a depth of about 100 km, the plates melt. Magma (**metamorphosed sediments and the melted part of the subducting plate**) has lower density and is at high pressure.
- It rises upwards due to the **buoyant force** offered by surrounding denser medium.
- The magma flows out to the surface. A continuous upward movement of magma creates constant volcanic eruptions at the ocean floor.



Subduction Zone Illustration (Eround1, via Wikimedia Commons)

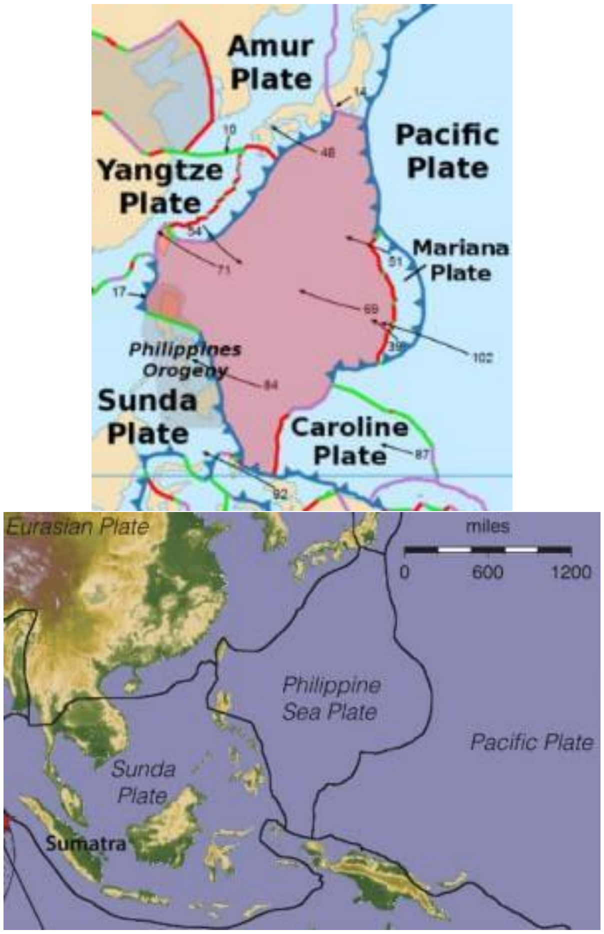
- Constant volcanism above the subduction zone creates layers of rocks. As this process continues for millions of years, a volcanic landform is created which in some cases rises above the ocean waters.
- Such volcanic landforms all along the boundary form a **chain of volcanic islands** which are collectively called as **Island Arcs** (Indonesian Island Arc or Indonesian Archipelago, Philippine Island Arc, Japanese Island Arc etc.).
- Orogenesis (mountain building) sets in motion the process of **building continental crust by replacing the oceanic crust** (this happens at a much later stage. For example, new islands are born around Japan in every few years. After some million years, Japan will be a single landmass because continental crust formation is constantly replacing the oceanic crust).

This explanation is common for all the island arc formations (ocean-ocean convergence). We only need to know the plates involved with respect to each island formation.

Formation of the Philippine Island Arc System

- Philippine Island Arc system is formed due to subduction of **Philippine Sea plate** under the **Sunda Plate** (major continental shelf of the **Eurasian plate**). The trench formed here is called **Philippine Trench**.
- **Sunda Shelf:** The extreme south-eastern portion of the Eurasian plate, which is a part of Southeast Asia, is a **continental shelf**. The re-

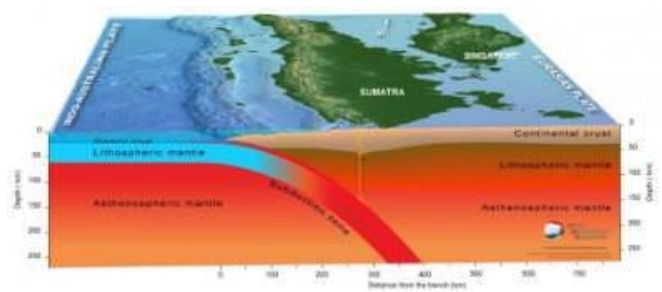
gion is called the **Sunda Shelf**. The Sunda Shelf and its islands is known as the **Sundaland block of the Eurasian plate**.



Minor plates in the Southeast Asia

Formation of the Indonesian Archipelago

- In the case of Indonesian Archipelago, the **Indo-Australian plate** is subducting below **Sunda Plate (part of Eurasian Plate)**. The trench formed here is called **Sunda trench** (**Java Trench** is a major section of Sunda trench).

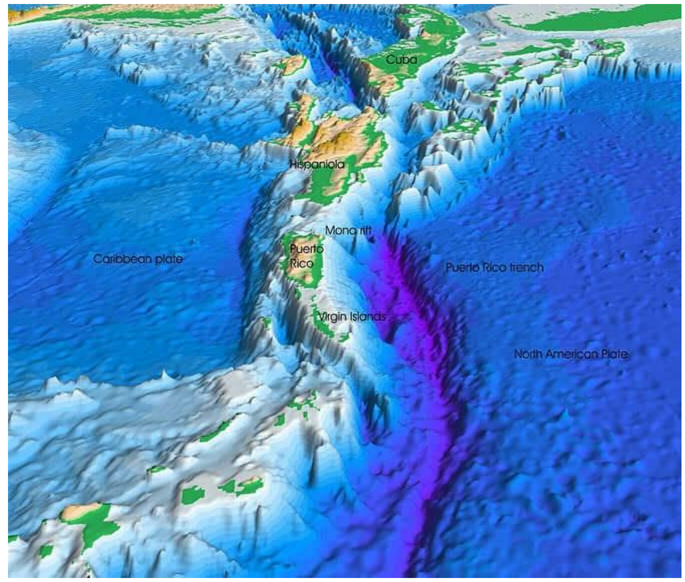


- **Anak Krakatau (child of Krakatau)** volcano lies close to the Java Trench. It is situated in the **Sunda Strait** between the Indonesians Islands of **Java** and **Sumatra**.
- Underwater land shifting on the Anak Krakatau volcano in December 2018 triggered a Tsunami that killed more than 400 people.

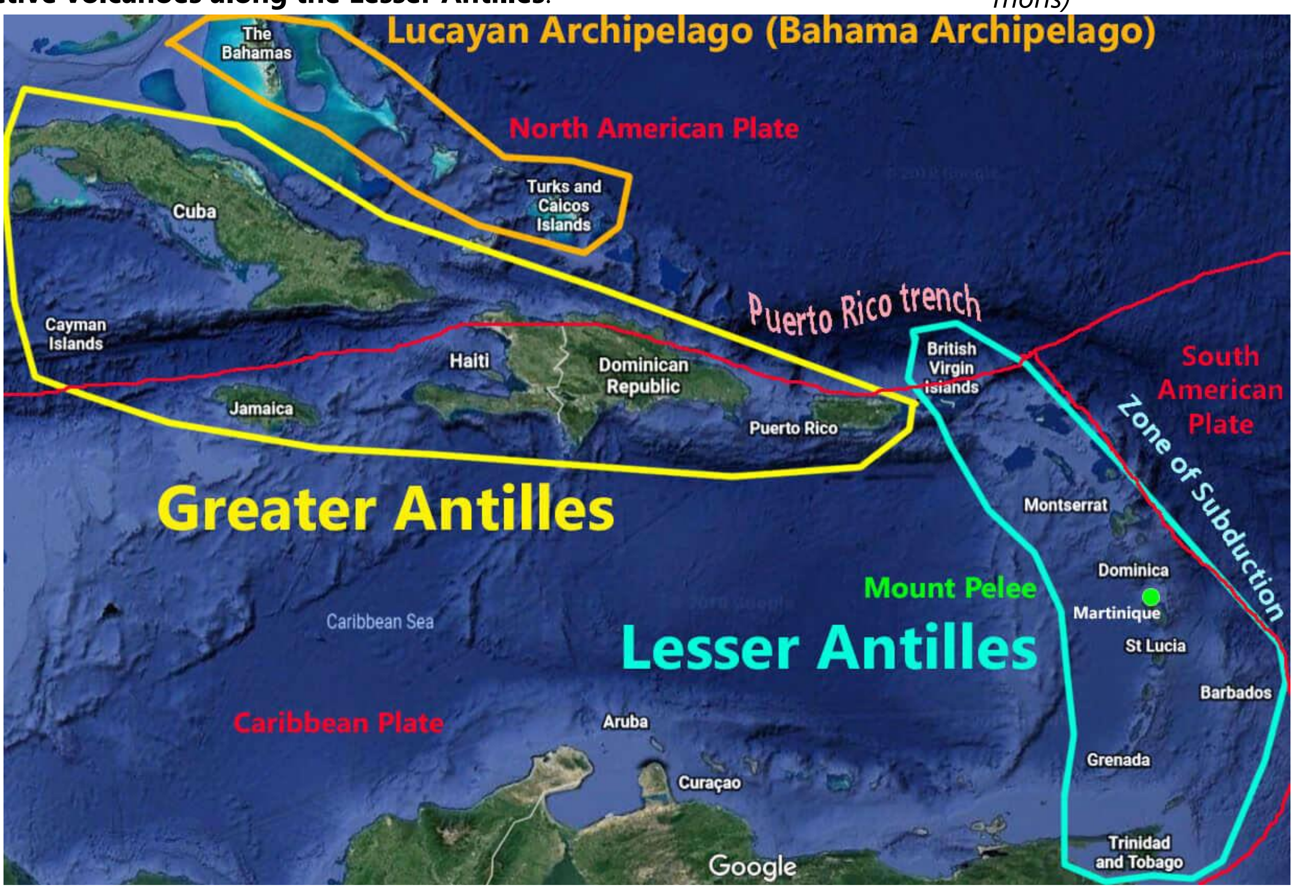
Anak Krakatau volcano situated between the Indonesians Islands of Java and Sumatra (Google Maps)

Formation of the Caribbean Islands

- The Caribbean Plate is a mostly oceanic tectonic plate. The northern boundary with the North American plate is a **transform or strike-slip boundary** (more about this in the subsequent chapters).
- The Caribbean Plate is moving to the east while the North American Plate is moving to the west.
- The **Puerto Rico Trench** is located at a boundary between the two plates that pass each other along a **transform boundary with only a small component of subduction**.
- The boundary between the two plates in the past has been convergent, and most of the **Greater Antilles** group of islands are formed due to the complex interaction between the two plates.
- The eastern boundary of the Caribbean Plate is a subduction zone, the **Lesser Antilles subduction zone**, where oceanic crust of the South American Plate is being subducted under the Caribbean Plate.
- This subduction zone explains the presence of **active volcanoes along the Lesser Antilles**.
- **Mount Pelée** is an active 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 eruption in 1902. The eruption killed about 30,000 people. Most deaths were caused by pyroclastic flows which destroyed the city of Saint-Pierre.



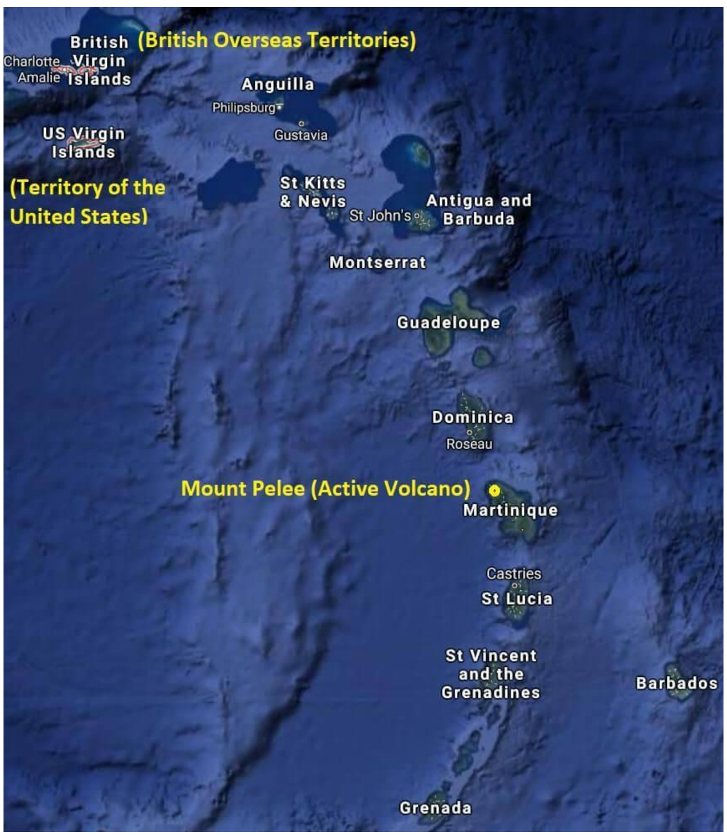
3D view of the Caribbean Islands (Wikipedia Commons)



The Greater Antilles and Lesser Antilles Island Arcs (Map from Google Earth)

The island groups in the Caribbean Sea

- The Greater Antilles is a grouping of the **larger islands** in the Caribbean Sea: Cuba, Hispaniola (containing Haiti and the Dominican Republic), Puerto Rico, Jamaica, and the Cayman Islands.
- Together, the **Lesser Antilles** and the **Greater Antilles** compose the Antilles (or the **Caribbean islands**).
- When combined with the **Lucayan Archipelago (Bahama Archipelago)**, all three are known as the **West Indies**.
- Lucayan Archipelago is an island group comprising the Commonwealth of The Bahamas and the British Overseas Territory of the Turks and Caicos Islands.



Islands in the Lesser Antilles Island Arcs (Map from Google Earth)

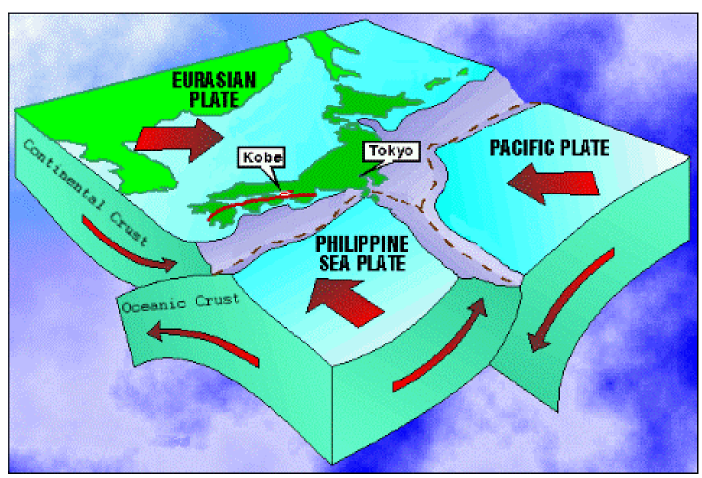
Formation of Isthmus of Panama

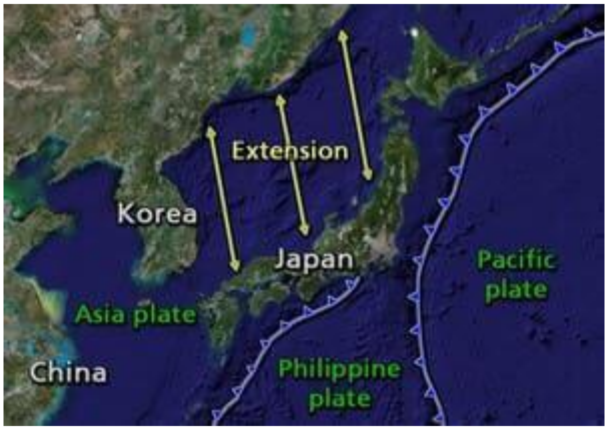
- Formation of the Isthmus of Panama involved subduction of the **Pacific-Farallon Plate** beneath the **Caribbean and South American plates**, forming a volcanic arc on the edge of the Caribbean Plate.
- The remains of the ancient Farallon Oceanic Plate are the Juan de Fuca Plate, parts of the North American Plate and the South American Plate, the Cocos Plate and the Nazca Plate.
- This initial Panama Arc began to form as the Caribbean Plate moved eastward.
- The North and South American plates continued to move westward past the Caribbean Plate.
- In addition to their east-west (strike-slip) motion, the plates also acquired a north-south component of convergence, leading to the collision of the Panama Arc with South America.
- This collision drove uplift in both the Northern Andes and the Panama Arc, forming the Isthmus of Panama.

Plates in the region of Isthmus of Panama

Formation of the Japanese Island Arc

- Japan's volcanoes are part of three volcanic arcs.





Triple Junction of the plates

- The arcs meet at a triple junction on the island of Honshu.
- Northern arc is formed due to the subduction of the **Pacific Plate** under the **Eurasian Plate**. The trench formed is **Japan Trench.**
- Central arc is formed due to the subduction of the **Pacific Plate** under the **Philippine Plate** (island formation is not significant along this arc). The trench formed is **Izu Trench.**
- Southern Arc is formed due to the subduction of the **Philippine Plate** under the **Eurasian Plate.** The trench formed is **Ryukyu Trench.**
- Japanese island arc was very close to the mainland.
- The force exerted by the Pacific plate and the Philippine plate tilted the arc towards its east giving rise to the **Sea of Japan.**

The Mariana Trench or Marianas Trench

- The Mariana Trench or Marianas Trench, the **deepest trench**, is located in the western Pacific Ocean.
- The Mariana Trench is formed due to the subduction of the **Pacific Plate** below the **Mariana Plate**.
- The maximum known depth is between 10,994 & 11,034 metres in its floor known as the **Challenger Deep**.

The Mariana trench is not the part of the seafloor closest to the centre of the Earth. This is because the Earth is not a perfect sphere (its Geoid); its radius is about 25 kilometres smaller at the poles than at the equator.

*As a result, parts of the **Arctic Ocean seabed** are at least 13 kilometres closer to the Earth's centre than the Challenger Deep seafloor.*

Explain the formation of thousands of islands in Indonesian and Philippines archipelagos (20 marks – Mains 2014)

20 marks = 200 words

- Indonesian archipelago and Philippine archipelago are located along the **plate margins**. Both the archipelagos were formed due to **ocean-ocean convergence**.
- Indonesian archipelago was formed due to convergence between Sunda oceanic plate (part of the Eurasian plate) and Indo-Australian plate whereas Philippine archipelago was formed due to convergence between Sunda oceanic plate and Philippine Sea plate.
- In ocean-ocean convergence, two oceanic plates converge or collide. The denser plate subducts into the **asthenosphere** below the convergence zone and forms a **trench** at the surface. This region below the convergence zone is called the **zone of subduction**.
- In the zone of subduction, due to high temperature and pressure, the rocks undergo **metamorphosis** and the **sediments** in the oceanic plate melt to form **magma**.
- The magma being lighter moves upwards due to the buoyant force offered by the surrounding **denser medium**. At the surface magma at high pressure escapes in the form of volcanic eruptions.
- The magma solidifies creating a volcanic layer. **Subsequent volcanism** builds a layer over layer and a volcanic mountain if formed. Such mountains are formed all along the converging edge above the less dense plate.
- Over time the mountains merge, and the oceanic crust **gets transformed** into continental crust.
- This is how Indonesian archipelago and Philippine archipelago were formed.

If asked for 10 marks = 100 words

- Indonesian and Philippine archipelagos are formed due to **ocean-ocean convergence**.

- In ocean-ocean convergence, the denser plate subducts into the **asthenosphere**. This region below the convergence zone is called the **zone of subduction**.
- In the zone of subduction, the rocks undergo **metamorphosis** and the **sediments** in the oceanic plate melt to form **magma**.
- At the surface magma escapes in the form of volcanic eruptions.
- Constant **volcanism** builds a layer over layer and a volcanic mountain if formed.
- Such mountains are formed all along the converging edge.
- Over time the mountains merge, and the oceanic crust **gets transformed** into continental crust.
- This is how Indonesian archipelago and Philippine archipelago were formed.

Related question

In spite of extensive volcanism, there is no island formation along the divergent boundary (mid-ocean ridge)

- **Basaltic magma** flows out along the divergent edge (fissure type or shield type volcano).
- Basaltic magma has **less silica,** and hence it is less viscous. It flows over a long-distance causing seafloor spreading but not volcanic islands.
- On the other hand, along the convergent boundary, **andesitic or acidic magma** flows out.
- **Andesitic or acidic magma** has **more silica** content, and hence it has higher viscosity. It doesn't move quickly and also solidifies faster. This helps in building a layer over layer on a confined region giving rise to a volcanic mountain.

5.2 Continent-Ocean Convergence or The Cordilleran Convergence

- The concept of Continent-Ocean Convergence is important to understand the formation of **the Rockies**, **the Andes** and other similar **fold mountain systems**.
- Continent-Ocean Convergence is also called **Cordilleran Convergence** because this kind of convergence gives rise to extensive mountain systems.
- A cordillera is an extensive chain of mountains or mountain ranges. Some mountain chains in North America and South America are called cordilleras.
- Continent-Ocean Convergence is similar to ocean-ocean convergence. One important difference is that in continent-ocean convergence **mountains are formed instead of islands**.
- When oceanic and continental plates collide or converge, the oceanic plate (denser plate) subducts or plunges below the continental plate (less dense plate) forming a **trench** along the boundary.
- The **trenches formed here are not as deep as those formed in ocean-ocean convergence**.
- As the ocean floor crust (oceanic plate) loaded with sediments subducts into the softer asthenosphere, the rocks on the continental side in the subduction zone become **metamorphosed** under high pressure and temperature (metamorphism: alteration of the composition or structure of rock by heat, pressure).

Formation of Continental Arcs

- After reaching a certain depth, plates melt. Magma (metamorphosed sediments and the melted part of the subducting plate) has lower density and is at high pressure.
- It rises due to the **buoyant force** offered by surrounding denser medium. The magma flows out, sometimes violently to the surface.
- A continuous upward movement of magma creates constant volcanic eruptions at the surface of the continental plate along the margin.
- Such volcanic eruptions all along the boundary form a chain of volcanic mountains which are collectively called as a **continental arc**. E.g. the **Cascade Range (parallel to the Rockies), the Western Chile range (parallel to the Andes)**
  - ✓ ***Arc:*** *narrow chain of volcanic islands or mountains.*
  - ✓ ***Island arc:*** *A narrow chain of volcanic islands (Japanese Islands).*

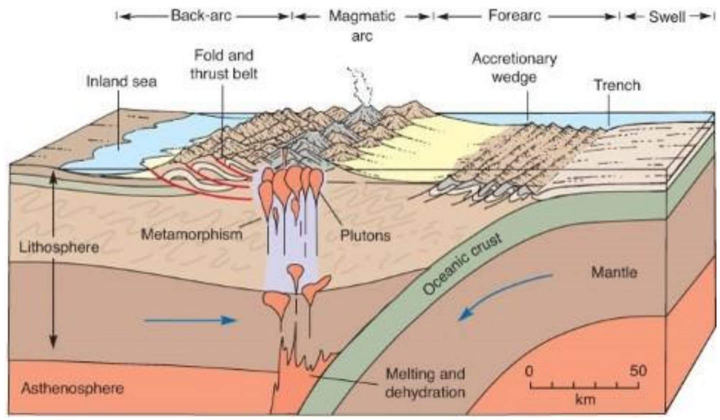
- ✓ ***Continental arc:*** *A narrow chain of volcanic mountains on continents (Cascade Range).*
- ✓ ***Accretionary wedge:*** *As the oceanic plate subducts, the sediments brought by it accumulates in the trench region. These accumulated sediments are called as* ***accretionary wedge****.*
- ✓ *The accretionary wedge is compressed into the continental margin leading to* ***crustal shortening****.*
- ✓ ***Convergence ➔ Crustal Shortening***
- ✓ ***Divergence ➔ Crustal Widening***
- ✓ ***Crustal Shortening at one place is compensated by Crustal Widening in some other place****.*

Formation of Fold Mountains (Orogeny)

Orogeny (Geology) *is a process in which a section of the earth's crust is* ***folded*** *and deformed by* ***lateral compression*** *(force acting sideways) to form a mountain range.*

Orogenic movements are 'Tectonic movements' of the earth involve the ***folding of sediments****,* ***faulting*** *and* ***metamorphism*** *(rocks that have transformed by heat, pressure).*

- Continental margins are filled with **thick sediments** brought by the rivers.
- As a result of convergence, the buoyant granite of the continental crust overrides (is placed above) the oceanic crust (continental crust in **upthrust** by the oceanic crust).
- As a result, the edge of the deformed continental margin is thrust above sea level.
- The advancing oceanic plate adds more compressive stress on the upthrust continental margin and leads to its **folding** creating a **fold mountain system (orogenic belt)**.
- In some cases, the advancing oceanic plate compresses the **orogenic belt** leading to its folding **(Rockies and Andes).**
- With the formation of the orogenic belt (fold mountain belt), resistance builds up which effectively stops convergence. Thus, the subduction zone progresses seaward.
- With the culmination of compression, erosion continues to denude mountains. This results in **isostatic adjustment** (denser regions sink, and less denser regions rise) which causes the ultimate exposure of the roots of mountains.
- Examples are found in the **Rockies**, deformed in the late Mesozoic and early Tertiary period, and the **Andes**, where the deformation began in the Tertiary Period is still going on.



Continent-Ocean Convergence

Formation of the Andes

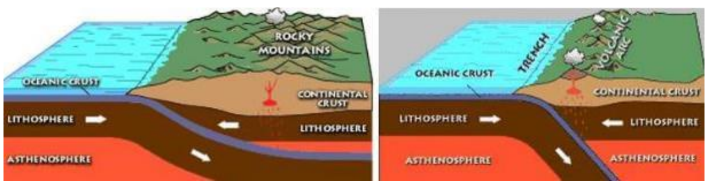
- The Andes are formed due to convergence between **Nazca plate** (oceanic plate) and the **South American plate** (continental plate). **Peru-Chile trench** is formed due to subduction of Nazca plate.
- The Andes are a continental arc (narrow, continental volcanic chain) formed due to the volcanism above the subduction zone.
- The pressure offered by the **accretionary wedge** folded the volcanic mountain, raising the mountains significantly.
- The folding process is continuing, and the mountains are constantly rising. Volcanism is still active.
- **Ojos del Salado active volcano** on the Argentina-Chile border is the **highest active volcano** on earth at 6,893 m. (**Olympus Mons** on Mars is the highest volcano in the solar system. It is 26 – 27 km high)
- **Mount Aconcagua** (6,960 m, Argentina) in the Andes is the highest peak outside the Himalayas and the highest peak in the western hemisphere. It is an **extinct volcano**.

Western Chile Range (Chilean Coast Range)

- The range was separated from the Andes during the Tertiary rise of the Andes due to the subsidence of the Intermediate Depression.

5.3 Formation of the Rockies

- The **North American plate** (continental plate) moved westwards while the **Juan de Fuca plate** (minor oceanic plate) and the **Pacific plate** (major oceanic plate) moved eastwards.
- The convergence gave rise to a series of parallel mountain ranges.
- Unlike the Andes, the Rockies are formed at a distance from the continental margin due to the **less steep subduction by the oceanic plates**.
- **Trenching is less conspicuous** as the boundary is filled with accretionary wedge and there are a series of fault zones (San Andreas Fault) that make the landform different from the Andes.



Left: Formation of the Rockies (less steep subduction); Right: Formation of the Andes

5.4 Continent-Continent Convergence or The Himalayan Convergence

Understanding Continent-Continent Convergence is important to understand the Formation of the Himalayas, the Alps, the Urals and the Atlas Mountains.

- In ocean-ocean convergence and continent-ocean convergence, **at least one of the plates is denser** and hence the subduction zone is **quite deep** (few hundred kilometres).
- At continent-continent convergent margins, due to **lower density**, both of the continental crustal plates are too light (buoyant) to be carried downward (subduct) into a trench.
- In most cases, neither plate subducts or even if one of the plates subducts, the **subduction zone will not go deeper than 40 – 50 km**. The two plates converge, buckle up (**suture zone**), fold, and fault.
- As the continental plates converge, the ocean basic or a sedimentary basin (geoclinal or geosynclinal sediments found along the continental margins) is squeezed between the two converging plates.
- Huge slivers of rock, many kilometres wide are thrust on top of one another, forming a towering mountain range.
- With the building up of resistance, convergence comes to an end. The mountain belt erodes, and this is followed by **isostatic adjustment**.
- As two massive continents weld, a single large continental mass joined by a mountain range is produced.
- Examples: **The Himalayas, Alps, Urals, Appalachians** and **the Atlas Mountains**.

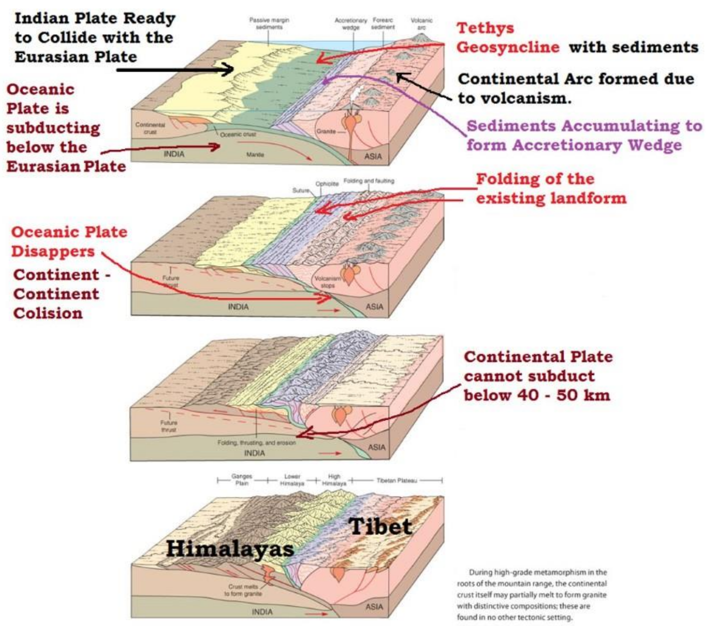
Suture zone: *The subduction of the continental crust is not possible beyond 40 km because of the normal buoyancy of the continental crust. Thus, the fragments of oceanic crust are plastered against the plates causing welding of two plates known as* ***suture zone****. Example: The Indus-Tsangpo suture zone.*

Formation of the Himalayans and the Tibetan Plateau

- The Himalayas are the **youngest mountain chain** in the world.
- Himalayan mountains have come out of a **great geosyncline** called the **Tethys Sea** and that the uplift has taken place in different phases.
- During **Permian Period (250) million years ago**, there was a supercontinent known as **Pangaea.**
- Its northern part consisted of the present-day North America and Eurasia (Europe and Asia) which is called as **Laurasia or Angaraland or Laurentia**.
- The southern part of Pangaea consisted of present-day South America, Africa, South India, Australia and Antarctica. This landmass was called **Gondwanaland.**
- In between Laurasia and Gondwanaland, there was a long, narrow and shallow sea known as the **Tethys Sea** (all this was explained earlier in Continental Drift Theory).
- There were many rivers which were flowing into the Tethys Sea (**some of the Himalayan rivers**

were older than the Himalayas themselves**. We will study this in Antecedent and Subsequent Drainage).

- Sediments were brought by these rivers and were deposited on the floor of the Tethys Sea.
- These sediments were subjected to powerful compression due to the northward movement of the Indian Plate. This resulted in the folding of sediments.
- An often-cited fact used to illustrate this process is that the **summit of Mount Everest is made of marine limestone** from this ancient ocean.



- Once the Indian plate started plunging below the Eurasian plate, these sediments were further folded and raised. This process is still continuing (India is moving northwards at the rate of about **five cm per year** and crashing into rest of Asia).
- And the folded sediments, after a lot of erosional activity, appear as the present-day Himalayas.
- Tibetan plateau was formed due to **upthrusting** of the southern block of the Eurasian Plate.
- The Indo-Gangetic plain was formed due to the consolidation of alluvium brought down by the rivers flowing from the Himalayas.
- The curved shape of the Himalayas convex to the south is attributed to the maximum push offered at two ends of the Indian Peninsula during its northward drift.

Phases of formation

- The Himalayas do not comprise a single range but a series of at least three ranges running more or less parallel to one another.
- Therefore, the Himalayas are supposed to have emerged out of the Himalayan Geosyncline, i.e. the Tethys Sea in **three different phases** following one after the other.
- The first phase commenced about **50-40 million years ago** when the **Great Himalayas** were formed. The formation of the Great Himalayas was completed about 30 million years ago.
- The second phase took place about **25 to 30 million years ago** when the **Middle Himalayas** were formed.
- The **Shiwaliks** were formed in the last phase of the Himalayan orogeny — say about **two million to twenty million years ago**.
- Some of the fossil formations found in the Shiwalik hills are also available in the Tibet plateau. It indicates that the past climate of the Tibet plateau was somewhat similar to the climate of the Shiwalik hills.

*Recent studies have shown that convergence of the Indian plate and the Asian plate has caused a **crustal shortening** of about 500 km in the Himalayan region. This shortening has been compensated by seafloor spreading along the oceanic ridge in the Indian Ocean.*

Evidence for the rising Himalayas

- Today's satellites that use high precision atomic clocks that can measure accurately even a small rise of one cm. The heights of various places as determined by satellites indicate that the Himalayas rise by few centimetres every year. The present rate of uplift of the Himalayas has been calculated at 5 to 10 cm per year.
- Due to uplifting, lakes in Tibet are desiccated (lose water) keeping the gravel terraces at much higher levels above the present water level. This could be possible only in the event of uplift of the region.
- The frequent tectonic activity (occurrence of earthquakes) in the Himalayan region shows that the Indian plate is moving further northwards and plunging into the Eurasian plate.

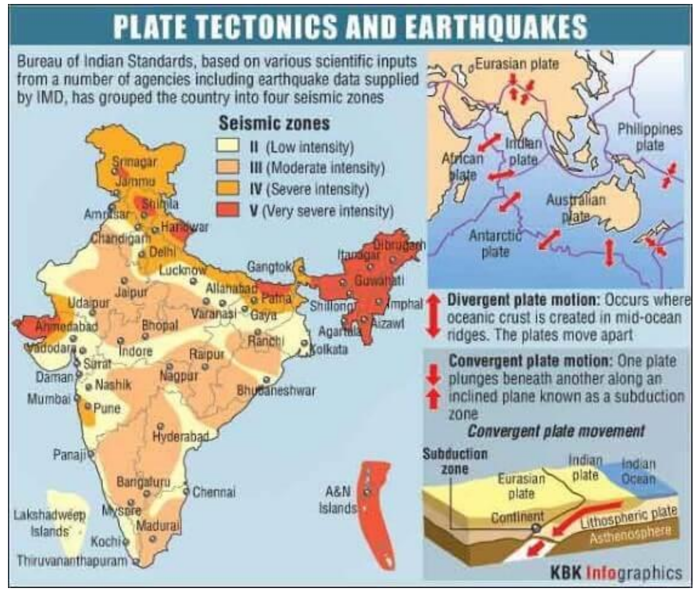
- This means that the Himalayas are still being raised due to compression and have **not yet attained isostatic equilibrium**.
- The Himalayan rivers are in their youthful stage and have been rejuvenated (make or cause to appear younger) in recent times. This shows that the Himalayan Landmass is rising, keeping the rivers in youth stage since a long time.

Formation of Alps, Urals, Appalachians and the Atlas Mountains

- The formation of each of these mountains is similar to the formation of the Himalayas.
- **The Alps** are **young fold mountains** which were formed due to the collision between **African Plate** and the **Eurasian Plate**.
- **The Atlas Mountains** are also **young folded mountains** which are still in the process of formation. They are also formed due to the collision between **African Plate** and the **Eurasian Plate**.
- **The Urals** are **very old fold mountains** which were formed even before the breakup of Pangaea. They were formed due to the collision between Europe and Asia.
- **The Appalachians** are also **very old fold mountains** which were formed even before the breakup of Pangaea. They were formed due to the collision between North America and Europe.

Volcanism and Earthquakes in Continent-Continent Convergence

- Oceanic crust is only 5 – 30 km thick. But the continental crust is 50 – 70 km thick. Magma cannot penetrate this thick crust, so there are **no volcanoes**, although the magma stays in the crust.
- **Metamorphic rocks** are common because of the stress the continental crust experiences.
- With enormous slabs of crust smashing together, continent-continent collisions bring on numerous and **large earthquakes** (Earthquakes in Himalayan and North Indian Region, Kachchh region).



Mains Question on Fold Mountains.

Why are the world's fold mountain systems located along the margins of continents? Bring out the association between the global distribution of Fold Mountains and the earthquakes and volcanoes.

Why fold mountains at the continental margin?

- Fold mountains are formed due to convergence between two continental plates (Himalayas, Alps) or between an oceanic and a continental plate (the Rockies, Andes).
- In Continent-Continent (C-C) convergence, oceanic sediments are squeezed and up thrust between the plates and these squeezed sediments appear as fold mountains along the plate margins.
- In Continent-Ocean (C-O) convergence, the continental volcanic arc formed along the continental plate margin is compressed and is uplifted by the colliding oceanic plate giving rise to fold mountains along the continental plate margin.

Earthquakes

- In both C-C convergence and C-O convergence, there is the formation of **fold mountains and frequent occurrence of earthquakes**.

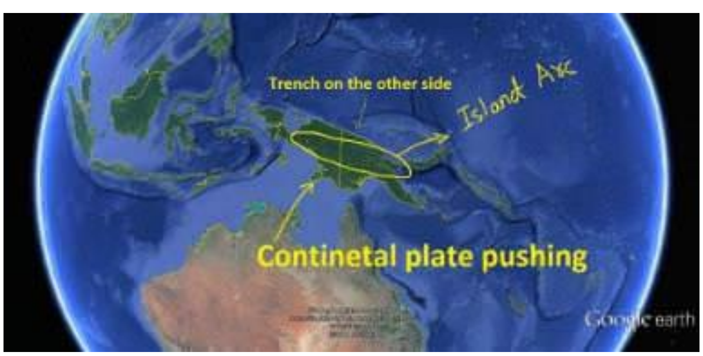
- This is because of the sudden release of friction between the subducting plate and up thrust plate.
- In C-C convergence, the denser plate pushes into the less dense plate creating a fault zone along the margin.
- Further collision leads to the sudden release of energy along this fault zone generating disastrous **earthquakes (shallow-focus earthquakes)**.
- In C-O regions the subducting oceanic plate grinds against the surrounding denser medium producing **mostly shallow-focus earthquakes**, and **deep in the subduction zone deep-focus earthquakes occur**.
- Volcanism is observed only in C-O convergence and is **almost absent in C-C convergence**.

Volcanism

- This is because of the thick continental crust in C-C convergence which prevents the outflow of magma. Magma here lies stocked within the crust.
- In C-O convergence, metamorphosed sediments and melting of the subducting plate form magma which escapes to the surface through the less thick continental crust.

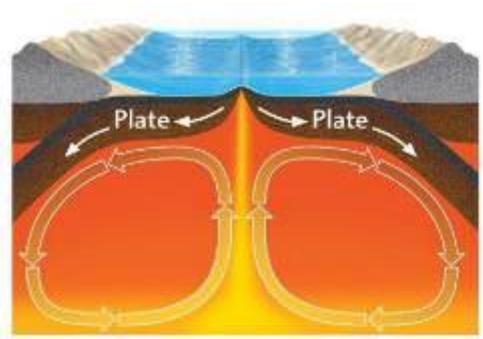
5.5 Continent-Arc Convergence or New Guinea Convergence

- New Guinea came into being about 20 million years ago as a result of continent-arc collision.
- The continental plate pushes the island arc towards the oceanic crust. The oceanic plate plunges under the island arc.
- A trench occurs on the ocean side of the island arc and, ultimately, the continental margin is firmly welded against the island arc.



6. Divergent boundary

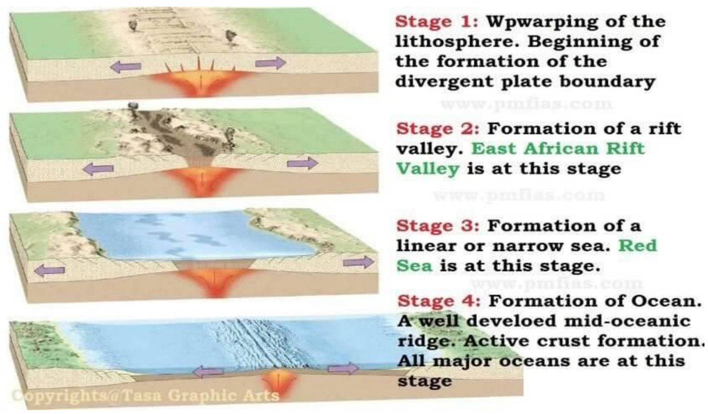
- In the Seafloor Spreading Theory, we have studied how divergent boundaries below the oceans are responsible for the spreading of the seafloor.
- In Plate Tectonics, we have learnt about the major and minor lithospheric plates and how these plates moved through the geological past.
- We have studied about **convection currents** in the mantle which are the primary reason behind plate movements — divergence and convergence of the lithospheric plates.
- The horizontal limbs of the convection currents, just below the lithosphere, drag the plates horizontally.
- The falling limbs of the convection currents create a negative pressure on the lithosphere, and this negative pressure (pulling force) is responsible for the formation of the convergent boundary.
- The **rising limbs**, on the other hand, create positive pressure on the lithosphere, and this positive pressure (pushing force) creates a divergent boundary.
- Divergence (divergent boundary) is responsible for the **evolution and creation of new seas and oceans** just like convergent boundaries are responsible for the formation of **fold mountains, volcanic arcs**.



6.1 Evolution – Formation of Rift Valleys, Rift Lakes, Seas and Oceans

- The formation of atmosphere and the oceans took millions of years. They were formed due to continuous 'degassing' of the Earth's interior.

- After the Earth's surface temperature came down below the boiling point of water, rain began to fall.
- Water began to accumulate in the hollows and basins, and the primeval (earliest) water bodies were formed.
- The primeval water bodies evolved to form seas and oceans.
- The process of formation of a new sea **begins with the formation of a divergent boundary**.
- **New lithosphere is created at the divergent boundary and old lithosphere is destroyed somewhere else at the convergent boundary**.



Basic Terms

- **Upwarp:** a broad elevated area of the earth's surface.
- **Plume:** a column of magma rising by convection in the earth's mantle.
- **Rift Valley:** a linear-shaped lowland (graben) between several highlands (horst) or mountain ranges created by the action of a geologic rift or fault.

Stage 1: Upwarping, fault zones

- Rising limbs of the convection currents create a **plume** that tries to escape to the surface by upwarping the lithosphere (doming the lithosphere upwards).
- During upwarping, a series of faults are created. Both normal and thrust faults (reverse fault) occur during upwarping. The divergence of plates begin.

Stage 2: Rift Valley Formation

- Faulting due to divergence creates extensive rift system (fault zones, rift valleys).
- The lithosphere is subject to a horizontal extensional force, and it will stretch, **becoming thinner (E.g. The crust above Yellowstone hotspot is thinning because of mantle plume)**.

  Eventually, it will rupture, leading to the formation of a rift valley.
- This process is accompanied by surface manifestations along the rift valley in the form of volcanism and seismic activity.
- Rifts are the initial stage of a continental breakup and, if successful, can lead to the formation of a new ocean basin.
- An example of a place on Earth where this has happened is the South Atlantic Ocean, which resulted from the breakup of South America and Africa around 138m years ago.
- The East African Rift is described as an active type of rift. Beneath this rift, the **rise of a large mantle plume** is doming the lithosphere upwards (Ethiopian Highlands), causing it to weaken.
- The rifting started in the **Afar region** in northern Ethiopia at around 30 million years ago and propagating southwards towards Zimbabwe. (It’s unzipping Africa!)
- Rifting is followed by **flood basalt volcanism** in some places that spread around the rift creating plateaus and highlands (Ethiopian Highlands, Kenya Dome).

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.

Narmada and Tapti Rift Valleys *(fault zones) are formed from a mechanism different from the one explained above. They are formed due to the bending of the northern part of the Indian plate during the formation of Himalayas.*

Stage 3: Formation of Linear Sea or Rift Lakes

- Rift valley deepens due to further divergence and makes way for ocean waters.

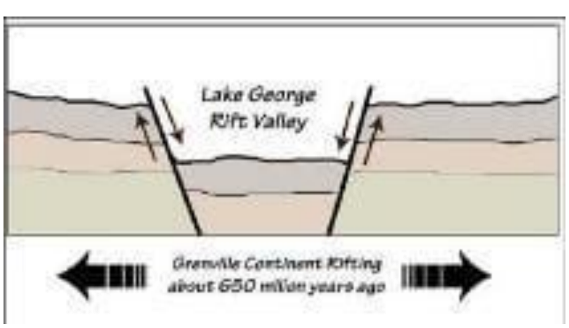
- If the rift valleys are formed deeper within the continents, rains waters accumulate forming rift lakes.
- Rift lakes form **some of the largest freshwater lakes** on earth.
- Rift valleys evolve into a volcanic vent. Block mountains on either side of the rift evolve into oceanic ridges.
- Successive volcanism and seafloor spreading create spreading sites where new crust is formed (divergent boundary is also called a **constructive edge**).
- Oceanic crust starts to replace continental crust. This stage is the formation of linear seas. Example: **Red Sea**.

Stage 4: Linear Sea transforms into Ocean

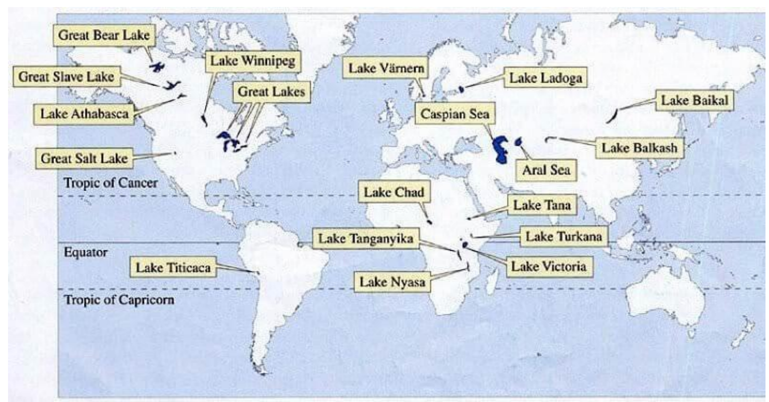
- The intense outpouring of basaltic magma accentuates **see floor spreading** and **oceanic crust formation**.
- Oceanic crust replaces the continental crust, and a mighty ocean is formed.
- Crust formation along the mid-oceanic ridge (divergent boundary) is compensated by crust destruction (crustal shortening) along the convergent boundary (destructive Edge). This is how the continents and oceans get transformed.

6.2 Rift valley lakes

- A rift lake is a lake formed as a result of subsidence related to movement on faults within a rift zone, an area of extensional tectonics in the continental crust.
- They are often found within rift valleys and may be very deep. The rift lakes are bound by large steep cliffs along the fault margins.



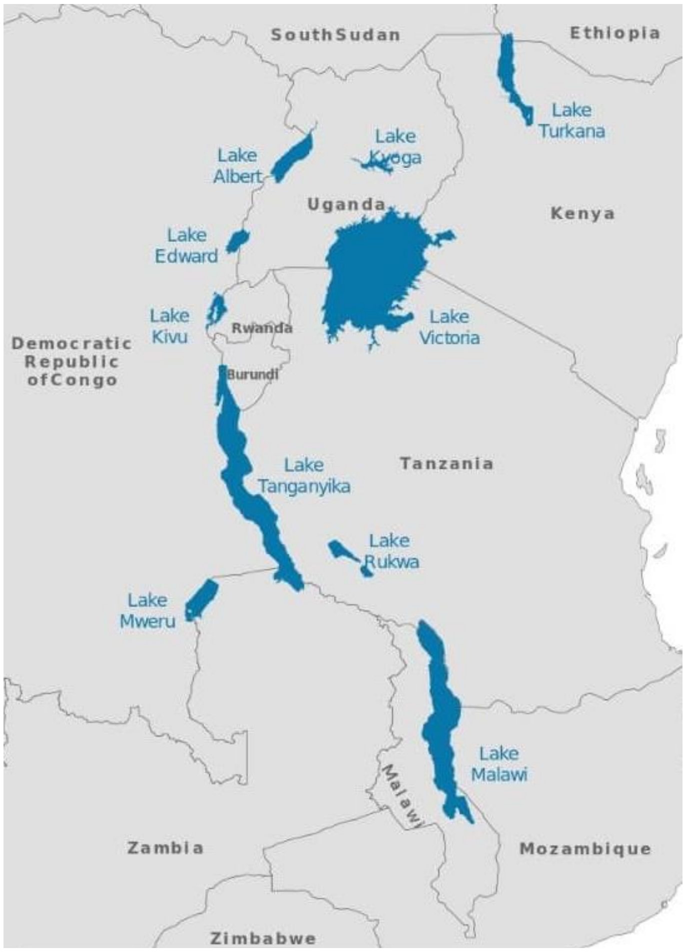
- Many of the **world's largest lakes are located in rift valleys**.
- **Lake Baikal** in Siberia lies in an active rift valley. It is the **deepest lake in the world** (the deepest point is 1642 meters below the surface).
- It is also the **largest (by volume) freshwater lake in the world**, containing roughly 20% of the world's unfrozen surface fresh water.
- **Lake Tanganyika**, **second largest freshwater lake by volume**, is in the **Albertine Rift**, the westernmost arm of the active East African Rift.
- **Lake Tanganyika** is also the **world's longest freshwater lake** and the **second deepest lake in the world** (the deepest point is 1470 meters below the surface).
- **Lake Superior** in North America, the **largest freshwater lake by area**, lies in the ancient and dormant Midcontinent Rift.
- **Lake Victoria** is the world's **second largest freshwater lake by surface area**.



Major Lakes of the World

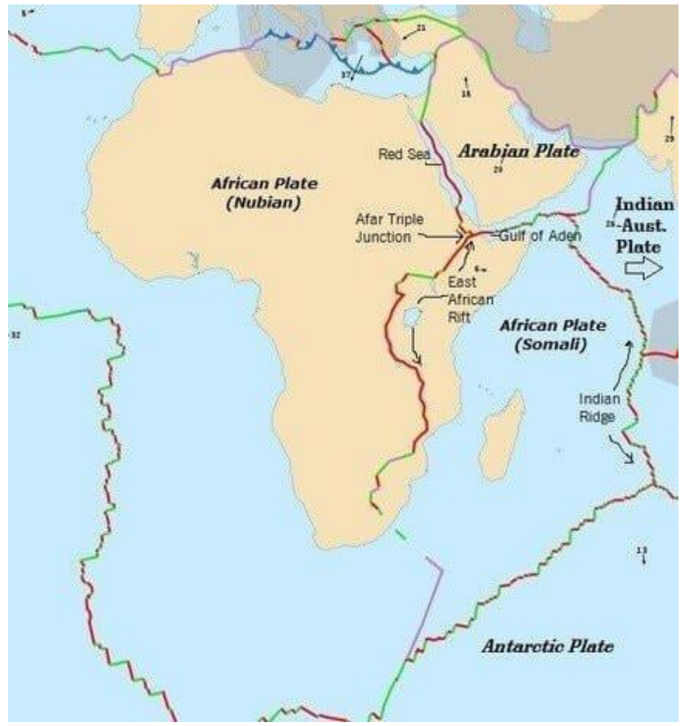
Great Lakes of North America (Phizzy, via [Wikimedia Commons]())

6.3 Great Rift Valley



African Great Lakes (MellonDor, from Wikimedia Commons)

- The Great Rift Valley is a geographical feature running north to south for around 6,400 kilometres from northern Syria to central Mozambique in East Africa.
- The northernmost part of the Rift forms the Beqaa Valley in **Lebanon**.
- Farther south, the valley is the home of the **Jordan River** which continues south through the Jordan Valley into the **Dead Sea** on the Israeli-Jordanian border.
- From the Dead Sea southward, the Rift is occupied by the **Gulf of Aqaba** and the **Red Sea**.
- The **Afar Triangle of Ethiopia and Eritrea** is the location of a triple junction.
- The Gulf of Aden is an eastward continuation of the rift, and from this point, the rift extends south-eastward as part of the mid-oceanic ridge of the Indian Ocean.
- In a southwest direction, the fault continues as the Great Rift Valley, which split the older **Ethiopian highlands** into two halves.
- In eastern Africa, the valley divides into the Eastern Rift and the Western Rift. The Western Rift, also called the **Albertine Rift** contains **some of the deepest lakes in the world**.

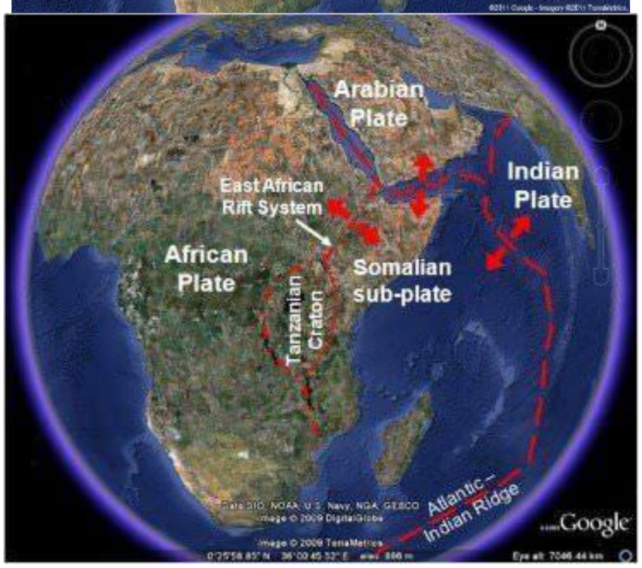


East African Rift Valley

- The Eastern Rift Valley (also known as **Gregory Rift**) includes the main **Ethiopian Rift**, running eastward from the **Afar Triple Junction**, which continues south as the **Kenyan Rift Valley**.
- The Western Rift Valley includes the **Albertine Rift**, and farther south, the valley of **Lake Malawi**.
- To the north of the **Afar Triple Junction**, the rift follows one of two paths: west to the **Red Sea Rift** or east to the **Aden Ridge in the Gulf of Aden**.
- The EAR transects through Ethiopia, Kenya, Uganda, Rwanda, Burundi, Zambia, Tanzania, Malawi and Mozambique.
- Before rifting, enormous continental flood basalts erupted on the surface and uplift of the **Ethiopian, Somalian, and East African plateaus** occurred.

Breaking up of Africa

- The East African Rift (EAR) is an **active continental rift zone** in East Africa.
- The EAR began developing around the onset of the Miocene, **22-25 million years ago**.
- In the past, it was considered to be part of a larger Great Rift Valley.
- The EAR is subjected to different stages of rifting along its length. To the **south, where the rift is young**, extension rates are low, and faulting occurs over a wide area. Volcanism and seismicity are limited.
- Towards the **Afar region**, however, the entire rift valley floor is covered with volcanic rocks.
- This suggests that, in this area, the **lithosphere has thinned almost to the point of complete break-up**.



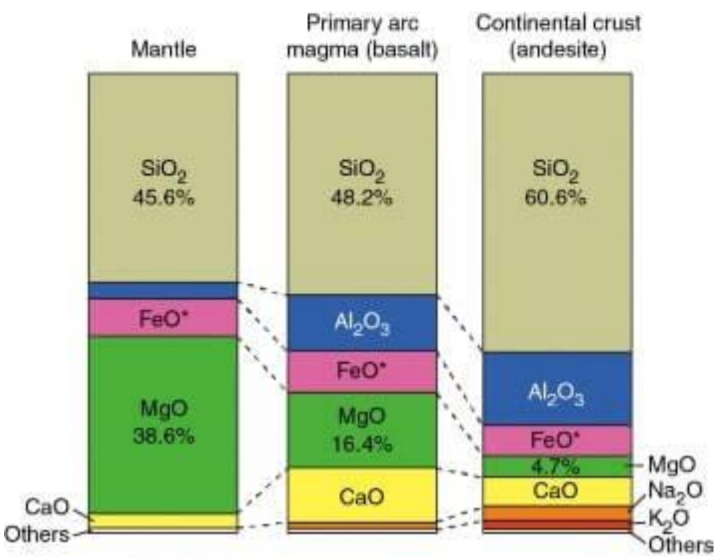
- The rift is a narrow zone that is a developing divergent tectonic plate boundary, in which the African Plate is in the process of splitting into two tectonic plates, called the **Somali Plate** and the **Nubian Plate (African Plate)**, at a rate of 6–7 mm annually.
- As extension continues, **lithospheric rupture** will occur within 10 million years, the Somalian plate will break off, and a new ocean basin will form.

Volcanism and seismicity along East African Rift Valley

- The East African Rift Zone includes many active as well as dormant volcanoes.
- **Mount Kilimanjaro** (it has three volcanic cones), is a **dormant** stratovolcano in Tanzania, **Mount Kenya** is an extinct stratovolcano.
- Although most of these mountains lie outside of the rift valley, the EAR created them.
- The EAR is the **largest seismically active rift system** on Earth today.
- The majority of earthquakes occur near the Afar Depression, with the largest earthquakes typically occurring along or near major border faults.

How come Mount Kilimanjaro and Mount Kenya that formed close to the divergent boundary are stratovolcanoes when the magma that flows out at the divergent boundary is basaltic?

- The formation of stratovolcano and shield volcano depends on the silica content of the magma.
- **Shield volcanoes** are formed from magma that contains a low proportion of silicates (**magma coming from the mantle, like in divergent boundary**).
- Stratovolcanoes are formed from magma that contains a high proportion of silicates (**magma formed due to the melting of crustal plates, like in convergent boundary**).
- Mt Kilimanjaro is a stratovolcano. It was formed during the process of formation of the African rift valley.
- During the formation of the African rift valley, there was a lot of faulting. The stress caused in the crustal plates led to the melting of the sub-surface layer into magma, and the volcanism around Kilimanjaro occurred due to this magma (high proportion of silicates).
- Take a look at the picture below to know the proportion of silicon content in mantle and crust.



Silicon content in the mantle, oceanic crust (mafic) and the continental crust (felsic)

- Majority of the stratovolcanoes occur along the convergent boundary, but there is no fixed rule that they should occur only along convergent boundaries. It all depends on the nature of magma that flows out.

7. Classification of Mountains

Classification of mountains on the basis of location

Continental mountains

Coastal mountains

- the Rockies,
- the Appalachians,
- the Alpine mountain chains,
- the Western Ghats and
- the Eastern Ghats (India);

Inland mountains

- the Vosges and the Black Forest (Europe),
- the Kunlun, Tienshan, Altai mountains of Asia,
- the Urals of Russia, the Aravallis,
- the Himalayas, the Satpura, and the Maikal of India.

Oceanic mountains

- Oceanic mountains are found on continental shelves and ocean floors.
- If the height of the mountains is considered from the ocean floor, **Mauna Kea (9140 m)**, would be the highest mountain. It is a dormant volcanic mountain in the Hawaii hotspot volcanic chain.

Mauna Kea, a dormant volcano in the island of Hawaii

Classification of mountains on the basis of the period of origin

- A total of nine orogenic or mountain building movements have taken place so far.

- Some of them occurred in Pre-Cambrian times between 600-3,500 million years ago.
- The three more recent orogenies are the **Caledonian, Hercynian and Alpine**.

Precambrian mountains

- They belong to the Pre-Cambrian period, a period that extended for more than 4 billion years.
- The rocks have been subjected to upheaval, denudation and metamorphosis.
- So, the remnants appear as **residual mountains.**
- Some of the examples are Laurentian mountains, Algoman mountains etc.

Caledonian mountains

- They originated due to the great mountain-building movements and associated tectonic movements of the late Silurian and early Devonian periods (approximately 430 million years and 380 million years ago).
- Examples are the **Appalachians, Aravallis, Mahadeo** etc.

Hercynian mountains

- These mountains originated during the upper Carboniferous to Permian Period in Europe (approximately 340 million years and 225 million years ago).
- Some examples are the mountains of **Vosges and the Black Forest, Altai, Tien Shan mountains of Asia, Ural Mountains etc**.

Alpine system

- Has its origin in the **Tertiary Period** (**65 million years to 7 million years ago)**.

Examples are

- **the Rockies of North America, the Alpine mountains of Europe,**
- **the Atlas Mountains of north-western Africa,**
- **the Himalayas of the Indian subcontinent**
- **the mountains radiating from Pamir knot like Pontic, Taurus, Elburz, Zagros and Kunlun etc**.
- Being the most recently formed, these ranges, such as the Alps, Himalayas, Andes and Rockies are the **loftiest with rugged terrain**.

Classification of mountains on the basis of mode of origin

Original or Tectonic mountains

- Original or Tectonic mountains are the product of tectonic forces.
- The tectonic mountains may be categorized into
  1. **fold mountains (the Himalayas, the Rockies, the Andes),**
  2. **block mountains (Vosges mountains in France, the Black Forest in Germany, Vindhya and Satpura in India) and**
  3. **volcanic mountains (Cascade Range in the USA, Mount Kenya, Mount Kilimanjaro, Mount Fujiyama)**.

Circum-erosional or Relict or Residual mountains

- Circum-erosional or Relict or Residual mountains (**Aravallis in India, Urals in Russia**) are the remnants of old fold mountains derived as a result of **denudation** (strip of covering).
- Residual mountains may also evolve from plateaus which have been dissected by rivers into hills and valleys.
- Examples of **dissected plateaux**, where the down-cutting streams have eroded the uplands into mountains of denudation, are the Highlands of Scotland, Scandinavia and the **Deccan Plateau**.

7.2 Fold Mountains

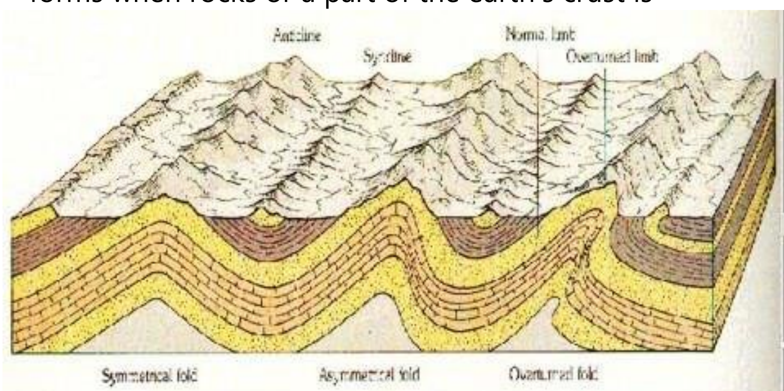
- Fold mountains are formed when sedimentary rock strata in **geosynclines** are subjected to compressive forces.

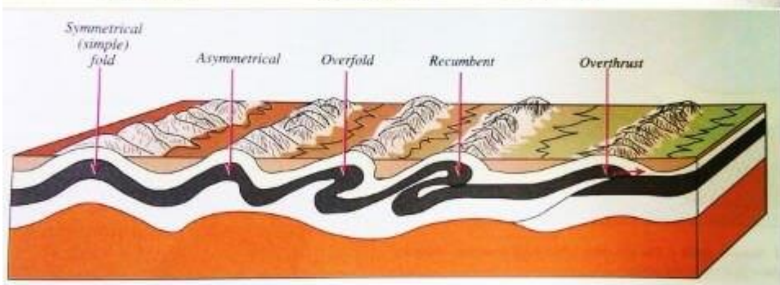
- They are the **loftiest** mountains, and they are generally concentrated along continental margins.

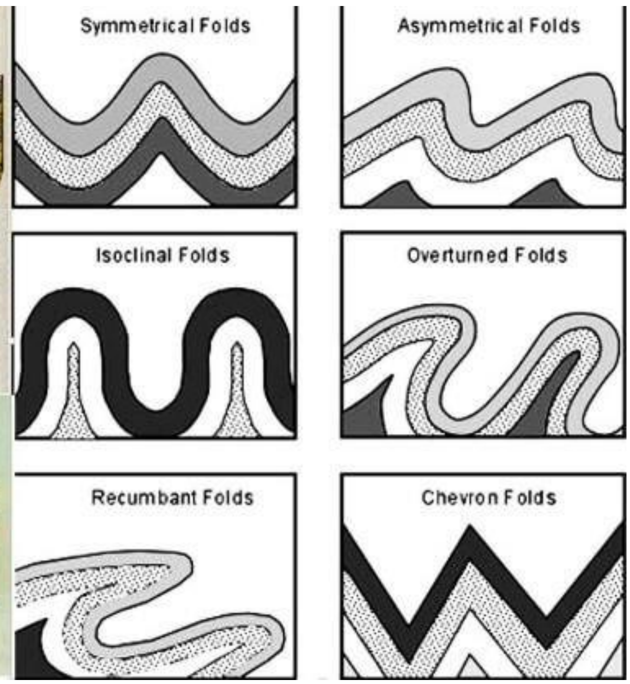
***Geosyncline**: a large-scale depression in the earth's crust containing very thick deposits. E.g. Tethys geosyncline.*

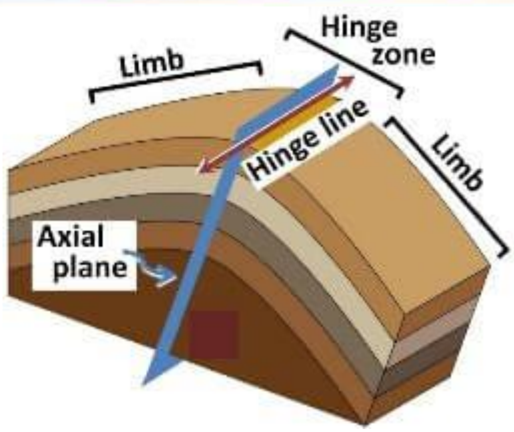
'Fold' in geology

- A fold is an undulating structure (wave-like) that forms when rocks or a part of the earth's crust is folded (deformed by bending) under compressional stress. The folds are made up of **multiple strata** (rock layers).
- The folds that are upwardly convex are called as **anticlines**. The core (centre) of an anticline fold consists of the older strata, and the strata are progressively younger outwards.
- In contrast, the folds that are downwardly convex are called **synclines**. The core of a syncline fold consists of the younger strata, and the strata are progressively older outwards.









- **Limbs:** The limbs are the flanks of the fold.
- **Hinge line:** the where the flanks join together (the line of maximum curvature).
- **Axial plane:** plane defined by connecting all the hinge lines of stacked folding surfaces (the plane in which hinge lines of various strata lie).

Types of folds

- A **symmetrical fold** is one in which the axial plane is vertical.
- An **asymmetrical fold** is one in which the axial plane is inclined.
- An **isoclinal fold** has limbs that are essentially parallel to each other and thus approximately parallel to the axial plane.
- An **overturned fold** has a highly inclined axial plane such that the strata on one limb are overturned.
- A **recumbent fold** has an essentially horizontal axial plane.

Classification of fold mountains

On the basis of period of origin

- On the basis of the period of origin, fold mountains are divided into very old fold mountains, old fold mountains and Alpine fold mountains.

Very Old Fold Mountains

- They are more than 500 million years old.
- They have rounded features (due to denudation).
- They are of low elevation.
- The **Appalachians** in North America and the **Ural Mountains** in Russia are the examples.

Old Fold Mountains

- Old fold mountains had their origin before the Tertiary period (tertiary period started 66 million years ago).
- The fold mountain systems belonging to **Caledonian** and **Hercynian** mountain-building periods fall in this category.
- They are also called **thickening relict fold mountains** because of lightly rounded features and medium elevation.
- Top layers are worn out due to erosional activity. Example: **Aravalli Range** in India.
- The **Aravalli Range** in India is the **oldest fold mountain systems in India**.
- The range rose in post-Precambrian event called the **Aravalli-Delhi orogeny.**

Alpine or young fold mountains

- Alpine fold mountains belonging to the Tertiary period (66 million years ago to present) can be grouped under the new fold mountains category since they originated in the Tertiary period.
- Examples are the **Rockies, the Andes, the Alps, the Himalayas**, etc.

Characteristics

- Rugged relief.
- Imposing height (lofty).
- High conical peaks.

On the basis of the nature of folds

Simple fold mountains

- Simple fold mountains with open folds in which **well-developed systems of synclines and anticlines** are found, and folds are of wavy patterns.

Complex fold mountains

- Complex fold mountains in which the rock strata are intensely compressed to produce a complex structure of folds.
- In the Himalayas, over folds and recumbent folds are often found detached from their roots and carried a few hundred kilometres away by the tectonic forces. These detached folds are called '**nappe**.'

Characteristics of Fold Mountains

- Fold mountains belong to the group of **youngest mountains of the earth**.
- The presence of fossils suggests that the **sedimentary rocks** of these folded mountains were formed after accumulation and consolidation of silts and sediments in a marine environment.
- Fold mountains extend for **great lengths** whereas their **width is considerably small**.
- Generally, fold mountains have a concave slope on one side and a convex slope on the other.
- Fold mountains are mostly found along continental margins facing oceans (C-O Convergence).
- Fold mountains are characterized by **granite intrusions** (formed when magma crystallises

and solidifies underground to form intrusions) on a massive scale.

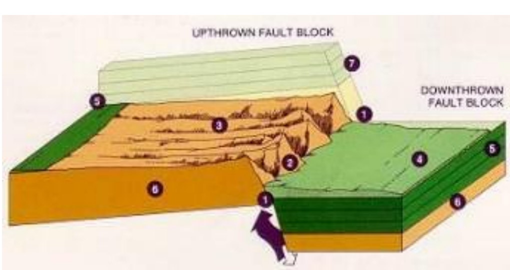
- **Recurrent seismicity** is a common feature in folded mountain belts.
- High heat flow often finds expression in **volcanic activity** (Himalayas is an exception, because of C-C convergence).
- These mountains are by far the most widespread and also the most important.
- They also contain rich mineral resources such as **tin, copper, gold** etc.

7.3 Block Mountains

- Block mountains are created because of faulting on a large scale (when large areas or blocks of earth are broken and **displaced vertically or horizontally**).
- The uplifted blocks are termed as **horsts,** and the lowered blocks are called **graben**.
- The **Great African Rift Valley (valley floor is graben)**, The **Rhine Valley (graben)** and the **Vosges mountain (horst)** in Europe are examples.
- Block mountains are also called **fault block mountains** since they are formed due to faulting as a result of tensile and compressive forces.

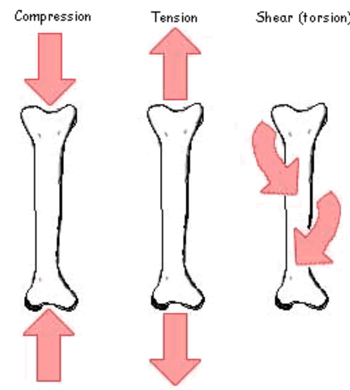
There are two basic types of block mountains:

1. **Tilted block** mountains have one steep side contrasted by a gentle slope on the other side.
2. **Lifted block mountains** have a flat top and extremely steep slopes.



'Fault' in Geology

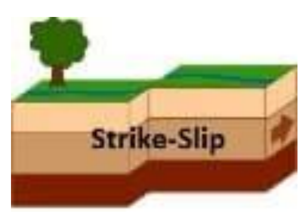
- When the earth's crust bends folding occurs, but when it cracks, faulting takes place.
- A fault is a planar fracture (crack) in a volume of earth's crust, across which there has been significant displacement of a block/blocks of crust.
- The **faulted edges are usually very steep**, e.g. the Vosges and the Black Forest of the Rhineland.
- Faults occur due to tensile and compressive forces acting on the parts of the crust.



- Large faults within the Earth's crust result from the action of plate tectonic forces, such as subduction zones or **transform faults**.
- Energy release associated with rapid movement on active faults is the cause of most **earthquakes**.
- In an active fault, the pieces of the Earth's crust along a fault move over time.
- Inactive faults had movement along them at one time, but no longer move.
- The type of motion along a fault depends on the type of fault.

Types of faults

Strike-slip fault



- In a strike-slip fault (also known **transcurrent fault**), the plane of the fault is usually **near ver-**

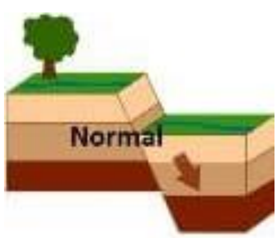
tical, and the blocks move laterally either **left or right** with very little vertical motion (the displacement of the block is **horizontal**).

Transform fault

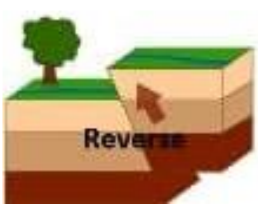
- A special class of strike-slip fault is the transform fault or transform boundary **when it forms a plate boundary**.
- **A transform fault is the only type of strike-slip fault that is classified as a plate boundary**.
- Most of these faults are hidden in the deep ocean, where they offset divergent boundaries in short zigzags resulting from seafloor spreading.
- They are less common within the continental lithosphere. The best example is the **Dead Sea transform fault**.
- The transform boundary ends abruptly and is connected to another transform, a spreading ridge, or a subduction zone.

Dip-slip faults

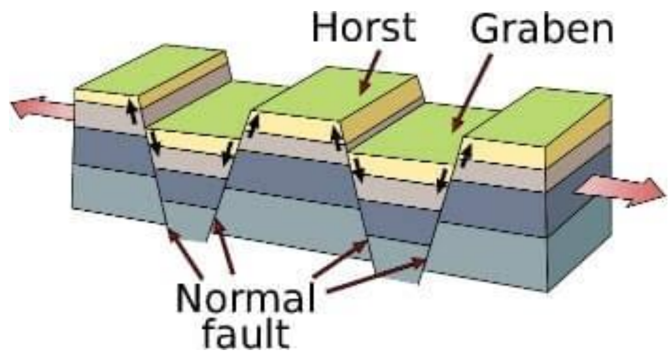
- Dip-slip faults can be either **normal or reverse**.
- In a normal fault, the hanging wall (displaced block of crust) moves **downward**, relative to the footwall (stationary block).



- In a **reverse fault (thrust fault)** the hanging wall moves **upwards**.



- Reverse faults occur due to compressive forces whereas normal faults occur due to tensile forces.
- A downthrown block between two normal faults is a **graben**.
- An upthrown block between two normal faults is a **horst**.
- Normal faults occur mainly in areas where the crust is being extended such as a **divergent boundary**.
- **Reverse faults** occur in areas where the crust is being shortened such as at a **convergent boundary**.



Rift Valley system

- Tension causes the central portion to be let down between two adjacent fault blocks forming a graben or rift valley, which will have steep walls.
- The East African Rift Valley system is the best example.
- In general, large-scale block mountains and rift valleys are due to tension rather than compression.

Block Mountains

- Block mountains may originate when the middle block moves downward and becomes a rift valley while the surrounding blocks stand higher as block mountains.

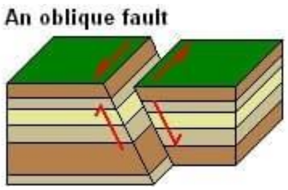
Plateaus

- Sometimes, the surrounding blocks subside leaving the middle block stationary. Such cases are found in high plateau regions.

Oblique-slip faults

- A fault which has a component of **dip-slip** and a component of **strike-slip** is termed an oblique-slip fault.
- Nearly all faults have some component of both dip-slip and strike-slip.

- **Many disastrous earthquakes** are caused along the oblique slip.



7.4 Volcanic mountains

- Volcanic mountains are formed due to volcanic activity.
- Mount Aconcagua, Mount Kilimanjaro, Mount Mauna Kea and Mount Fujiyama are examples of such mountains.
- These are, in fact, volcanoes which are built up from material ejected from fissures in the earth's crust.
- The materials include molten lava, volcanic bombs, cinders, ashes, dust and liquid mud.
- They fall around the vent in successive layers, building up a characteristic volcanic cone.
- Volcanic mountains are often called **mountains of accumulation**.
- They are common in the Circum-Pacific belt.

7.5 Significant mountains and mountain ranges

Basics

Ridge

- Mountain ridges refer to mountains which originate as a result of local folding and faulting.
- Generally, the slope of one side of the ridge is steep in contrast to the moderate slope on the other side (**in case of Himalayas, the southern slope is steeper compared to the northern slope**).
- In some cases, a ridge may have a symmetrical slope on both sides.

Mountain range

- It refers to a series of ridges which originated in the same age and underwent the same processes.
- The most prominent or characteristic feature of mountain ranges is their long and narrow extension.
- Example: the Himalayas is a mountain range with Himadri ridge, Himachal ridge and Shiwalik ridge.

Mountain System

- A group of mountain ranges formed in a single period, similar in their form, structure and extension, is termed a mountain system.
- Examples are the Basin Range of Nevada (USA), the Rocky mountain system of North America and the Appalachian.

Mountain Chain

- It consists of mountain ranges which differ in size and period of formation.

Cordillera

- Cordillera is a community of mountains which includes ridges, ranges, mountain chains and mountain systems.
- The best example is the Western Cordillera in the western part of North America.

Longest Mountain Ranges

1. The Andes - 7,000 km
2. The Rockies - 4,830 km
3. The Great Dividing Range - 3,500 km
4. The Transantarctic Mountains - 3,500 km
5. The Ural Mountains - 2,500 km
6. The Atlas Mountains - 2,500 km
7. The Appalachian Mountains - 2,414 km
8. The Himalayas - 2,400 km
9. The Altai Mountains - 2,000 km (1,243 mi)
10. The Western Ghats - 1,600 km
11. The Alps - 1,200 km
12. Drakensberg - 1,125 km
13. The Aravalli Range - 800 km

The Andes

- The Andes is the **longest** continental mountain range in the world.
- The Andes is the world's highest mountain range outside of Asia with an **average height of 4000 m**.
- The highest peak is **Mount Aconcagua (6,962 m)** (volcanic origin, but now it's dormant).
- **World's highest volcanoes are in the Andes**.
- **Ojos del Salado (6,893 m)** (active volcano) on the **Chile-Argentina** border is the highest volcano on earth.

The Rockies

- Rocky Mountain range forms a part of the American Cordillera

American Cordillera

- The American Cordillera is a chain of mountain ranges (cordilleras) that consists of an almost continuous sequence of mountain ranges that form the western backbone of the Americas and Antarctica.
- It is also the backbone of the volcanic arc that forms the **eastern half of the Pacific Ring of Fire**.

North Cordillera

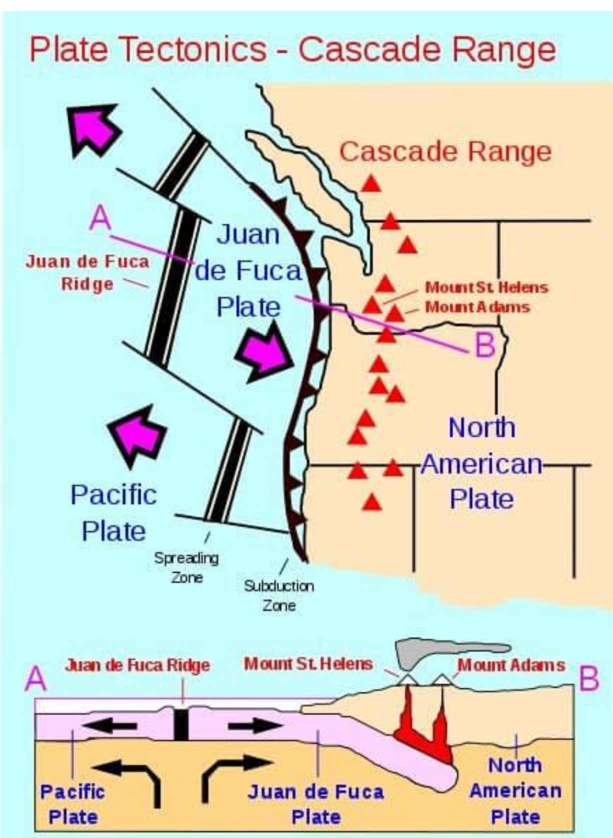
- The ranges of the Cordillera from Mexico northwards are collectively called the North American Cordillera.
- They include the Alaska Range and the Brooks Range in Alaska, main belt of the Rocky Mountains along with the parallel Columbia Mountains, the Sierra Nevada, the Cascades, and various small Pacific coastal ranges.
- In Mexico, the Cordillera continues through the Sierra Madre Occidental and the Sierra Madre Oriental.

South Cordillera

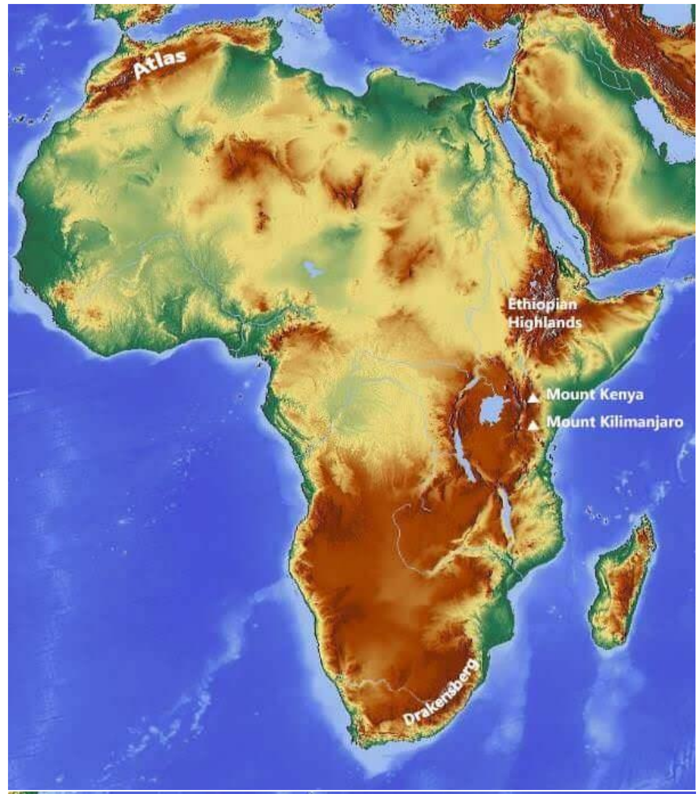
- The Cordillera continues through the mountain ranges of Central America in Guatemala, Honduras, Nicaragua, Costa Rica, and Panama, and becomes the Andes Mountains of South America.
- The Andes with their parallel chains continue to the very tip of South America at **Tierra del Fuego**.
- The Cordillera continues along the Scotia Arc before reaching the mountains of the Antarctic Peninsula.

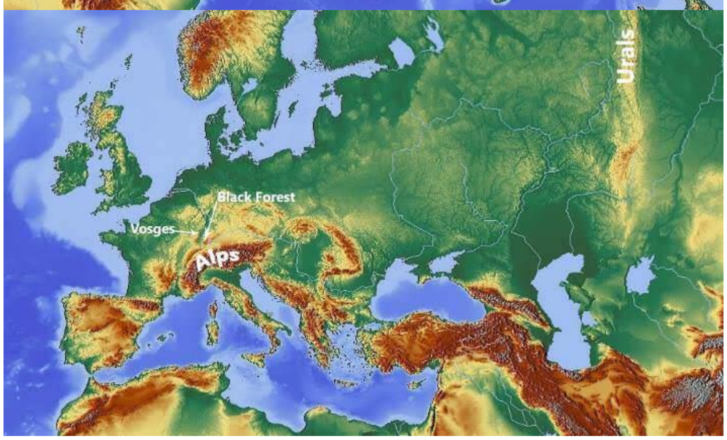
Cascade Range

- The Cascade Range or the Cascades is a major mountain range of western North America.
- The Cascades (Cascade volcanoes) are part of the Pacific Ocean's Ring of Fire.
- They are made up of a band of thousands of **very small, short-lived volcanoes**.
- The Cascade Range has few strikingly large volcanoes, like **Mount St. Helens**.
- The volcanoes and earthquakes in the Cascades arise from a common source: subduction, where the dense **Juan de Fuca oceanic plate** plunges beneath the **North American Plate**.



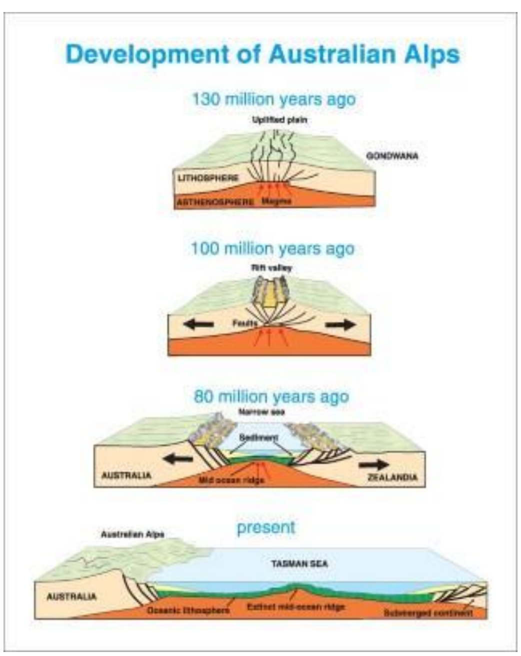
Cascade Volcanism ([Wikipedia Commons](#))





The Great Dividing Range

- The Great Dividing Range, or the Eastern Highlands, is Australia's most substantial mountain.
- It is also known as the **Australian Alps** and was formed due to rifting.



Transantarctic Mountains

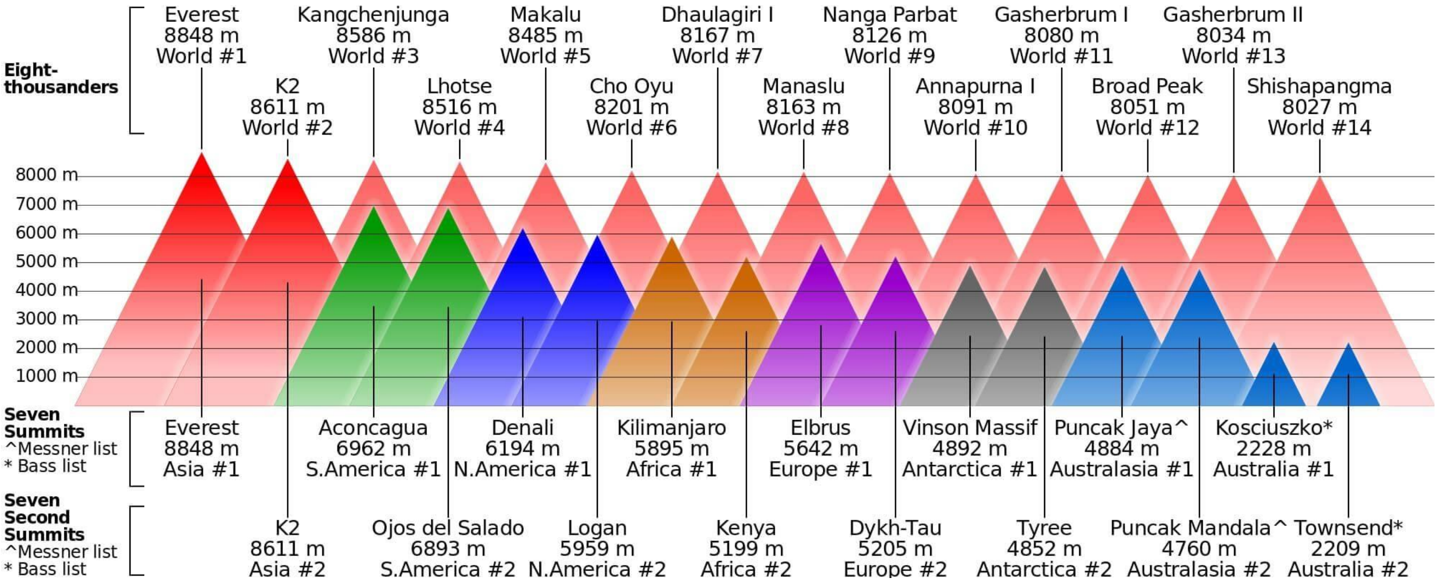
Transantarctic Mountains (krill oil [CC0], via [Wikimedia Commons](https://commons.wikimedia.org))

The Ural Mountains

- Mountain range that runs approximately from north to south through western Russia, from the coast of the Arctic Ocean to the **Ural River** and northwestern Kazakhstan.
- They are formed due to **Continent-Continent collision of** supercontinent **Laurussia** with the young and weak continent of **Kazakhstania**.
- Their eastern side is usually considered the natural boundary between Europe and Asia.
- Since the 18th century, the mountains have been a **major mineral base of Russia**.

Atlas Mountains

- Mountain range across the north-western stretch of Africa extending about 2,500 km (1,600 mi) through **Algeria, Morocco and Tunisia.**
- The highest peak is **Toubkal** (4,165 metres) in southwestern Morocco.
- These mountains were formed when Africa and Europe collided.



Highest Mountains on Earth

The Himalayas

- The Himalayan range is home to the planet's highest peaks, including the highest, **Mount Everest.**
- Its western anchor, **Nanga Parbat**, lies just south of the northernmost bend of Indus river, its eastern anchor, **Namcha Barwa**, just west of the great bend of the Brahmaputra river (Tsangpo river).
- The range varies in width from 400 kilometres in the west to 150 kilometres in the east.

Geology

- The Himalaya are among the **youngest mountain ranges** on the planet and consist mostly of **uplifted sedimentary and metamorphic rock**.
- According to the modern theory of plate tectonics, their formation is a result of a continental collision or orogeny along the convergent boundary between the Indo-Australian Plate and the Eurasian Plate.
- The Arakan Yoma highlands in Myanmar and the Andaman and Nicobar Islands in the Bay of Bengal were also formed as a result of this collision.

Impact on climate

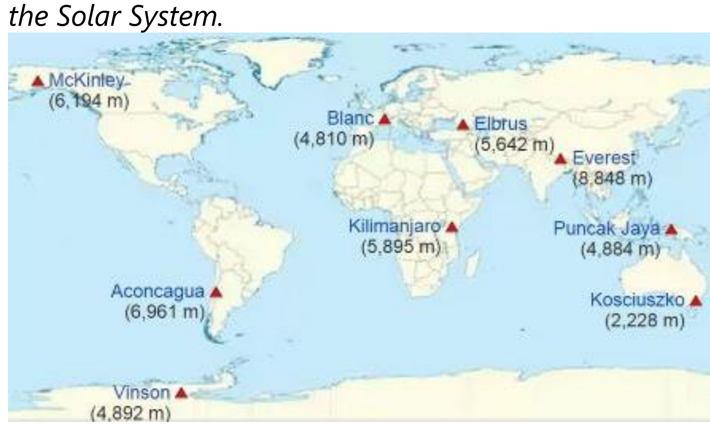
- The Himalayas are believed to play an important part in the formation of Central Asian deserts, such as the **Taklamakan and Gobi**.

The Alps

- The mountains were formed as the African and Eurasian tectonic plates collided.
- Extreme folding caused by the event resulted in marine sedimentary rocks rising by thrusting and folding into high mountain peaks such as **Mont Blanc** (4,810 m) (French–Italian border).
- The Alpine region area contains about a hundred peaks higher than 4,000 m, known as the **four-thousanders.**

Highest mountain peaks

*The highest known mountain on any planet in the Solar System is **Olympus Mons** on Mars (~26 km in elevation). It is also the **highest active volcano** in the Solar System.*



*Highest Mountain of each continents (The other name of Mount McKinley is **Mount Denali**.)*