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PHYSICAL GEOGRAPHY

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1 The Origin, Evolution and Geodesy of Earth

THEORIES OF EARTH'S ORIGIN

Early Theories

- **Nebular Hypothesis**
  - **Proposed by:** Immanuel Kant (1755) and later revised by Pierre-Simon Laplace (1796).
  - **Concept:** The theory suggests that the Sun and planets formed from a large, slowly rotating cloud of gas and dust (solar nebula). Over time, this cloud contracted due to gravity, flattened into a disk, and began spinning faster. The Sun formed at the center, and the leftover material formed planets.
  - **Supporting Evidence:**
    - Similar disk-like structures are observed around young stars, supporting the idea of disk formation leading to planetary systems.
    - The **conservation of angular momentum** explains the increase in spinning speed as the nebula contracted.
  - **Challenges:**
    - This model does not explain the detailed mechanisms for planet formation, particularly how the initial dust particles grew into larger planetary bodies.
- **Revised Nebular Hypothesis**
  - **Proposed by:** Otto Schmidt (Russia) and Carl Weizascar (Germany).
  - **Concept:** This theory expanded on the original Nebular Hypothesis by adding details about how planets formed. The solar system started as a large cloud of gas (mostly hydrogen and helium) mixed with dust. Through the process of **accretion**, dust particles collided and stuck together to form larger bodies. Eventually, these formed planets, moons, and other celestial objects.
  - **Supporting Evidence:**
    - Accretion processes are seen in modern astronomy, where small dust grains stick together to form larger clumps.
    - Dust clouds around stars are observed in space, suggesting this process occurs in other solar systems.
  - **Challenges:**
    - It does not fully explain the observed distribution of angular momentum in the solar system, as the Sun has very little compared to the planets.
- **Planetesimal Hypothesis**
  - **Proposed by:** Thomas Chamberlain and Forest Moulton (1900), later supported by Sir James Jeans and Sir Harold Jeffrey.
  - **Concept:** This theory suggests that a large star passed near the Sun, pulling off material due to gravitational forces. This material cooled and condensed into planetesimals (small, solid bodies), which later grew into planets through accretion.
  - **Supporting Evidence:**
    - The hypothesis was developed before modern understanding of nuclear fusion and the Sun's heat. It attempted to explain how solid materials could form into planets.
    - The idea of gravitational influence from passing stars is supported by gravitational tidal forces seen in cosmic interactions today.
  - **Challenges:**
    - This theory fell out of favor due to its reliance on a close encounter with another star, a rare event.

Modern Theories

- **Big Bang Theory (Expanding Universe Hypothesis)**
  - **Proposed by:** Georges Lemaitre (1927) and strengthened by Edwin Hubble's observations (1929).

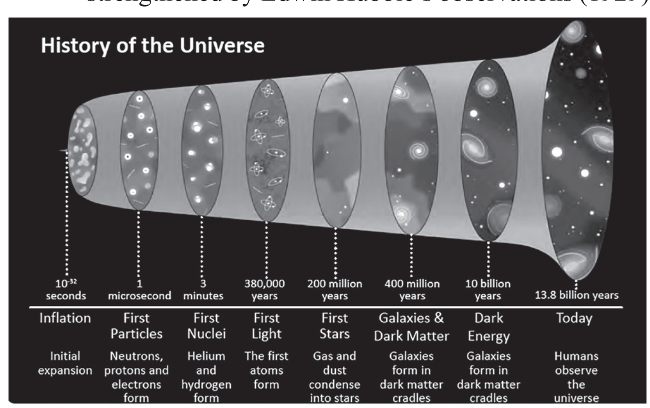


Fig. Big Bang Theory

- **Concept:** According to this theory, around 13.7 billion years ago, the universe began from a singular, extremely dense and hot point (referred to as a "tiny ball"). This point exploded in an event known as the **Big Bang**, causing the universe to expand rapidly. As the universe expanded, it cooled, allowing energy to convert into matter. Over time, galaxies, stars, and planets formed.
- **Supporting Evidence:**
  - **Redshift of Galaxies:** Hubble observed that galaxies are moving away from us, implying the universe is expanding. This is seen through the redshift of light from distant galaxies.
  - **Cosmic Microwave Background Radiation (CMB):** Discovered by Penzias and Wilson, this faint radiation is the remnant heat from the early universe, providing strong evidence for the Big Bang.
  - **Abundance of Light Elements:** The Big Bang model predicts the relative amounts of hydrogen, helium, and lithium in the universe, matching observed quantities.
- **Challenges:**
  - While it explains the large-scale structure of the universe, the Big Bang does not account for what happened before the explosion or why the universe's expansion is accelerating (which is attributed to dark energy).

- Steady State Theory
  - **Proposed by:** Fred Hoyle (1948).
  - **Concept:** In contrast to the Big Bang, this theory suggests that the universe has always existed in its current state. It is infinite in both time and space, with matter continuously being created to maintain a constant density as the universe expands.
  - **Supporting Evidence:**
    - At the time, it was appealing because it avoided questions about the universe's origin and why an explosion would occur.
    - The idea that the universe is eternal and unchanging is philosophically attractive to some.
  - **Challenges:**
    - The discovery of the CMB and observations of an evolving universe over time (such as the formation of galaxies and stars) contradicted the steady-state model. As a result, this theory has largely been abandoned.

STAR FORMATION

- **Initial Universe and Density Differences:** After the Big Bang, matter and energy were not evenly distributed. These small density variations led to regions where gravitational forces were stronger, pulling nearby matter toward these areas. This process was the foundation for the creation of galaxies.
- **Nebula and Galaxy Formation:** A nebula is a large cloud of hydrogen gas, which acts as the birthplace of stars and galaxies. Galaxies begin to form as hydrogen gas accumulates into these large clouds. Over time, localized areas within the nebula grow denser, eventually leading to the formation of clumps of gas.

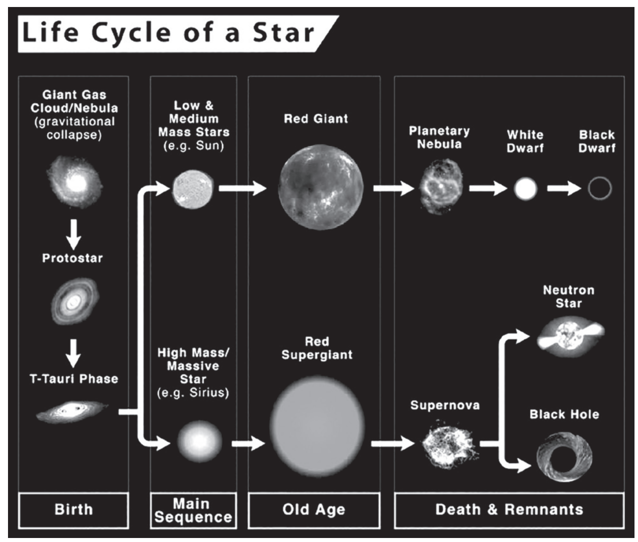


Fig. Life Cycle of Star

- **Birth of Stars:** These gas clumps continue to gather more material, becoming even denser. As the gravitational forces increase, the core temperature rises until nuclear fusion ignites in the center. This process marks the formation of a star. Over millions of years, more stars form within the galaxy.

Formation of Planets

- **Formation of Stars within a Nebula:** Stars are essentially large lumps of gas formed inside a nebula. When a star forms, it creates a core within a dense gas cloud. Around this core, a rotating disc of gas and dust develops.
- **Development of Planetesimals:** As the gas surrounding the core starts condensing, smaller rounded objects begin to form through cohesion. These smaller objects are called planetesimals. Over time, these planetesimals start to collide and stick together due to gravitational attraction.

- **Planet Formation:** The planetesimals continue to merge and accrete, eventually forming fewer but larger bodies that develop into planets. This process is driven by both collisions and the gravitational pull of nearby objects.
- **Accretion Process:** The term *accretion* refers to the gradual accumulation of matter to form larger bodies. This process continues over millions of years, eventually leading to the creation of full-sized planets that orbit their parent star.

Timeline of Earth's Evolution

- **13.7 Billion Years Ago - Big Bang**
  - The universe originated from a singularity, leading to the formation of galaxies, including the Milky Way, which hosts our solar system.
- **5-6 Billion Years Ago - Formation of Stars**
  - Within galaxies, stars formed from clouds of gas and dust due to gravitational forces, leading to the creation of various stellar bodies.
- **4.6 Billion Years Ago - Formation of Planets**
  - The solar system began to take shape as particles in a rotating disk around the young Sun collided and coalesced, forming the planets, including Earth.
- **4.4 Billion Years Ago - Formation of the Moon**
  - A significant impact event involving a Mars-sized body led to debris that eventually coalesced to form the Moon, influencing Earth's tides and axial tilt.
- **4 Billion Years Ago - Formation of Oceans**
  - As the Earth cooled, water vapor condensed and accumulated, forming oceans. This process was vital for developing the planet's climate and supporting life.
- **3.8 Billion Years Ago - Life Begins to Evolve** **[UPSC 2018]**
  - Simple life forms, likely prokaryotic microbes, emerged in the oceans, marking the beginning of biological evolution on Earth.
- **2.5-3 Billion Years Ago - Evolution of Photosynthesis**
  - Photosynthetic organisms, particularly cyanobacteria, began converting sunlight into energy, releasing oxygen as a byproduct. This process drastically altered Earth's atmosphere and paved the way for more complex life forms.

GEOLOGICAL TIMESCALE

- **Definition:** A system of chronological dating used to describe Earth's history, dividing it into eons, eras, periods, epochs, and ages.
- **Major Divisions:**
  - **Eons** (largest): *Hadean, Archean, Proterozoic, Phanerozoic*.
  - **Eras** (within Phanerozoic): *Paleozoic, Mesozoic, Cenozoic*.
  - **Periods**: Examples include *Cambrian, Jurassic, Quaternary*.
  - **Epochs** (within Cenozoic): *Pleistocene, Holocene*.
- **Time Span:** Spans approximately 4.6 billion years, from Earth's formation to the present.
- **Key Events:**
  - **Precambrian** (4.6 billion to 541 million years ago): Formation of Earth and early life (unicellular organisms).
  - **Paleozoic Era:** Explosion of marine life, first land plants, and reptiles.
  - **Mesozoic Era:** Age of dinosaurs and first mammals.
  - **Cenozoic Era:** Rise of mammals and humans.
- **Current Epoch:** *Holocene*, beginning around 11,700 years ago, marked by human civilization.
- **Importance:** Helps scientists understand Earth's evolution, climate changes, and life forms over time.

Geological Time Scale

Relative Duration of Eons	Era	Period	Epoch	Age (Millions of Years Ago)	Some Important Events in the History of Life
Phanerozoic	Cenozoic	Quaternary	Holocene	0.01	Historical time
			Pleistocene	1.8	Ice ages; Origin of genus Homo
		Neogene	Pliocene	5.3	Appearance of bipedal human ancestors.
			Miocene	23	Continued radiation of mammals and angiosperms; earliest direct humans ancestors
Proterozoic		Paleogene	Oligocene	33.9	Origins of many primate group
			Eocene	55.8	Angiosperm dominance increases; continued radiation of most modern mammalian orders
			Paleocene	65.5	Major radiation of mammals, birds and pollinating insects
	Mesozoic	Cretaceous		145.5	Flowering plants (angiosperms) appear, many groups of organisms, including most dinosaurs, become extinct at end of period
		Jurassic		199.6	Gymnosperms continue as dominant plants; dinosaurs abundant and diverse
		Triassic		251	Cone-bearing plants (gymnosperms) dominate landscape; radiation of dinosaurs; origin of mammal
	Paleozoic	Permian		299	Radiation of reptiles; origin of most present-day groups of insects; extinction of marine and terrestrial organisms many at end of period
Archaean		Carboniferous		359.2	Extensive forests of vascular plants; first seed plants appear, origin of reptiles; amphibians dominant
		Devonian		416	Diversification of bony fishes; first tetrapods and insects appear
		Silurian		443.7	Diversification of early vascular plants
		Ordovician		488.3	Marine algae abundant; colonization of land by diverse fungi, plants and arthropods
		Cambrian		542	Sudden increase in diversity of many animal phyla (Cambrian explosion)
		Ediacaran		600	Diverse algae and soft-bodied invertebrate animals
				2,100-2500	Oldest fossils of eukaryotic cells
				2,700	Concentration of atmospheric oxygen begins to increase
				3,500	Oldest fossils of cells (prokaryotes) appear
				3,800	Oldest known rocks on Earth's surface
				App. 4,600	Origin of Earth

Our Solar System

Parameter	Description
Solar System	A celestial system including the Sun, planets, asteroids, comets, dust, and gases.
Location	Orbits in the Milky Way's outer spiral arm (Orion arm).
Inner/Terrestrial Planets	High density, smaller size, solid rocky surfaces due to intense solar winds. Examples: **Mercury, Venus, Earth, Mars.**
Outer/Jovian Planets	Low density, larger size, gaseous surfaces due to weak solar winds. Examples: **Jupiter, Saturn, Uranus, Neptune.**
Total Planets	8 (Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune)
Mercury	Smallest and nearest to the Sun.
Venus	Earth's twin; hottest planet due to carbon dioxide atmosphere and sulfuric acid clouds.
Jupiter	Largest planet with hydrogen, helium, methane, and ammonia atmosphere.
Axis Tilt	Venus and Uranus rotate opposite to other planets due to extreme axial tilt.

Overview of Planets

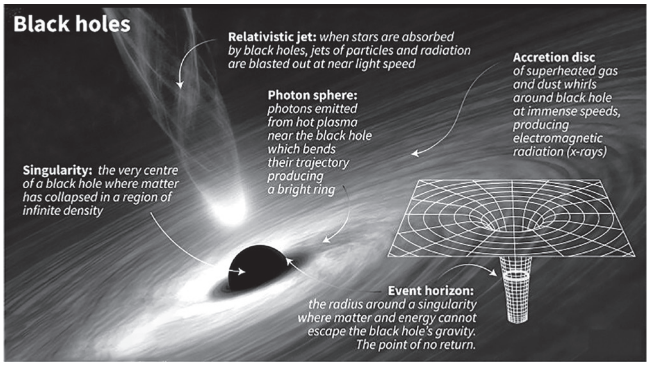
Planet	Type	Time of Rotation	Axial Tilt (°)	Composition	Distance from Sun (AU)	Key Features
Mercury	Terrestrial	59 Earth days	0.03	Rocky, metallic core	0.39	Closest to Sun, no atmosphere, extreme temperature fluctuations.
Venus	Terrestrial	-243 Earth days (retrograde)	177.4	Rocky, dense CO_2 atmosphere	0.72	Hottest planet due to greenhouse effect; rotates in opposite direction.
Earth	Terrestrial	24 hours	23.5	Rocky, water on surface, N_2-O_2 atmosphere	1	Only planet with liquid water and life; located in the Goldilocks zone.
Mars	Terrestrial	24.6 hours	25.2	Rocky, thin CO_2 atmosphere	1.52	Known as the "Red Planet"; has the largest volcano (Olympus Mons) in the Solar System.
Jupiter	Jovian (Gas Giant)	9.9 hours	3.1	Hydrogen, helium, ammonia, methane	5.2	Largest planet; Great Red Spot (a massive storm); faint ring system.
Saturn	Jovian (Gas Giant)	10.7 hours	26.7	Hydrogen, helium, methane	9.539	Iconic ring system; low density (could float in water).
Uranus	Jovian (Ice Giant)	-17.2 hours (retrograde)	97.8	Hydrogen, helium, methane, water, ammonia	19.2	Spins on its side due to extreme axial tilt; pale blue-green color due to methane.
Neptune	Jovian (Ice Giant)	16.1 hours	28.3	Hydrogen, helium, methane	30.05	Deep blue color; fastest winds in the Solar System; has faint rings.

OVERVIEW OF ASTRONOMICAL OBJECTS AND CONCEPTS

Key Celestial Objects

- **Exoplanets**
  - Planets orbiting stars outside our Solar System.
  - Discovered using methods like radial velocity and transit photometry. Example: Proxima Centauri b.
- **Dwarf Planets**
  - Celestial bodies that orbit the Sun, have enough mass for a nearly round shape, but haven't cleared their orbital paths.
  - Examples: Pluto, Eris, Haumea, Makemake, Ceres.
- **White Dwarfs**
  - Remnants of stars like the Sun after exhausting their nuclear fuel.
- **Comets**
  - Icy bodies from regions like the Kuiper Belt or Oort Cloud.
  - Develop tails (gas and dust) when near the Sun due to sublimation.
- **Asteroids**
  - Rocky remnants from the Solar System's formation, mostly located in the Asteroid Belt.

- **Black Holes**
  - Regions of spacetime with gravitational forces so strong that not even light can escape.
  - **Event Horizon:** Boundary beyond which nothing escapes.
  - Formed from collapsing massive stars beyond the **Chandrasekhar Limit** (~1.4 solar masses).



- **Pulsars**
  - Highly magnetized, rotating neutron stars emitting beams of electromagnetic radiation.
  - Detected as regular pulses when the beam aligns with Earth.
- **Supernovae**
  - Explosions marking the death of massive stars, dispersing elements into space and forming neutron stars or black holes.
- **Neutron Stars**
  - Compact remnants of massive stars that exploded as supernovae. Composed mostly of neutrons.
- **Quasars**
  - Extremely bright and energetic centers of distant galaxies, powered by supermassive black holes.
  - Emit vast amounts of radiation as matter spirals into the black hole.

Advanced Concepts

- **Gravitational Lensing**
  The bending of light from distant objects by a massive intervening object, as predicted by Einstein's **General Relativity**.
  - Used to detect dark matter and distant galaxies.

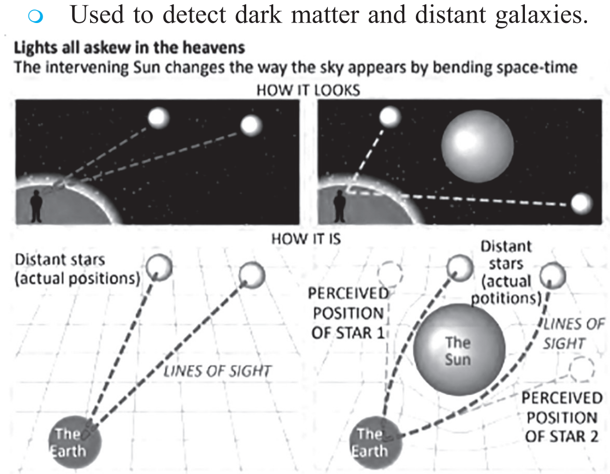


Fig. Gravitational Lensing

- **General Relativity**
  - Einstein's theory describing gravity as the warping of spacetime by mass and energy.
  - Predicts phenomena like gravitational waves and time dilation near massive objects.
- **Chandrasekhar Limit**
  - Maximum mass (~1.4 solar masses) a white dwarf can have before collapsing into a neutron star or black hole.
- **Event Horizon**
  - A boundary around a black hole where escape velocity equals the speed of light.

Other Celestial Phenomena

- **Meteoroids, Meteors, and Meteorites**
  - **Meteoroid:** Small rocky or metallic body in space.
  - **Meteor:** A meteoroid entering Earth's atmosphere, producing a bright streak.
  - **Meteorite:** A meteoroid that survives its journey and lands on Earth.
- **Oort Cloud**
  - Hypothetical outermost boundary of the Solar System, source of long-period comets.
- **Planetary Nebulae**
  - Clouds of gas ejected by dying stars, often forming beautiful, colorful structures.
- **Supernovae**
  - Explosions marking the death of massive stars, dispersing elements into space and forming neutron stars or black holes.
- **Interstellar Medium**
  - The gas and dust filling the space between stars, crucial for star formation.
- **Dark Matter and Dark Energy**
  - **Dark Matter:** Unseen matter influencing galaxy rotation and structure.
  - **Dark Energy:** Mysterious force driving the accelerated expansion of the Universe.

THE MOON: EARTH'S NATURAL SATELLITE

- **Basic Facts**
  - The Moon is the only natural satellite of Earth, with a diameter approximately one-quarter that of Earth.
- **Tidal Locking**
  - The Moon is tidally locked to Earth, meaning it takes about **27 days** to complete both its orbit around Earth and its rotation on its axis. As a result, only one side of the Moon is visible from Earth.
- **Formation**
  - The prevailing theory regarding the Moon's formation is the **giant impact hypothesis**, also known as the "big splat." This theory suggests that the Moon formed from the debris resulting from a collision between a Mars-sized body and the early Earth.

- **Super Moon**
  - A **Super Moon** occurs when the Moon is at its closest distance to Earth (known as **perigee**) during a full moon. During this event, the Moon can appear **14% larger** and **30% brighter** than usual, making it a spectacular sight.

Moons of Various Planets

Planet	Number of Moons	Notable Moons	Key Features
Mercury	0	None	-
Venus	0	None	-
Earth	1	Moon	Influences tides; stabilizes axial tilt.
Mars	2	Phobos, Deimos	Phobos: irregular, spiraling inward; Deimos: smaller, distant.
Jupiter	80	Io, Europa, Ganymede, Callisto	Io: volcanically active; Europa: potential ocean; Ganymede: largest moon; Callisto: heavily cratered.
Saturn	80+	Titan, Rhea, Lapetus	Titan: thick atmosphere, methane lakes; Rhea: icy surface; Iapetus: two-tone coloration.
Uranus	27	Titania, Oberon, Miranda	Titania: largest moon; Oberon: heavily cratered; Miranda: unique surface features.
Neptune	14	Triton	Triton: retrograde orbit, geologically active.

RETROGRADE AND PROGRADE MOTION AND ROTATION

- **Prograde Motion**
  - **Definition:** The apparent eastward motion of a planet against the background of stars as observed from Earth. It is the usual, counterclockwise orbital motion of planets around the Sun (when viewed from above the Sun's north pole).
  - **Cause:** Planets orbit the Sun in nearly the same plane and direction due to the conservation of angular momentum from the rotating disk of gas and dust that formed the Solar System.
- **Retrograde Motion**
  - **Definition:** The apparent westward motion of a planet against the backdrop of stars as seen from Earth.
  - **Cause:** Retrograde motion is an optical illusion caused by the relative positions and motions of Earth and the other planets. When Earth overtakes a slower-moving outer planet (like Mars), that planet appears to move backward temporarily in the sky.

Key Differences Between Retrograde Motion and Rotation

- **Retrograde Motion:** Apparent backward movement in the sky, observed due to relative orbital dynamics (optical illusion).
- **Retrograde Rotation:** Physical spinning or axial rotation of a planet in the opposite direction of most planets in the Solar System.

Retrograde Rotation of Venus and Uranus

Venus (Retrograde Rotation): Venus rotates backward (clockwise) compared to its orbit around the Sun, with a very slow rotation period of 243 Earth days.

- **Reasons:**
  1. **Giant Impact Hypothesis:** A massive collision early in Venus's history might have reversed its spin direction.
  2. **Atmospheric Effects:** Venus's thick atmosphere might have interacted with its surface through tidal friction, contributing to the reversal over millions of years.

Uranus (Axial Tilt and Retrograde-like Rotation)

- **Axial Tilt:** Uranus has an extreme tilt of about 98 degrees, causing it to essentially "roll" along its orbit. This results in retrograde-like rotation relative to the Sun.
- **Reasons:**
  1. **Massive Collisions:** Multiple or a single catastrophic impact with a large proto-planet during the formation of the Solar System likely knocked Uranus onto its side.
  2. **Gravitational Interactions:** Strong interactions with massive bodies during the early stages of Solar System development could have altered its axial tilt.

EARTH : GOLDILOCKS ZONE, LATITUDE AND LONGITUDE

Earth is the fifth largest planet in the Solar system; also called Blue Planet as two-thirds surface is covered by water.

- **Shape: Geoid** (oblate spheroid) - slightly flattened at the Poles and bulging at the Equator.
- Earth lies in the **Goldilocks Zone** - water can exist in a liquid state.
- **Densest** planet in the solar system.(**About 5.513 g/cm^3)**
- Speed of rotation around the axis is maximum at the equator and decreases poleward.
- The **axis of the earth,** which is an imaginary line, **makes an angle of 66½°** with its orbital plane.

Polestar **[UPSC-2012]**

A **pole star** is a visible star nearly aligned with the rotational axis of an astronomical body. For Earth, Polaris marks the North.

If a person in a desert needs to walk 5 km **east** to reach their village and can locate the **polestar**, they should walk in a direction **keeping the polestar to their left**, as this will align them with the **eastward direction**.

Goldilocks Zone

The **Goldilocks Zone**, or **habitable zone**, is the region around a star where conditions are just right for liquid water, essential for life.

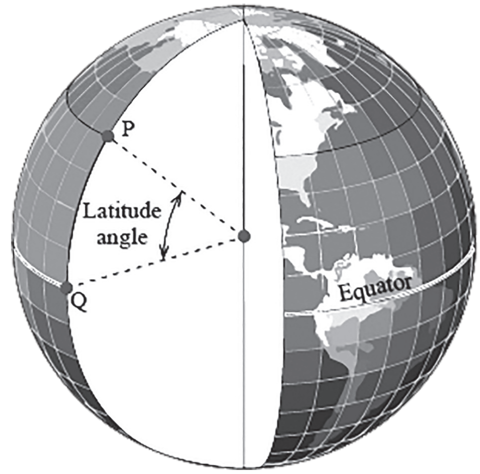
- **Temperature Range**
  - This zone allows water to remain liquid; too close to a star results in evaporation (too hot), while too far leads to freezing (too cold).
- **Influencing Factors**
  - The size and brightness of a star determine the Goldilocks Zone's boundaries. Larger or hotter stars have habitable zones farther out.
- **Earth as a Reference**
  - Earth lies within the Sun's Goldilocks Zone, enabling it to support life due to favorable average temperatures for liquid water.
- **Exoplanets**
  - An **exoplanet** (or **extrasolar planet**) is a planet that orbits a star outside our solar system.
  - **Proxima Centauri b:** Closest known exoplanet to Earth, located in the habitable zone of Proxima Centauri.
  - **TRAPPIST-1 System:** Contains seven Earth-sized planets, with three in the habitable zone.
  - **Kepler-186f:** The first Earth-sized exoplanet found in the habitable zone of its star.

Importance

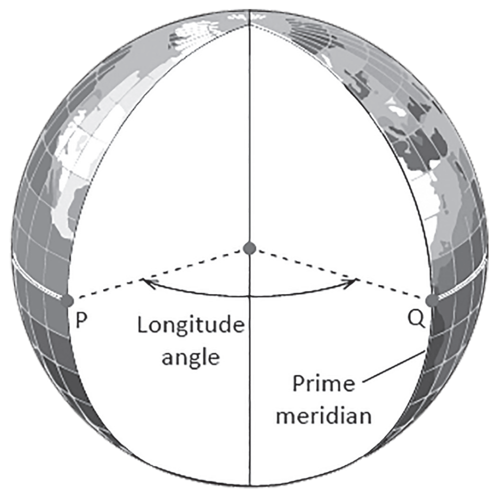
The Goldilocks Zone is crucial in astrobiology, guiding the search for extraterrestrial life by identifying where habitable worlds might exist.

Latitude and Longitude

- **Latitude:** Angular distance from the Earth's centre, measured in degrees. Parallels of latitude are parallel to the equator.
  - **Distance:** Each degree of latitude is about 69 miles (111 km).



Latitude: The latitude of a parallel is the angle between a point on the parallel (P) and a point on the Equator at the same meridian (Q), as measured from the Earth's center.



Longitude: The longitude of a meridian is the angle between a point on the meridian at the Equator (P) at a point on the prime meridian at the Equator (Q), as measured at the Earth's center.

- **Longitude:** Angular distance east or west of the Prime Meridian (0°). Measured in degrees from 0° to 180°.
  - **Prime Meridian:** Passes through the UK, France, Algeria, and Antarctica.
  - **International Date Line:** Located at 180°, it alters date and time across the Pacific. It is not a straight line to avoid dividing the same landmass in two dates.
  - **Distance:** Between longitudes decreases from the equator to the poles, converging at the poles.

- **Standard Time:**
  - **Indian Standard Time (IST):** Based on the **82½° E** meridian, passing through Uttar Pradesh, Chhattisgarh, Odisha, Madhya Pradesh, and Andhra Pradesh.
    - **Important Cities:** Kanpur, Raipur, Bhubaneswar, Bhopal, Vijayawada.
  - **Time Difference:** IST is **5 hours and 30 minutes** ahead of GMT.
- **Great Circle:** A great circle is the intersection of a sphere (like Earth) with a plane that passes through its centre. It represents the shortest path between two points on the surface of the sphere.
  - The **Equator** (0° latitude) is a great circle because it divides the Earth into two equal hemispheres (Northern and Southern). Other latitudes are not Great circles.
  - All **meridians** (lines of longitude) are considered great circles when paired with their antipodal (opposite) meridians. For example, the line at 0° (Prime Meridian) and its opposite at 180° create a great circle.
  - **Navigation and Great Circles**
    - **Shortest Path:** When navigating long distances, pilots and sailors often use great circles to determine the shortest route between two points. This is crucial for saving time and fuel.
    - For example, a flight from New York to Tokyo typically follows a great circle route, appearing as a curve on a flat map.

Major Latitudes of Earth

Latitude	Name	Countries
0°	Equator	**Africa:** Gabon, Republic of the Congo, Democratic Republic of the Congo, Uganda, Kenya, Somalia **Asia:** Indonesia, Maldives **South America:** Ecuador, Colombia, Brazil, São Tomé and Príncipe
23½° N	Tropic of Cancer	**North America:** Mexico, Bahamas **Africa:** Egypt, Libya, Niger, Algeria, Mali, Mauritania **Asia:** Taiwan, China, Myanmar, Bangladesh, India, Oman, UAE, Saudi Arabia
23½° S	Tropic of Capricorn	**South America:** Argentina, Brazil, Chile, Paraguay **Africa:** Namibia, Botswana, South Africa, Mozambique, Madagascar **Australia:** Australia
66½° N	Arctic Circle	**Europe:** Norway, Sweden, Finland **Asia:** Russia **North America:** United States (Alaska) **North America:** Canada **Oceania:** Greenland (Denmark), Iceland
66½° S	Antarctic Circle	**Antarctica:** Antarctica

EARTH'S GEOMAGNETIC FIELD

It is the field of a **magnetic dipole** currently tilted at an angle of about 11 degrees with respect to Earth's rotational axis, as if there were a bar magnet placed at that angle at the centre of the Earth.

- The geomagnetic field is a **dynamic field** and it changes across geological time scale.
- Study of this magnetic field and its variations gives us a better **understanding about the metallic core of the Earth**.
- The intensity of the geomagnetic field is greatest near the poles and weaker near the Equator.

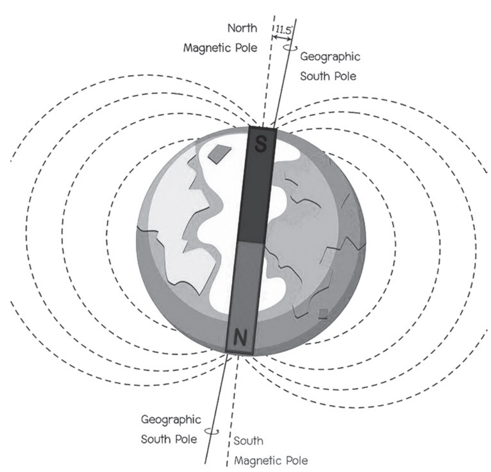


Fig. Geo-magnetic Field

Causes of Geomagnetic Field

The magnetic field of the Earth is generated by the **motion of molten iron alloys** in the **Earth's liquid outer core**.

- Differences in temperature, pressure and composition within the core cause **convection currents in the molten metal**.
- This flow of liquid iron generates **electric currents**, which in turn produce **magnetic fields**. This effect is known as **Dynamo Effect**.

Geomagnetic Reversal

A geomagnetic reversal is a change in a planet's magnetic field such that the **positions of magnetic north and magnetic south are interchanged**. This happens in a cycle of a few hundred thousand years.

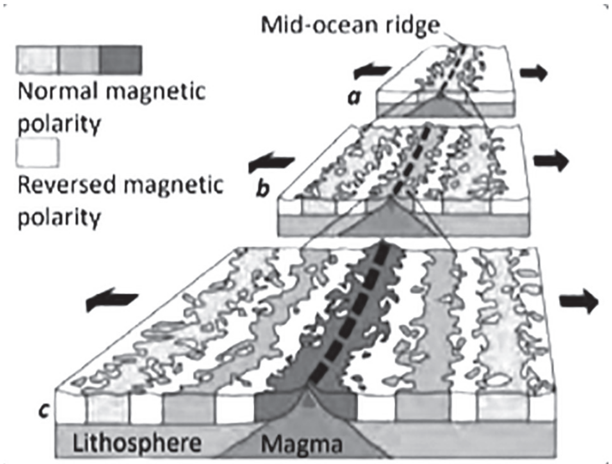


Fig. Geomagnetic Reversal recorded along mid-Oceanic Ridges (Sea Floor Spreading Theory)

Geomagnetic Poles

The Geomagnetic poles are the intersections of the Earth's surface and the axis of a bar magnet hypothetically placed at the centre of the Earth.

- If the Earth's magnetic field were a perfect dipole, the field lines would be vertical to the surface at the Geomagnetic Poles, and they would coincide with the North and South magnetic poles.
- However, the approximation is imperfect, and so the Magnetic and Geomagnetic Poles lie some distance apart.

Significance Of Geomagnetic Field

- This field acts as a **shield** that **blocks the solar winds** emanating from the sun, consisting of energetically electrically charged particles which can severely damage life on the planet. **[UPSC-2012]**
- Some particles manage to enter our planet, being directed by the magnetic field towards the poles, and excite the molecules of nitrogen and oxygen in the atmosphere. These excited molecules produce light seen as **Auroras**. In Northern Hemisphere: **Aurora Borealis** and in Southern Hemisphere: **Aurora Australis.**
- Helps in **navigation** by use of compass.
- **Magneto-Perception:** Some **animals** can use this magnetic field to navigate while migrating over long distances.
- The study of paleo-magnetism provides us with information about the past record of geomagnetism and the age of rocks on the surface of the planet.
- It also helped in developing the theories of **Seafloor spreading and Plate Tectonics**.
- Geomagnetic field is the cause of the formation of the magnetosphere around the Earth.

Magnetosphere

A magnetosphere is a region of space surrounding the Earth (or any other planet or star) that is affected by the geomagnetic field (or magnetic field of that body).

- It traps charged particles from the solar winds (ions and electrons emitted by the Sun) and funnels them into a plasma.

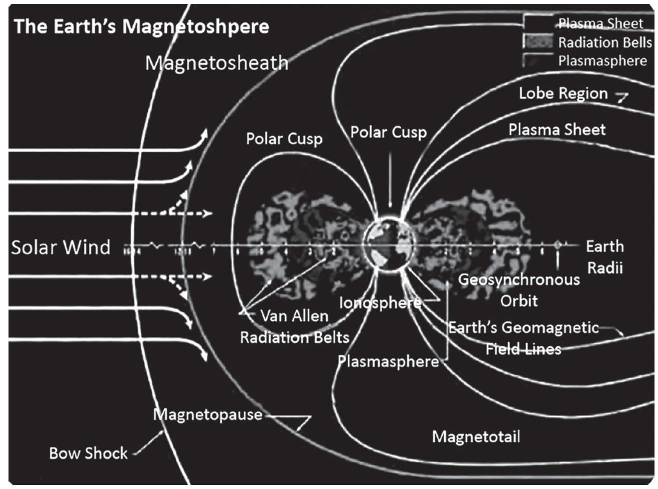


Fig. Magnetosphere and Magnetotail

- **Magnetotail:** It **extends up to 60,000 km** on the side **facing the Sun** and to a **greater extent on the opposite side which is called Magnetotail.**
- Its boundary is known as **Magnetopause**, outside which is a turbulent magnetic region known as magneto-sheath.
- It contains the **Van Allen radiation belts,** which contain high energy charged particles.
  - The lower belt contains electrons and protons extending from 1000 to 5000 km above the Earth's equator.
  - The upper belt has mainly electrons extending from 15000 to 25000 km above the equator.

Magnetic Storm

When the **strong gusts of solar wind collide with the magnetosphere of the Earth**, resulting in rapid magnetic field variation, this is known as magnetic storm.

- This results in generation of electric currents in near earth space, which can **harm our artificial satellites** (eg. GPS) and **long-range radio communication**.
- Magnetic storms are known as **Ring currents** and they are **mostly concentrated over the equator**.

HEAT ZONES OF EARTH

The Earth has three primary heat zones based on the Sun's rays:

- **Torrid Zone (Tropical Zone)**

  Located between the Tropics of Cancer and Capricorn, this is the hottest region. It receives direct sunlight year-round, leading to high temperatures and abundant rainfall. Examples include the Amazon and Congo Basins.

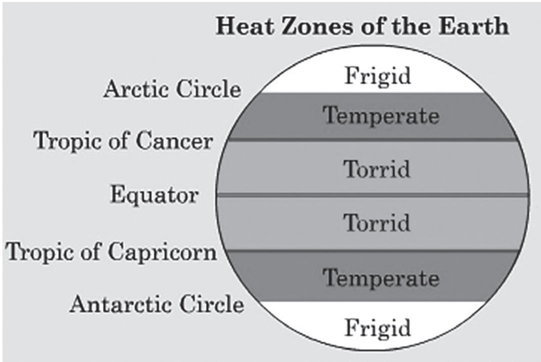
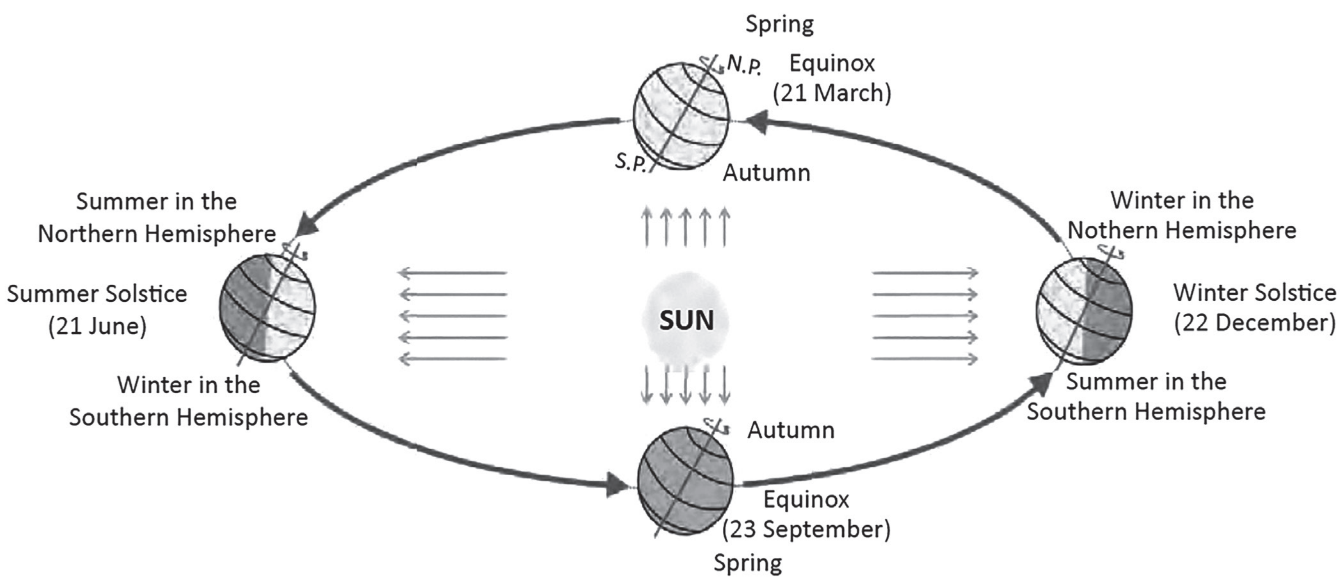


Fig. Heat Zones of Earth

- **Temperate Zone**
  Found between the tropics and polar circles, this zone has moderate temperatures with four seasons. Sunlight is slanted, resulting in diverse climates. Examples are Europe and North America.
- **Frigid Zone (Polar Zone)**
  Located between the polar circles and the poles, it experiences extreme cold with slanted sunlight. Long winters and harsh conditions are typical. Examples include Antarctica and Greenland.

EARTH'S MOVEMENTS AND CYCLES

- **Rotation of the Earth**
  - **Definition:** The Earth rotates around its axis from west to east.
  - **Speed:** Rotation is fastest at the equator (about 1670 km/h) and decreases toward the poles.
  - **Effects:**
    - **Day & Night:** Alternating periods of daylight and darkness across the globe.
    - **Coriolis Force:** Deflects wind and ocean currents, causing clockwise circulation in the Northern Hemisphere and counterclockwise in the Southern Hemisphere.
- **Revolution of the Earth**
  - **Definition:** Earth revolves around the Sun in an elliptical orbit.
  - **Perihelion and Aphelion**:
    - **Perihelion** (closest to the Sun): January 3rd.
    - **Aphelion** (farthest from the Sun): July 4th.
  - **Effects:**
    - **Seasons:** Seasonal changes occur due to Earth's axial tilt (23.5°) and its changing position around the Sun. **[UPSC 2013]**
    - **Daylight Variations:** The length of day and night varies throughout the year, with regions near the poles experiencing continuous daylight or darkness for months.

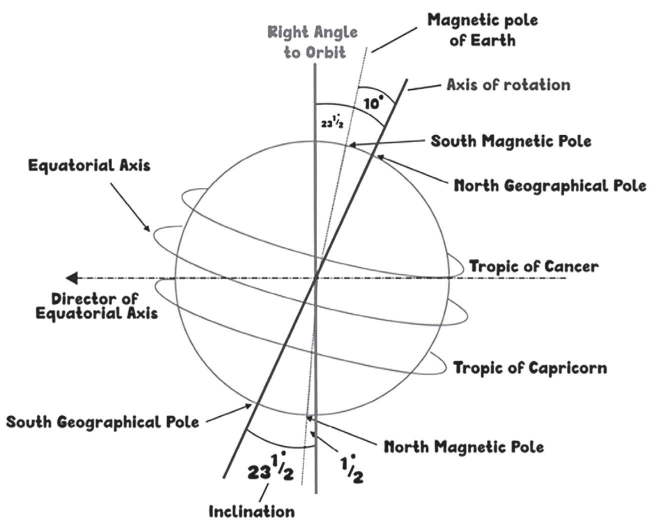


- **Earth's Axial Tilt and Precession**
  - **Axial Tilt (Obliquity):** Earth's axis is tilted at 23.5° relative to its orbit around the Sun, which causes the seasonal variation.
  - **Cycle of Tilt:** Over 41,000 years, the tilt varies between 22.1° and 24.5°, affecting the intensity of the seasons.
  - **Axial Precession:** The slow wobbling of Earth's axis (like a spinning top) completes one cycle every 26,000 years. This influences the timing of the seasons relative to Earth's orbit.

- **Milankovitch Cycles**

  These are long-term cycles that influence Earth's climate and seasons:

THE EARTH'S INCLINATION ON ITS AXIS



- **Eccentricity:** The shape of Earth's orbit fluctuates between more circular and more elliptical over a 100,000-year cycle. A more elliptical orbit increases temperature extremes between seasons.
- **Obliquity (Axial Tilt):** As Earth's tilt changes over a 41,000-year cycle, it affects the strength of seasonal variations.
- **Precession (Axial Wobble):** Over 26,000 years, the direction of Earth's tilt changes, shifting the timing of seasons.
- **Magnetic Axis and Magnetic Pole Reversal**
  - **Magnetic Axis:** Earth's magnetic field is generated by its liquid outer core and is tilted about 11° from the rotational axis.
  - **Wobble of the Magnetic Axis:** The magnetic poles slowly drift due to changes in the outer core. This movement is gradual but significant for navigation and geophysics.
  - **Magnetic Reversals:** Earth's magnetic field reverses periodically, with the North and South magnetic poles switching places. These reversals occur over tens of thousands to millions of years and are detected through magnetic patterns in rocks.
- **Other Cycles and Influences**
  - **Chandler Wobble:** A small, irregular movement of Earth's poles with a period of about 433 days. This wobble affects Earth's rotation slightly.
  - **Solar Activity Cycles:** The Sun undergoes cycles of increased and decreased solar activity, approximately every 11 years, which affects solar radiation reaching Earth and influences climate patterns.

Solstice and Equinoxes

Solstice: The point during Earth's orbit where the Sun reaches its highest or lowest point in the sky at noon, resulting in the longest or shortest day of the year.

[UPSC 2024, 2022 and 2019]

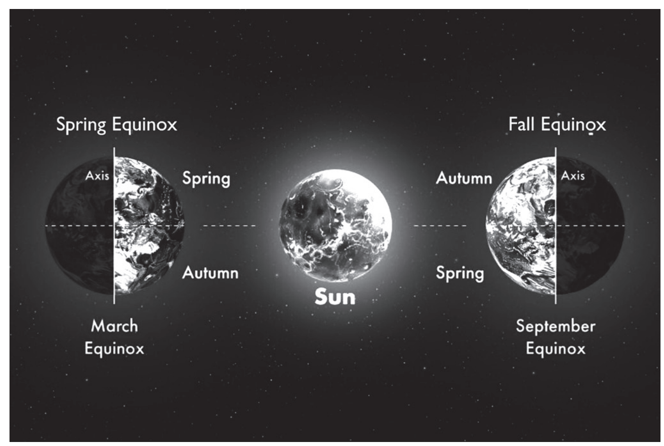


Fig. Equinox

Equinox: The time when day and night are of approximately equal length, occurring when the Sun is directly over the equator.

Solstices and Equinoxes

Event	Date (Approximate)	Daylight in Northern Hemisphere	Daylight in Southern Hemisphere	Arctic Circle (66.5°N)	Antarctic Circle (66.5°S)
Summer Solstice	June 21	Longest day (most daylight)	Shortest day (least daylight)	24 hours of daylight	24 hours of darkness
Winter Solstice	December 22	Shortest day (least daylight)	Longest day (most daylight)	24 hours of darkness	24 hours of daylight
Spring Equinox	March 21	Equal day and night (12 hours)	Equal day and night (12 hours)	12 hours of daylight	12 hours of daylight
Autumn Equinox	September 23	Equal day and night (12 hours)	Equal day and night (12 hours)	12 hours of daylight	12 hours of daylight

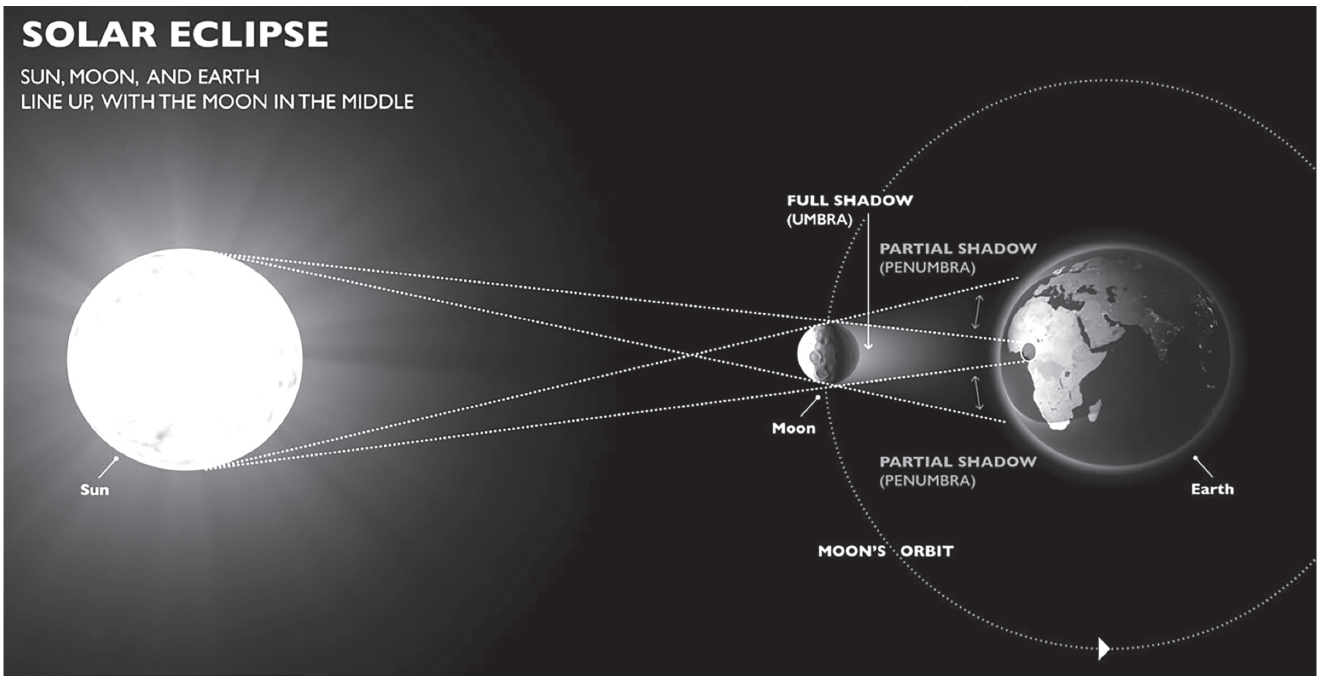
MOON'S ORBITAL PLANE, EARTH'S ORBITAL PLANE AND ECLIPSES

The Moon's orbital plane is tilted by about **5 degrees** relative to Earth's orbital plane (the **ecliptic**). This tilt affects the occurrence of the **new moon**, **full moon**, and eclipses.

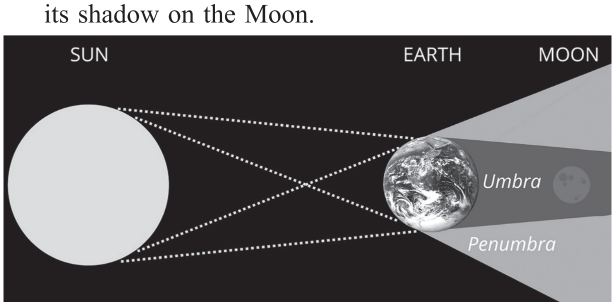
- **Phases of the Moon**
  - **New Moon:** New moon occurs when the Moon is between Earth and the Sun, and thus the side of the Moon that is in shadow faces Earth.
  - **Full Moon:** The Earth is between the Sun and Moon, but the Moon usually passes above or below Earth's shadow, preventing a lunar eclipse most months.

Solar and Lunar Eclipses

- **Solar Eclipse**
  - **Mechanism:** Occurs during a **new moon** phase when the Moon comes between the Earth and the Sun. This blocks sunlight from reaching the Earth.
  - **Conditions:** The Moon's orbit must align with the **ecliptic plane**, allowing a perfect alignment.
  - **Types**:
    - **Total Solar Eclipse:** When the Moon completely covers the Sun as observed from Earth.
    - **Partial Solar Eclipse:** When the Sun is partially obscured.
    - **Annular Eclipse:** When the Moon appears smaller and leaves a "ring of fire."



- **Lunar Eclipse**
  - **Mechanism:** Happens during a **full moon** when the Earth comes between the Sun and the Moon, casting its shadow on the Moon.



  - **Types**:
    - **Total Lunar Eclipse:** The Moon is fully covered by Earth's umbra (darkest shadow). Appears red due to **Rayleigh scattering** (same phenomenon that causes sunsets to appear red) and atmospheric refraction.
    - **Partial Lunar Eclipse:** Only a part of the Moon enters the Earth's umbra.
    - **Penumbral Eclipse:** The Moon passes through the Earth's penumbra, causing a subtle dimming.

Key Notes

- **Ecliptic Plane:** The imaginary plane containing Earth's orbit around the Sun, essential for the alignment needed for eclipses.
- **Red Moon During Lunar Eclipse:** The Earth's atmosphere bends sunlight, filtering out blue light and illuminating the Moon with red hues.
- **Rarity:** Eclipses do not occur every month because the Moon's orbit is tilted (~5°) relative to Earth's orbit, so perfect alignment is infrequent.Because of the Moon's tilt, eclipses don't occur every new or full moon. Eclipses happen during **eclipse seasons** when the Moon's orbit crosses the ecliptic plane during these phases.

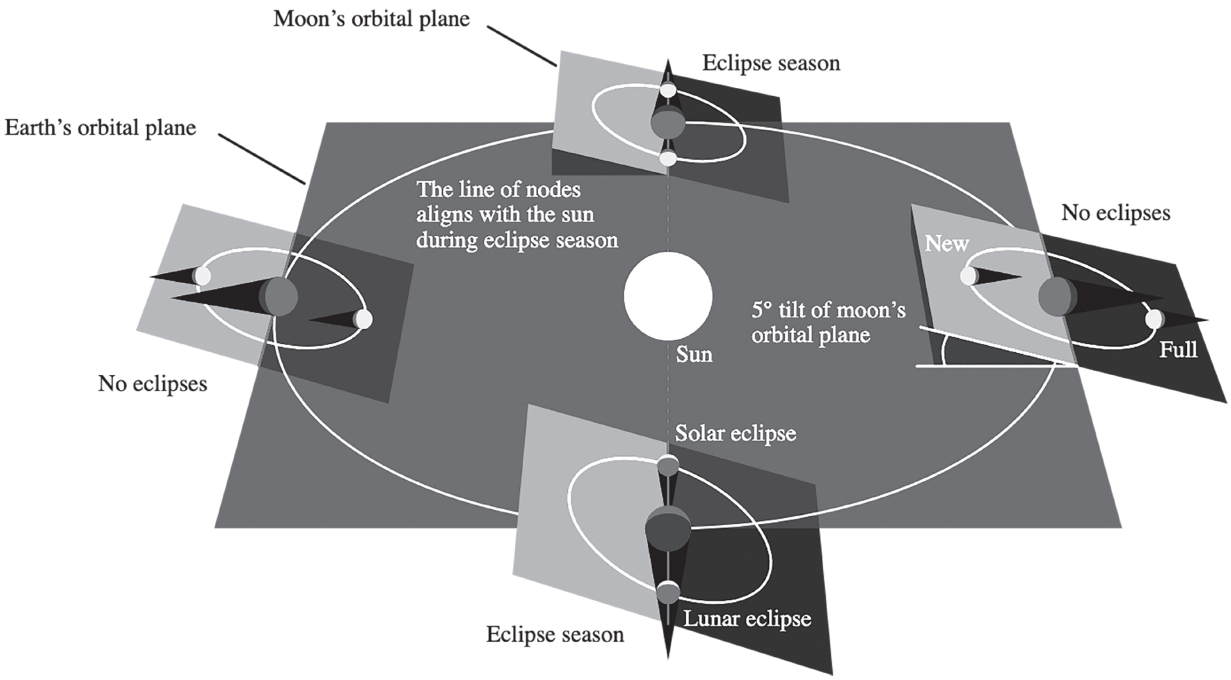


Fig. Eclipse Formation

2 Interior of Earth, Plate Tectonics and Related Phenomenon

EARTH'S INTERNAL STRUCTURE: CRUST, MANTLE, AND CORE

Crust

The **crust** is Earth's outermost, rigid layer. It is solid and brittle, and can be divided into Continental and Oceanic Crust.

- **Continental Crust**
  - **Mean Thickness:** ~30 km (can be thicker in mountainous regions).
  - **Density:** ~2.7 g/cm³.
  - **Rock Type:** Predominantly granite, rich in minerals like **Silica** and **Aluminium**, collectively known as **SIAL**.
  - **Conrad Discontinuity:** The boundary separating the upper continental crust from the lower crust, marking a shift in rock composition.

Internal Structure of the Earth

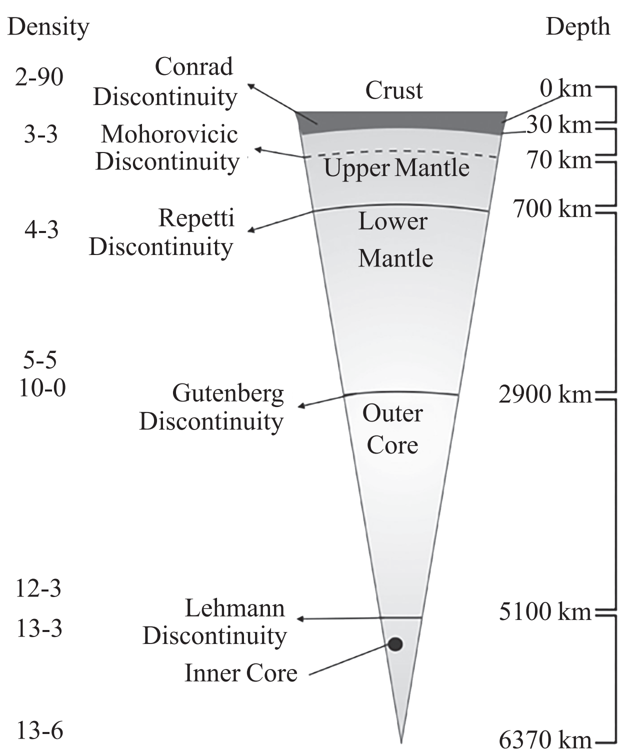


Fig. Internal Structure of Earth and Discontinuity

- **Oceanic Crust**
  - **Mean Thickness:** Thinner than continental crust, around 5 km.
  - **Density:** ~3 g/cm³.
  - **Rock Type:** Mostly basalt, which is denser and younger than the granitic continental crust.
  - **Mineral Composition:** Silica, Iron, and Magnesium, collectively referred to as **SIMA**.

The crust forms the upper layer of the **lithosphere**, which, along with the upper mantle, is responsible for tectonic activity like earthquakes and plate movements.

Oceanic vs Continental Crust

About **98 per cent of the total crust** of the earth is composed of **eight elements - oxygen, silicon, aluminium, iron, calcium, sodium, potassium and magnesium.**

Oceanic Crust		Continental Crust	
Element	**Percentage by Mass**	**Element**	**Percentage by Mass**
Oxygen (O)	43.00%	Oxygen (O)	46.60%
Silicon (Si)	21.00%	Silicon (Si)	27.70%
Aluminum (Al)	8.00%	Aluminum (Al)	8.10%
Iron (Fe)	7.00%	Iron (Fe)	5.00%
Magnesium (Mg)	7.00%	Calcium (Ca)	3.60%
Calcium (Ca)	11.00%	Sodium (Na)	2.80%
Sodium (Na)	3.50%	Potassium (K)	2.60%
Other Elements	1.50%	Magnesium (Mg)	2.10%
Other elements			1.50%

The **oceanic crust** is denser than the **continental crust** due to its composition and mineral types.

Composition

- Oceanic crust is primarily made up of **mafic minerals** like **olivine** $(Mg, Fe)_2 SiO_4$ and **pyroxene** $(Mg, Fe)SiO_3$, which are rich in **iron (Fe)** and **magnesium (Mg)**.
- Continental crust consists mainly of **felsic rocks** like **granite**, containing lighter minerals such as **quartz** (SiO_2) and **feldspar**, rich in **silicon** and **aluminum**.

Density

- The tightly packed atomic structure of mafic minerals in the oceanic crust contributes to a higher density, averaging around **3.0 g/cm³**.
- In contrast, the less dense, more open structure of felsic minerals in the continental crust leads to an average density of about **2.7 g/cm³**.

Formation

- The oceanic crust forms from **rapid cooling** of magma at mid-ocean ridges, creating **fine-grained, dense** basaltic rocks.
- Continental crust forms over a longer period and can include lighter minerals, resulting in a thicker, less dense structure.

Overall, the greater density of the oceanic crust is due to its higher content of heavy elements and a more compact mineral structure compared to the continental crust.

Mantle

The **mantle** extends from the **Mohorovicic Discontinuity (Moho)** to a depth of 2,900 km. It makes up approximately 84% of Earth's total volume and is composed of **silicate rocks rich in iron and magnesium.**

- **Asthenosphere**
  - The **upper portion** of the mantle (depth of ~100-200 km) is called the **asthenosphere**. This layer is semi-fluid, highly viscous, and acts as the source of magma that rises to form volcanic eruptions. It plays a crucial role in plate tectonics by allowing the lithosphere to "float" and move.
  - The asthenosphere is hotter and more ductile than the rigid lithosphere.
- **Lithosphere**
  - The **lithosphere** includes both the crust and the uppermost part of the mantle. It is rigid and divided into tectonic plates that float on the more fluid asthenosphere below.
  - **Thickness varies:** 10-200 km depending on whether it's beneath oceans or continents.
- **Lower Mantle**
  - Located below the asthenosphere, it extends to a depth of 2,900 km. Although it is under intense pressure, it remains solid due to the extreme conditions.
  - **Repetti Discontinuity** marks the transition between the upper and lower mantle. The lower mantle is more stable and less involved in plate tectonics but contributes to heat transfer to the upper mantle.

Core

The **core** starts at a depth of 2,900 km and is composed **predominantly of iron and nickel**, collectively referred to as the **"NiFe" layer**.

- **Outer Core**
  - **State:** Liquid, due to high temperatures (~4,000–5,000°C), which are sufficient to overcome the pressure at this depth and keep iron and nickel in a molten state.
  - The **outer core** is responsible for generating Earth's magnetic field through the movement of molten iron and nickel (geodynamo effect).
  - **Gutenberg Discontinuity:** The boundary separating the lower mantle from the liquid outer core.
- **Inner Core**
  - **State:** Solid, despite temperatures reaching ~5,000–6,000°C, due to the immense pressure that prevents the core from melting.
  - **Lehmann Discontinuity:** The boundary between the outer liquid core and the solid inner core. The solid inner core may grow over time as the planet cools.

Sources to Study the Interior of the Earth

Direct- Surface rocks, volcanic eruption, Deep ocean drilling project etc.

Indirect- Mining activity, meteors, gravitation, magnetic field, and seismic activity.

ISOSTASY

Isostasy is the concept of **gravitational equilibrium** between the **Earth's crust** and the **mantle.** It suggests that Earth's crust "floats" on the denser, more fluid-like mantle below, much like icebergs floating in water. This balance maintains the relative heights of different parts of the crust, such as continents and ocean basins.

Models of Isostasy

- **Pratt's Model (Variable Density)**
  - Crust blocks have **uniform thickness below sea level** but **varying densities**.
  - Less dense regions (continents) float higher, while denser regions (oceans) sit lower.
  - **Example:** Continental crust is less dense (granite) than oceanic crust (basalt), causing elevation differences.
- **Airy's Model (Variable Thickness)**
  - Crust blocks have **uniform density** but **varying thickness below sea level**.
  - Thicker regions, like mountains, have **deeper roots** extending into the mantle.
  - **Example:** The Himalayas have thick roots to balance their elevation.
- **Vening Meinesz Model (Flexural Isostasy)**
  - Earth's lithosphere behaves like a **flexible plate** rather than individual blocks.
  - The lithosphere bends under large loads (e.g., mountains or ice sheets), causing broader regional compensation.

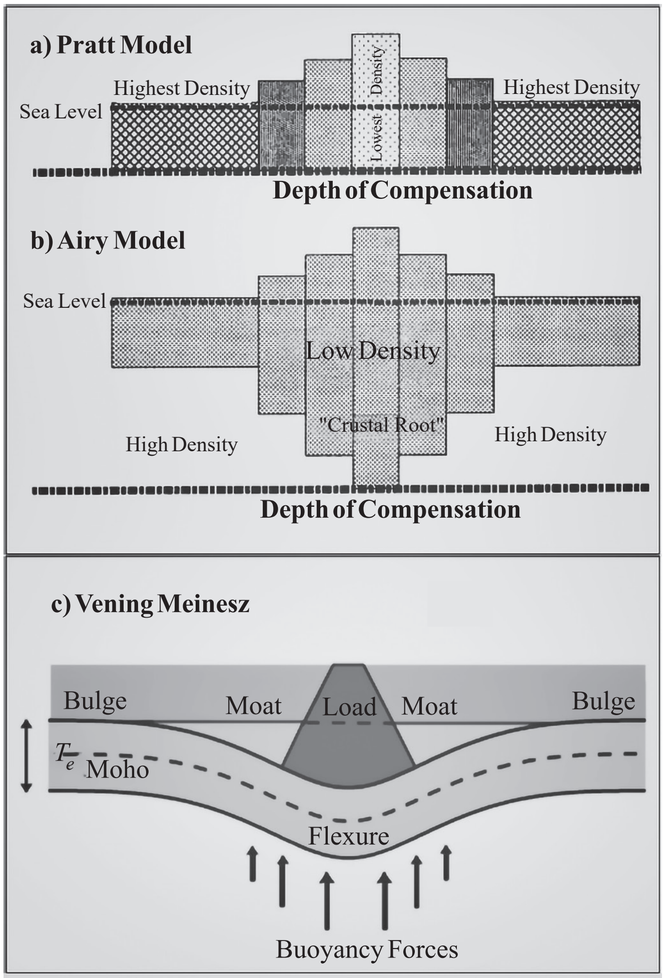


Fig. Isostasy Model

COMPOSITION OF THE EARTH

Element	Percentage by Mass
Iron (Fe)	32.10%
Oxygen (O)	30.10%
Silicon (Si)	15.10%
Magnesium (Mg)	13.90%
Sulfur (S)	2.90%
Nickel (Ni)	1.80%
Calcium (Ca)	1.50%
Aluminum (Al)	1.40%
Other Elements	1.20%

CLASSIFICATION OF MINERALS

Minerals can be broadly classified into two main categories: **silicate** and **non-silicate** minerals.

- **Silicate Minerals:** Silicate minerals are characterised by the presence of silicon and oxygen. They form the majority of the Earth's crust and are essential to many geological processes.
  - **Feldspar**
    - **Composition:** Composed mainly of silicon, aluminium, sodium, potassium, and calcium.
    - **Properties:** Constitutes about 50% of the Earth's crust.
    - **Uses:** Widely used in ceramic and glass production.
  - **Quartz**
    - **Composition:** Consists of silicon dioxide (SiO_2).
    - **Properties:** Important component of sand and granite; hard and resistant to weathering.
    - **Uses:** Essential in glass-making and various industrial applications.
  - **Pyroxene**
    - **Composition:** Contains calcium, aluminium, magnesium, iron, and silica.
    - **Properties:** Commonly found in igneous and metamorphic rocks; often dark in colour.
    - **Uses:** Used as a geological indicator; important in understanding rock formation.
  - **Amphibole**
    - **Composition:** Comprises aluminium, calcium, silica, iron, and magnesium.
    - **Properties:** Dark-colored.
    - **Uses:** Historically used in the asbestos industry, though its use is limited today due to health risks.
  - **Mica**
    - **Composition:** Contains potassium, aluminium, magnesium, iron, and silica.
    - **Properties:** Characterised by perfect cleavage, allowing it to be split into thin sheets.
    - **Uses:** Used in electrical instruments and cosmetics due to its insulating properties.
  - **Olivine**
    - **Composition:** Composed of magnesium, iron, and silica.
    - **Properties:** Typically olive green in colour; high melting point.
    - **Uses:** Valued in the jewellery industry; found in basaltic rocks.
- **Non-Silicate Minerals:** Non-silicate minerals do not contain silicon-oxygen tetrahedra. They can be classified further into metallic and non-metallic minerals.
  - **Metallic Minerals**
    - Contain significant metal content and are essential for various industrial applications.
    - **Precious Metals:** Gold, silver, platinum, etc.
      - **Uses:** High economic value; used in jewellery, electronics, and as investment assets.
    - **Ferrous Metals:** Iron and alloys (e.g., steel).
      - **Uses:** Fundamental in construction and manufacturing.

- **Non-Ferrous Metals:** Includes copper, lead, zinc, tin, aluminium, etc.
  - **Uses:** Copper for wiring, aluminium for lightweight structures, and lead in batteries.
- **Non-Metallic Minerals:**
  - Do not contain metal content and have various applications.
  - **Examples:** Sulphur, phosphates, nitrates.
    - **Uses:** Sulphur in fertilisers, phosphates in agriculture, and cement production (a mixture of non-metallic minerals).

ROCKS

Definition: Rocks are naturally occurring aggregates of one or more minerals or mineraloids. They possess variable physical properties, including texture, hardness, and colour, and do not have a fixed chemical composition. The study of rocks falls under the discipline of **petrology**.

Rocks are primarily classified into three main categories based on their formation processes: **igneous**, **sedimentary**, and **metamorphic**.

Igneous Rocks

Formation: Igneous rocks form from the solidification of molten material known as **magma** (below the surface) or **lava** (on the surface). The cooling rate of this molten rock determines the size of the crystals within the igneous rock:

- **Slow Cooling**: Results in large crystal sizes, characteristic of **intrusive** igneous rocks.
- **Rapid Cooling:** Leads to small or no visible crystals, typical of **extrusive** igneous rocks.

Types of Magma

- **Felsic Magma:** High in silica (SiO_2), typically light in colour; has a composition of approximately 70% SiO_2.
- **Intermediate Magma:** Contains about 55-65% SiO_2; has properties between felsic and mafic.
- **Mafic Magma:** Lower in silica (about 45-55% SiO_2) and rich in iron and magnesium; typically dark in colour.
- **Ultramafic Magma:** Very low in silica (less than 45% SiO_2) and high in magnesium and iron, often containing olivine.

Classification

- **Intrusive Igneous Rocks:** Solidify from magma beneath the Earth's surface. Their large mineral grains indicate slow cooling.
  - **Examples:**
    - **Granite:** A coarse-grained rock rich in quartz (SiO_2) and feldspar, often used in construction.
    - **Gabbro:** A dark, coarse-grained rock, chemically similar to basalt, commonly found in oceanic crust.
    - **Pegmatite:** Contains exceptionally large crystals and may include rare minerals.
- **Extrusive Igneous Rocks:** Form from lava that cools quickly upon reaching the surface.
  - **Examples:**
    - **Basalt:** A fine-grained, dark-coloured rock (approximately 50% SiO_2), which makes up much of the ocean floor.
    - **Andesite:** Intermediate in composition, often found in volcanic arcs (about 60% SiO_2).
      - Volcanic Arc**:** An arc volcano is a volcano that forms part of a chain of volcanoes that runs parallel to a subduction zone. These chains can be hundreds or thousands of miles long
    - **Rhyolite:** A light-coloured, fine-grained rock (over 70% SiO_2), rich in silica.

Features of Igneous Rocks

- **Hardness:** Generally hard and durable due to the crystalline structure.
- **Non-fossiliferous:** Do not contain fossils as they form from molten material.
- **Permeability:** Typically impermeable due to the tight interlocking of mineral grains.
- **Weathering Resistance:** Less affected by chemical weathering compared to sedimentary rocks.

Chemical Composition Classification

- **Acidic Rocks:** High in silica (SiO_2); lighter in colour (e.g., granite).
- **Basic Rocks:** High in iron (Fe) and magnesium (Mg); darker in colour (e.g., basalt).
- **Felsic Rocks:** Rich in feldspar ($KAlSi_3Os$) and quartz; typically light-coloured.
- **Mafic Rocks:** Rich in magnesium (Mg) and iron (Fe); typically dark-coloured.
- **Ultramafic Rocks:** Extremely high in magnesium and iron; e.g., peridotite.

Sedimentary Rocks

Formation: Sedimentary rocks arise from the accumulation, compaction, and cementation of sediments derived from pre-existing rocks, biological activity, or chemical precipitation. This process is known as **lithification.**

Types

- **Mechanically Formed:** Composed of rock fragments and mineral grains.
  - **Examples:** Sandstone (formed from sand), conglomerate (rounded gravel), shale (compressed mud).
- **Organically Formed:** Formed from biological processes or accumulation of organic materials.
  - **Examples:**
    - **Chalk:** Composed of calcareous remains of marine organisms ($CaCO_3$).
    - **Limestone:** Often formed from coral reefs and shells ($CaCO_3$).
    - **Coal:** Formed from the remains of ancient plant material.

- **Chemically Formed:** Result from chemical precipitation of minerals from solution.
  - **Examples:**
    - **Rock Salt:** Formed from evaporated seawater (NaCl).
    - **Chert:** Formed from siliceous organisms or chemical processes (SiO_2).

Features of Sedimentary Rocks

- **Layering:** Characterised by distinct layers (strata), indicating the environment of deposition.
- **Fossils:** Commonly contain fossils, providing insights into past life and environments.
- **Permeability:** Often porous and permeable, allowing fluid movement, which is crucial in groundwater and hydrocarbon reservoirs.

Metamorphic Rocks

Formation: Metamorphic rocks form from the alteration of existing rocks (igneous, sedimentary, or other metamorphic rocks) through **metamorphism**, a process involving heat, pressure, and chemically active fluids, leading to recrystallization and mineralogical changes.

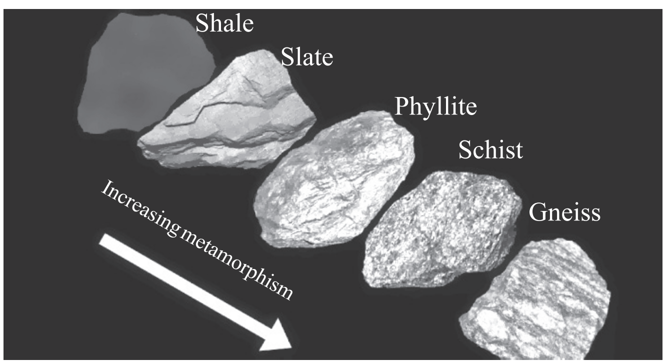


Fig. Metamorphism

Types

- **Foliated Metamorphic Rocks**: Have a layered or banded appearance due to directional pressure.
  - **Examples**:
    - **Gneiss**: Exhibits bands of light and dark minerals.
    - **Schist**: Contains larger, visible minerals (e.g., micas).
    - **Slate**: A fine-grained rock derived from shale, characterised by its ability to split into thin layers.
- **Non-Foliated Metamorphic Rocks**: Lack a layered appearance and are usually uniform in texture.
  - **Examples**:
    - **Marble**: Formed from limestone; primarily composed of calcite ($CaCO_3$).
    - **Quartzite**: Formed from sandstone; primarily composed of quartz (SiO_2).

Features of Metamorphic Rocks

- **Texture**: Can be very smooth due to recrystallization.
- **Colour Variability**: Wide range of colours depending on mineral composition.
- **Fossil Absence**: Rarely contain fossils due to high temperature and pressure conditions.

Metamorphic Processes

- **Dynamic Metamorphism**: Results from mechanical forces and shear stress without significant chemical changes.
- **Thermal Metamorphism**: Alteration due to increased temperature, often near igneous intrusions.
- **Contact Metamorphism**: Occurs when rocks are heated by nearby molten magma, causing localised changes.
- **Regional Metamorphism**: Involves large-scale changes due to tectonic forces, often resulting in mountain-building processes.

Table: Rock Transformation

Original Rock	Metamorphic Rock
Granite (Igneous)	Gneiss
Basalt (Igneous)	Hornblende
Limestone (Sedimentary)	Marble
Coal (Sedimentary)	Graphite
Sandstone (Sedimentary)	Quartzite
Shale (Sedimentary)	Slate

THE ROCK CYCLE

The **rock cycle** is a continuous process describing the transformation of rocks through various geological processes, including igneous, sedimentary, and metamorphic phases:

- **Weathering and Erosion**: Existing rocks are broken down into sediments.
- **Sedimentation:** Sediments accumulate and undergo lithification to form sedimentary rocks.
- **Metamorphism**: Sedimentary or igneous rocks are subjected to heat and pressure, leading to metamorphic rocks.
- **Melting**: Metamorphic or igneous rocks can melt to form magma.
- **Cooling and Solidification**: Magma cools to form new igneous rocks.

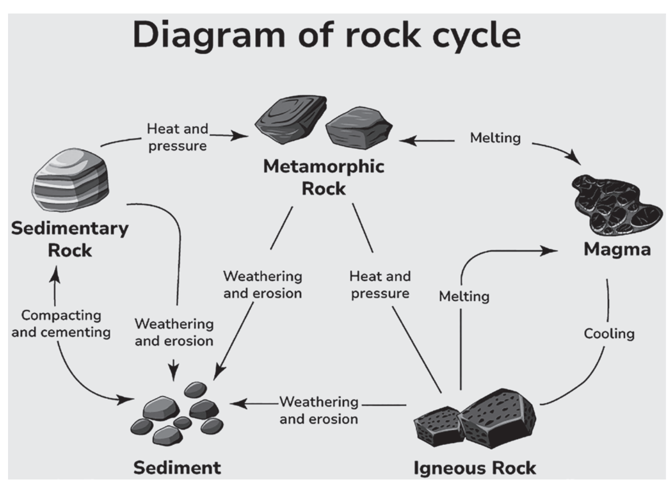


Fig. Rock Cycle

CONTINENTAL DRIFT THEORY

In 1912, German meteorologist **Alfred Wegener** proposed the **continental drift theory**, which suggested that continents were once part of a single supercontinent known as **Pangaea**, surrounded by a vast ocean called **Panthalassa**. Wegener's hypothesis revolved around several key points:

- **Supercontinent Cycle**: Pangaea existed around 200 million years ago and began to split into two major landmasses: **Laurasia** in the north and **Gondwanaland** in the south.
- **Continental Movement**: Over millions of years, these landmasses further fragmented into the continents we recognize today.

Forces Driving Continental Drift

Wegener proposed several forces that influenced continental movement:

- **Pole-Fleeing Force**: Caused by the Earth's rotation, leading to a centrifugal effect that pushes continents outward from the poles.
- **Tidal Force**: The gravitational influence of the Moon and the Sun creates tidal forces that can subtly shift the position of landmasses.

Impact on Biological Evolution

The separation of landmasses significantly influenced the evolution and distribution of organisms. For example, fossil evidence shows similar species across continents now separated by oceans, suggesting a common ancestry before their separation **[UPSC-2014]**.

This idea is crucial in understanding biogeography and the distribution of species.

Evidence Supporting Continental Drift

The Matching of Continents

One of the most compelling pieces of evidence for continental drift is the **jigsaw fit** of coastlines, particularly between Africa and South America. The alignment of these coastlines suggests that they were once joined.

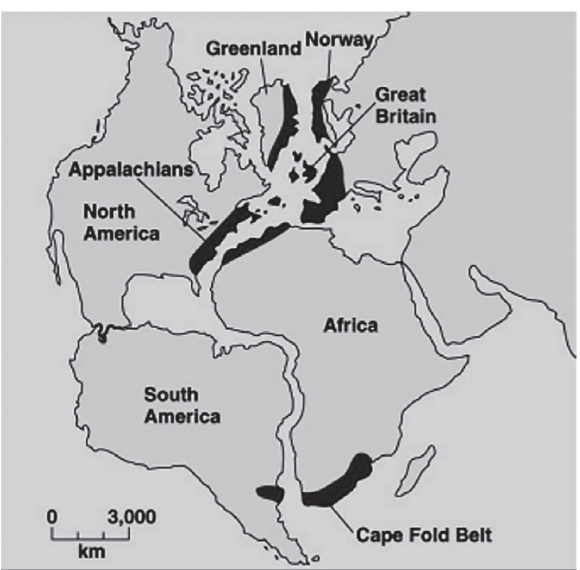


Fig. Matching of Continent

Geological Similarities

- **Rocks of the Same Age**: A notable example includes a 2,000-million-year-old rock formation in Brazil that shares geological characteristics with formations in western Africa, indicating they were once part of the same landmass.
  - **Tillite**: Sedimentary rocks formed from glacial deposits (tillites) found in Gondwanaland suggest that these continents were connected. Indian tillites have counterparts in Africa, Madagascar, and Antarctica, reflecting shared geological histories.

Fossil Distribution

Fossils of specific species, such as lemurs, are found across present-day India, Madagascar, and Africa, despite these regions now being separated by vast oceans. This fossil distribution supports the idea that these continents were once connected.

Placer Deposits

The existence of placer deposits, such as gold along the Ghanaian coast, despite the absence of nearby gold source rocks, indicates a shared geological history with regions like the Brazilian plateau, where similar gold-bearing veins are found.

POST-DRIFT THEORIES AND MECHANISMS

Convection Current Theory

In the 1930s, **Arthur Holmes** proposed that **convection currents** within the Earth's mantle drive the movement of tectonic plates. These currents arise from thermal differences caused by the radioactive decay of elements in the mantle. The mechanism can be described as follows:

- **Heat Generation**: Radioactive isotopes, such as uranium and thorium, decay within the mantle, generating heat.
- **Mantle Convection**: The heated material becomes less dense and rises toward the surface, cools, and then sinks back down, creating a cyclical flow pattern.

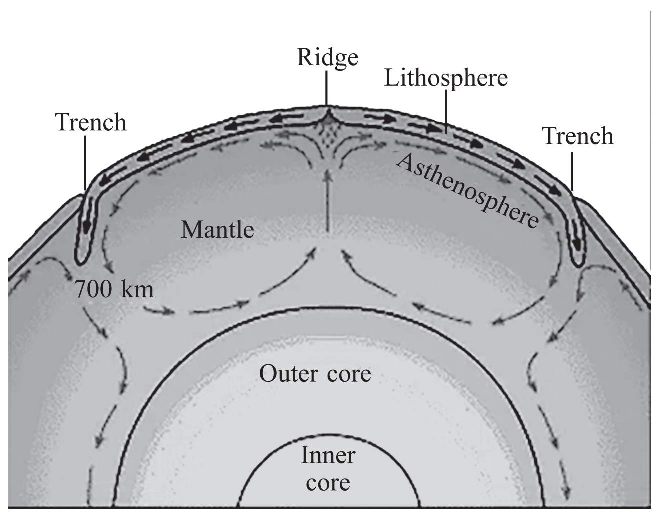


Fig. Convectional Current Theory

Seafloor Spreading

Seafloor spreading is the process where new oceanic crust forms at mid-ocean ridges and is destroyed at deep-sea trenches. First proposed by **Harry Hess** in the 1960s, it explains how ocean basins expand and contract through tectonic activity.

Hess's Seafloor Spreading Hypothesis

- **New Crust Formation**: Volcanic eruptions at mid-ocean ridges cause fractures in the crust. Magma rises and forms new basaltic crust, gradually pushing older crust away from the ridge.
- **Expansion of the Ocean Floor**: As new crust forms, the ocean floor expands. This motion acts like a conveyor belt, moving older crust outward.
- **Destruction of Oceanic Crust**: Old oceanic crust subducts into the mantle at deep-sea trenches, balancing the formation of new crust at ridges. This recycling of oceanic crust prevents the Earth's surface from expanding.

Heat Source and Driving Mechanism

The heat driving seafloor spreading comes from radioactive decay within the Earth's interior. This heat generates convection currents in the mantle, causing the movement of tectonic plates. Rising hot material at mid-ocean ridges and sinking cooler material at subduction zones create a cycle of crust formation and destruction.

Key Observations Supporting Seafloor Spreading

- **Volcanic Activity**: Continuous eruptions along mid-ocean ridges create new crust as magma rises, cools, and solidifies into basaltic rock.
- **Age of Oceanic Rocks**: Rocks nearest to mid-ocean ridges are younger, with older rocks found farther away. This pattern, along with the symmetrical magnetic polarity, supports seafloor spreading. Magnetic reversals are recorded in these rocks as they cool, aligning with the Earth's magnetic field at the time.
- **Thin Oceanic Sediments**: The ocean floor has relatively thin sediment layers, indicating that the oceanic crust is continuously replenished and relatively young.
- **Seismic Activity**: Shallow earthquakes occur along mid-ocean ridges, while deeper ones are recorded near deep-sea trenches, where old crust subducts back into the mantle.

Key Geologic Features associated with Sea Floor Spreading

- **Mid-Ocean Ridges**: Underwater mountain ranges formed at divergent boundaries where seafloor spreading occurs, such as the Mid-Atlatntic Ridge.
- **Deep-Sea Trenches**: Formed at convergent boundaries where the oceanic crust subducts, like the Mariana Trench.
- **Magnetic Striping**: Symmetrical patterns of magnetic stripes on the ocean floor record Earth's magnetic field reversals, providing strong evidence for seafloor spreading.

PLATE TECTONICS: THEORY AND DYNAMICS

Tectonic plates are large, rigid slabs of solid rock that make up Earth's lithosphere, which includes both continental and oceanic crust. These plates float on the semi-fluid **asthenosphere** beneath them.

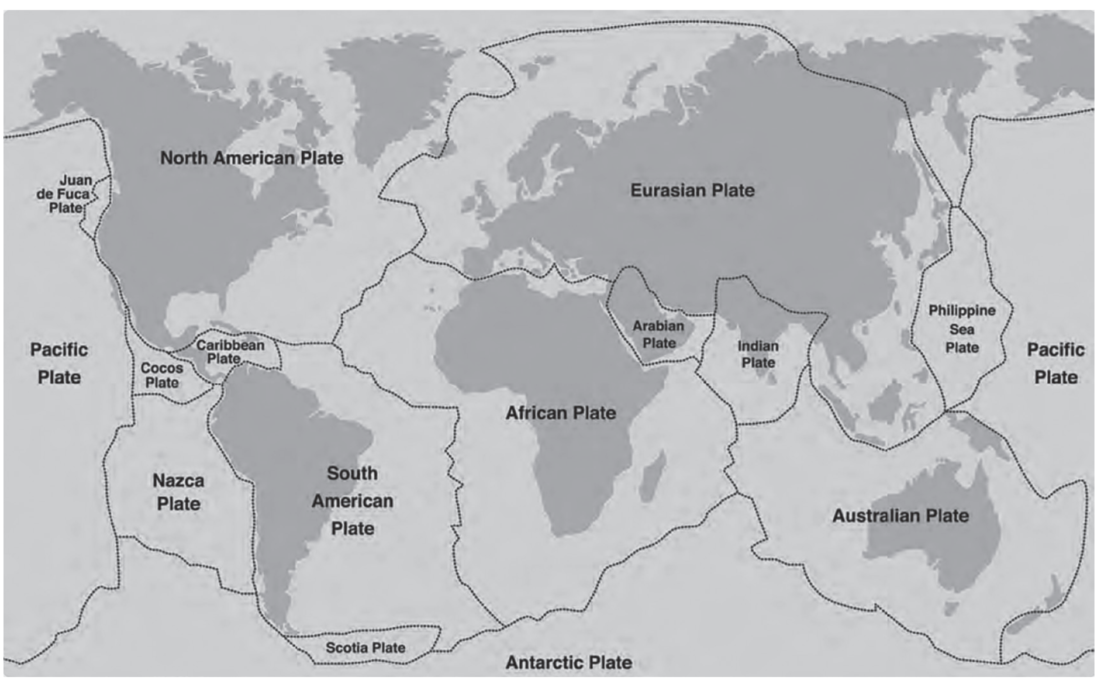


Fig. Major and Minor Plates

Major and Minor Plates

- **Major Plates**: Include the **North American Plate**, **South American Plate**, **Eurasian Plate**, **African Plate**, **Pacific Plate**, **Indian-Australian Plate**, and the **Antarctic Plate**.
- **Minor Plates**: Include the **Cocos Plate**, **Nazca Plate**, **Arabian Plate**, **Philippine Plate, etc.**

Mechanisms of Plate Movement

The movement of tectonic plates is primarily driven by convection currents in the mantle, resulting from:

- **Heat Generation**: Radioactive decay within the Earth generates heat that causes mantle material to rise.
- **Slab Pull and Ridge Push**: As plates move apart at divergent boundaries, new material rises to create oceanic crust, resulting in a push (ridge push) at mid-ocean ridges. Conversely, the weight of a subducting plate pulls the rest of the plate down (slab pull).

Types of Plate Boundaries

1. **Divergent Boundaries**: Plates move apart, creating new crust. A prime example is the **Mid-Atlantic Ridge**, where the North American and Eurasian plates drift apart.
2. **Convergent Boundaries**: Plates collide, leading to various geological outcomes depending on the types of plates involved:
   - **Oceanic-Oceanic Convergence**: Forms island arcs (e.g., the **Aleutian Islands**).
   - **Ocean-Continental Convergence**: The denser oceanic plate subducts, leading to mountain formation (e.g., the **Andes**).
   - **Continental-Continental Convergence**: Both plates are buoyant, resulting in the formation of fold mountains (e.g., the **Himalayas**).
3. **Transform Boundaries**: Plates slide past each other horizontally without creating or destroying crust. The **San Andreas Fault** in California exemplifies this boundary.

Movement of the Indian Plate

- **Ancient Position**: About 225 million years ago, India was situated as an island off the Australian coast, separated by the **Tethys Sea**.
- **Northward Movement**: Approximately 200 million years ago, India began its journey northward, eventually colliding with Asia about 40-50 million years ago, leading to the rapid uplift of the Himalayas.

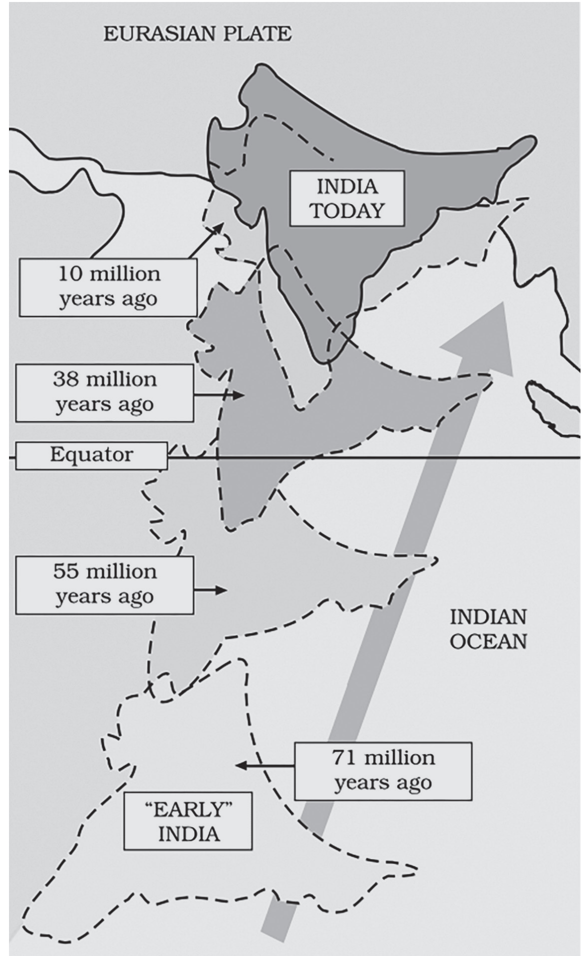


Fig. Movement of the Indian Plate

Major Plate Boundaries of the Indian Plate

- **Northern Boundary**: Convergent boundary with the **Eurasian Plate**, leading to the formation of the **Himalayas**.
- **Western Boundary**: Convergent boundary with the **Arabian Plate**.
- **Eastern Boundary**: Convergent boundary with the **Burmese Plate**, resulting in the **Arakan Yoma**.
- **Southern Boundary**: Divergent boundary with the **Australian Plate**, contributing to the creation of the **Indian Ocean Ridge**.

Significant Geological Events

- **Deccan Traps Formation**: Approximately 60 million years ago, extensive volcanic activity resulted in the formation of the **Deccan Traps**, a large volcanic province in India.
- **Continued Northward Movement**: The ongoing collision between the Indian and Eurasian plates causes frequent seismic activity in the region, contributing to a high risk of earthquakes.

MAGMA, LAVA AND VOLCANISM

Magma is classified based on its **silica (SiO_2) content**, which determines its **viscosity** (resistance to flow), **eruption style**, and the type of rocks it forms. Volcanic eruption contains Pyroclastic debris, Ash and dust, Nitrogen compounds and Sulphur compounds. **[UPSC-2024]**

- **Felsic Magma**
  - **Silica Content**: High (>65%).
  - **Viscosity**: High, thick, and slow-flowing.
  - **Temperature**: Low (600-850°C).
  - **Gases**: High gas content (water vapor, CO_2), causing explosive eruptions.
  - **Rocks Formed**: **Granite** (intrusive), **Rhyolite** (extrusive).
  - **Example**: **Yellowstone Caldera**.
- **Intermediate Magma**
  - **Silica Content**: Moderate (55-65%).
  - **Viscosity**: Intermediate.
  - **Temperature**: 800-1000°C.
  - **Gases**: Moderate gas content.
  - **Rocks Formed**: **Andesite** (extrusive), **Diorite** (intrusive).
  - **Example**: **Mount St. Helens**.
- **Mafic Magma**
  - **Silica Content**: Low (45-55%).
  - **Viscosity**: Low, runny.
  - **Temperature**: High (950-1200°C).
  - **Gases**: Low gas content.
  - **Rocks Formed**: **Basalt** (extrusive), **Gabbro** (intrusive).
  - **Example**: **Hawaiian volcanoes**.
- **Ultramafic Magma**
  - **Silica Content**: Very low (<45%).
  - **Viscosity**: Very low, extremely fluid.
  - **Temperature**: Very high (>1200°C).
  - **Rocks Formed**: **Peridotite**, common in the mantle.

Viscosity and Eruption Style

- **Silica content** affects viscosity. High silica content in felsic magma forms strong Si-O bonds, making it viscous and prone to explosive eruptions due to trapped gases.
- **Low silica** mafic magma flows easily, leading to more fluid lava flows and less explosive eruptions.

Magma Generation and the Role of Depth

- **Decompression Melting:** Occurs at **divergent boundaries** where pressure decreases as plates move apart, allowing mantle rock to melt.
- **Hydration Melting:** At **subduction zones**, water from the subducting slab lowers the melting point of the overlying mantle, generating magma.
- **Heat Transfer Melting:** Rising plumes of hot material (mantle plumes) transfer heat to the lithosphere, generating magma (e.g., **Hawaiian hotspot**).

Types of Volcanoes and their Lava

- **Shield Volcanoes**
  - **Lava Type**: Mafic (basaltic), low viscosity.
  - **Shape**: Broad, gently sloping dome-like structure due to the free-flowing, less viscous lava.
  - **Eruption Style**:
    - Effusive eruptions where lava flows smoothly and spreads over great distances.
    - Non-explosive, slow lava movement.
  - **Notable Features**:
    - Formed by successive layers of basaltic lava.
    - Can be several kilometers wide and relatively low in height compared to other types.
  - **Examples**:
    - **Mauna Loa** (Hawaii, USA): Largest active volcano in the world.
    - **Kilauea** (Hawaii, USA): One of the most active volcanoes.
    - **Skjaldbreiður** (Iceland): Example of a shield volcano in the North Atlantic.
- **Composite Volcanoes (Stratovolcanoes)**
  - **Lava Type**: Intermediate to felsic, viscous lava rich in silica (andesitic, dacitic, or rhyolitic).
  - **Shape**: Steep, conical profile due to alternating layers of solidified lava, volcanic ash, and tephra.
  - **Eruption Style**:
    - Explosive eruptions due to high gas content and high viscosity of magma.
    - Can produce pyroclastic flows, ash clouds, and lava domes.
  - **Notable Features**:
    - Tall, symmetrical volcanic cones.
    - Highly destructive eruptions with potential for large-scale pyroclastic flows.
  - **Examples**:
    - **Mount Fuji** (Japan): Iconic stratovolcano with periodic explosive eruptions.
    - **Mount St. Helens** (USA): Erupted violently in 1980, reshaping the landscape.
    - **Mount Vesuvius** (Italy): Famous for the AD 79 eruption that destroyed Pompeii.
    - **Mount Etna** (Italy): One of the most active stratovolcanoes in Europe.
- **Cinder Cone Volcanoes**
  - **Lava Type**: Typically basaltic, but can vary.
  - **Shape**: Small, steep-sided cones formed from volcanic debris (cinders) ejected during eruptions.
  - **Eruption Style**:
    - Explosive eruptions that eject lava fragments, ash, and cinders.
    - Lava rarely flows, mostly ejecta forms around the vent.

- **Notable Features**:
  - Usually short-lived eruptions and smaller in size compared to other types.
  - Often found on the flanks of larger volcanoes.
- **Examples**:
  - **Parícutin** (Mexico): Emerged suddenly from a cornfield in 1943.
  - **Sunset Crater** (USA): A prominent cinder cone in Arizona.
  - **Lava Butte** (Oregon, USA): An example of a cinder cone in the Cascade Range.

- **Lava Domes**
  - **Lava Type**: Felsic, highly viscous (rich in silica).
  - **Shape**: Dome-shaped, mound-like structures due to slow extrusion of lava.
  - **Eruption Style**:
    - Slow, effusive eruptions where viscous lava piles up near the vent.
    - Eruptions can be followed by dome collapse, leading to pyroclastic flows.
  - **Notable Features**:
    - Tend to grow over time with repeated lava extrusion.
    - Commonly associated with stratovolcanoes.
  - **Examples**:
    - **Novarupta** (Alaska, USA): Site of one of the largest volcanic eruptions of the 20th century.
    - **Mount St. Helens Lava Dome** (USA): Repeated lava dome growth following the 1980 eruption.
    - **Puy de Dôme** (France): A famous lava dome in the Auvergne region.

- **Calderas**
  - **Formation**: Formed when a large volcanic eruption causes the collapse of a magma chamber, leaving a large depression (caldera).
  - **Lava Type:** Can vary but often felsic or intermediate

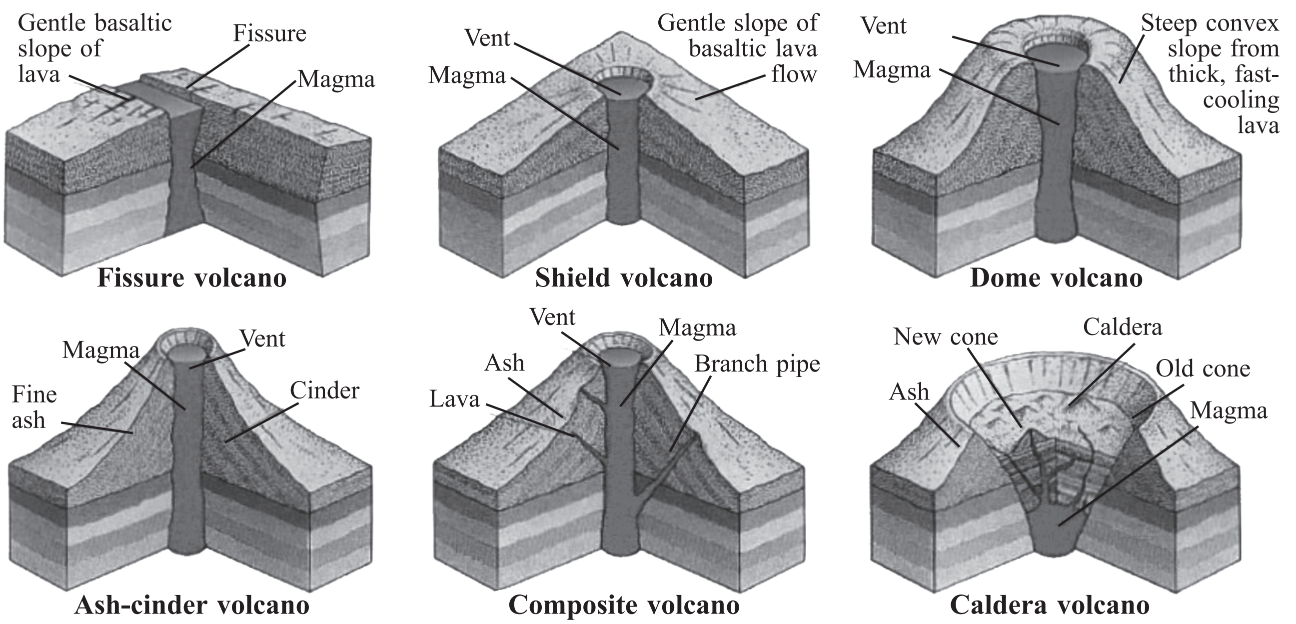


Fig. Types of Volcano

  - **Shape**: Large, circular depressions that can be tens of kilometers across.
  - **Eruption Style**:
    - Extremely explosive eruptions known as "supervolcanic" eruptions.
    - Often followed by collapse of the central volcanic structure.
  - **Notable Features**:
    - Can later form lakes within the caldera or host renewed volcanic activity.
  - **Examples**:
    - **Yellowstone Caldera** (USA): Site of massive past eruptions, located over a mantle plume.
    - **Krakatoa** (Indonesia): Famous for its 1883 eruption, the caldera collapse generated massive tsunamis.
    - **Santorini** (Greece): A caldera in the Aegean Sea associated with the Minoan eruption.

- **Flood Basalt Provinces**
  - **Lava Type**: Highly fluid basaltic lava with low viscosity.
  - **Shape**: Vast, flat regions of basaltic lava that cover large areas.
  - **Eruption Style**:
    - Effusive eruptions of enormous lava flows that cover large land areas.
    - Typically associated with mantle plumes or hotspots.
  - **Notable Features**:
    - Can cause global climate changes due to the massive release of gases.
    - Can flow for hundreds of kilometers before solidifying.
  - **Examples**:
    - **Deccan Traps** (India): One of the largest volcanic features on Earth, formed 66 million years ago.
    - **Siberian Traps** (Russia): Thought to be associated with the Permian-Triassic extinction event.
    - **Columbia River Basalt Group** (USA): Large igneous province in the Pacific Northwest.

7. **Mid-Ocean Ridge Volcanoes**
  - **Lava Type**: Mafic (basaltic).
  - **Shape**: Long, linear underwater volcanic ridges.
  - **Eruption Style**:
    - Effusive, submarine eruptions of basaltic lava.
    - Volcanic activity is continuous but often unnoticed as it occurs deep under the sea.
  - **Notable Features**:
    - Forms new oceanic crust through the process of seafloor spreading.
    - Mid-ocean ridges are key sites for tectonic plate divergence.
  - **Examples**:
    - **Mid-Atlantic Ridge** (Atlantic Ocean): A major site of seafloor spreading between the American and Eurasian/ African plates.
    - **East Pacific Rise** (Pacific Ocean): One of the fastest spreading mid-ocean ridges.
    - **Reykjanes Ridge** (North Atlantic Ocean): Part of the Mid-Atlantic Ridge near Iceland.

Types of Volcano Based on Periodicity of Eruption

- **Active Volcanoes:** Frequent eruptions, often around the Ring of Fire.
  - **Examples:** Mount Stromboli - Lighthouse of Mediterranean (Italy), Mount St. Helens (US), Mount Vesuvius (Italy).
- **Dormant Volcanoes:** Inactive but can erupt in future.
  - **Example:** Mount Kilimanjaro (Tanzania).
- **Extinct Volcanoes:** Inactive since the distant past; In most cases, the crater of the Volcano is filled with water forming a lake.

DISTRIBUTION OF VOLCANOES

The distribution of volcanoes matches that of seismic activity in many places. A volcanic activity zone occurs along the **divergent** and **convergent** boundaries. E.g.- Mid-oceanic ridges (Divergent), Pacific rim/ Rim of fire (Convergent).

- The **Ring of Fire** is a long chain of volcanoes and other tectonically active structures that surround the Pacific Ocean. Many of these volcanoes were created through the tectonic process of subduction.
- In general, foci of the earthquakes 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.
- **Ring of fire** runs up along the western coast of South and North America, runs down the eastern coast of Asia past New Zealand and into the northern coast of Antarctica
- Hot Spots- Found away from plate boundaries where mantle plumes rise to the surface.
- **Examples-**
  - Hawaiian Islands, Yellowstone Caldera,
  - Reunion Island in the Indian Ocean.

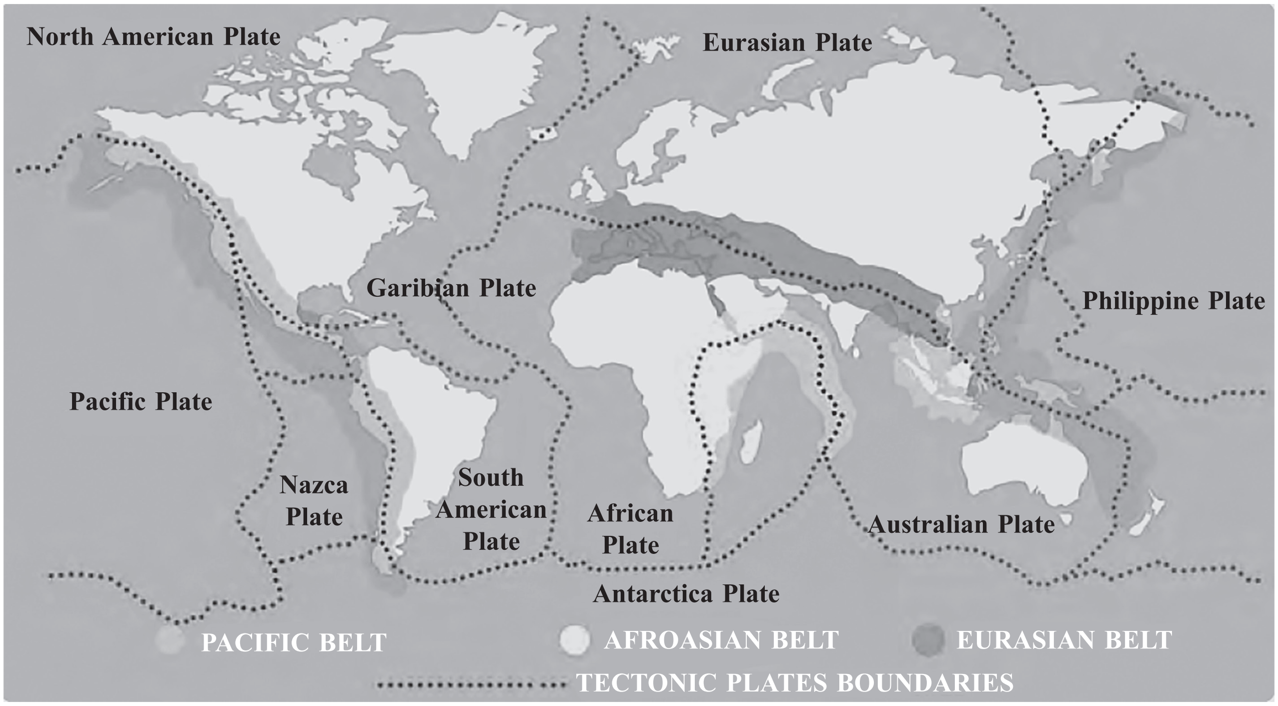


Fig. Distribution of Volcanoes

Volcanic Landforms

Intrusive Landforms

- Depending on the location of the cooling of the lava, igneous rocks are classified as **volcanic rocks (cooling at the surface**) and **plutonic rocks (cooling within the crust).**
- The lava that cools within the crustal portions assumes different forms called intrusive forms.

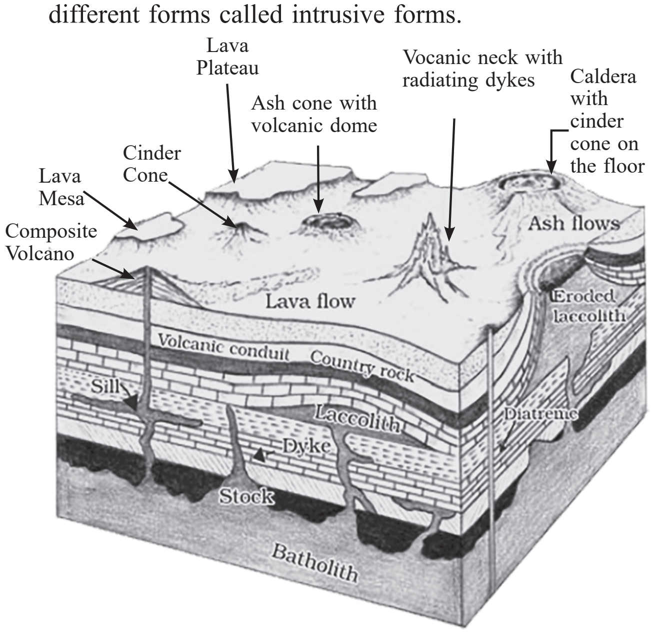


Fig. Volcanic Landforms

- **Batholiths: Magmatic material cools deep** within the crust to form **large domes** known as batholiths (**granite bodies)**, i.e., they are the cooled remnants of magma chambers.
- **Lacoliths:** Lacoliths are **underground formations** resembling **dome shapes,** characterised by a **flat underside** and **connected through a conduit,** similar to surface volcanic domes but positioned at greater depths; Found in the **Karnataka** plateau.
- **Lapoliths:** Lava moving horizontally in weak planes can form **saucer-shaped bodies** called **Lapoliths.**
- **Phacolith**: **Wavy masses** of intrusive rocks at the base of synclines or top of anticlines, connected to magma chambers.
- **Sills & Sheets:** Horizontal intrusive igneous rocks are classified as **sills (thicker deposits)** or **sheets (thinner layers).**
- **Dykes: Lava solidified** almost **perpendicular to the ground** like a wall; Found in abundance in the **western Maharashtra** area.

SEAFLOOR SPREADING, MANTLE PLUMES, AND HOTSPOT VOLCANISM

- **Seafloor Spreading:** Occurs at **mid-ocean ridges** where tectonic plates diverge. Magma rises from the mantle, creating new oceanic crust and pushing the older crust away. Magnetic anomalies and the age of seafloor rocks provide evidence for this process.
- **Mantle Plumes and Hotspots:** Mantle plumes are columns of hot, buoyant rock rising from deep within the Earth. These plumes create volcanic activity **away from plate boundaries** (e.g., **Hawaiian Islands**). As the tectonic plate moves over the stationary plume, a chain of volcanic islands forms.

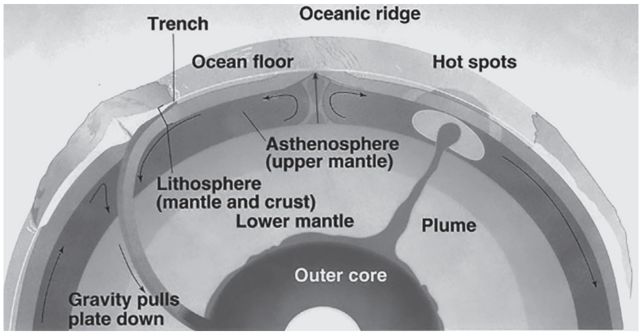


Fig. Mantle plume

- **Hotspot:** Hotspots are volcanic regions formed by plumes of hot mantle material rising to the Earth's surface, independent of tectonic plate boundaries. These stationary plumes create chains of volcanoes as plates move over them. **Examples** include the **Hawaiian, Yellowstone, Icelandic, Galápagos, Réunion, and Easter Island hotspots.**
- **Asthenosphere and Mantle Dynamics:** The **asthenosphere**, located beneath the lithosphere, is partially molten and allows for the movement of tectonic plates. The **D" layer**, situated near the core-mantle boundary, plays a critical role in heat transfer. **Mantle plumes** arise from this layer, leading to hotspot volcanism (e.g., **Hawaiian Islands**).

EARTHQUAKES

An earthquake is the shaking of the earth triggered by the release of energy which creates waves radiating in all directions. All natural earthquakes arise within the lithosphere, i.e., up to a depth of 200 km from the earth's surface.

> **Focus/Hypocentre**: Point inside the earth where the earthquake originates.
>
> **Epicentre**: Point on the earth's surface directly above the focus. It's the point that feels the earthquake waves first.

Seismic Waves and Earthquakes

- **Body Waves**

  These waves travel through the Earth's interior and are generated from the earthquake's focus. Body waves are further divided into two types:

  - **Primary Waves (P-waves):**
    - **Motion:** Longitudinal, where particles vibrate parallel to the direction of wave propagation.
    - **Speed:** Fastest seismic wave.
    - **Medium:** Can travel through solids, liquids, and gases.
    - **Shadow Zone:** Between 105° and 145° from the epicenter, due to refraction in the outer core.
    - The first to be recorded on a seismograph.

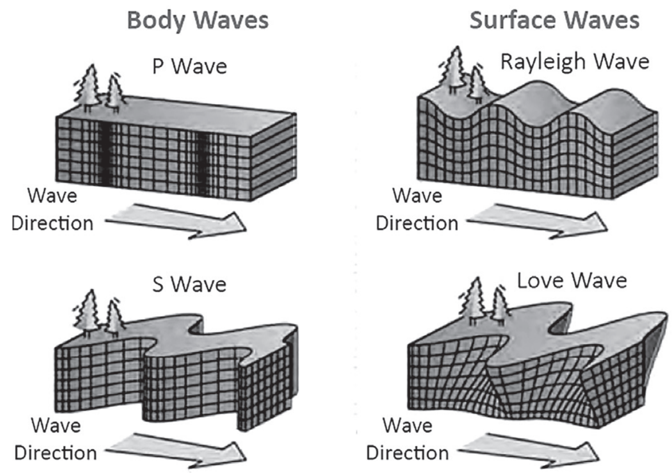


Fig. Type of Seismic Waves

  - **Secondary Waves (S-waves):**
    - **Motion:** Transverse, where particles vibrate perpendicular to the direction of wave propagation.
    - **Speed:** Slower than P-waves.
    - **Medium:** Can only travel through solids (cannot pass through liquids or gases).
    - **Shadow Zone:** Beyond 105° from the epicenter.
    - **Key Feature:** Responsible for much of the ground shaking felt during an earthquake.

- **Surface Waves**

  These waves travel along the Earth's surface and are generally more destructive than body waves. They are the last waves to be recorded on a seismograph.

  - **Love Waves (L-waves):**
    - **Motion:** Transverse, move horizontally (side-to-side).
    - **Speed:** Faster than Rayleigh waves, slower than S-waves.
    - **Medium:** Can travel through solids.
    - **Damage:** Responsible for the most lateral ground movement, causing significant building damage.
  - **Rayleigh Waves (R-waves):**
    - **Motion:** Both transverse and longitudinal, creating rolling movements.
    - **Speed:** Slower than Love waves.
    - **Medium:** Can travel through both solids and liquids.
    - **Damage:** Cause a rolling sensation on the surface, contributing to the heaving and shaking of the

- **Speed of Seismic Waves**

  Seismic waves have different speeds depending on their type, with body waves moving faster than surface waves. The general trend in speed is:

  - **P-Waves** > **S-Waves** > **Love Waves** > **Rayleigh Waves**

Shadow Zones

A **seismic shadow zone** is an area on the Earth's surface where seismographs cannot detect direct P-waves or S-waves from an earthquake. This occurs because P-waves are refracted when they pass through the Earth's liquid outer core, and S-waves cannot travel through the outer core at all.

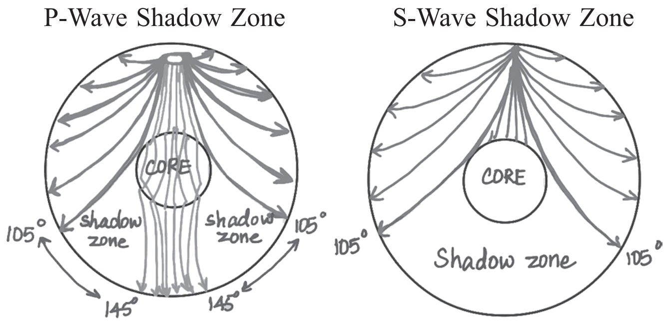


Fig. P-Wave and S-Wave Shadow Zone

- **P-Wave Shadow Zone:** Between 105° and 145° from the earthquake's epicenter.
- **S-Wave Shadow Zone:** S-waves create a much larger shadow zone, beyond 105°, because they cannot travel through the liquid outer core, which results in no direct S-wave detection over a significant portion of the Earth's surface.

Causes of Earthquakes

Earthquakes are geological events caused by the sudden release of energy in the Earth's crust, resulting in seismic waves. They can be classified into natural and anthropogenic (human-induced) causes.

- **Tectonic Activity**

  Most earthquakes result from tectonic processes associated with the movement of the Earth's lithospheric plates. Key factors include:
  - **Plate Boundaries:** Earthquakes occur at the interfaces of tectonic plates:
    - **Divergent Boundaries:** Plates move apart, causing tension (e.g., Mid-Atlantic Ridge).
    - **Convergent Boundaries:** Plates collide, leading to powerful earthquakes in subduction zones (e.g., Himalayas due to the Indian and Eurasian Plate collision).
    - **Transform Boundaries**: Plates slide past each other, generating shear stress
      - E.g. San Andreas Fault.
      - **Turkey** is located at the convergence of the Eurasian, Arabian, and African Plates. The **North Anatolian Fault, a major strike-slip transform fault**, allows lateral movement between the Eurasian and Anatolian Plates, leading to significant seismic activity. For e.g.- The 2023 Turkey-Syria Earthquake
  - **Faults:** Movement along faults can be:
    - **Normal Faults:** Extensional forces pull the crust apart.
    - **Reverse (Thrust) Faults:** Compressional forces push one block over another.
    - **Strike-Slip Faults:** Horizontal movement occurs at transform boundaries.
- **Volcanic Activity**

  Volcanic earthquakes arise from magma movement towards the surface, fracturing surrounding rocks. These earthquakes can occur before, during, or after volcanic eruptions.
- **Collapse Earthquakes**

  Minor earthquakes result from the sudden collapse of underground cavities, often linked to mining or natural cave formations.
- **Anthropogenic Activities**

  Human activities can induce seismic events, known as induced earthquakes, including:
  - **Reservoir-Induced Seismicity**: Filling large reservoirs can increase pressure on faults, as seen in Koyna Dam, India.
  - **Mining and Quarrying**: Extraction alters stress distribution in the crust.
  - **Geothermal and Hydrocarbon Extraction**: Fluid injection during processes like fracking can induce seismicity.
- **Other Factors**
  - **Isostatic Rebound:** Adjustments of the Earth's crust after the melting of ice sheets can generate earthquakes.
  - **Landslides:** Movement of large volumes of rock can produce seismic waves.

Shallow and Deep Earthquakes

Earthquakes are classified by depth, which influences their intensity and impact.

- **Shallow Earthquakes**
  - **Depth:** <70 km.
  - **Characteristics:** More destructive due to proximity to the surface, with strong shaking.
  - **Tectonic Setting:** Found along mid-ocean ridges, transform faults, and rift zones.
  - **Examples:**
    - **San Andreas Fault** (California) – transform faulting.
    - **Mid-Atlantic Ridge** – plate divergence.
- **Deep Earthquakes**
  - **Depth:** >300 km (up to 700 km).
  - **Characteristics:** Less surface damage as energy dissipates. Occur in subduction zones.
  - **Tectonic Setting:** Subduction zones, associated with **Benioff zones**. Also in Alpine Himalayan

- **Examples:**
  - **Tonga-Kermadec Trench** – deep subduction.
  - **Japan Trench** – subduction of the Pacific Plate.
- **Intermediate Earthquakes**
  - **Depth:** 70–300 km.
  - **Characteristics:** Found in subduction zones, less common but still damaging.
- **Continent-Continent Collision Earthquakes**

  Characteristics:
  - **Depth:** Generally classified as shallow, occurring at depths of less than 70 km.
  - **Mechanism:** The collision causes intense folding and faulting of the crust, leading to the buildup of strain until it's released as an earthquake.
  - **Seismic Activity:** Characterized by high magnitude and can be very destructive due to their shallow depth and proximity to populated areas.
  - **Tectonic Settings for Earthquake**
- **Major Examples**
  - **Himalayan Region:** The collision between the Indian Plate and the Eurasian Plate has led to frequent and powerful earthquakes, including the 2015 Gorkha earthquake in Nepal.
  - **Alps Mountain Range:** The collision between the African Plate and the Eurasian Plate contributes to seismic activity in the region, resulting in occasional earthquakes.

Scales for Measuring Earthquakes

- **Richter Scale:**

  Measures the magnitude (energy released) of an earthquake on logarithmic scale, with each whole number increase representing a tenfold increase in amplitude.

  a. The formula for calculating the magnitude of an earthquake on the Richter scale is

$$M = \log_{10}(A/A_0),$$

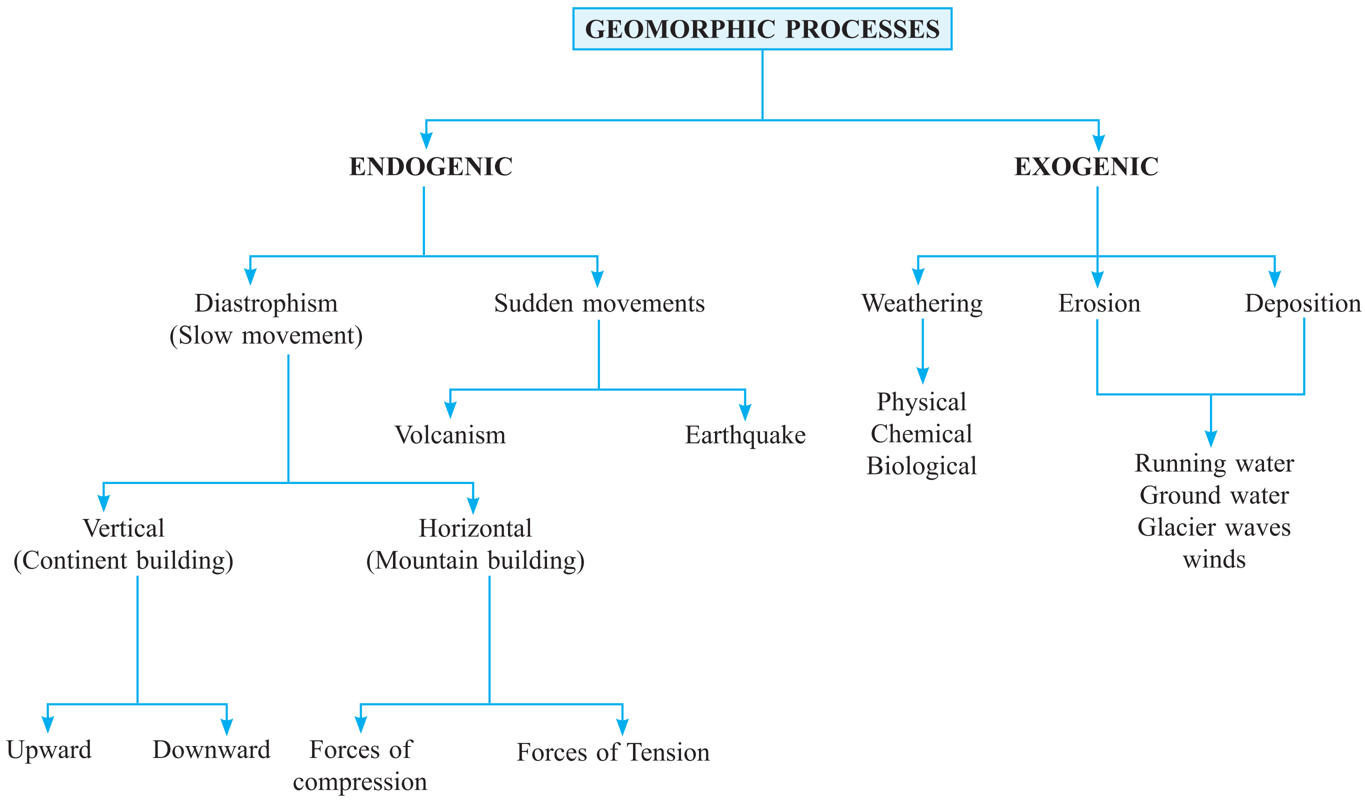
- **Moment Magnitude Scale (Mw):**

  Modern scale, similar to the Richter but more accurate for large earthquakes as it accounts for fault slip and the area of the rupture.
- **Modified Mercalli Intensity Scale:**

  Measures the intensity (effects on people and buildings) of an earthquake, ranging from I (not felt) to XII (total destruction).

3 Geomorphic Processes and Landforms

GEOMORPHIC PROCESSES



- The endogenic and exogenic forces causing physical stresses (such as pressure and temperature changes) and chemical actions (such as oxidation and carbonation) on earth materials and bringing about changes in the configuration of the surface of the earth are known as **geomorphic processes.**
- **Weathering, mass wasting, erosion and deposition** are exogenic geomorphic processes.
- **Running water, groundwater, glaciers, wind, waves and currents** are **geomorphic agents.**

ENDOGENIC FORCES (LAND BUILDING FORCES)

Endogenic forces **occur due to** the **energy emanating from within the earth's surface.** They are of two types:

Diastrophism

It includes processes causing **slow movement, elevation or building up portions of the Earth's crust**.

It can cause different types of movements, including **warping** (bending of the Earth's crust), **folding** (bending of rock layers), **faulting** (breaking and displacement of rock layers), and **uplifting** or **subsiding** of the Earth's crust. They include:

- **Orogenic Process (Mountain Building)**
  - It involves **mountain building** through severe **folding** and affects long and narrow belts of the Earth's crust.
  - Orogenic forces operate in a **horizontal manner (tangential forces)**. It is called **tensional force** when it operates in opposite directions and creates ruptures, fractures, cracks and faults in the crustal parts; also called **divergent force**. When forces operate towards each other face to face, they are called **compressional forces or convergent forces**.

- **Epeirogenic Process (Continent Building)**
  - Involves **upliftment (emergence)** and **subsidence (submergence)** of large parts of the earth's crust (continental masses) through **vertical** upward and downward movements. It is a **continental building process.**

Sudden Endogenic Processes

Sudden endogenic processes include earthquakes, volcanism, and landslides, originating from rapid energy release in the Earth's crust.

EXOGENIC FORCES (LAND WEARING FORCES)

- These are external forces that originate at or near the Earth's surface, are influenced by solar energy and tectonic gradient, and **draw energy** from the **atmosphere**.
- Exogenic forces, mostly slow and gradual, include denudational/destructional processes such as weathering, erosion, and mass wasting. However, events like flash floods and cyclones are rapid exogenic processes.
- **Actions** of **exogenic forces result** in **wearing down (degradation**) of relief/elevations and **filling up (aggradation)** of basins.
- Phenomenon of wearing down of relief variations through erosion is known as gradation. All the exogenic geomorphic processes are covered under a general term, **denudation** (weathering, mass wasting/movements, erosion and transportation).
- **Rock type and structure** significantly affect the intensity of exogenic processes.
- **Climatic factors:** Temperature, precipitation, insolation, wind patterns, etc. affect exogenic processes.

Factors responsible for bringing dynamic changes on the surface of the earth [UPSC-2013]

Electromagnetic radiation; Geothermal energy; Gravitational force; Plate movements; Rotation of the earth; Revolution of the earth.

WEATHERING

- Weathering is defined as the **mechanical disintegration** and **chemical decomposition** of rocks through the actions of various elements of weather and climate. It is an **In-Situ** or **Onsite** process.
- **Factors Influencing Weathering:** Geology, weather and climate, topography, and vegetative factors.

Weathering processes are classified into the following categories:

Chemical Weathering Processes

It includes **solution, carbonation, hydration, oxidation** and **reduction**. Water, air and heat are vital for accelerating chemical reactions.

- **Solution:** Dissolution in **water or acid**. Minerals like **calcium carbonate** and **calcium magnesium bicarbonate** present in **limestone** are soluble in water containing carbonic acid.
- **Carbonation:** Process of **atmospheric carbon dioxide** causing **solution weathering;** common process helping in breaking down of **feldspar** and **carbonate** minerals. Rainfall, containing dissolved carbon dioxide, forms carbonic acid. This acid reacts with carbonate minerals in rocks, leading to their dissolution. **[UPSC-2024]**
- **Hydration:** Minerals **take up water** and expand which **increases the volume** of the material (Calcium sulphate + water = Gypsum). Continued repetition leads to **physical weathering** through exfoliation and granular disintegration.
- **Oxidation and Reduction:** In **oxidation,** rock breakdown occurs due to the disturbance caused by **addition of oxygen**. When oxidized minerals are placed in an environment where **oxygen is absent** (eg: below water table/ waterlogged areas) **reduction** takes place.

Physical or Mechanical Weathering Processes

Physical or mechanical weathering refers to a process that relies on applied forces. Most of the processes are caused by thermal expansion and pressure release. These forces could be **gravitational forces, expansion forces**, and **water pressures.**

- **Unloading and expansion:** In areas of **curved ground surface**, **arched fractures** tend to **produce** massive sheets or **exfoliation slabs** of rock. Large smooth rounded domes called exfoliation domes are a result of this process.
- **Temperature changes and expansion:** Most **effective** in **dry climates** and **high elevations** where **diurnal temperature changes** are **drastic.**
- **Freezing, Thawing and Frost Wedging:** Most **effective** at **high elevations** in **mid-latitudes** where freezing and melting are often repeated.
  - **Freezing** involves the transformation of water into ice.
  - **Thawing** is the process of melting ice back into water, and
  - **Frost Wedging** is the mechanical breakup of rocks caused by repeated freezing and thawing cycles.

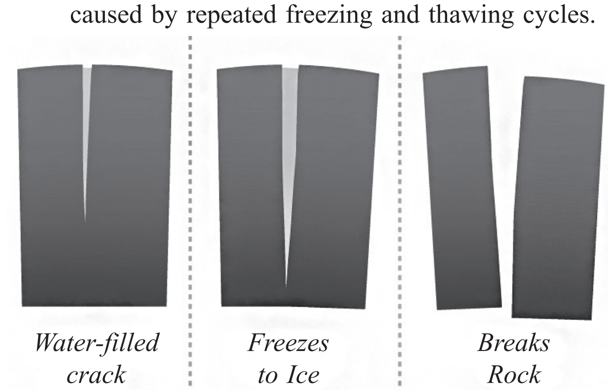
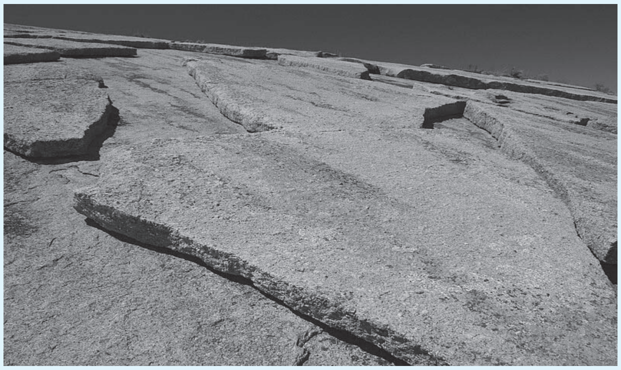


Fig. Frost Wedging

- **Salt weathering: Salts** in rocks **expand** due to **thermal action**, **hydration** and **crystallisation**. Salt crystallisation is the most effective of all salt weathering processes.

- **Exfoliation** occurs when curved sheets of material peel away from rocks due to temperature-induced expansion and contraction.



- **Exfoliation domes** are large and smooth rounded domes formed due to unloading and expansion of rocks.
- **Exfoliation tor** are smooth surfaced and rounded small to big size boulders, formed due to temperature changes and expansion in rocks.

Biological Weathering

It involves **organisms** and includes:

- **Organism Growth:** It involves burrowing and wedging activities by creatures like earthworms, termites, and rodents that expose fresh surfaces.
- **Organic Matter Decay:** Decomposing plant and animal matter generates humic, carbonic, and other acids, promoting the decay and solubility of certain elements.
- **Root pressure:** Mechanically breaking apart earth materials.

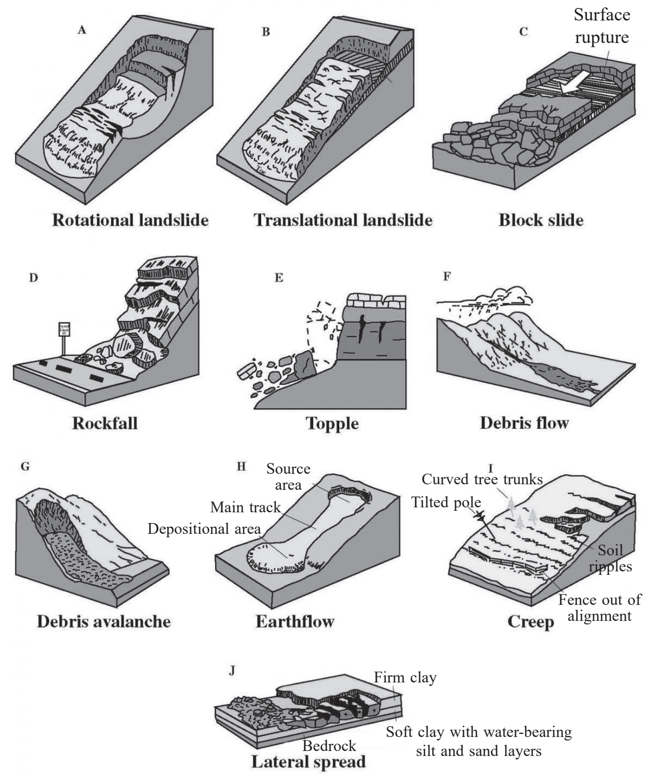
EROSION AND DEPOSITION

Erosion involves the acquisition and transportation of rock debris by various geomorphic agents (running water, groundwater, glaciers, wind and waves). Abrasion by rock debris carried by these geomorphic agents also aids greatly in erosion.

- Though **weathering aids erosion,** it is **not a precondition** for erosion to take place. **Weathering, mass-wasting and erosion** are **degradational processes.**
- **Deposition** is a consequence of erosion; it occurs in the reverse order of particle size, with coarser materials depositing first.
- **Agents of Deposition:** running water, glaciers, wind, waves, and groundwater.

MASS MOVEMENTS

Mass movements involve the transfer of rock debris down the slope under the **direct influence** of **gravity**. **Factors favouring mass movements: weak materials, steep slopes, rainfall,** and **lack of vegetation.**



- Mass movements occur in forms like flow (e.g., mudflows), slide (e.g., rockslides), and creep (e.g., solifluction). Mass movements can be **slow (creep, heave)** or **rapid (flow, slide)**, categorized by their speed.

Slow Movements

It occurs on **moderately steep, soil-covered slopes**; involves extremely **gradual** and imperceptible material displacement.

- **Creep can occur on moderately steep slopes; movement of material is extremely slow;** material involved can be **soil or rock debris.**
- **Solifluction:** It is another form of creep that consists of **slow downslope flow** of **saturated soil** or **fine-grained rock debris**; occurs in **moist temperate areas** due to surface melting of frozen ground and prolonged rainfall.

Rapid Movements

Most prevalent in **humid climatic regions** and occur over **gentle to steep slopes.**

- **Earthflow** is the movement of **water-saturated clayey or silty materials** down **low-angle terraces** or hillsides.
- **Mudflows** occur when **heavy rainfall saturates thick layers** of weathered materials, **flowing slowly or rapidly** down the channels **like a stream of mud.**
- **Debris avalanches** are **fast-moving** mass movements that occur in narrow tracks on steep slopes, resembling snow avalanches and can be **much faster than mudflows.**

Types of Rapid Mass Movements

Types of Mass Wasting	Material Involved	Speed	Characteristics
Earthflow	Clay, silt	Slow	Occurs on low-angle terraces or hillsides
Mudflow	Mud (water-saturated weathered materials)	Rapid	Flows down channels like a stream of mud
Debris Avalanche	Loose rocks, soil, and other debris	Very rapid	Occurs on steep slopes, resembles snow avalanches

Landslide

Landslide refers to rapid and perceptible movements; the materials involved are relatively dry. **Depending upon the type of movement of materials,** there are several types:

- **Slump** is the **slipping** of **one or several units of rock debris** with a **backward rotation** with respect to the slope over which the movement takes place.
- **Debris slide is rapid rolling or sliding** of earth debris **without backward rotation** of mass.
- **Rockslide is the sliding of individual rock masses** down bedding, joint or fault surfaces.
- **Rockfall is the free fall** of **rock blocks** over steep slopes while maintaining some distance from the slope's surface.

- **Himalayas** are mostly made up of **sedimentary rocks** and **unconsolidated and semi-consolidated** deposits; **slopes** are **steep.** Thus, landslides are quite frequent.
- **Nilgiris** are relatively **tectonically stable** and are mostly made up of very hard rocks; mechanical weathering due to temperature changes is pronounced. They receive heavy amounts of rainfall over short periods. So, it is a landslide prone zone.

LANDFORMS AND THEIR EVOLUTION

Small to medium tracts or parcels of the earth's surface are called **landforms** and **several landforms together** are called **landscape. Geomorphology** is the **science of landforms.** Various geomorphic agents form different types of erosional and depositional landforms.

RUNNING WATER (FLUVIAL LANDFORMS)

It is an important geomorphic agent in **humid regions with heavy rainfall.** It has **2 components: (*a*) Overland Flow or Sheet** and **(*b*) Linear Flow** as streams and rivers in valleys.

Landforms formed due to running water develop in **3 stages:** Youth, Mature and Old.

- **Features of Youth Stage:** V-shaped valleys, gorges due to vertical erosion; river capture with headward erosion; Waterfalls, Rapids and Interlocking spurs.
- **Features of Mature Stage:** Valley widening due to lateral erosion; flood plains; Meanders, Incised Meanders, Terraces, Point bars, River cliffs and Slip off slopes.
- **Features of Old Stage:** Extensive flood plains; Meanders and Oxbow lakes; Braided streams, Levees, Point bars, cliffs and Deltas

Over time, stream erosion can create plains called **Peneplain,** in which some **sturdy rock remnants**, known as **Monadnocks** can be seen.

Erosional Landforms Formed by Running Water

- **Valleys**
  - Its evolution starts from narrow **rills** to long, wide **gullies** and eventually to **valleys**. Various types of valleys, such as **V-shaped valleys**, **Gorges, and Canyons,** may form depending on rock type and structure.
  - **Gorges** have **steep sides** and are **equal in width at top and bottom** and they are formed in hard rocks.
  - **Canyons** exhibit steep, **step-like slopes** and tend to be **wider at the top than at the bottom; formed** in **horizontal bedded sedimentary rocks;** found in dry areas. E.g. **Grand Canyon**

Fig. Canyon

Table: Canyons and Gorges of India

Canyon/Gorge	River	State	Nearest City/Town	Nickname or Special Feature
Gandikota Canyon	Pennar	Andhra Pradesh	Kadapa (or Jammalamadugu)	"Grand Canyon of India"
Bhedaghat Marble Rocks	Narmada	Madhya Pradesh	Jabalpur	Known for stunning marble cliffs and Dhuandhar Waterfalls
Satanur Gorge	Pennar	Andhra Pradesh	Kadapa	Noted for its steep rock walls
Chambal Ravines	Chambal	Madhya Pradesh, Rajasthan, Uttar Pradesh	Kota, Gwalior, Dholpur	Rugged terrain, historically linked to bandits
Papi Hills	Godavari	Andhra Pradesh, Telangana	Rajahmundry	Scenic gorge, part of Papikonda National Park
Mekedatu Gorge	Kaveri	Karnataka	Kanakapura, Bengaluru	"Goat's Leap," where the river flows through a narrow gorge
Idukki Gorge	Periyar	Kerala	Idukki	Known for Idukki Dam and natural beauty
Stok Gorge	Indus	Ladakh	Leh	High-altitude gorge with trekking trails
Lohit Gorge	Lohit	Arunachal Pradesh	Tezu	Rugged and pristine terrain in northeastern Himalayas
Araku Valley Gorges	Varaha	Andhra Pradesh	Araku Valley	Picturesque valleys with waterfalls and tribal heritage

- **Potholes and Plunge Pools**
  - **Potholes** are **circular depressions** formed on rocky streambeds due to erosion and the abrasion of rock fragments. Pebbles and boulders get collected in these holes and rotated and make depression wider and deeper.
  - Plunge pools form at the base of waterfalls due to the force of the water on soft rocks.

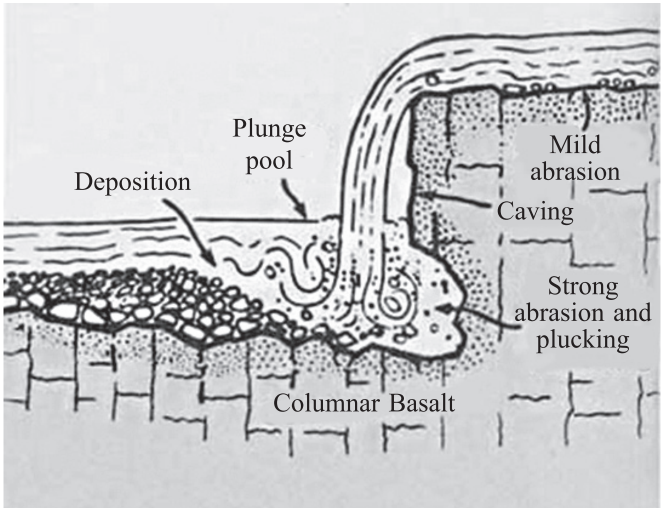


Fig. Potholes and Plunge Pools

- **Incised Meanders**
  - **Types of Rocks:** Incised meanders typically form in harder, more resistant rocks like sandstone, limestone, or granite. These rocks resist erosion, causing rivers to cut deeply, creating entrenched meanders, canyons, and gorges.
  - **Mechanism:** They develop in areas where a river initially meanders over a gently sloping plain. A combination of tectonic uplift and a change in base level causes the river to erode vertically, deepening and entrenching its meanders into the underlying rock layers.
  - **Factors**
    - **Tectonic uplift:** Uplift of the land increases the river's erosive power.
    - **Base level drop:** A decrease in sea level or lake level, forcing the river to cut deeper.
    - **Rock resistance:** Harder rocks resist lateral erosion, promoting vertical cutting.

Fig. Incised Meanders

- **River terraces**

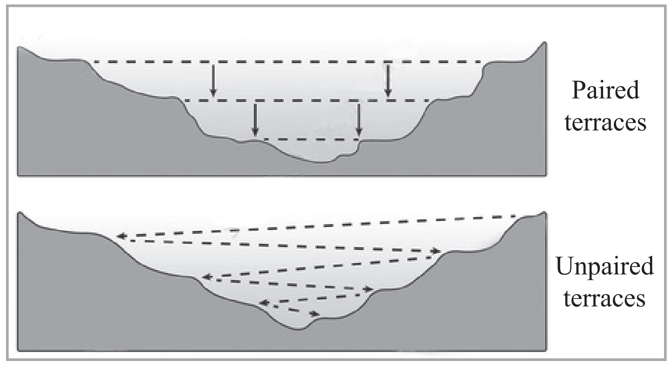


Fig. River Terrace

  - River terraces are surfaces marking **old valley floor** or **floodplain levels**. They **result** from **vertical erosion** by the stream into its own depositional plain.
  - Terraces are the **result of receding water after a peak flow**, **change in hydrological regime** due to climatic changes, **tectonic uplift** of the land, and **sea level changes** in the case of rivers closer to the sea.
  - **Paired Terraces:** Occur at the same elevation on either side of the rivers.
  - **Unpaired Terraces:** Terraces present at one side only or present at different elevations. **They** are **typical in areas of slow uplift of land** or where the **water column changes are not uniform along both banks.**

- **River Valleys**

Stage	Valley Shape	Channel Pattern	Other Features
Youth	V-shaped	Straight, with rapids and waterfalls	Steep slopes, narrow valleys
Mature	U-shaped	Meandering, with wider channel	Floodplains, oxbow lakes
Old	Wide, shallow valley	Meandering, with many oxbow lakes	Floodplains, deltas

- **Rapids**
  - Fast-flowing, turbulent water with abrupt elevation changes; typically found in steep or mountainous river sections.

Depositional Landforms Formed by Running Water

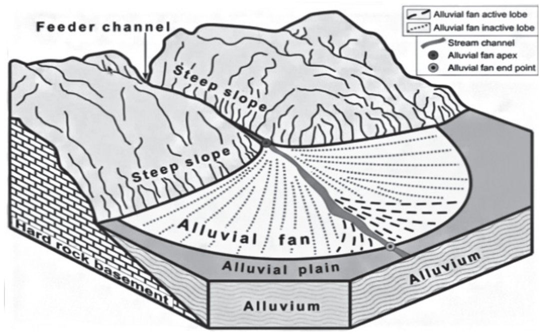


Fig. Alluvial Fans or we can also name it as Delineation of Alluvial Fans, and this should come after explaining Alluvial fans.

- **Alluvial Fans**
  - Created by mountain streams carrying **heavy coarse sediment** when they **reach low-gradient foot slope plains**, leading to the **deposition** of a cone shaped alluvial fan;
  - Streams which flow over the fan usually shift their position across the fan forming many channels called distributaries.
  - Alluvial fans in **humid regions** have **gentle slopes**, while **arid regions** exhibit **steep, high cones.**
- **Deltas**
  - It is a **triangular depositional feature** at river **mouths** entering lakes or seas.
  - Occur at the meeting point of rivers and the sea due to the **accumulation of river sediments.**
  - Unlike in alluvial fans, the **deposits** making up the deltas are **very well sorted with clear stratification.** This is due to slow speed and high sediment load which results in sorting and segregation of sediments according to size.
  - **Ideal conditions** for formation: Shallow sea/lake shores, long river courses, medium-sized sediments, sheltered sea conditions, ample sediment supply, accelerated catchment area erosion, and stable coastal/oceanic conditions.
- **Floodplains**
  - Deposition that occurs as river channels transition to gentler slopes. Floodplains comprise an **active floodplain (river bed made of river deposits)** and an **inactive floodplain** (floodplain above the bank). **Inactive floodplains** basically contain **two types of deposits** — **flood deposits and channel deposits**. Floodplains within deltas are referred to as **delta plains**.
- **Natural Levees and Point Bars:** They are found in floodplains.

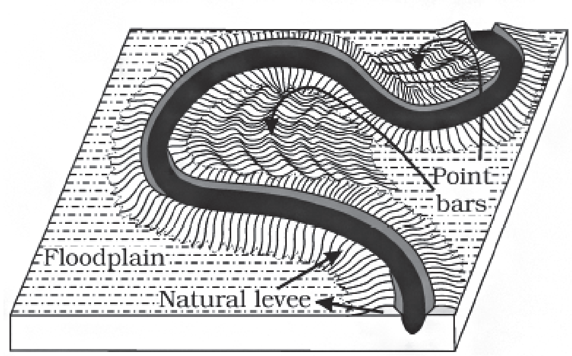


Fig. Natural Levee and Point Bars

  - **Natural Levees:** are found along the banks of large rivers. They are **low, linear and parallel ridges of coarse deposits** along the **banks of rivers**, quite often cut into individual mounds. These are steep near the banks and slope gently away from the river.
  - **Point Bars (Meander Bars**) are **linear sediments deposited** by flowing water on the **convex side** of meanders in large rivers; **cut-off bank** is the concave bank of a meander and **slip-off** is the convex side.
- **Meanders**
  - Not a landform, just a type of channel pattern; Meanders are **loop-like channel patterns** found on large floodplains and delta plains as water works laterally on banks.
  - Deposition is along concave bank, normally undercutting takes place at convex bank as speed of water is greater on the outer side of the meander.
  - They are formed due to **low channel gradients, unconsolidated alluvial deposits**, and the **impact of coriolis force on water flow.**
  - Meanders that are cut off can further evolve into **oxbow lakes.**

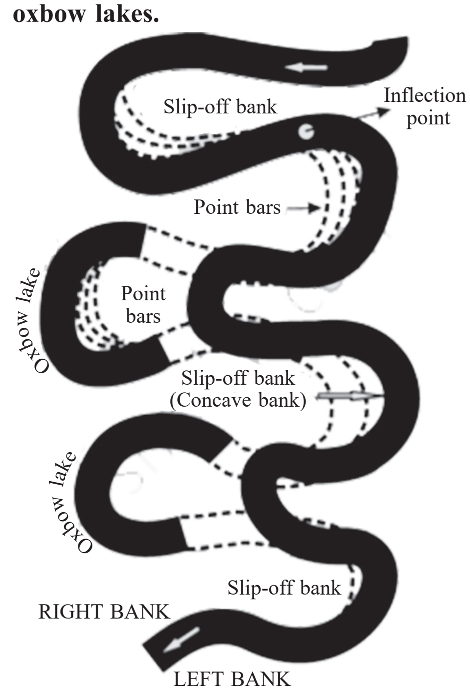


Fig. Meander and Oxbow Lake

- **Oxbow Lakes**
  - Crescent-shaped water bodies created by abandoned meanders. Deposition at the loop neck, isolating it from the main channel.
- **Braided Channels**
  - When **discharge is less and sediment load is more** in the valley, **channel bars and islands of sand, gravel and pebbles develop** on the floor of the channel and the **water flow is divided into multiple threads**.
  - These thread-like streams rejoin and subdivide repeatedly to form a braided pattern. **Deposition and lateral erosion of banks** are essential for their formation.

Fig. Braided Channels

GROUNDWATER

Groundwater plays a significant role in eroding landmasses and shaping landforms, especially in regions with **calcium carbonate-rich** rocks like **limestone** and **dolomite.**

- Key groundwater processes involve **solution** and **deposition**. **Groundwater activity** forms a **distinctive landform in limestone regions** known as **Karst topography**.

Erosional Landforms Formed by Groundwater

The process involves rainwater mixed with atmospheric carbon dioxide (CO_2), acting as a solvent agent that disintegrates and dissolves carbonate rocks both on the surface and below.

- The rate of dissolution is influenced by groundwater temperature, the presence of joints in rocks, and the contact time of the solvent with carbonate rocks.

Features

- Karst landscapes are characterised by rugged terrains with features like solution holes, ravines, gullies, clefts, narrow valleys, caves, stalagmites, and stalactites.
- **Swallow Holes:** Small to medium sized round to sub-rounded **shallow depressions** formed **on the surface** of limestones **through solution.**
- **Sinkholes: Depressions** that are **circular at the top** and **funnel shaped at the bottom.** Formed in 2 ways:
  - **Solution Sinks** are formed solely through the solution process, where limestone dissolves over time, creating depressions.
  - **Collapse Sinks or dolines,** occur when the **roof** of an underground void or **cave collapses**, leaving a noticeable depression or hole on the surface.
- **Valley Sinks or Uvalas:** When **sinkholes** and **dolines** merge due to slumping of materials or collapse of cave roofs, they form long, narrow to wide trenches known as **valley sinks** or **uvalas.**
- **Lapies** or **ridges:** These are **irregular limestone surfaces** characterised by a maze of **points**, **grooves, and ridges**. They develop due to differential solution activity along parallel or subparallel joints in the limestone.
- **Caves or caverns:** Caves form in areas with **alternating rock layers** (like limestone sandwiched between other rock types). Some caves even have openings at both ends, earning them the name **"tunnels."**
- **Ponors:** Vertical pipe-like chasms or passages connecting caves and swallow holes formed through the downward extension of sinkholes via the continuous solution of carbonate rocks.
- **Natural Bridges:** Natural bridges in limestone regions form primarily due to the collapse of cave roofs or erosion by surface streams that later turn into subterranean streams.

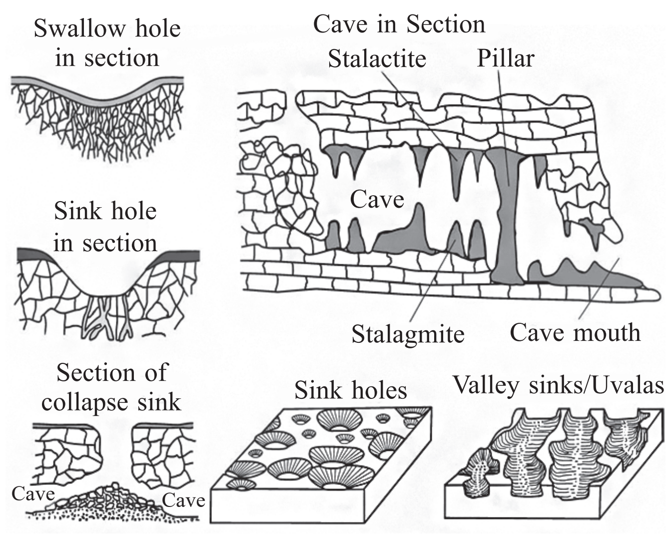


Fig. Various Karst Topography Features

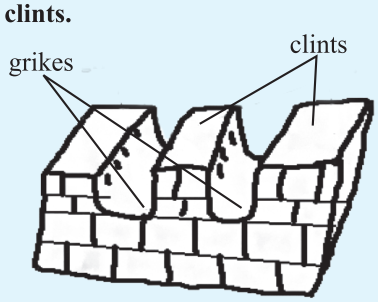
Depositional Landforms Formed by Groundwater

Deposition happens when there's an obstruction in the groundwater's flow path, water evaporates due to temperature changes, or there's reduced solution capacity.

- **Stalactites:** They **hang from the cave ceiling**; broad at their base, and taper towards the free-hanging ends.

- **Stalagmites:** These formations **rise from the cave floor**, typically originating from dripping water from the cave ceiling.
- **Pillar:** Form when **Stalactites and stalagmites fuse** together.
- **Dripstones:** Calcite deposits formed from dripping water in dry caves.
- **Drapes or Curtains:** Needle-shaped dripstones that hang from the cave ceiling.
- **Helictites and Heligmites:** Dripstones growing sideways from stalactites and stalagmites, respectively, with globular helictites called **'globulites.'**
- **Flowstones:** Deposits on the cave floor formed by seepage water and water flowing out of stalagmites.

Limestones are well jointed and it is through these joints and cracks that rain-water finds its way into the underlying rock. Progressive widening by solution enlarges these cracks into trenches and a most intriguing feature called limestone pavement is developed. The **enlarged joints** are called **grikes** and the **isolated, rectangular blocks** are termed **clints.**



The landforms of chalk are rather different from those of other limestones. There is little or no surface drainage and valleys which once contained rivers are now dry. These are often called **coombes**

GLACIERS

- Glaciers are masses of ice that move over the land in various forms, covering approximately 10% of the Earth's surface. **E.g. Continental glaciers** cover vast plains at the foot of mountains, while **piedmont glaciers** spread over plains.

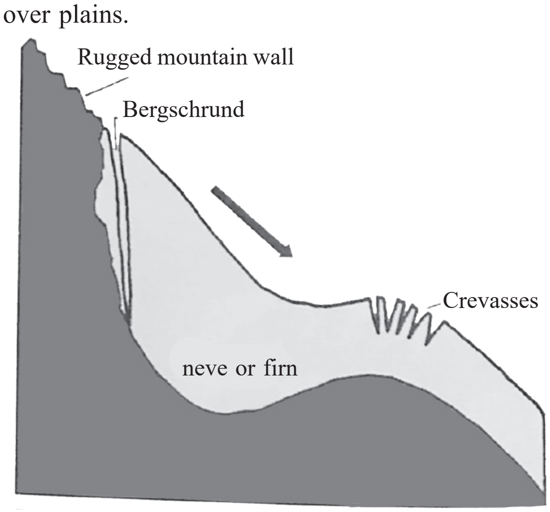


Fig. Glacial Erosion

Glacial Erosional Landforms

- A glacier erodes its valley by two processes: **plucking and abrasion.**
  - **Plucking:** Glacier **freezes the joints** and beds of the underlying rock, **tears out individual blocks** and **drags** them away.
  - **Abrasion:** Glacier **scratches, scrapes, polishes** and scours the **valley floor** with the help of debris frozen into it.

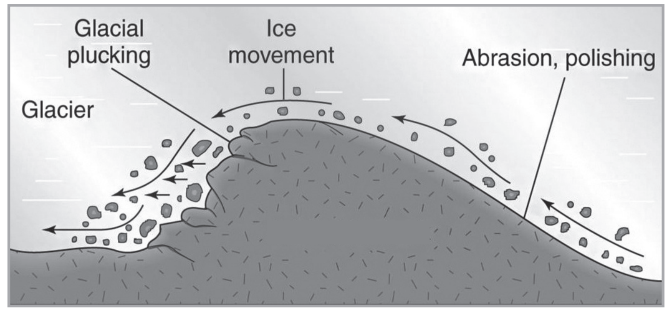


Fig. Glacial Erosional Process

- **Cirque (Corrie):** They are amphitheatre-like, steep-walled depressions at the head of glacial valleys. They are deep, long and wide troughs or basins with very steep concave to vertically dropping high walls at its head as well as sides
  - Typically located at the **heads of glacial valleys**. It is also known as a **corrie**.
  - Cirques often contain lakes known as **cirque or tarn lakes**.
  - Cirques are formed by glacial erosion, primarily abrasion and plucking. **E,g.** Chandra Taal, Himachal Pradesh.

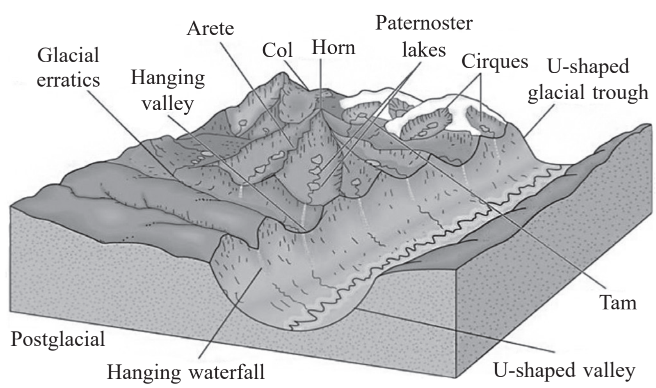


Fig. Glacial Erosional Landform

- **Aretes:** When two corries cut back on opposite sides of a mountain, knife-edged ridges are formed called aretes.
  - Where three or more cirques cut back together, their ultimate recession will form an angular horn or **pyramidal peak**.
- **Bergschrund:** At the **head of a glacier,** where it begins to leave the snowfield of a corrie, a **deep vertical crack** opens up called a **bergschrund (in German) or rimaye (in French)**

- **Glacial Valleys/Troughs**
  - Glaciated valleys are U-shaped valleys with broad floors and relatively smooth, steep sides. These valleys may contain debris or moraines, and sometimes, lakes.
  - **A Ribbon lake/ Finger lake/ Trough lake** is a long and very deep, finger-shaped lake, usually **found** in a **glacial trough**
  - **Hanging Valley:** After the ice has melted a **tributary valley hangs above** the **main valley** so that its stream plunges down as a waterfall. After deglaciation, meltwater from hanging valleys often forms waterfalls when joining the main valley. **Example-** Har-Ki-Doon Valley, Uttarakhand
  - In high latitudes, deep glacial troughs filled with seawater create **fjords or fiords.**
- **Roche Moutonnee:** This is a **resistant residual rock hummock**. The surface is striated by ice movement . Its **upstream side** is **smoothed** by **abrasion** and its **downstream side** is **roughened** by **plucking.**
- **Crag and Tail:** A crag is an outcropping of hard rock with a high upward slope that keeps the ice from entirely wearing down the softer leeward slope.
- **Horns (Pyramidal peak):** Horns are pyramidal or triangular peaks created when three or more cirques intersect, leading to the steepening and sharpening of the peak.
- **Nunataks:** Isolated peaks or mounds surrounded by glacial ice; They resemble small islands within the ice mass and decrease in size over time due to glacial lateral erosion and frost action.

Glacial Depositional Landforms

- **Glacial Till:** Glacial till is **unsorted coarse and fine debris** left behind as glaciers melt; It mainly consists of angular to sub-angular rocks.
- **Outwash Deposits:** Some amount of rock debris small enough to be carried by melt water streams is washed down and deposited. Such **glacio-fluvial deposits** are called outwash deposits.
- **Moraines:** Moraines are **long ridges of glacial till deposits**; named differently on basis of locations they found:
  - **Terminal moraines** are found **at the end** (toe) of glaciers, while **lateral moraines** form **along the sides** parallel to glacial valleys. These moraines may join to create horse-shoe-shaped ridges.
  - Valley glaciers retreating rapidly, often leave irregular sheets of till called **ground moraines on** their **valley floors.**
  - **Medial moraines** are found **in the center** of glacial valleys.

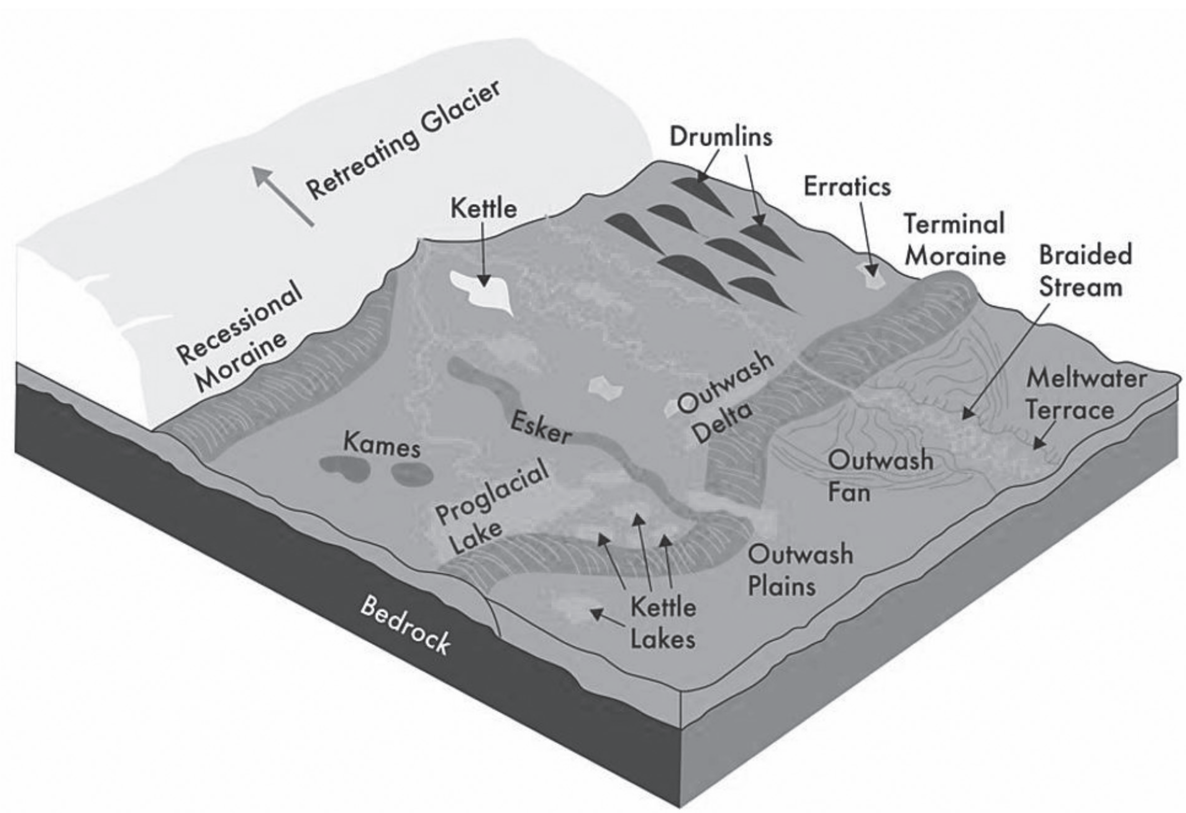


Fig. Depositional Features of Glaciers

- **Eskers:** These are **sinuous ridges** formed by water flowing beneath melting glaciers. When glaciers melt, water gathers beneath them and carries coarse materials. As the glacier vanishes, these materials form ridges called **eskers.**
- **Outwash Plains:** The plains **at the foot** of the **glacial mountains** are covered with **glacio-fluvial deposits** in the form of broad flat alluvial fans which join to form **outwash plains** of gravel, silt, sand and clay.
- **Drumlins:** These are smooth, **oval-shaped hills** made of rocks and dirt. These hills have **two ends.** One end, called the **stoss end**, is **flatter and steeper**, while the other end is called the **tail**. They are typically the result of glacial deposition and can occur in clusters, creating a **"basket of eggs" topography**.
- **Kettle lake:** This is a **depression** in the **outwash plain** left by the melting of masses of stagnant ice. Large kettles may contain numerous low mounds called **hummocks**.
- **Fjords:** Fjords are deep, narrow, and elongated inlets of the sea, typically flanked by steep cliffs or slopes.It is formed through a combination of glacial, geological, and hydrological processes. It is characterised by U-shaped glacial valleys submerged in the sea.

COASTAL LANDFORMS

Coastal landforms are shaped by coastal erosion and deposition and are driven by factors such as wave action, tides, currents, and sediment availability.

Coastal landforms are shaped by the interplay of various processes:

- **Hydraulic action:** The force of water erodes coastal rocks.
- **Abrasion:** Erosive action of sand, pebbles, and boulders carried by waves.
- **Attrition:** Mechanical breakdown of rock fragments.
- **Corrosion:** Chemical alteration of coastal rocks.

Types of Coasts

- **High Rocky Coasts**
  - **Dominant features:** Erosional features, irregular coastline, fjords.
  - **Examples:** West coast of India, Norway, Chile.
  - **Processes:** Erosion, abrasion, corrosion.
  - **Landforms:** Cliffs, sea stacks, arches, caves.
- **Low Sedimentary Coasts**
  - **Dominant features:** Depositional features, smooth coastline, lagoons, deltas.
  - **Examples:** East coast of India, Gulf Coast of the United States.
  - **Processes:** Deposition, sedimentation.
  - **Landforms:** Coastal plains, beaches, sandbars, spits, lagoons.

Coastal Erosional Landforms

- **Capes and Bays:** On exposed coasts, the **continual action of waves** on **rocks of varying resistance** causes the **coastline** to be **eroded irregularly**.
  - Capes and Bays are particularly pronounced where **hard rocks**, like granites and limestones, occur in **alternate bands with softer rocks**.
  - **Softer rocks** are worn back into **inlets, coves or bays** and the **harder ones** persist as **headlands or capes.**

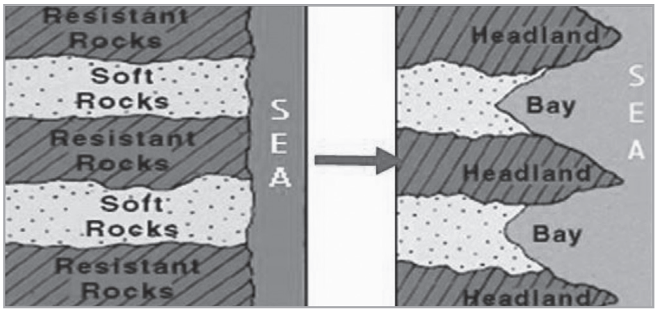


Fig. Bays and Headland

- **Wave cut cliffs:** Waves break forcefully against rocky coasts, forming cliffs; **Constant wave impact** causes **cliffs** to **recede,** creating **wave-cut platforms** where eroded material is deposited.

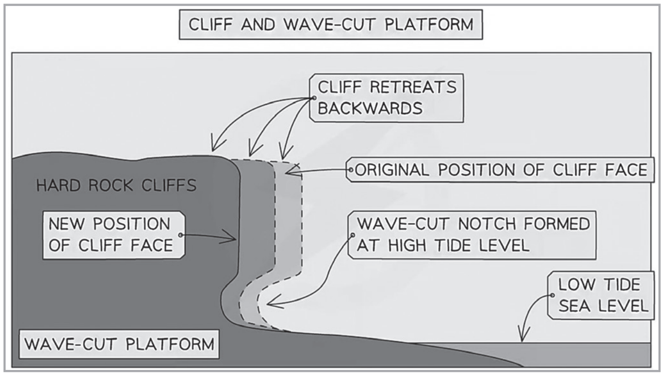


Fig. Cliff and Wave Cut Platform

- **Wave cut terraces:** Flat platforms made of **rock debris** at the base of cliffs, elevated above the average wave height. Wave-cut cliffs and terraces are major landforms where erosion is the dominant process.
- **Caves:** Hollows formed by the **impact of waves** and rock debris against cliffs. Roofs of these caves collapse, giving way for **stacks**.
- **Sea Stacks:** Resilient **rock masses,** originally part of cliffs or hills, **standing alone** just **off the shore.**
- **Stumps:** In the course of time, these 'stubborn' stacks will gradually be removed. The vertical rock pillars are eroded, leaving behind only the stumps which are just visible above the sea level.
- **Wave-Cut Platforms:** Flat surfaces created by wave pounding in front of cliffs. These **flat, slightly concave surfaces** are formed in front of cliffs due to the relentless pounding of waves.

- **Arches:** Natural arches are formed when caves on opposite sides of a headland merge over time.

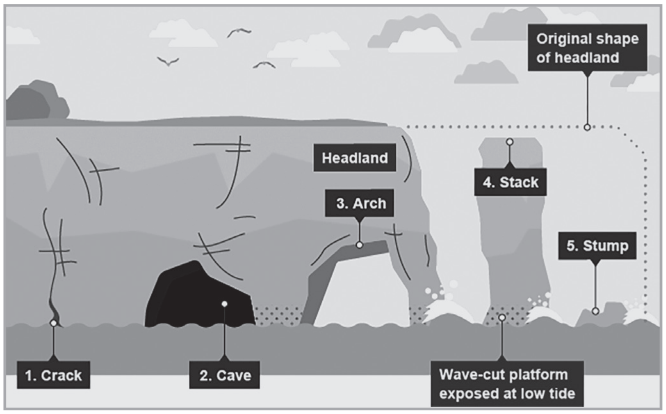


Fig. Coastal Erosional Landform

Coastal Depositional Landforms

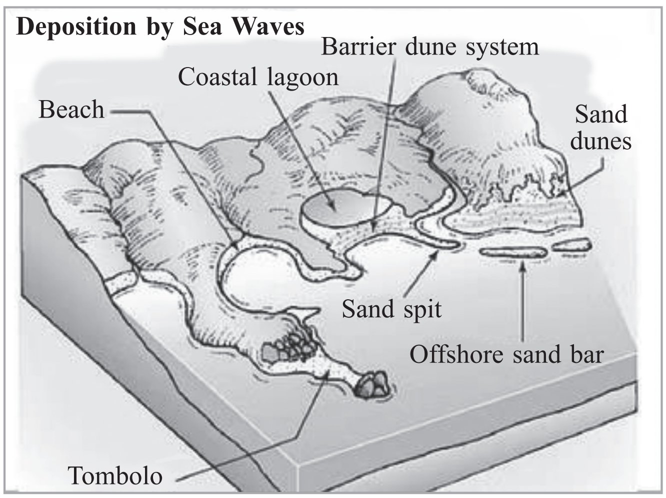


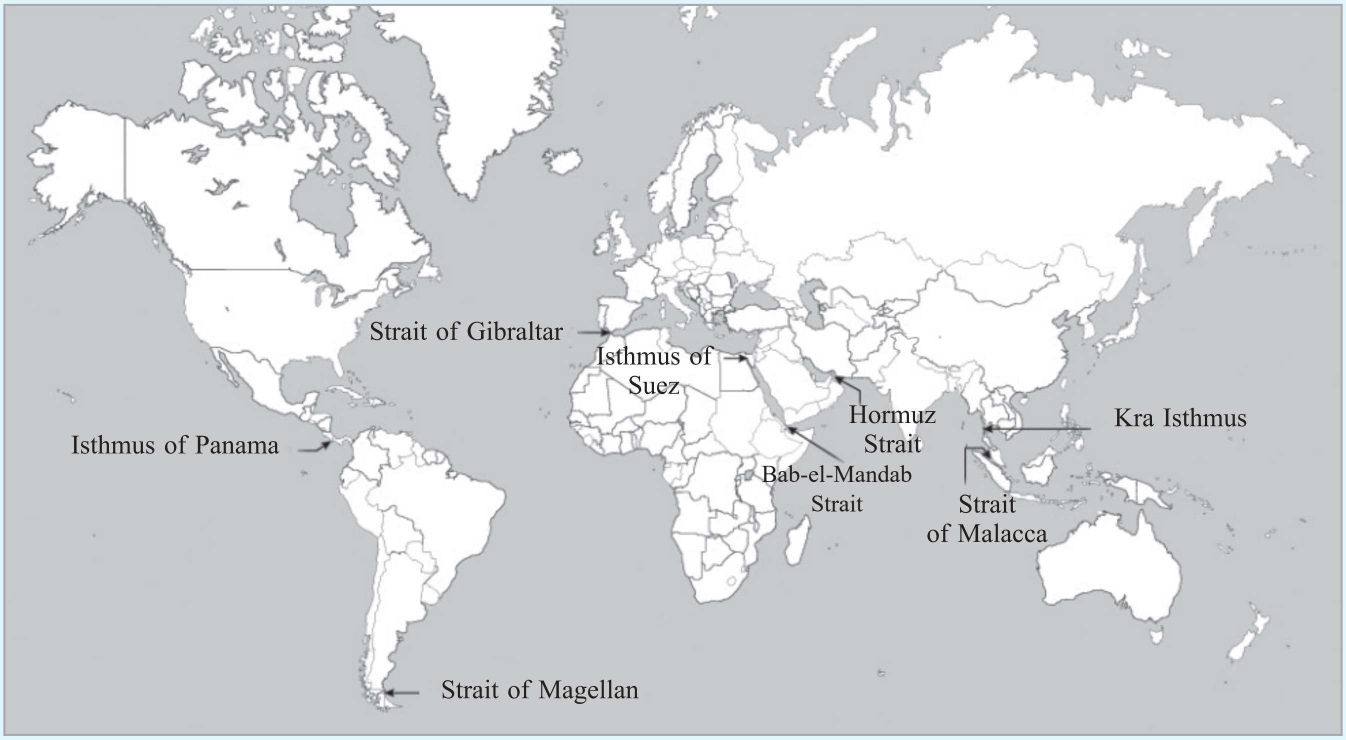
Fig. Coastal Depositional Landform

- **Beaches: Beaches are not permanent** and can change in size and composition seasonally by the continuous action of waves. They are formed by the accumulation of sand and pebbles along the shoreline.
- **Dunes:** Sand lifted and sorted from the beach surface is deposited just behind the beach, forming sand dunes. These are **commonly found** along **low sedimentary coasts** and appear as long ridges **parallel to the coastline**.
- **Off-shore Bar:** It is a **ridge of sand** and shingle that forms in the sea in the off-shore zone, typically running **parallel to the coast**. They Offer the first buffer or defence against storm or tsunami.
- **Barrier Bar:** It is an **off-shore bar** that becomes **exposed** due to the accumulation of sand.
- **Spit:** Spits are elongated depositional landforms that extend from the coast into a body of water, typically formed by **longshore drift**, where waves transport and deposit sediments along the coast. When **barrier bars** and **spits form** at the **mouth** of a **bay** and **block it**, a **lagoon** is formed.
- **Tombolos:** It connects an island to the mainland or another island; it is created by the deposition of sediments by waves and tides, which gradually build up to connect the two land masses.
- **Lagoons:** Lagoons are shallow, often brackish water bodies located between barrier islands or spits and the mainland, formed when sandbars or spits enclose an area of water behind them.
- **Estuaries:** Partially enclosed coastal bodies of water where freshwater from rivers and streams mixes with seawater. The deposition of sediments from river runoff creates unique habitats.
- **Mudflats:** Soft, muddy sediments exposed during low tide.
- **Salt Marshes:** Coastal wetlands dominated by salt-tolerant vegetation, formed by the deposition of fine sediments carried by tidal waters.

- **Strait:** Naturally formed **waterway** that **connects** two **large water bodies.**
- **Isthmus:** An **isthmus** is a narrow strip of land connecting two larger landmasses and is bordered by water on both sides.
  - It plays a crucial role in geography, serving as a natural bridge for terrestrial and marine ecosystems and as strategic passageways for human trade and migration.
  - Examples include the **Isthmus of Panama**, connecting North and South America and separating the Pacific and Atlantic Oceans; the **Isthmus of Suez**, linking Africa and Asia with the Suez Canal; and the **Kra Isthmus**, joining Thailand with the Malay Peninsula.
  - Historically, the **Palk Strait** linked India and Sri Lanka through Adam's Bridge, though it is now submerged. Isthmuses are typically formed by tectonic activity, sediment deposition, or volcanic processes and are significant for their ecological and human connectivity, often being modified for canals or transportation.

- **Gulf and Bay:** Gulfs and bays are both water formations along coastlines.

	Gulf	Bay
Size and shape	Generally larger and more extensive indentations of the coastline.	Typically smaller and shallower compared to gulfs.
Degree of Enclosure	More open connection to the ocean or sea	May have a narrower entrance compared to gulfs.



WINDS

Wind is a **major force** in **hot deserts**. Winds contribute to erosion through:

- **Deflation** involves lifting and removing dust and small particles from rock surfaces. During transportation, sand and silt act as effective tools, **abrading** the land.
- **Impact**, on the other hand, is the sheer force generated when sand collides with rock surfaces, similar to a **sand-blasting operation.**

Five different types of desert landscape:

- **Hamada or rocky desert:** It is dominated by barren, exposed rocky surfaces. Formed by the deflation of finer particles by wind, leaving rocks and boulders behind.
- **Reg or stony desert:** It is characterized by a surface of closely packed, angular gravel or pebbles.
- **Erg or sandy desert:** In Turkestan, sandy deserts are also known as **koum.**
- **Badland:** where the hills were badly eroded by occasional rain-storms into gullies and ravines.
- **Mountain deserts:** found on highlands such as plateau and mountain ranges.

Desert Erosional Landforms

- **Pediments and Pediplains: Pediments** are **gently inclined rocky surfaces** found **near** the **bases of mountains**, sometimes covered with a thin layer of debris. They are **formed** through a **combination** of **lateral erosion** by streams and **sheet flooding.** This erosion process leads to the extension of pediments at the expense of mountain fronts. Over time, the mountains reduce in size, leaving behind **inselbergs** as remnants. Ultimately, the high-relief desert areas transform into low, **featureless plains** known as **pediplains**.
- **Zeugen:** These are **tabular masses** that have a **layer of soft rocks lying beneath** a surface layer of more **resistant rocks**. **Wind abrasion eats** into the **underlying softer layer** so that **deep furrows** are developed. The **hard rocks** then stand above the furrows **as ridges or zeugen.**

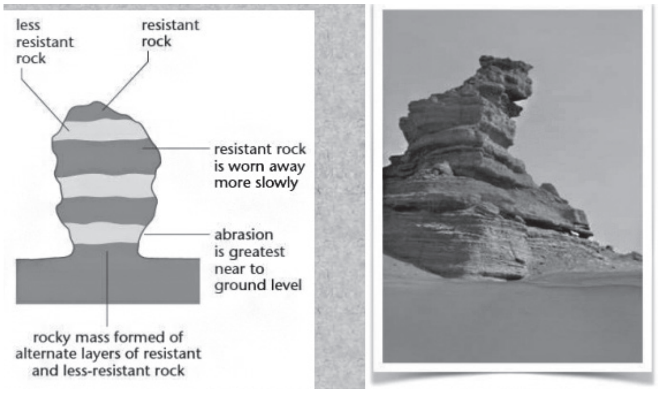


Fig. Zeugen

- **Yardangs:** Instead of lying in horizontal strata upon one another, the **hard and soft rocks** of yardangs are **vertical bands** and are **aligned** in the **direction of** the **prevailing winds.**

Fig. Yardang

- **Playas:** Playas are **shallow lakes** formed at the **centre of basins** surrounded by mountains and hills; Have short-lived water retention due to high evaporation rates and often contain salt deposits.

Fig. Playa

- **Mesas and Buttes:** It is a **flat, table-like land mass** with a very resistant horizontal top layer and **very steep sides. Continued denudation** through the ages may reduce mesas in the area so that they become **isolated flat-topped hills** called **buttes.**

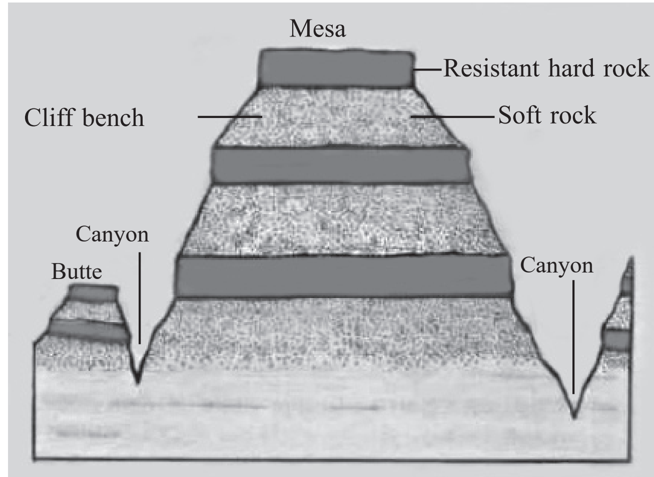


Fig. Mesa and Butte

- **Inselberg:** It is characterised by their **steep slopes** and rather **rounded tops.** They are often composed of granite or gneiss, and are probably the relics of an original plateau that has been almost entirely eroded away.

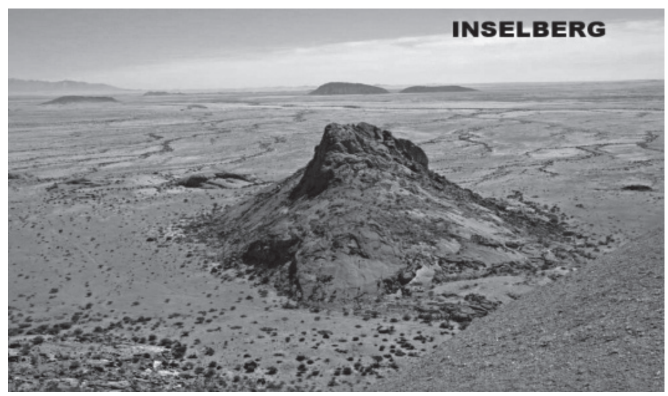


Fig. Inselberg

- **Deflation Hollow:** Winds lower the ground by blowing away the unconsolidated materials, and **small depressions** may form. Water then seeps out forming oases or swamps, in the deflation hollows or depressions.

Fig. Deflation Hollow

- **Mushroom, Table, and Pedestal Rocks:** Resistant rock remnants polished by wind erosion take on various shapes such as,

- **Mushroom rocks** which have a slender stalk and a rounded, pear-shaped cap.
- **Table rocks** have broad, flat tops.
- **Pedestal rocks** stand tall like pillars.

- **Badland:** Badland Topography refers to a dry, eroded landscape characterised by steep slopes, ridges, and deep gullies, often resulting from intense water erosion in semi-arid or arid regions. It is commonly seen in regions with soft, easily erodible rocks, such as shale or mudstone.

  This landform is marked by a lack of vegetation due to the harsh conditions. Badlands form when alternating layers of resistant and soft rock erode unevenly, leading to sharp ridges and valleys.

  Examples: Chambal Ravines in M.P, Ladakh, Kutch etc.

Landforms: Works of Wind and Water

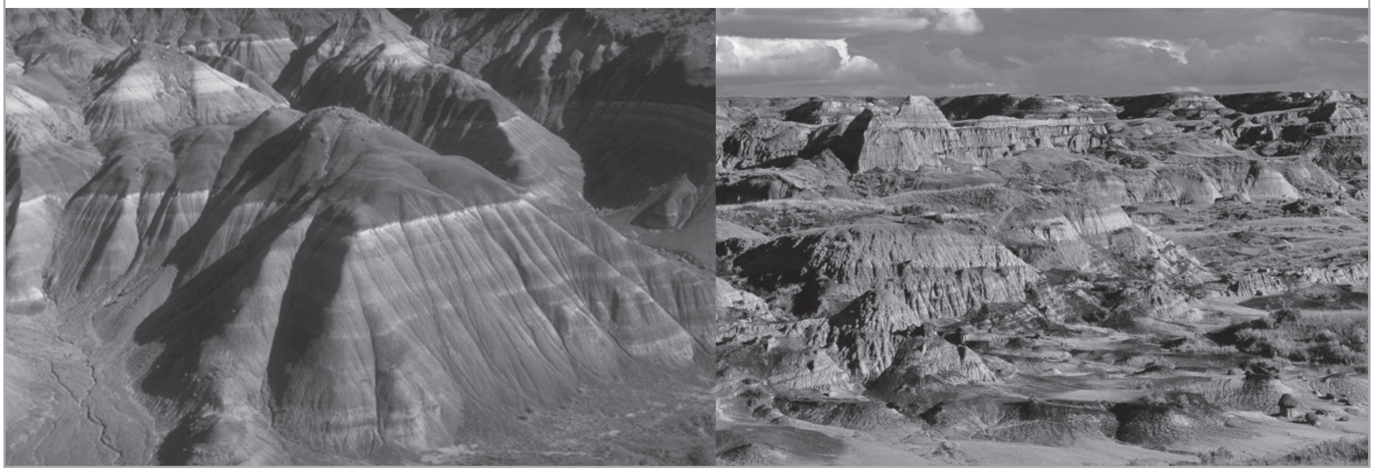


Fig. Badland

Desert Depositional Landforms

- **Sand Dunes**

  Dry, hot deserts are ideal for sand dune formation. Dune formation requires both sand availability and obstacles. Various dune forms include:

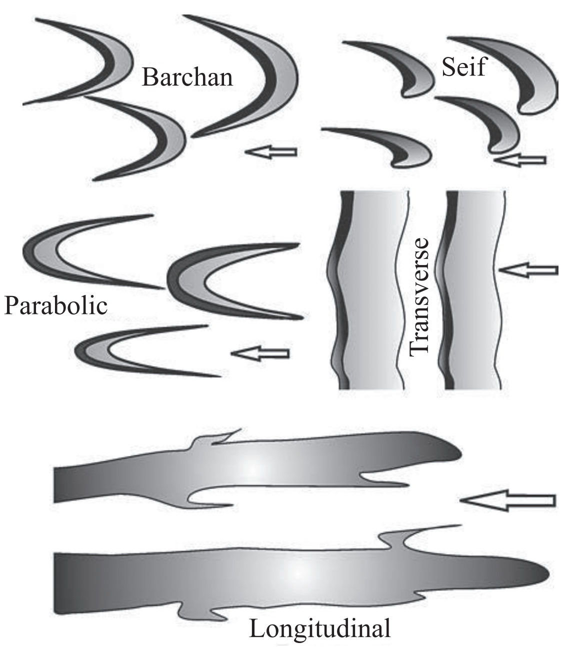


Fig. Types of Sand Dunes

- **Barchans:** It is **crescent shaped** dunes with **wings** directed **away from wind direction.**
- **Parabolic dune: Reversed barchans** with wind direction being the same, it is formed when the **sandy surface** is **covered with vegetation.**
- **Seif:** It is similar to barchans but has **only one wing** due to shift in wind condition.
- **Longitudinal dunes:** They appear as **long ridges,** in the **direction of wind**, but are low in height. They are formed when supply of sand is poor and wind direction is constant.
- **Transverse dunes:** It is aligned **perpendicular to wind direction.**

Fig. Sand Dunes

- **Bajadas: Depositional plains** with a moderate slope that are situated between playa and pediments. **Alluvial fans combine** to **create** a **bajada.**

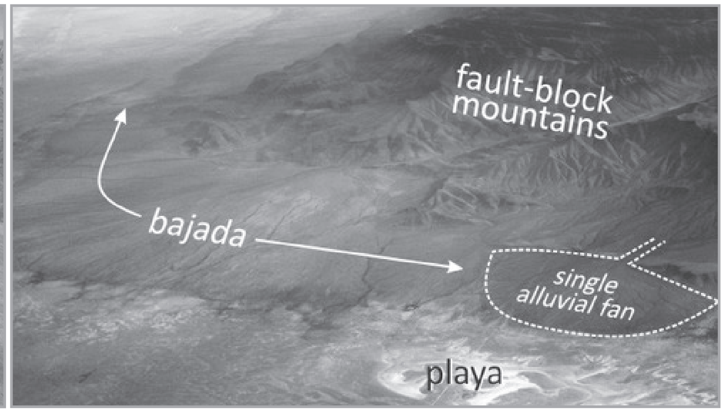


Fig. Bajadas

4 Atmosphere and Heat Balance

ATMOSPHERE: STRUCTURE AND COMPOSITION

The Earth's atmosphere is a complex mixture of gases, water vapour, and dust particles, vital for life and various climatic and meteorological phenomena. About **99% of the atmosphere's total mass** is concentrated within 32 kilometres from the Earth's surface.

Composition of the Atmosphere

The atmosphere is primarily composed of **permanent gases** and **variable gases**, as outlined below:

Permanent Gases:

- **Nitrogen (N_2):** 78.084% - Essential for diluting oxygen and slowing combustion processes. Critical for protein synthesis in living organisms.
- **Oxygen (O_2):** 20.946% - Vital for respiration and combustion.
- **Argon (Ar):** 0.934% - A noble gas, inert and used in industrial applications.

Variable Gases:

- **Water Vapor (H_2O):** Highly variable (0-4%) - Plays a crucial role in the hydrological cycle, weather patterns, and heat retention through absorption of infrared radiation **[UPSC 2023].** It is a gas, the amount of which decreases with altitude. Its percentage is minimum at the poles. **[UPSC 2024].**
- **Carbon Dioxide (CO_2):** 0.04% - Transparent to incoming shortwave solar radiation but opaque to outgoing longwave radiation, making it a key greenhouse gas. **[UPSC-2024]**
- **Ozone (O_3):** Concentrated in the stratosphere - Absorbs harmful ultraviolet (UV) rays.
- **Other gases:** Includes methane (CH_4), neon (Ne), helium (He), hydrogen (H_2), and krypton (Kr), which are present in trace amounts but play important roles in atmospheric chemistry.

Atmospheric Composition (Volume-wise)

Gas	Symbol	Volume (%)
Nitrogen	N_2	78.084%
Oxygen	O_2	20.946%
Argon	Ar	0.934%
Carbon Dioxide	CO_2	0.042%
Neon	Ne	18.182 ppm
Helium	He	5.24 ppm
Methane	CH_4	1.92 ppm
Krypton	Kr	1.14 ppm
Hydrogen	H_2	0.55 ppm
Ozone	O_3	0.07 ppm

Note: Water vapor varies significantly based on location and altitude, ranging from nearly 0% in desert regions to up to 4% in tropical climates.

Structure of Atmosphere

The Earth's atmosphere is divided into several distinct layers, each with its unique characteristics in terms of temperature, pressure, and composition. Understanding these layers is essential from both **meteorological** (weather-related) and **climatological** (climate-related) perspectives.

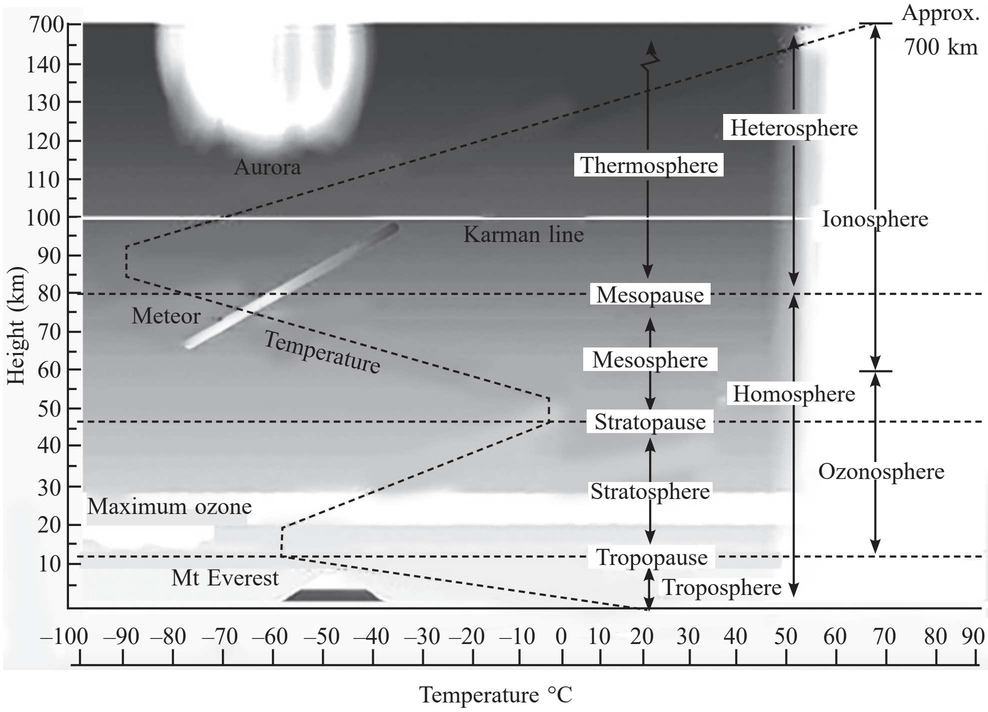


Fig. Layers of Atmosphere

- **Troposphere (0-13 km)**
  - **Role:** All weather changes and biological activities occur in this layer.
  - **Features:** Contains the bulk of water vapor and clouds, making it crucial for weather patterns. Thickness of the troposphere at the equator is much greater as compared to poles. Because, at the equator, heat is transported to great heights by strong convectional currents. **[UPSC-2024]**
  - Height of troposphere varies from 8 kms at the poles to 18 kms at the equator.
  - **Temperature:** Decreases with height at a rate of 1°C for every 165 meters, known as the **lapse rate**.
  - **Climate Impact:** Acts as the primary zone for heat exchange, cloud formation, and precipitation, influenced by the uneven heating of Earth's surface.
  - **Tropopause:** The tropopause is the boundary that demarcates the troposphere below from the stratosphere above and varies from 8-18 kms in height.
- **Stratosphere (13-50 km)**
  - **Role:** Contains the **ozone layer**, which absorbs harmful ultraviolet (UV) radiation from the sun.
  - **Temperature:** Increases with altitude due to ozone absorption of UV radiation.
  - **Meteorological Importance:** Jet streams, which influence weather patterns in the troposphere, are present in the lower stratosphere.
  - **Aircraft Flight:** Commercial planes fly in this region due to its stable conditions, free from water vapour and clouds (except for **polar stratospheric clouds**). **[UPSC-2011]**
- **Mesosphere (50-80 km)**
  - **Role:** Meteors burn up in this layer, creating "shooting stars."
  - **Temperature:** Decreases with altitude, reaching the coldest temperatures in the atmosphere at the **mesopause**.
  - **Meteorological Impact:** The mesosphere is largely free of greenhouse gases, so it does not contribute to the greenhouse effect but plays a role in atmospheric circulation.
- **Ionosphere/Thermosphere (80-400km)**
  - **Role:** Contains electrically charged particles (ions) that reflect radio waves back to Earth, enabling long-distance radio communication.
  - **Layers:** Divided into D, E, and F layers, where the F layer is most critical for radio transmission.
  - It is also a high temperature zone with temperatures ranging upto 1200 degrees celsius, thus also known as the **thermosphere.**

- **Space Weather:** Solar activity can influence the ionosphere, affecting communication systems.
- The thermosphere is the region where auroras occur, influenced by charged particles from the sun interacting with Earth's magnetic field.

- **Exosphere (400 km and above)**
  - **Role:** The outermost layer where the atmosphere gradually transitions into space.
  - **Composition:** Predominantly hydrogen and helium, with extremely low density.
  - **Meteorological Impact:** Though not directly related to weather, it is where satellites orbit and measure atmospheric conditions.

Atmospheric Divisions: Homosphere and Heterosphere

- **Homosphere:** Extends up to 80-100 km, where the gases are uniformly mixed.
- **Heterosphere:** Beyond 100 km, the atmosphere becomes less mixed, and lighter gases (like hydrogen and helium) dominate.

SOLAR RADIATION AND INSOLATION

Solar radiation is **radiant energy** emitted by the Sun as a result of **nuclear fusion reaction.** The Earth's surface primarily receives energy in **short wavelengths**, which is termed as **"incoming solar radiation"** or **"insolation."** The **amount** and **intensity** of insolation **vary** during **a day, in a season and a year**

Distribution of Solar Radiation

Factors influencing insolation variability:

- **Rotation of earth** on its axis causing day and night; poles experience continuous daylight or darkness.
- **Changing distance between the Earth and the Sun: Aphelion position (farthest from the sun)** on 4th July and Perihelion position (nearest to the sun) on 3rd January. Thus the annual insolation on 3rd January is slightly more than on 4th July.
- **Earth's axis is angled at 66 1⁄2°** with its orbital plane that influences insolation received at different latitudes.
- **Angle of the sun's rays** depends on the **latitude** of a place - Higher the latitude, lesser the angle. Net energy received per unit area decreases with latitude. Moreover, slant rays pass through a greater depth leading to more absorption, scattering, and diffusion.
- **Transparency of the atmosphere:** Higher transparency leads to higher insolation. Clouds, pollutants, and atmospheric composition impact insolation. Clouds reflect, scatter, and absorb sunlight. Dry season reduces cloud cover, affecting insolation.
- **Albedo:** Measure of surface reflectivity (0 to 1 scale).
- **Configuration of land:** Aspect (land orientation) influences sunlight reception; south-facing slopes are warmer and north-facing cooler in the Northern hemisphere and reverse is true for the Southern hemisphere.

Albedo

- **Albedo:** The proportion of the incident light or radiation that is reflected by a surface, typically that of a planet or moon.
- The average albedo of the Earth is approximately 0.3. This means that around 30% of the sun's energy hitting the planet's surface is reflected back into space, while about 70% is absorbed
- Decreasing Order of the Albedo: Fresh Snow (0.80) > Ocean ice > Sand > Green gross > Soil > Forest > Open ocean (0.06) > Charcoal (0.04)

The red colour of the rising and setting sun and the blue colour of the sky are the **result of scattering of light** within the atmosphere.

Spatial Distribution of Insolation on Earth's Surface

- **Subtropical deserts** receive the **highest insolation** due to minimal cloudiness.
- **Equator** receives **less insolation compared to the tropics.**
- At the **same latitude, continents** generally **receive more insolation than oceans** as **clouds** over the ocean reflect back the sunlight.
- During winter, middle and higher latitudes receive less radiation compared to summer.

- The **Equator receives 5 times more insolation than polar regions**. **[UPSC 2023]**
- The specific heat capacity of water is much greater than that of land; thus, it slowly warms in the summer and slowly cools in the winter.
- The **temperature contrast** between **continents and oceans** is **greater** during **summer than in winter**. **[UPSC 2013, 2023]**

Heating and Cooling of Atmosphere

The four different ways of heating and cooling of the atmosphere are:

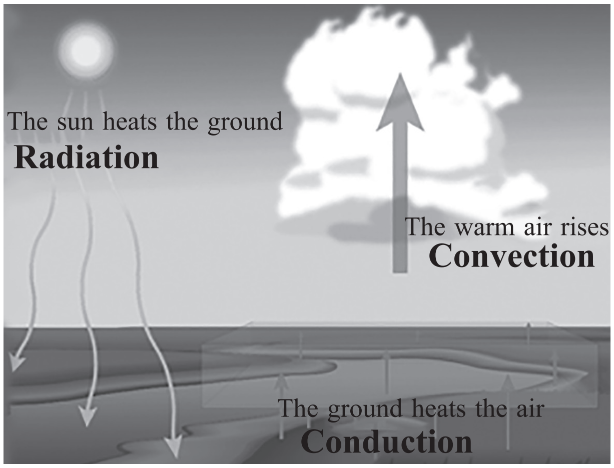


Fig. Radiation, Convection and Conduction

- **Conduction:** Process in which heat flows from objects with higher temperature to objects with lower temperature through molecular movement. It primarily heats the atmosphere's lower layers.
- **Convection:** Transfer of heat by the movement of a fluid (liquid or gas) between areas of different temperatures. Air in contact with the earth rises vertically when heated, forming currents that transmit atmospheric heat. It is limited to the troposphere.
- **Advection:** Transfer of heat through horizontal movement of air. In middle latitudes, most diurnal (day & night) variations in daily weather and in tropical regions effects of loo are the result of the advection process.
- **Terrestrial Radiation:** Heat transfer from one body to another without actual contact or movement. Earth absorbs shortwave radiation (UV and Visible portion of electromagnetic spectrum) warming the surface; it emits long wave radiation (Infrared rays) which heats up the atmosphere. **[UPSC 2023]**. The atmosphere is heated more by terrestrial radiation than by incoming solar radiation. **[UPSC-2024]**

Plank's law states that the **hotter** body radiates more energy and **short wavelength radiation**.

HEAT BUDGET OF THE PLANET EARTH

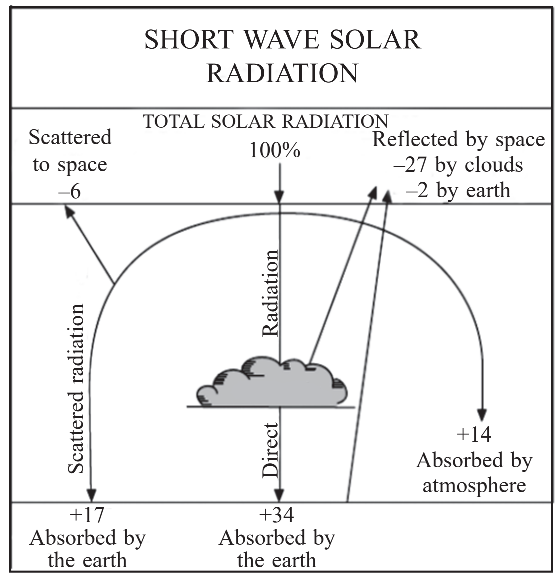
The earth maintains a constant temperature by ensuring the heat it receives (**insolation**) equals the heat it emits (**terrestrial radiation**). Thus, the earth as a whole neither accumulates nor loses heat.

- A **heat budget** is a perfect **balance** between incoming heat absorbed by the earth and outgoing heat escaping it in the form of radiation.

Absorption Pattern

As insolation travels through the atmosphere, it undergoes reflection, scattering, and absorption.

- Roughly about **35 units** of the insolation are **reflected** into space before reaching the Earth's surface. Of these, **27 units** are reflected back from the **top of the clouds** and **2 units from the snow and ice-covered areas** of the earth. The other details pertaining to the heat budget of the earth can be understood from the diagram given below.



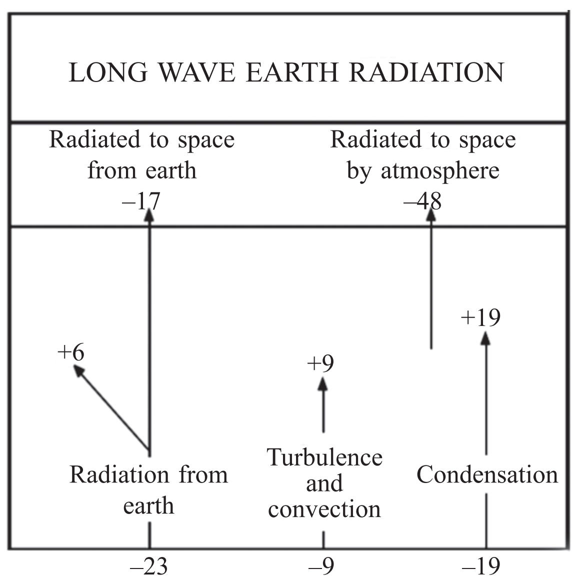


Fig. Heat Budget of The Earth

Variation in the Net Heat Budget at the Earth's Surface

- **Latitudinal Radiation Distribution: Between 40 degrees north and south,** there is a notable **surplus** in radiation balance; regions closer to the **poles** have a **radiation deficit.**
- **Natural Heat Redistribution:** The excess heat from the tropics is systematically moved towards the poles.

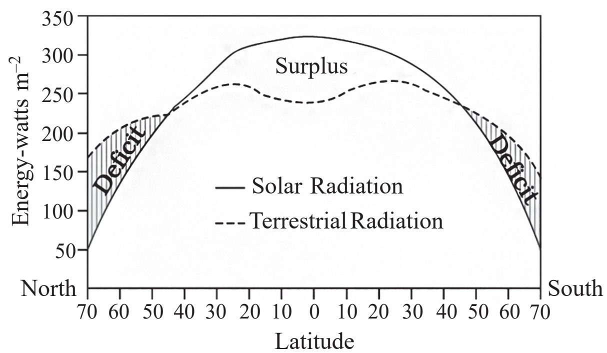


Fig. Latitudinal Variation in net Radiation Balance

TEMPERATURE

- Temperature is the measurement in degrees of how hot (or cold) a thing (or a place) is.
- Isobars are lines connecting places with equal temperatures. Isotherms shift with the apparent movement of the sun across the equator.
  - In the **Northern Hemisphere**, isotherms are **irregular** and **closely spaced** (due to higher proportion of landmass than oceans).
  - In the **Southern Hemisphere**, they are more **regular** and **widely spaced** (Higher proportion of oceans to landmass).

Shifting of isotherms

- Isotherms, meant to align with latitudes on a uniform Earth, **bend due to land-water heat differences**.
- The general rule is that **isotherms** crossing from **land to sea bend towards the pole (In winter)/equator (In summer)**.
- The isotherms deviate to the north over the ocean and to the south over the continent in the month of January. The presence of Warm ocean currents, Gulf Stream and North Atlantic Drift make the North Atlantic Ocean warmer and the isotherms bend towards the north. **[UPSC-2024]**

- **Temperature anomaly** indicates a place's temperature differing from its latitude's mean, with **positive anomaly** (e.g., Sahara Desert, temp > mean) and **negative anomaly** (e.g., Mt. Everest, temp < mean).

Factors Controlling Temperature Distribution

- **Latitude** It has direct control on temperature as the **insolation** is **inversely proportional** to the **latitude**.
- **Altitude: Higher** the altitude, **lower is the temperature.** Normally, the temperature decreases with the increase in height from the Earth's surface, because the atmosphere is heated upwards only from the Earth's surface. The air is less dense in the upper atmosphere. **[UPSC-2012]**
- **Distance from the sea:** The places situated near the sea come under the **moderating influence** of the **sea and land breezes thus preventing extreme temperatures.**
- **Air-mass circulation** and **ocean currents**
  - Warm air-masses/warm currents: Higher temperature
  - Cold air-masses/cold currents: Low temperature
- **Prevailing Winds:** Wind origin and speed affect temperature distribution.
- **Aspect of Slope:** Orientation of slopes influences sunlight exposure, affecting temperature.
- **Day-Night Cycle:** Rotation-induced temperature variations.
- **Urban Heat Island (UHI) Effect:** Human activities elevate temperatures in urban areas.

TEMPERATURE INVERSION

It is a **reversal of the normal behaviour of temperature** (temperature drops as altitude increases) in the **troposphere,** in which a **layer of cool air at the surface is overlain by a layer of warmer air.**

- **Ideal conditions for temperature inversion:**
  - **Long winter night** (outgoing radiation is greater than the incoming radiation);
  - **Clear and cloudless sky;**
  - **Still air** (no/slow horizontal movement of air) which avoids mixing of air;
  - **Dry air** near the ground surface
  - **In polar regions**, temperature inversion is **normal throughout the year**.
- **Effects of Surface Temperature Inversion:**
  - The **lower atmosphere** becomes **stable;** causing smoke, dust, and other particles to get trapped beneath the inversion layer, leading to **formation of dense fog.**
  - In **hilly and mountainous terrains**, inversion is due to a process called **air drainage** (downward flow of cold air from mountain slopes to valleys during night). It acts as a protective shield for plants, saving them from frost damage.

Temperature Inversion Types

- **Surface Temperature Inversion**
  - Takes place on the **layers in contact with the surface** through the process of **conduction**.
  - **Fog formation** is possible if the temperature of surface air drops below its dew point.
  - **Common** in the **higher latitudes**; In **lower & middle latitudes** it occurs during **cold nights** and gets destroyed during the daytime.
- **Valley Inversion**
  - Takes place in **hills and mountains** due to air drainage.
  - **Cold air** (heavy and dense) produced during the night, flows under the influence of gravity and **moves down the slope** to pile up in valley bottoms with warm air above. This is called **air drainage**.
  - **Protects plants** from frost damages

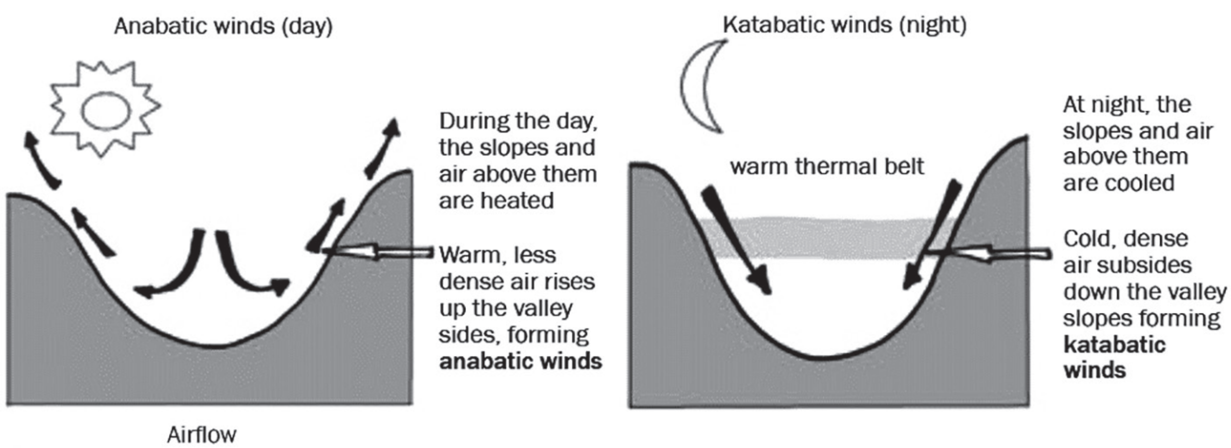


Fig. Valley Inversion

- **Frontal Inversion (Advectional type)**
  - Occurs when a **cold air mass** undercuts a **warm air mass** and **lifts it** aloft.
  - It is **unstable** and is **destroyed** as the weather changes.

Consequences of Temperature Inversion

- **Fog Formation:** Warm air sits above cold air which causes fog by cooling the warm air from below; Hazardous in polluted areas, limits the diffusion of air pollutants that aid Fog or Smog formation
- **Frost Impact:** When warm air condenses at freezing temperatures due to cooling by cold air below; Damages crops and orchards.
- **Atmospheric Stability:** Restricts vertical air movement that discourages rainfall and promotes dry conditions and aridity.

5 Atmospheric Circulation and Weather Systems

Atmospheric pressure is the weight of a column of air contained in a unit area. It decreases with height; rate of decrease is roughly **1 millibar/10 metres.**

Wind is the horizontal movement of air that flows from high pressure to low pressure areas.

DISTRIBUTION OF AIR PRESSURE

It is not uniform and varies both vertically and horizontally on the Earth's surface. Lower layers have a higher density and exert more pressure.

- **Vertical Variation**:
  - Decreases with an increase in altitude in the lower atmosphere but not at an uniform rate due to variations in air density controlling factors such as temperature, water vapour and gravity.
  - The vertical pressure gradient force is much larger than that of the horizontal pressure gradient.
  - A rising pressure indicates stable weather whereas a falling pressure indicates cloudy and unstable weather.
- **Horizontal Variation**:
  - Studied by drawing isobars (line connecting points that have equal values of pressure).
  - Close spacing of isobars expresses a steep pressure gradient.

Factors Responsible for Variation

- **High temperatures** lead to rise of air, hence low pressure and vice versa.
- **Earth's rotation** leads to application of **Coriolis force and Centrifugal force** which influence Global Pressure belts. For E.g: Due to the earth's rotation, the winds surrounding the Polar region blow towards the Equator. Centrifugal forces operating in this region create the low-pressure belt appropriately called the Subpolar Low-Pressure Belt.
- Air with a higher **quantity of water vapour** has lower pressure. This happens because dry air density is more than water vapour and as water vapour increases, overall density of air decreases.

FORCES AFFECTING THE VELOCITY AND DIRECTION OF WIND

- **Pressure Gradient Force** from high pressure to low pressure; closely spaced isobars indicate strong pressure gradients and hence stronger winds.
  - Pressure gradient is the ratio between the pressure difference and the actual horizontal distance between two points.
- **Frictional Force:** Affects the **speed of the wind** due to Earth's surface irregularities; **greatest at the surface and minimal over the sea surface** and generally extends up to an elevation of 1 - 3 km.
- **Centripetal Force:** It acts perpendicular to the wind, converging inward; influential in circular airflow around weather systems, creating convergence at low/ high-pressure centres; more impactful in smaller-scale circulations than mid-latitude cyclones.
- **Coriolis Force:** The rotation of the earth about its axis produces a pseudo force **affecting the direction of the wind**; deflects the wind to the **right direction** in the **northern hemisphere** and to the **left** in the **southern hemisphere (Ferrel's Law),** which depends on the **wind velocity**;
  - **It is directly proportional to the angle of latitude; maximum at the poles** and is **absent at the equator** (thus cyclones are not formed at the equator) **[UPSC-2024]**
  - **Acts perpendicular to the pressure gradient force creating cyclonic conditions**, **higher** the **pressure gradient force**, **higher** the **velocity of the wind** and the **larger is the deflection** of the wind.

General Circulation of the Atmosphere

Pattern of movement of the planetary winds also sets in motion the ocean water circulation and they **together influence the earth's climate.** The pattern of planetary winds largely depends on:

- **Latitudinal variation** of **atmospheric heating**.
- Emergence of **pressure belts.**
- The **migration of belts** follows the apparent path of the sun.
- The **distribution of continents and oceans**.
- The **rotation of the earth**.

GLOBAL PRESSURE BELTS

The horizontal distribution of air pressure across the latitudes is characterised by high or low pressure belts.

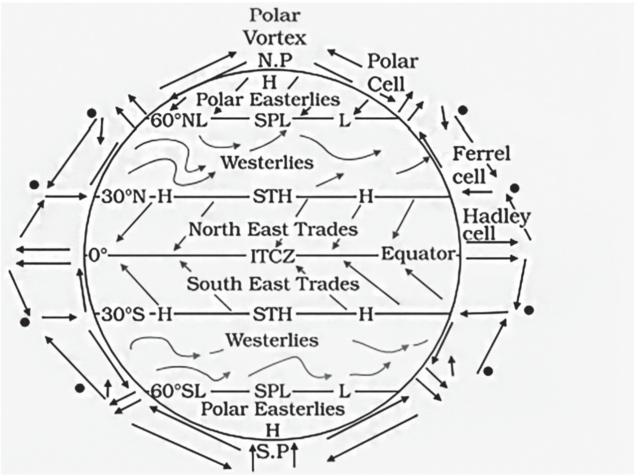


Fig. Major Pressure Belts and Wind System

- **Equatorial Low pressure belt** (zone of wind convergence) along the equator and within 5 degrees north and south; this belt is often termed as **Doldrums.**
  - **Thermally induced pressure belt** as it is formed because of the **differential heating** of the earth.
  - Due to the **overhead sun** throughout the year, the air gets **warm** and **rises** over the equatorial region, producing equatorial low pressure.
  - Only **conventional currents** are present, **horizontal movement of air is absent** due to excessive heating.
  - **Zone of convergence** of **trade winds** from two hemispheres from subtropical high pressure belts.
  - Vertical winds (convection) carry moisture to cumulonimbus clouds and lead to **thunderstorms (convectional rainfall)**.
  - It is also known as **Inter Tropical Convergence Zone (ITCZ)** or **Thermal Equator** because the winds flowing from sub-tropical high-pressure belts converge here.

> **Intertropical Convergence Zone (ITCZ)**
>
> **Low pressure** forms due to **air convection** driven by **intense sunlight; Winds from the tropics converge** into this low-pressure area, **ascend within the convective cell**, reach the troposphere's upper limit (approximately 14 km), and subsequently **travel poleward, accumulating around 30°N and 30°S latitudes.**

  - The **position** of the belt **varies** with the **apparent movement of the Sun**.
  - **'Zero' Coriolis force,** so no cyclones at the equator.
  - **Doldrums** (zone of calm air) due to virtual absence of surface winds at 0° Latitude.
- **Subtropical high pressure belt** (Zone of wind divergence) along **30° N and 30° S** latitude**.**
  - **Dynamically induced pressure belt** as it is formed because of the **rotation** of the earth.
  - Uprising air of the equatorial region moves towards the poles and gets deflected due to the earth's rotation. After becoming **cold and heavy**, it **descends** at these **high-pressure belts**.
  - The corresponding latitudes of sub-tropical high pressure are called **Horse latitudes** due to calm weather conditions and absence of strong winds.
  - **Subsiding air** is **warm and dry**; therefore, most of the **deserts** are present along this belt, in both hemispheres. **Cold ocean current** increases the **aridity** of these **deserts** on the western margin of continents.
  - Winds blow out of this region towards the equator: **North East trade winds (Northern Hemisphere) and South East trade winds (Southern Hemisphere)**. These winds bring **rainfall** to the **east** and **aridity** (Deserts) to the **west coast** of continents within the tropics.
  - Winds blow out of this region towards the Temperate low-pressure belt: **South Westerlies (Northern Hemisphere)** and **North Westerlies (Southern Hemisphere)**. These carry **warm equatorial waters** and **to western coasts** of **temperate lands. [UPSC 2015]**
  - In the **southern hemisphere Westerlies** are referred to as **Roaring Forties, Furious Fifties**; and **Shrieking or Stormy Sixties** according to their speed at different latitudes.
- **Sub Polar low pressure belts** (Zone of wind convergence) towards the pole along **60° N and 60° S** latitudes.
  - **Dynamically induced pressure belt** as it is formed because of the **rotation** of the earth.
  - Winds coming from the subtropical and the polar high belts converge here to produce **cyclonic storms** or **low-pressure conditions.** This zone of convergence is also known as the **polar front.**
- **Polar High pressure belt** close to the poles between 80° – 90° N and S latitudes
  - **Thermally induced pressure belt** as it is formed because of the **differential heating** of the earth.
  - In Polar Regions, Sun Rays are always slanting, resulting in **low temperatures**.
  - Because of **low temperature**, air compresses and its density increases. Hence, **high pressure** is found here.
  - Winds from these belts blow towards the subpolar low pressure belt.

Pressure Cells

The wind belts girdling the planet are organised into three cells in each hemisphere**:**

- **Hadley cell**
  - Warm air at the **ITCZ** rises, creating a **low pressure zone** and winds from the tropics blow towards this **equatorial low pressure zone**.
  - The converged air rises and moves towards the poles. This causes accumulation of air at about **30° N and S**.
  - This air gets cooled and sinks to ground and forms a **Subtropical High.**
  - Again this sunk air flows towards equatorial low from the Subtropical High as **Easterlies**.
- **Ferrel Cell**
  - Circulation of air with **sinking air at Subtropical high** and **rising air at Subpolar Low** forms Ferrel Cell.
  - These winds blowing at the surface are called **westerlies.**
  - A large part of the energy that drives the Ferrel cell is provided by the Polar cell and Hadley cell circulating on both sides, which drag the Ferrel cell with it.
- **Polar Cell**
  - At **polar latitudes**, the **cold dense air subsides** near the poles and blows towards **middle latitudes (Sub polar low)** as the **Polar easterlies**.
  - Near **60° latitude,** air **rises** to the tropopause and moves poleward. As it does so, the upper level air mass deviates toward the east.
  - When the air reaches the **polar areas**, it has cooled and is considerably denser than the underlying air. It **descends**, creating a **cold**, **dry**, **high-pressure** area.
  - At the polar surface level, the mass of air is driven towards **60° latitude**, replacing the air that rose there, and the polar circulation cell is complete.

GEOSTROPHIC WINDS

They are the winds of **upper atmosphere**, 2 - 3 km above the surface, that are **free from frictional effect** of the surface and are controlled mainly by the pressure gradient and the Coriolis force.

- They **flow parallel to the isobars** because of the **balancing of the Pressure Gradient Force by the Coriolis force** in the upper troposphere**.**
- These winds can also form in a **cyclonic or anticyclonic circulation.**
- It is also the reason why the air rising from the equatorial belt does not go straight towards the pole but descends in the subtropics.
- **Gradient Wind:** Considers airflow along a curved path, extending the concept of geostrophic wind moving along straight and parallel isobars.
- One important type of geostrophic wind is the **Jet Stream.**

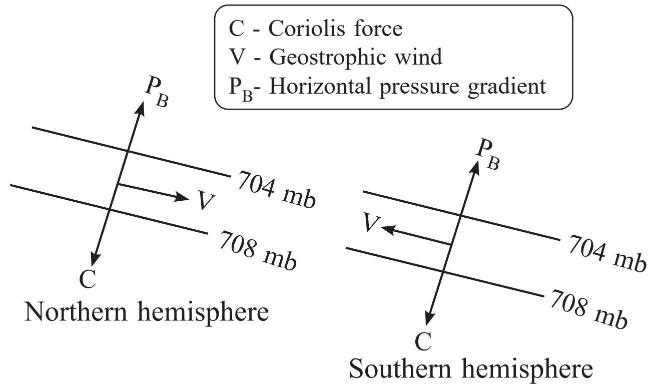


Fig. Geostrophic Wind

JET STREAMS

Jet streams are **fast, narrow** and **meandering** winds in the upper atmosphere circumnavigating the globe and reach **speeds of 400-500 km/h**.

- These winds blow **from west to east** in both hemispheres (**Westerlies**).
- **Seasonally shifting with the sun**. In **summer**, its position shifts towards the **poles** and in **winter** towards the **Equator**.
- Disturbances in jet streams affect **weather, precipitation patterns**, and **agriculture**.

Formation and Characteristics

- Jet streams form due to **temperature disparities**, with greater differences intensifying wind speed.
- **Coriolis force** and **low friction at high altitudes** contribute to their formation.
- Jet streams undergo a **geostrophic flow** and form **atmospheric cells**.

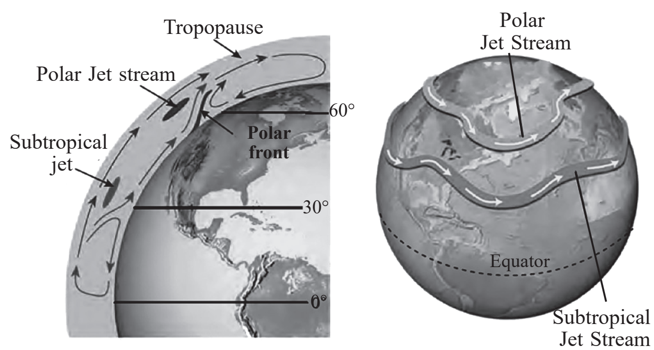


Fig. Jet Streams

Types

- **Permanent Jet Streams**
  - **Subtropical Jet Stream (STJ):** Flows between **Hadley and Ferrel** cells, continuous in the southern hemisphere, intermittent in the northern hemisphere during summer; Nearly continuous in both hemispheres during winter; Influences Indian monsoons.
  - **Polar Front Jet Stream (PFJ):** Flows between **Ferrel and Polar** cells, more variable position than the subtropical jetstream; stronger and more regular in winters
- **Temporary Jet Streams (Tropical)**
  - **Tropical Easterly Jet Stream (TEJ):** Dominant in the **northern hemisphere in summer**; found between 5° to 20°N; influences **South Asian monsoon**.
  - **Somali Jet Stream:** Occurs during the **summer** over **northern Madagascar and off the coast of Somalia**; intensifies from June to August; Impacts **South Asian monsoon**; major cross-equatorial flow from the southern Indian Ocean to the central Arabian Sea

Significance

- Jet streams play a vital role in the onset and progression of **monsoons** and influence the **general circulation patterns** in tropical, temperate, and polar regions.

Meandering of Jet Streams

The meandering of jet streams refers to the phenomenon where the normally narrow and fast-flowing bands of air in the upper atmosphere, develop pronounced wave-like patterns. Instead of flowing in a relatively straight path from west to east, these air currents undulate north and south in large arcs, called Rossby waves.

- **Mechanism Behind Meandering**
  - The **conservation of angular momentum** plays a key role in the meandering of jet streams. As air moves from the equator towards the poles, the Earth's rotation causes it to curve due to the **Coriolis effect.** However, due to the conservation of angular momentum, air masses near the poles must move faster (as they are closer to the Earth's axis), while those near the equator move slower. This differential velocity creates **instabilities** in the jet stream, leading to meanders or **Rossby waves.**
  - Jet streams can meander in response to **temperature differences** caused by changing seasons, mountain ranges, and other climatic variations.
  - **Mountains** (e.g., the Rockies or Himalayas) and **large-scale ocean currents** can disrupt the flow, causing jet streams to bend and shift their path.

Impact of Meandering:

- **Climate Impact**
  - **Heatwaves:** When the jet stream shifts northward and stays locked in a position, it can lead to prolonged periods of **hot, dry conditions** (e.g., heatwaves in North America and Europe). The warmer air is trapped in regions, and precipitation is suppressed, leading to droughts.
  - **Cold Waves:** Conversely, when the jet stream dips southward, it can bring **cold Arctic air** down into temperate regions, leading to severe cold waves (e.g., Canada and the northern United States). This results in a sharp drop in temperatures and heavy snowfalls.
- **Climate Change and Meandering**
  - Climate change is affecting the **stability** of jet streams. As the **Arctic warms faster than the tropics,** the **temperature gradient** between the polar and tropical regions weakens, slowing down the jet stream. This can lead to **more meandering** and slower-moving jets, causing longer and more extreme weather patterns—like extended heatwaves or deep cold spells—because the jet stream no longer moves as swiftly to shift air masses.
- **Impact on Polar Stratospheric Clouds and Ozone Depletion**
  - The meandering of the polar jet stream also affects the **polar stratospheric clouds (PSCs),** which form at extremely low temperatures in the stratosphere. When the jet stream is weak or meandering, **cold air** can become trapped, leading to **extended periods of cold** and conditions favorable for the formation of these clouds. PSCs contribute to **ozone depletion** because they provide a surface for reactions that break down ozone molecules, thus accelerating ozone depletion.

CLASSIFICATION OF WINDS

Planetary/ Permanent Winds	Periodic Winds (meso scale)	Local Winds	
		Hot Winds	Cold Winds
• Trade winds • Westerlies • Polar easterlies	• Monsoon • Land and Sea Breezes • Mountain & Valley winds	• Loo • Foehn • Chinook • Zonda	• Bora • Pampero • Gregale • Tramontane • Mistral

Planetary Winds

The pattern of the movement of the planetary winds is called the general circulation of the atmosphere. It also sets in motion the ocean water circulation which influences the earth's climate. They blow in the same direction throughout the year.

There are 3 types of planetary wind:

- **Trade winds or Easterlies:** Blow from **sub-tropical high-pressure** belt towards **equatorial low-pressure** belt.
  - Because of the Coriolis effect, trade winds in the **northern hemisphere** move away from the subtropical high towards the equatorial low in **north-east direction (North East Trade Winds).**
  - In the **southern hemisphere,** they diverge out of the subtropical high towards the equatorial low in **south-east direction (South East Trade Winds).**

- Blow mainly from the east, so also known as **Tropical easterlies.**
- In the tropical zone, the western sections of the oceans are warmer than the eastern sections owing to the influence of trade winds. **[UPSC-2021]**

- **Westerlies:** Blow from **sub-tropical high-pressure** belt towards **sub polar low-pressure** belt. The winds which blow between 30 N and 60 N latitudes in northern hemisphere and Between 30 S and 60 S latitudes in southern Hemisphere throughout the year are known as westerlies. In India, the moist air masses that cause winter rains in North-Western region of India are part of westerlies. **[UPSC-2015]**
  - Deflected to the right in the **northern hemisphere** and thus blow from the **south-west**.
  - Deflected to the left in the **southern hemisphere** and blow from the **north-west**.
  - **Westerlies** of the **Southern hemisphere** are **stronger** (known as **Roaring forties, Furious fifties, and Screaming sixties**) and more **consistent** in direction due to the predominance of water (lower resistance). **[UPSC-2011]**
  - In the temperate zone, westerlies make the eastern sections of oceans warmer than the western sections. **[UPSC-2021]**

- **Polar Easterlies:** Blow from **polar high-pressure** belt towards **subpolar low-pressure** belt.
  - In **northern** hemispher**e:** From **north-east to southwest** & in **southern hemisphere:** From **south-east to northwest.**

Periodic Winds

The direction of these winds changes with the change of seasons. Monsoon winds are the most important periodic winds. **E.g., land and sea breeze, mountain and valley breeze.**

- **Land and Sea Breezes:** Due to **differential heating of land and water** a pressure gradient is created causing **Sea breeze during day** and **land breeze during nights.**
  - **Day time: Land heats up faster** than the sea; pressure gradient is from the sea to the land.
  - **Night time: Land loses heat faster** than the sea; pressure gradient is from the land to the sea,
- **Mountain and Valley Breezes:** Due to **differential heating of mountains and valleys** and **radiational loss** of heat from mountain slopes at night, a pressure gradient is created, causing **valley breeze during day and mountain breeze during night.**
  - Daytime heating up of mountain slopes and high pressure in the valley setting up a **Valley breeze**.
  - **At night**, as slopes cool, **dense air descends** into the valley.

Local winds

Local differences in temperature and pressure produce local winds. Such winds are local in extent and are confined to the lowest levels of the troposphere.

Fig. Local Winds of World (Warm and Cold not specified)

Cold Winds

- **Pampero:** A west or southwest wind in **Southern Argentina**.
- **Bora: Cold, dry wind;** Blows from **Hungary to North Italy.**
- **Mistral:** Very **cold and dry** with a **high speed,** channelled through the **Rhine valley.** It brings **blizzards into southern France**

Warm Winds

- **Loo: Harmful** and **Warm** wind in the plains of **northern India and Pakistan.**
- **Chinook: Warm** and **beneficial** wind; Moves down the **eastern slopes of the Rockies (U.S.A. and Canada)**. It is beneficial to ranchers east of the rockies as it keeps the grasslands clear of snow during much of the winter.
- **Sirocco:** Warm and harmful wind
  - A **Mediterranean wind** that comes from the **Sahara** and reaches hurricane speeds in **North Africa and Southern Europe**.
  - Causes **dusty dry conditions** along the northern coast of Africa, **storms** in the Mediterranean Sea and **cool wet weather** in Europe.
- **Foehn or Fohn**: **Hot** and **beneficial** wins in **Alps**.
  - A strong, gusty, dry and warm wind that develops on the **leeward side of Alps**.
  - Helps animal grazing by **melting snow** and aids in **ripening of grapes**.

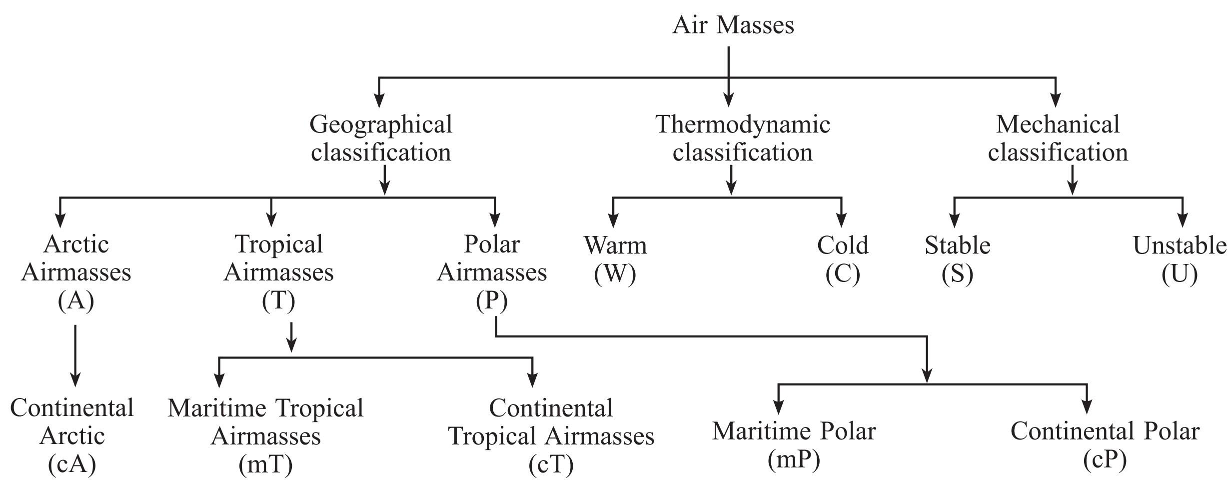
AIR MASSES

A large body of air having distinctive characteristics in terms of temperature and humidity **with little horizontal variation,** originating over areas known as **source regions.**

Source Region

When air remains over a **homogenous area** for a sufficiently long time, it acquires the **characteristics of the area**. These are known as Source Regions.

- It imparts **heat and moisture characteristics** to the overlying air mass.
- This can be the vast **ocean surface** or vast **plains** and **plateaus**.
- There **are no major source regions in the mid-latitudes** as these regions are dominated by cyclonic and other disturbances.



Types of Air Masses

- **Cold Air Mass:** Air Mass which is **colder** than the underlying surface. E.g., **Air mass over Siberia is not cold for Siberia**. This air mass might be cold air mass for the warmer regions down south.
- **Warm Air Mass:** Air Mass which is **warmer** than the underlying surface. E.g., Air mass over Siberia might be warm air mass for the Arctic region.

Types of Air Masses		
Air Mass Type	**Source Region**	**Characteristics**
Continental Polar (cP)	Cold, dry land areas	Cold and dry, frigid temperatures, low humidity
Continental Tropical (cT)	Hot, desert regions	Hot and dry, high temperatures, low humidity
Maritime Polar (mP)	Cold oceanic regions	Cool and moist, cool to cold temperatures, moisture
Maritime Tropical (mT)	Warm oceanic regions	Warm and humid, warm temperatures, higher humidity
Continental Arctic (cA)	Polar regions	Extremely cold and very dry, bitterly cold, dry
Continental Equatorial (cE)	Desert regions near the equator	Extremely hot and dry, scorching temperatures, low humidity

Fronts

Front is a three dimensional **boundary zone** between **two converging air masses** with **contrasting physical properties** like temperature, humidity etc.

- Commonly formed in the **middle** and **higher latitudes** (40°- 65° latitudes) where warm and moist subtropical air masses come in contact with cold and dry polar air masses.
- **Process of formation** of a front is known as **Frontogenesis** and it involves convergence of two distinct air masses.
- **Dissipation/weakening** of the front is known as **Frontolysis** where one of the air masses overrides another.
- In the **northern hemisphere** Frontogenesis happens in an **anticlockwise** direction (**clockwise** in the **southern hemisphere**) due to Coriolis Effect.
- It is the reason for the formation of **temperate cyclones** in mid latitudes.

Types of Fronts based on the mechanism of **frontogenesis**

- **Stationary Front:** Air masses are not moving against each other; Wind motion is parallel to the front.
- **Cold Front:** Transition zone where an advancing cold dry air mass violently displaces a warm moist air mass; Cold air advances toward warm air; more steep.
  - **Cumulonimbus** clouds are formed resulting in heavy rainfall.
  - Thunderstorms and tornadoes (e.g in the USA) are common features in warm sectors of cold front.
- **Warm Front**: Warm air advances toward cold air and makes a gradual front; less steep.
  - Causes moderate to gentle precipitation over a large area
- **Occluded Front:** When a cold air mass overtakes a warm air mass and goes underneath it. Warm air mass is lifted entirely off the land surface

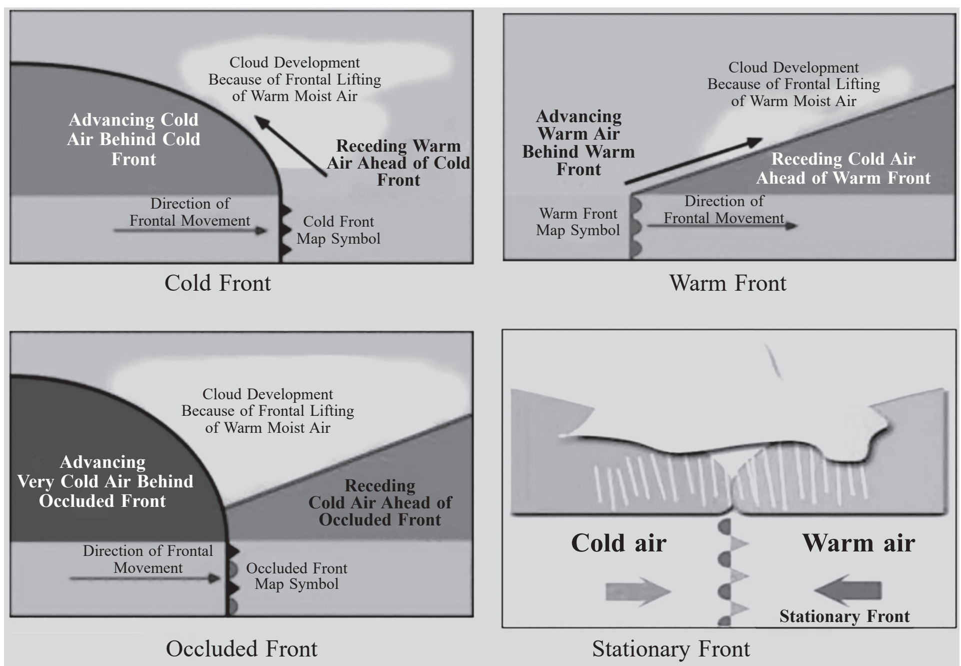


Fig. Types of Fronts

CYCLONES: TROPICAL AND TEMPERATE

A cyclone is a large-scale air mass rotating around a strong centre of low atmospheric pressure. Cyclones can be classified on the basis of their origin into tropical and extratropical cyclones.

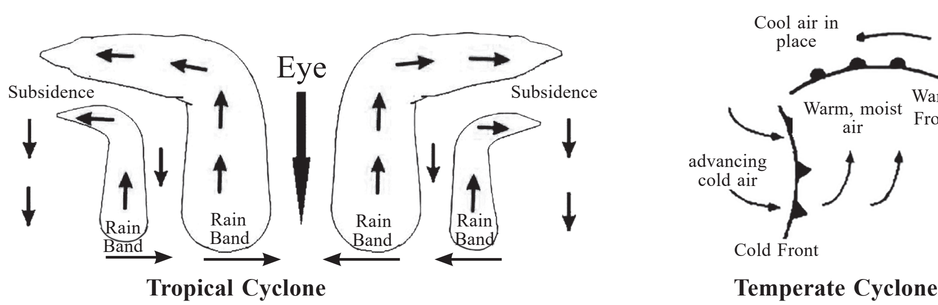


Fig. Types of Cyclones

- Wind circulation **around a low pressure system** is called **cyclonic circulation** and around a **high pressure system** is called **anticyclonic circulation**.

Pressure System	Pressure Condition at the Centre	Pattern of Wind Direction	
		Northern Hemisphere	Southern Hemisphere
Cyclone	Low	Anticlockwise	Clockwise
Anticyclone	High	Clockwise	Anticlockwise

Temperate Cyclones

The low-pressure systems developing in the **mid and high latitude**, beyond the tropics are called the **Temperate/ Extra-Tropical/ Mid-Latitude/ Frontal/ Wave** Cyclones.

- Most commonly formed at the **polar fronts**, where **warm and moist** air masses meet **cold and dry** air masses from poles.
- Occur mostly in winter, late autumn and spring.
- They stretch over **large areas** under the influence of westerlies.
- Approach of a temperate cyclone is marked by fall in temperature and pressure and a thin veil of cirrus clouds.
- These cyclones move from west to east under the influence of **westerlies**.
- The **western disturbances** arriving in North West India during winter are remnants of such cyclones.

Process of Formation

- Pressure drops along the polar front initiates an **anticlockwise cyclonic circulation**.
- Warm air (from the south) moves northward, and cold air (from the north) moves southward.
- This circulation forms a well-developed **extratropical cyclone** with a warm and cold front.
- The cold air pushes the warm air upwards from underneath, resulting in **cloud formation and precipitation** ahead of the warm front.
- As the cold front displaces the warm air, **occlusion** occurs, leading to cyclone dissipation.

Tropical Cyclones

They are strong **low pressure** centres that originate over **oceans** in **tropical areas** and move over to the coastal areas bringing about large scale destruction due to violent winds, very heavy rainfall (torrential rainfall) and storm surge.

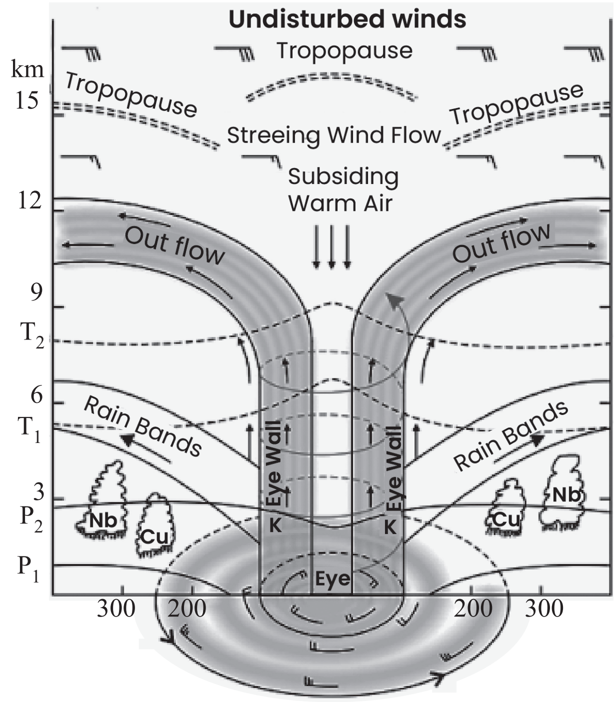


Fig. Vertical Section of Tropical Cyclone

- **Violent storms; Originate** over oceans in tropical areas.
- **Compact size**, ranging from 80 - 2000 km in diameter.
- A roughly circular **calm** area of comparatively **light winds** and **fair weather** at the centre is known as the **Eye** of the cyclone. It has **lowest surface pressure** and **warmest temperatures** and **air descends** at the centre.
  - The eye **temperature may be 10°C warmer or more at an altitude of 12 km** than the surrounding environment, but **only 0-2°C warmer at the surface** in the tropical cyclone. **[UPSC 2020]**
- Eye is surrounded by the **eye wall** with **strong spiraling ascent of air** where **winds** blow the **fastest** resulting in **torrential rains**.
- **Latent heat of evaporation** released by the condensation of moist rising air over oceans is the driving engine for tropical cyclones.
- They **dissipate** after they make **landfall** because the latent heat of evaporation is not available (moisture supply is cut-off).
- They move in a parabolic path towards the **west under the influence of trade winds**.
- **Different names: Cyclones** (Indian Ocean), **Hurricanes** (Atlantic), **Typhoons** (Western Pacific and South China Sea; Philippines islands, eastern China and Japan), and **Willy-willies** (North West Australia).
- **Favourable Conditions** for the formation
  - Large **sea surface** with **temperature> 27° C;**
  - Presence of the **Coriolis force**;
  - Small **variations** in the **vertical wind speed;**
  - A **pre-existing weak low-pressure area** or low-level-cyclonic circulation and
  - **Upper divergence above** the **sea level system.**

- In the **South Atlantic** and **South-Eastern Pacific** regions in tropical latitudes, cyclones **do not originate** because of **low sea surface temperatures.** **[UPSC 2015]**

Characteristic	Tropical Cyclone	Temperate Cyclone
Origin	Thermal Origin	Dynamic Origin - Coriolis Force, Movement of Air Masses
Latitude	10-30° N and S of the equator	35-65° N and S of the equator. More pronounced in Northern hemisphere due to greater temperature contrast
Frontal System	Absent	Formation due to frontogenesis
Formation	Forms at sea (>26-27°C); dissipates on land	Can form on land and seas
Season	Seasonal: Late summers (Aug-Oct)	Irregular, fewer in summers, more in winters
Size	Limited to smaller area: 100-500 km diameter	Larger area: 300-2000 km diameter
Shape	Elliptical, Anvil Shaped	Inverted 'V' (middle latitude cyclones)
Rainfall	Heavy but short-lasting	Slow, continuous rainfall for days or weeks
Wind Velocity	Much greater (100-250 kmph)	Comparatively low (30-150 kmph)
Isobars	Complete circles, steep pressure gradient	'V' shaped, low pressure gradient
Lifetime	Lasts <1 week	Lasts 2-3 weeks
Path	East to West (Trade Winds)	West to East (Westerlies)
Calm Region	Eye at the center, calm region with no rainfall	No single region with inactive winds or rains
Driving Force	Energy from latent heat of condensation	Energy depends on air mass densities
Influence of Jet Streams	Relationship with upper-level airflow less clear	Distinct relationship with upper-level airflow (Jet streams, Rossby waves)
Clouds	Few varieties (cumulonimbus, nimbostratus)	Variety of cloud development at various elevations; occluded front clouds
Influence on India	Affects both coasts; East coast more impacted	Brings rains to North-West India; associated with 'Western Disturbances'

Special Cyclones

- **Twin Cyclones**
  - Twin cyclones refer to two tropical cyclones that form and interact in the same region, typically on either side of the equator, within a similar longitude but in opposite hemispheres.
  - **Cause:** Twin cyclones are caused by Equatorial Rossby waves. Equatorial Rossby waves are long, low-frequency water waves that occur near the equator. They are also known as planetary waves and are a type of inertial wave that form due to the Earth's rotation.

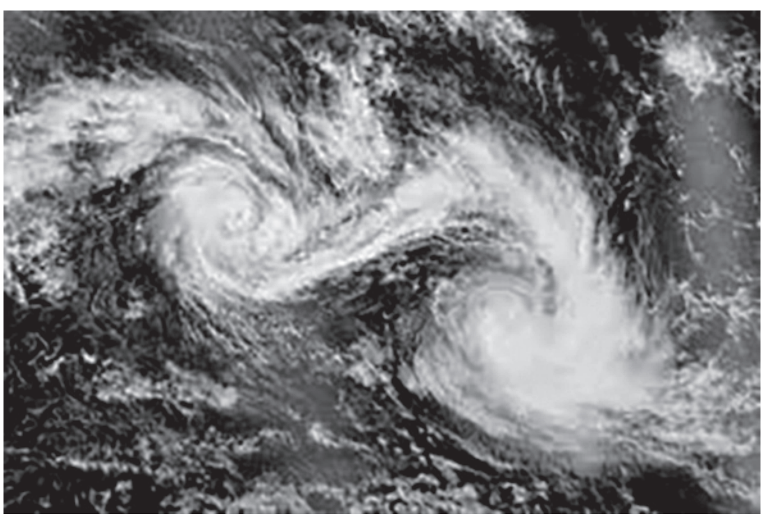


Fig. Twin Cyclones

- **Characteristics:**
  - Twin cyclones often develop around the **same time** due to a common disturbance, such as a large-scale atmospheric wave near the equatorial region.
  - They have **opposite rotations,** in the Northern Hemisphere, cyclones rotate counterclockwise.
  - Whereas in the Southern Hemisphere, they rotate clockwise. This is due to the Coriolis effect acting in opposite directions on either side of the equator.
  - They are typically **mirror images** in terms of structure and intensity due to the similar atmospheric conditions in both hemispheres.
- **Favourable Conditions:** Positive vorticity, air lifting, warm ocean (>27°C), low wind shear.
- **Development:** Starts as tall vortices, intensifies and moves westward.
- **Fujiwhara Effect:**
  - **Definition:** Interaction between simultaneous tropical storms within 1,400 km. It is to be noted that both cyclones here have same direction of spinning vortices unlike twin cyclones
  - **Impact:** Alters track and intensity; can lead to merging.
- **Bomb Cyclone**
  - **Characteristics:** A bomb cyclone is a rapidly intensifying mid-latitude storm system characterized by a dramatic drop in atmospheric pressure of at least 24 millibars within 24 hours. This process is called explosive cyclogenesis.

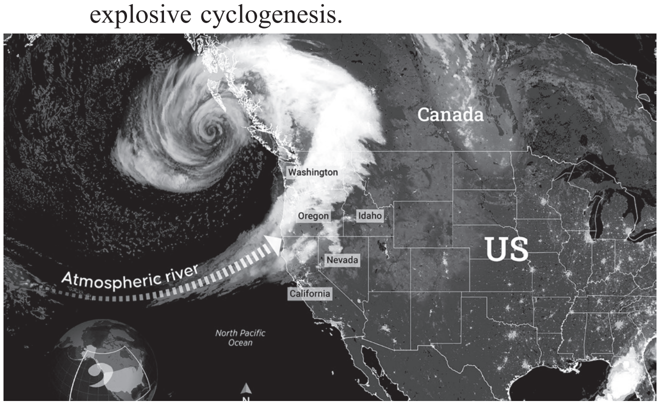


Fig. Bomb Cyclone

  - **Genesis:** Forms at the boundary between warm, moist air from the tropics and cold, dense polar air. Intense pressure gradients generate strong winds, warm air rises rapidly, causing the system to intensify.
  - **Areas:** Common on the US coast, colder months. The 2018 "Bomb Cyclone" in the northeastern U.S caused significant snow and hurricane-strength winds.

THUNDERSTORMS AND TORNADOES

Thunderstorms and tornadoes are brief but highly destructive, typically limited to a small area.

- **Thunderstorms:** A well grown cumulonimbus cloud producing thunder and lightning. **[UPSC-2013]**
  - Caused by **intense convection** during **hot, humid conditions.**
  - **Short duration** occurring over a **small area**; **Violent upward movement of air and water Particles** .
  - When these clouds reach altitudes with **sub-zero temperatures**, hailstones form and fall as **hailstorms**. In cases of limited moisture, dust storms are created.
- **Tornadoes:** Sometimes **severe thunderstorms** generate a spiralling wind with **very low pressure at the center that descends** like the trunk of an elephant, causing massive destruction on its way; generally occur in **middle latitudes**; tornadoes over the sea are called **waterspouts**.

Polar Vortex

Polar vortex is a large area of **low pressure** and cold air surrounding both of the Earth's poles.

- It always exists **near the poles**, but weakens in summer and **strengthens in winter**.
- It is **counter-clockwise** flow of air that helps keep the colder air near the Poles.
- It is usually contained above the poles by the **polar front jet streams**.

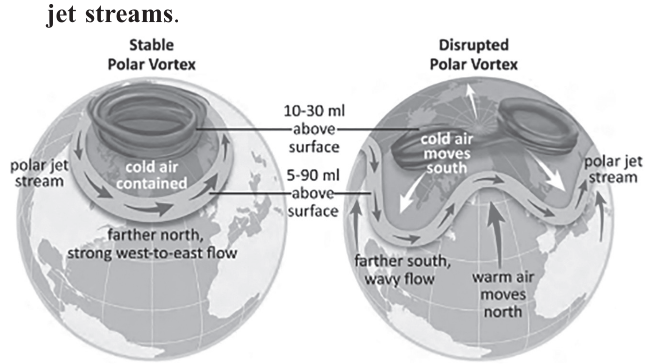


Fig. Stable (Left) and Disrupted (Right) Polar Vortex

In winters, the vortex becomes stronger and bigger in extent and the polar front jets also shift towards the Equator. As a result, a part of the polar vortex may split and intrude into the mid latitudes, called **Polar Outbreak**, bringing extremely cold weather there. E.g. **large outbreaks of Arctic air in the United States.**

WATER IN THE ATMOSPHERE

The continuous transformation and circulation of water among oceans, the atmosphere, and land is referred to as the water or hydrological cycle.

Humidity

Water vapour present in the air is known as humidity.

- **Absolute Humidity:** The actual amount of water vapour present in the atmosphere; represents the **mass of water vapour per unit volume of air**; measured in **grams per cubic meter**. It depends entirely on the temperature of the air (Greater over the ocean and less over the continent).

- **Relative Humidity:** Percentage of moisture present in the atmosphere as compared to its full capacity at a given temperature.
- **Specific Humidity: It** is the mass of water vapour per unit mass of air. It is preferred over Absolute Humidity as it doesn't change with changes in the condition of temperature & pressure.
- **Saturated Air (100% RH):** Holds maximum moisture at that temperature; any moisture in excess causes condensation. Saturation is achieved by raising absolute humidity (adding moisture) or lowering temperature**.**
- **Unsaturated Air (<100% RH):** Holds moisture below max capacity; can absorb more without saturation.
- **Dew Point:** The **temperature** at which **saturation** occurs in a given sample of air.

EVAPORATION AND CONDENSATION

Evaporation

The process by which water is transformed **from liquid to gaseous state**.

- **Latent Heat of Vaporisation:** The **amount of heat** that is required to **convert a unit mass of liquid substance** into a **gaseous phase** at **constant temperature** conditions.
- **Factors influencing evaporation**
  - **Higher temperatures** lead to **increased water absorption and retention capacity** in a given volume of air.
  - **Air with a lower moisture content** has the **ability to absorb and retain** moisture. The movement of air replaces saturated air with unsaturated air, which promotes evaporation. Consequently, **greater air movement** results in **higher rates of evaporation.**
- **Evaporation Variability:** Factors like temperature, air pressure, wind, and water salinity impact evaporation rates. Globally, **oceans have higher evaporation** due to extensive coverage. Evaporation **decreases from equator to poles**. The western North Atlantic shows the highest rates.

Condensation

Process of transformation of water vapour into water; caused by the **loss of heat.**

- **Sublimation:** Process of condensation of **water vapour directly into the solid form**.
- **Conditions for Condensation**
  - Temperature of the air reduced to dew point with its volume remaining constant.
  - Both the volume and the temperature are reduced.
  - Moisture is added to the air through evaporation.
- **Condensation Nuclei:** Small particles in the atmosphere that provide surfaces for water vapour to condense. E.g., Dust, smoke, pollen, and salt;
- **Factors Influencing Condensation:** Air movement, Lower temperature, Higher humidity, altitude and Pressure changes.

Forms of Condensation

When **Dew Point > Freezing Point**: Outcomes are **Dew, fog, and clouds** and

When **Dew Point < Freezing Point**: Outcomes are **White frost, snow, hailstones and cirrus clouds**.

- **Dew:** When the moisture is deposited in the form of water droplets **on cooler surfaces of solid objects** (rather than nuclei in air above the surface);
  - **Dew point** is **above** the **freezing point = Formation of Dew** (**Dew point < Freezing point = Formation of frost).**
  - **Ideal conditions** for Dew **formations: Clear sky** as clouds will reflect back the long wave radiations coming out of the earth's surface thus keeping the earth warm**, calm air, high relative humidity, and cold and long night**. **[UPSC 2019]**
  - Ideal conditions for the formation of **white frost**: Same as those for the formation of dew, except that the **air temperature must be at or below the freezing point**.
- **Fog:** Essentially a **cloud** that **forms either at or extremely close to the Earth's surface.**
  - Occurs when the **temperature of an air mass** with a substantial amount of water vapour, **suddenly drops**, leading to **condensation** on tiny dust particles **within the air mass itself**;
  - Prevalent in areas where warm currents of air come in contact with cold currents; fog is **drier than the mist**.
  - **Ideal Conditions:** High humidity, dew point, presence of condensation nuclei.
  - **Types of Fog:**
    1. **Cooling fogs - Radiation fog:** Formed due to night cooling.
    2. **Advection fog:** When warm air moves over cold surface.
    3. **Upslope fog:** When air rises over a slope, orographic lifting.
    4. **Evaporation fogs - Steam fog:** Forms over warm water, common over lakes.
- **Mist:** More moisture content than fog; Occurs in moist air (>75% humidity); short-lived; Common over mountains.
- **Haze:** Reduced visibility; Linked to low humidity (<75%); Caused by uneven light refraction and industrial particles.
- **Smog:** Combination of **smoke and fog**; caused due to Urban/industrial air pollution; Greyish, brownish, hazy appearance; 3 Types**:** Classical (London), Photochemical (Summer/Los Angeles) and VOG (Volcanic Smog)
  - **Classical Smog:** Caused by coal combustion, high concentration of **sulphur dioxide and particulate matter**; Weather conditions**:** Cold and humid climate.

- **Photochemical Smog:** A mixture of pollutants that are formed when **nitrogen oxides and Volatile Organic Compounds (VOCs) react to sunlight,** creating a **brown haze**; Creates secondary pollutants**:** **Ozone**, PAN, and, aldehydes.
- **VOG (Volcanic Smog):** From volcanic eruptions; hazy mixture of **SO_2 gas and aerosols**.

CLOUDS

- A cloud is a collection of small water droplets or tiny ice crystals (0.02 mm) that result from the condensation of water vapour in the open atmosphere at a significant altitude.
- They have a dual impact: **Cooling** (reflecting sunlight) and **warming** (trapping heat).

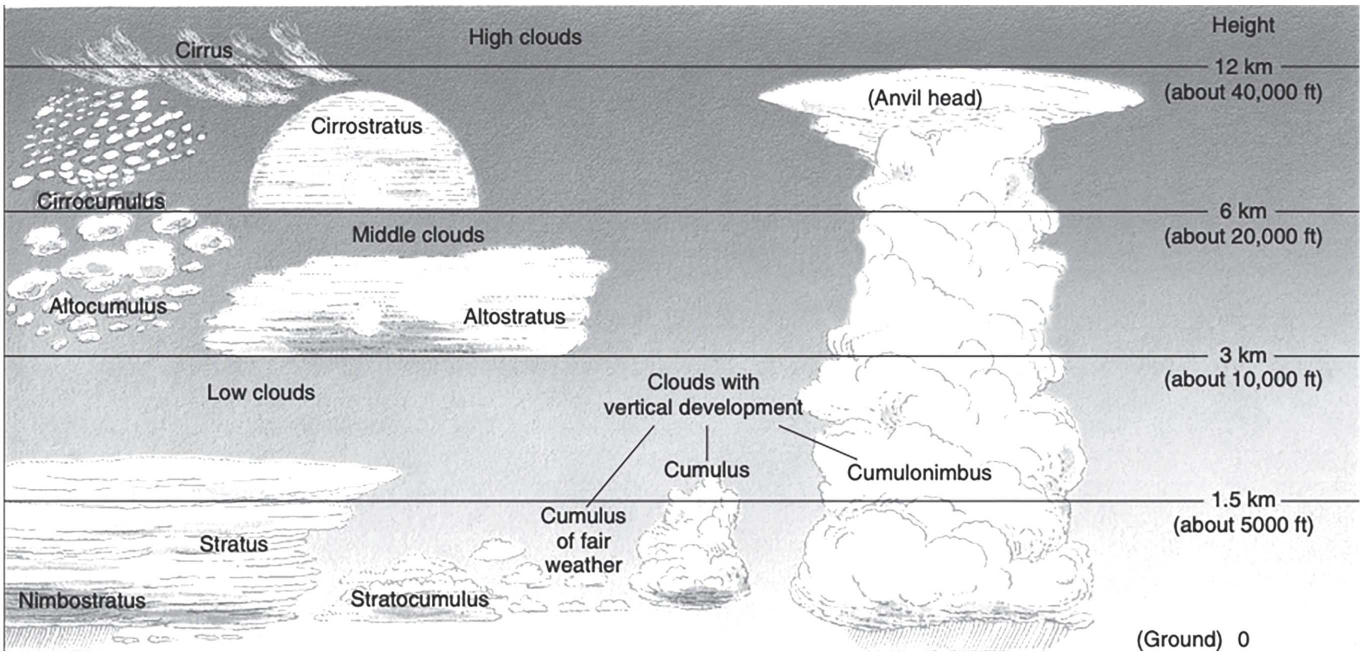


Fig. Classification of Clouds

Types of Clouds

- **Cirrus:** They are thin, separate clouds with a delicate, **feather-like appearance**.
  - Develop at elevated heights (8,000 to 12,000 m).
  - Always white and composed of ice crystals.
- **Nimbus:** Formed at intermediate altitudes or extremely close to the Earth's surface with no specific shape
  - Have a dark, black, or deep grey colouration.
  - Possess an **exceptionally dense and sun-blocking opacity.**
  - They are **shapeless masses of thick vapour.**
  - **Cumulonimbus**, with its strong vertical updraft, extends well into the high level of clouds.
- **Stratus:** Extensive, layered clouds that envelop significant sections of the sky. Generally formed either due to loss of heat or the mixing of air masses with different temperatures.
- **Cumulus:** Cumulus clouds look like **cotton wool** and have a **flat base**. Generally formed at a height of **4,000 - 7,000 m** and exist in patches.

A combination of these four basic types can give rise to the following types of clouds**:**

- **High clouds:** Cirrus, cirrostratus, cirrocumulus;
- **Middle clouds:** Altostratus and altocumulus;
- **Low clouds:** Stratocumulus and nimbostratus;
- **Clouds with extensive vertical development:** Cumulus and cumulonimbus.

Other Clouds

- **Lenticular Clouds:** Formed by **wavy airflow** around obstacles, with a lens or saucer-like shape and defined edges; formation involves **wave development, adiabatic cooling, condensation, and evaporation**; crucial indicators of **turbulence** for pilots.
- **Polar Stratospheric Clouds (PSCs):** Formed in winter in the polar stratosphere (15,000-25,000 meters) with a composition of **ice crystals and liquid droplets**, displaying an iridescent, **mother-of-pearl appearance**.
- **Noctilucent Clouds (NLCs):** Formed in the **Mesosphere** (80-90 km); Earth's highest clouds; composed of **ice crystals**; visible only at night and illuminated by scattered sunlight, known as "**night-shining clouds**."

Thick, low clouds mainly **cool down** the **Earth's surface** by **reflecting solar radiation**. **High, thin clouds** in addition to **transmitting incoming solar radiation** also **retain part of the outgoing infrared heat** that the Earth emits and reflect it back downward, **warming the Earth's surface.** **[UPSC 2022]**

PRECIPITATION

Precipitation refers to the release of moisture that occurs after the condensation of water vapour.

- **Rainfall**: Precipitation in the form of liquid water.
- **Snowfall:** When the temperature is below freezing point, precipitation takes the form of fine **snowflakes.**
- **Sleet:** Consists of frozen raindrops or refrozen melted snow-water; Occurs when there's a layer of air with a temperature above freezing point overlying a sub-freezing layer near the ground.

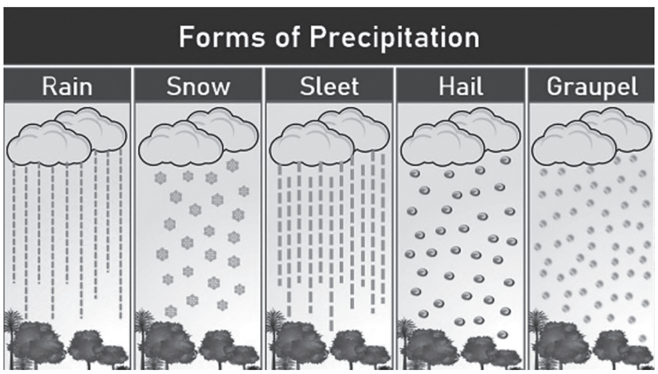


Fig. Forms of Precipitation

- **Hailstones:** Formed when rainwater droplets solidify into small, rounded pieces of ice while passing through colder layers; Typically have multiple concentric layers of ice.
- **Freezing Rain:** Drizzles or light rains occurring below 0° C temperature and being frozen before reaching the ground.
- **Virage:** Raindrops evaporate before reaching Earth in dry air.
- **Graupel:** forms where supercooled water droplets (water below 0°C that remains liquid) freeze onto the surface of a snowflake as they come into contact.

Types of Rainfall

- **Convectional Rainfall**
  - Warm air rises due to **convection currents,** expands, cools down, and subsequently undergoes condensation, resulting in the formation of cumulus clouds & precipitation.
  - Prevalent during the **summer or in the warmer hours of the day.**

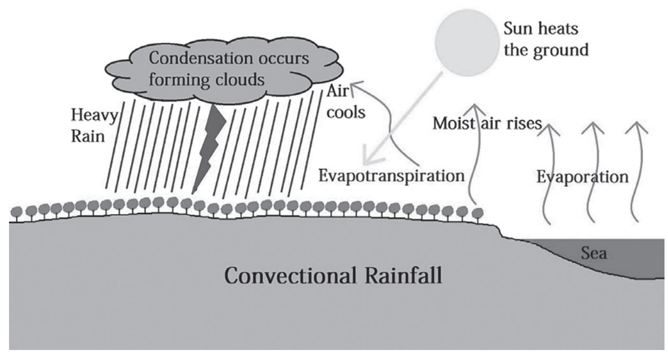


Fig. Convectional Rainfall

  - Particularly common in **equatorial regions and the inner regions of continents**, **especially** in the **northern hemisphere**.
  - Heavy rainfall accompanied by thunder and lightning occurs, but it tends to be of shorter duration.
- **Orographic Rainfall (Relief Rainfall)**
  - Occurs when a moisture-saturated air mass encounters a mountain and is compelled to rise. With ascendance, adiabatic expansion and cooling takes place resulting in condensation and precipitation.

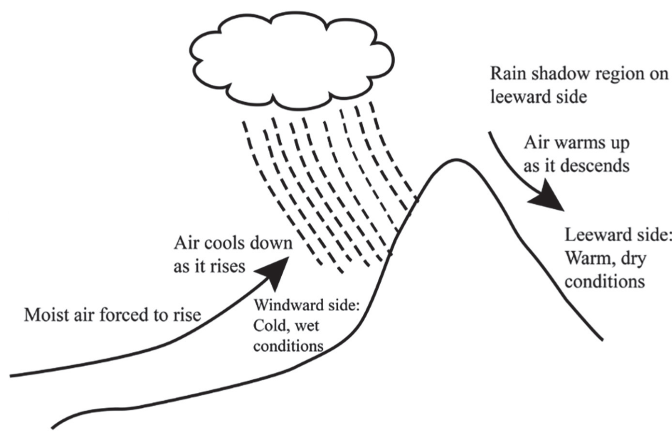


Fig. Orographic Rainfall

  - More rainfall towards windward slopes, while on the leeward side (rainshadow area), adiabatic heating (temperatures increase) takes place, allowing for greater moisture absorption and resulting in dry conditions without rain.
  - Area situated on the leeward side is known as the rain-shadow area.
- **Cyclonic Rainfall**
  - Widespread precipitation associated with weather fronts and cyclones; includes **tropical and extra-tropical cyclonic rain.**

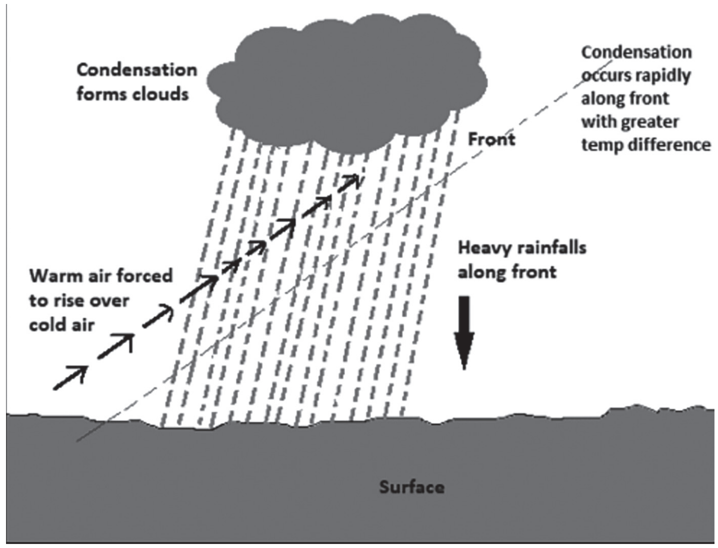


Fig. Cyclonic Rainfall

World Distribution of Rainfall

- **Rainfall diminishes** steadily **from the equator towards the poles.**
- **Equatorial regions** receive consistent **year-round rainfall.**
- **Coastal areas** receive **more rainfall than inland regions**.
- Between latitudes **35° and 40° N and S, eastern coasts get heavier rainfall** due to **easterly winds,** decreasing westward. Between **45° and 65° N and S**, **westerly winds bring rainfall** first to western continental margins, **decreasing eastward.**

Rainfall Regions

- **Heavy Rainfall (greater than 200 cm annually):** Equatorial region; coastal monsoon region; Windward side of coastal mountains.
- **Moderate Rainfall (between 100 to 200 cm annually):** Adjacent regions of very heavy rainfall areas; Coastal regions in the warm temperate region.
- **Inadequate Rainfall (between 50 to 100 cm annually):** Eastern part of the continents in temperate regions; Interior of continents in tropical regions.
- **Low Rainfall (less than 50 cm annually):** Rain shadow regions; Western part of continents in tropical regions.

6 World Climate

WORLD CLIMATE AND ITS CLASSIFICATION

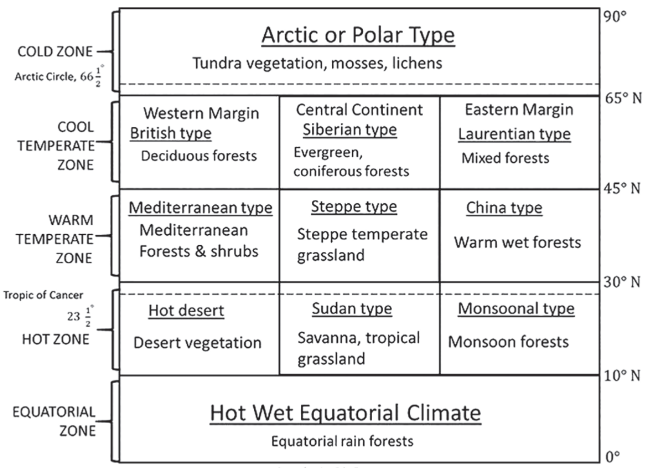


Fig. Climatic Regions of the World

HOT AND WET EQUATORIAL CLIMATE

Located **from 5° and 10° N and S** of the equator (in the lowlands of the **Amazon, the Congo, Malaysia and the Indonesia**). Away from the equator, the influence of the onshore trade winds gives rise to a modified type of equatorial climate with monsoonal influence.

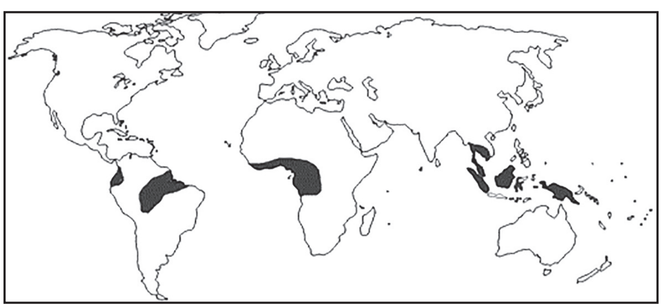


Fig. Equatorial Climate

Climate

- **Temperature: uniformly** high throughout the year with **average monthly temperatures** above **18°C,** mean annual temperature around **20°C**.
  - Cloudiness and heavy precipitation with thunder and lightning help to moderate the daily temperature. **[UPSC-2015]**
- **Precipitation: Heavy and well distributed** throughout the year, with average **above 200-250 cm; mostly convectional rain** and **orographic rainfall** in mountains.
- **No distinct dry season**; very high **Relative Humidity** (>80%).
- **Double rainfall peaks** coincide with the equinoxes in April & October

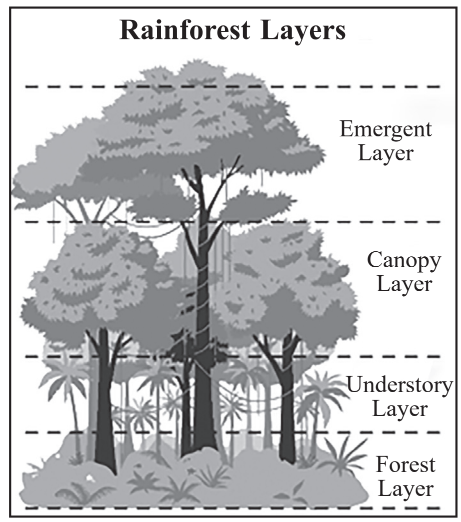


Fig. Rainforest Vegetation

Vegetation **[UPSC-2013, 2021]**

Tropical Evergreen Rainforest (Lungs of the Planet) with dense canopy cover **(Selvas in Amazon)**.

E.g., **mahogany, ebony**; Creepers - **epiphytes** & woody climbers like **'Lianas'; Lalang (tall grass).**

- **Distinct layer arrangement** in forests.
- **High Diversity: Trees** are **not** found in **pure stands** of a single species.
- **Soil:** Leaf litter decomposes faster than in any other biome and as a result the soil surface is often almost bare.
- A less luxuriant secondary forest called **Belukar** is also found.

Economic Activity

- Sparsely populated area with primitive people practising **hunting and gathering**;
- Shifting cultivation is practised here: **Ladang (Malaysia), Taungya (Burma), Tamrai (Thailand), Caingin (Philippines); Humah (Java); Chena (Sri Lanka); Milpa (Africa and Central America); Jhum (North-east India).**

- **Tropical hardwoods** make lumbering difficult.
- **Cocoa industry (Ghana, Cote d'Ivoire, Nigeria) [UPSC-2024] and Natural Rubber** and **Oil Palm** (Malaysia and Indonesia) are thriving here.
- Crops like **coconuts**, **sugar**, **coffee**, **tea**, **tobacco**, **spices**, **and sago** are cultivated.
- **Cobalt mining (Congo); Gold** mining in the Amazonian forests of Brazil and Peru.
- **Livestock Farming** in Africa is handicapped by **Tsetse** Flies that cause **Nagana**, a deadly disease.
- **Tribes: Pygmies (Congo Basin), Orang Asli (Malaysia).**

TROPICAL MONSOON CLIMATE

This climate is typically found in the latitudes from **5° to 30° N and S of the Equator**.

The region witnesses complete **seasonal reversal of winds**. Best developed in the **Indian subcontinent, Burma, Thailand, Laos, Cambodia,** parts of **Vietnam and south China** and **northern Australia** **[UPSC-2014]**

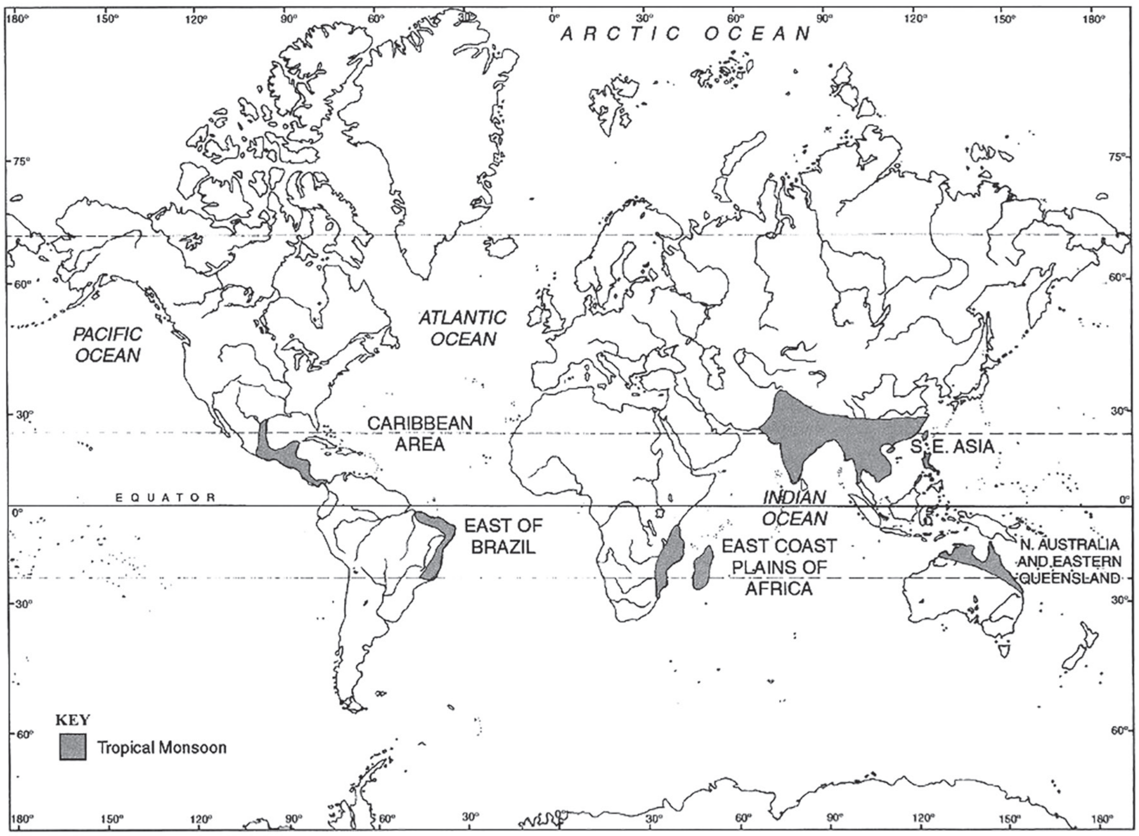


Fig. Tropical Monsoon Climate

Trade winds after crossing the equator are drawn towards the continental low-pressure area reaching the **Indian sub-continent** as the **South-West Monsoon.**

Climate

- **Temperature: Average monthly temperature > 18°C**, **Maximum temperature** can reach **45°C**; Average temperature in **summer** is around **30°C** and during winters is around **25°C**.
- **Seasons: Cool, dry season** (October to February); the **hot dry season** (March to mid June); the **rainy season** (mid June to September).
  - Concentrated heavy **rainfall** in **summers; Mean annual rainfall** is about **150 cm** but there are temporal and spatial variations.

Vegetation

- **Dry-deciduous** forests with **broad-leaved hardwood trees**. E.g., Teak.
- Less luxuriant than tropical forests with fewer species

Economic Activity

- Supports high-population density.
- **Subsistence farming** with **intensive cultivation** in regions with irrigation facilities.
- **Shifting cultivation** is followed in **North-East India** and **South-East Asian countries.**
- **Agriculture:** Wet paddy cultivation, lowland cash crops (sugarcane, jute, Indigo, cotton), Highland plantation crops (Tea, coffee, spices).
- **Cattle** and **sheep rearing is** prevalent.

TROPICAL MARINE CLIMATE

Climate is under the influence of the **on-shore Trade Winds** all the year-round. Experienced along the **eastern coasts of tropical lands: Central America, West Indies, north-eastern Australia, Philippines, parts of East Africa, Madagascar, Guinea Coast and eastern Brazil.**

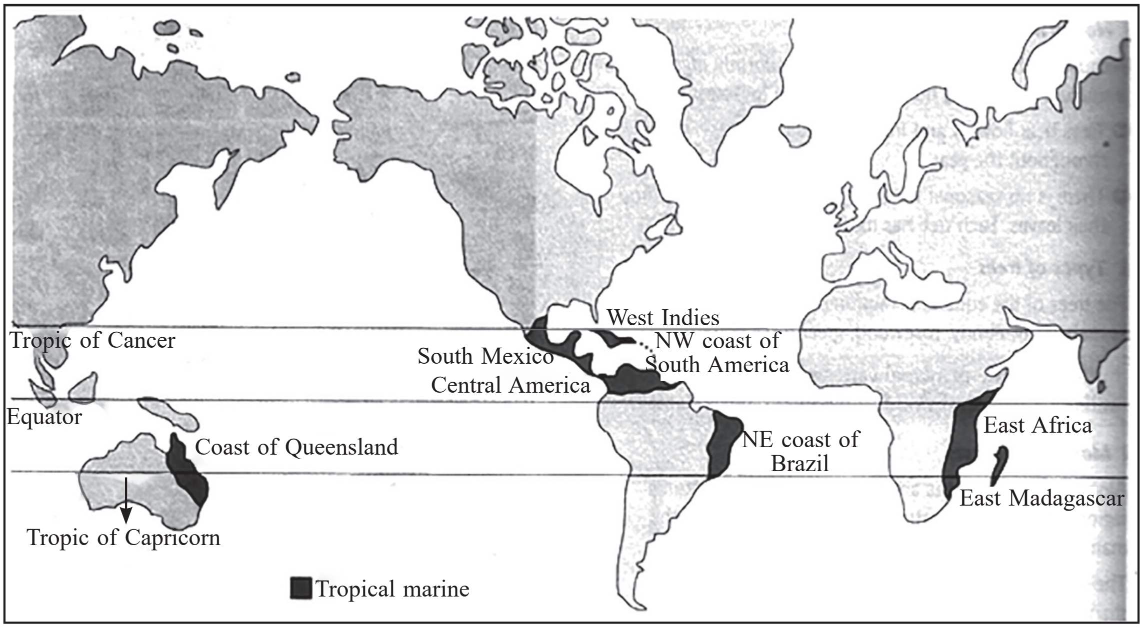


Fig. Tropical Marine Climate

Climate

- **Rainfall:** Rainfall (both orographic and convectional) is maximum in **summer**, but without any distinct dry period; Influence of onshore trade winds**.**
- Prone to severe tropical cyclones, hurricanes or typhoons.

Vegetation

- **Rainforests**, **mangroves**, and **coastal vegetation;** Constant moisture and warmth contribute to the growth of diverse plant species.

SAVANNA OR SUDAN CLIMATE

Transitional type found between the **equatorial forests and the hot deserts. It is confined within the Tropics i.e found between the Tropic of Cancer and Capricorn.**. Generally found in Africa (Sudan, East and Southern Africa), Australia, South America and some parts of India. In **South America: Llanos** of Orinoco Basin, **Campos** of Brazilian Highlands.

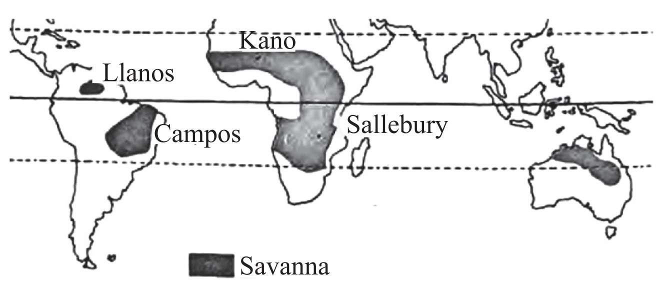


Fig. Tropical Savanna Climate

Climate

- **Temperature:** Mean annual temperature is **greater** than **18°C**; **extreme diurnal range** of temperature.
- **Rainfall: Alternate hot, rainy season and cool, dry season;** rainfall is concentrated in summer; A definite dry and wet season. Floods and droughts are common. Mean annual rainfall - 80-160 cm. **[UPSC-2012]**
- **Winds:** Prevailing winds are the **trade winds**. **Trade winds** bring **rains** to the **eastern coasts** but become dry by the time they reach the interiors of the continents.
  - **Harmattan,** meaning the doctor winds, are the dry local winds which blow from interior Africa to the Atlantic coast in Guinea and gives relief from hot & humid climate by increasing the rate of evaporation with resultant cooling effect.

Vegetation

Tall grass (elephant grass) and **short trees; deciduous trees** usually having broad trunks, with water-storing devices to survive (like acacia tree).

- Grasslands are called bush-veld or parkland.
- Trees decrease in height and density polewards.
- As the rainfall diminishes towards the desert the savanna merges into thorny scrub. In Australia, this scrubland is represented by species like: **Mallee, Mulga, Spinifex grass** etc;
- Many trees are **umbrella shaped**, exposing only a narrow edge to the strong winds.
- Tall Savanna grasses (elephant grass) have deep roots. It lays dormant during the cool, dry season.

Wildlife

The savanna is known as the **big game country** as thousands of animals are trapped or killed each year ; **Two main groups of animals-**grass-eating **herbivorous** animals and the flesh-eating **carnivorous** animals- found.

Tribes: Masai (Kenya and Tanzania), **Hausa** (Nigeria)

DESERT CLIMATE

Deserts are regions of **scanty rainfall** that may be **Hot** like the hot deserts of the Saharan type or **Temperate as are the mid-latitude deserts** like the Gobi.

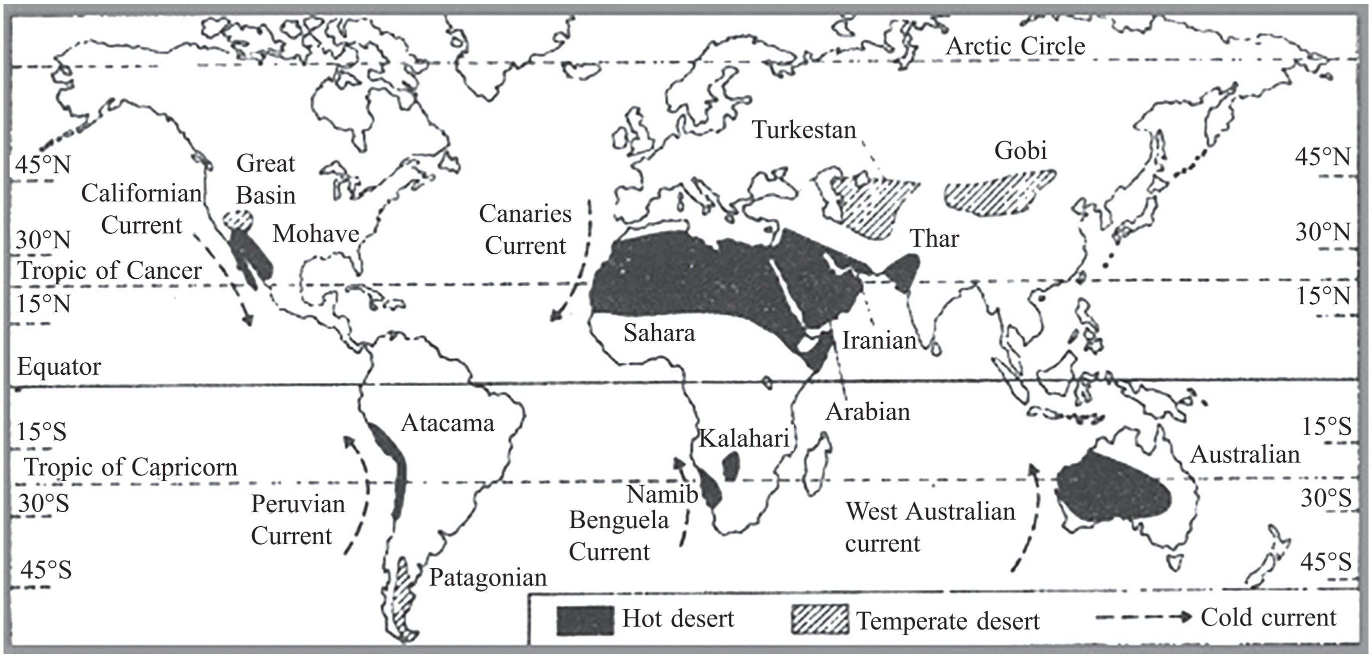


Fig. Hot and Temperate Desert

Hot Desert Climate

Major hot deserts of the world are **located on the western coasts** of the continent between 15° and 30° N and S.

- **Aridity** of the hot deserts is mainly due to the effects of **off-shore Trade Winds**; thus also called as **Trade Wind Deserts**.
- **Example: Sahara Desert, Great Australian Desert, Arabian, Iranian, Thar, Kalahari, Namib, Mohave, Sonoran, Atacama Desert.**

Climate Conditions in Hot Deserts (Trade Wind Deserts)

- Average summer temperature is around **30°C.**
- **Rainfall: scarce** (less than **25 cm**) and most unreliable.
- **Aridity is high** due to subtropical high-pressure belt (descending air), offshore trade winds, and desiccating effect of cold currents. **[UPSC -2011]**
- **Temperature: high throughout the year**. **Coastal deserts,** due to **maritime influence,** have much lower temperatures; desert interiors however experience much higher summer temperatures and winter months are rather cold.
- **Diurnal temperature range is very great, frost** may occur at **night in winters**. The annual range of temperature in the interior of the continents is high as compared to coastal areas because of the thermal difference between land and water **[UPSC-2013]**.

Mid-Latitude Desert Climates

Among the mid-latitude deserts (usually between **30°** and **50° N** and **S** of the equator), many are found on plateaus.

Climate Conditions in the Mid-Latitude Deserts

- They are cutoff from the rain-bearing winds; **Rainfall** less than **25 cm**.
- Occasionally depressions may penetrate the Asiatic continental mass or unexpected convectional storms may bring rain in summer and falls in winter.
- Rainless because of either **continentality (Gobi Desert)** or **rain-shadow effect (Patagonian Desert)**.
  - **Patagonian Desert** is drier due to its rain-shadow position on the leeward side of the **lofty Andes.**

Vegetation of Desert Climate

- Xerophytic/drought-resistant scrubs, grasses and plants.
- Most desert shrubs have long roots to gather moisture
- Few or no leaves; foliage is waxy, leathery, hairy, or needle-shaped to prevent moisture loss.

Economy of Desert Climate

- Gold mining in Great Australian Desert (e.g., Kalgoorlie, Coolgardie); Diamonds and copper in Kalahari; Sodium nitrate extraction in Atacama.
- North American deserts (silver in Mexico, uranium in Utah, copper in Nevada)
- Oil exploration in Sahara and Arabian Deserts (Saudi Arabia, Iran, Iraq, Kuwait, Algeria, Libya, Lebanon, Nigeria)
- **Tribes: Bedouin** (Arabs), **Bushman** (Kalahari), **Bindibu** (Australia), **Tuaregs** (Sahara), **Gobi Mongols** (Gobi)

WARM TEMPERATE WESTERN MARGIN (MEDITERRANEAN) CLIMATE

Confined to the **western portion of continental masses**, between **30 and 45 degrees north and south** of the equator. Basic cause of this type of climate is the **shifting of the wind belts.** Found in areas **around Mediterranean sea, central Chile, California, south- western tip of Africa, Southern and south west Australia.**

Fig. Distribution of Warm Temperate Western Margin Climate regions of the World

Climate

- **Temperature: Monthly average in summer is around 25° C and in winter below 10°C.**
- **Dry, warm summer** with **offshore trade winds,** a concentration of **rainfall in winter** with **on shore westerlies**; **annual precipitation** ranges between **35-90 cm**.
- **Local winds** around the Mediterranean Sea:
  - **Sirocco: Hot, dry, dusty wind** which originates in the Sahara Desert (Most frequent in spring).
  - Other names of **Sirocco: Chili (Tunisia), Ghibli (Libya), Leveche (Spain), Khamsin (Egypt), Gharbi (Adriatic and Aegean sea)**.
  - **Mistral: Cold wind** from the north, rushing down the Rhone valley France, intensified by the **funnelling effect** in the valley between the **Alps** and the **Central Massif** (Plateau in France).
  - **Bora: Cold north easterly wind** in Adriatic sea.
  - **Tramontane and Gregale: Cold winds** of Mediterranean sea.

Vegetation

Shrubs- **Maquis (South France), Macchia (Italy), Chaparral (California), Mallee (Eucalyptus) forests** in Australia, and Giant Sequoias or **Redwoods** in California; **Species** found include **Pines, Firs, Cedars**. Bushes and Shrubs are the most predominant type.

Economic Activity

- World's orchard lands: **Famous for citrus fruits- Sunkist oranges (California), Seville oranges (Spain), Jaffa oranges (Israel**) etc;
- Wine production: Viticulture is by tradition a Mediterranean occupation, **sherry (Wine from southern Spain), Port wine (Portugal), Chianti, asti and marsala (Italy), Champagne, Bordeaux and Burgundy (France).**
- Nut-bearing trees like **chestnuts, walnuts, hazelnuts**, and almonds.
- **Cattle Rearing:** Mountain pastures, with their cooler climate, support sheep, goats and sometimes cattle. **Transhumance** is widely practised (moving up and down the hills in search of pastures according to seasons).

TEMPERATE CONTINENTAL (STEPPE) CLIMATE

Lies in the **westerly wind belt** but they are so **remote from maritime influence** that the grasslands are practically treeless (between **40° and 55° N and S** of the equator).

- They are known as
  - Steppe (Eurasia), Pustaz (Hungary), Prairies (North America), Pampas (Argentina and Uruguay), Bush-Veld (North South Africa), High-Veld (Southern South Africa), Downs (Australia), Canterbury (New Zealand).

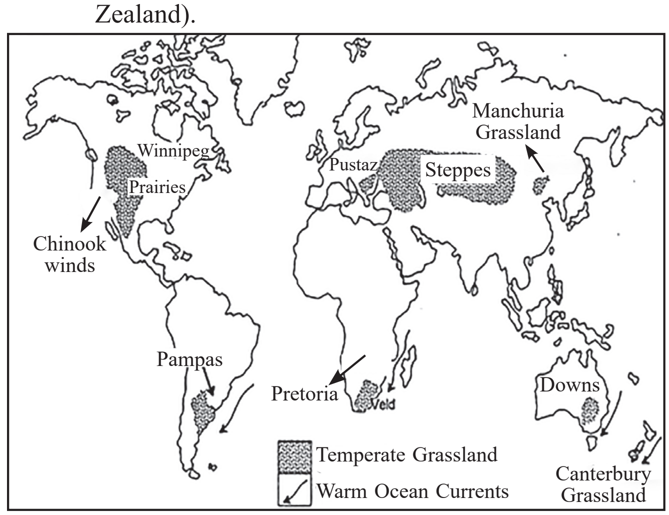


Fig. Geographical Distribution of Steppe Climate

Climate

- **Temperature:** Seasonal variations with warm to hot summers (often exceeding 30°C) and cold winters.
  - **Extremes** of temperature **in northern hemisphere**, steppe type of climate **in the southern hemisphere** is **never severe** (maritime influence) and winters are mild. **[UPSC-2013]**

- **Precipitation:** Low annual rainfall (25-75 cm); the dry season is particularly pronounced in temperate grasslands adjoining desert.
  - **Summer** rainfall (Maximum) from **convectional** sources when **continental interiors are heated**.
  - **Winter** rainfall (lesser) by occasional **depressions of the Westerlies**.
  - Maritime influence in the **southern hemisphere**, greater rainfall because of **warm ocean currents**.
- In **Prairies** a local hot wind called the **Chinook** (also called **'snow eater')** comes melting the snow covered pastures.

Vegetation

- **Grasslands are practically treeless;** grass is nutritious thus promoting livestock rearing in the region.
- Grasses are not only **shorter but also wiry** and **sparse.** In arid areas like Asia's continental interiors, wiry grasses favour ranching over arable farming.
- Moving **polewards**, increased precipitation results in **wooded steppes**, where conifers gradually appear.

Economic Activity

Extensive mechanized **wheat cultivation, nomadic herding, pastoral farming** etc; Due to extensive, mechanised wheat cultivation they are known as the '**granaries of the world'.**

WARM TEMPERATE EASTERN MARGIN (CHINA TYPE)

It is a modified form of monsoonal climate, found on the **eastern margins of continents** in warm temperate latitudes. In summer, the regions are under the influence of moist, maritime airflow from the subtropical **anti-cyclonic cells**.

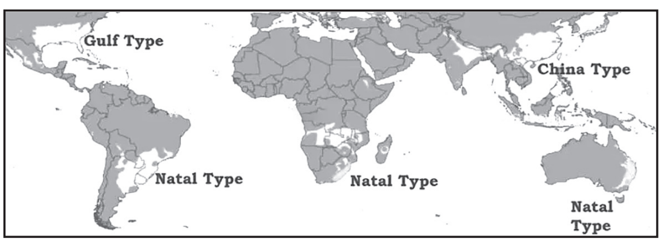


Fig. Warm Temperate Eastern Margin Climate Around the World

Climate

Warm moist summer and **cool, dry winter**; **strong maritime influence**; small annual temperature range.

- In summer, the regions are under the influence of **moist, maritime airflow** from the subtropical anti-cyclonic cells.
- **Rainfall throughout the year (60 to 150 cm); Rainfall** from **convectional sources or as orographic rain** in **summer**, or from **depressions** in **winter**.
- **Local storms:** Typhoons (tropical cyclones), and Hurricanes, also occur Subdivided into three main types:
- **China Type (Central and North China, South Japan):** temperate monsoonal; great annual temperature range; rain in summer and winter; occurrence of typhoons in late summer.
- **Gulf Type (South Eastern USA):** slight monsoonal; no distinct dry period; occurrence of hurricanes and tornadoes.
- **Natal type:** Natal, Eastern Australia, Southern Brazil, Paraguay, Uruguay and Northern Argentina and **all warm eastern temperate margins of southern hemisphere;** Dominance of maritime influence.

Vegetation

Lush vegetation with evergreen broad-leaved forests and deciduous hardwood trees in lowlands due to well-distributed rainfall all year round.

- Conifer species like pines and cypresses in highlands.
- No dry or cold seasons, allowing uninterrupted perennial plant growth.

Economic Activity

- Warm temperate eastern margins are the most productive parts of the middle latitudes.
- World's greatest rice-growing areas, warm wet and lowland favour rice cultivation.
- **Sugarcane**, **cotton**, **tobacco**, **maize**, **dairy products etc**.
- **Timber:** Economic value in China and southern Japan (oak, camphor); Eucalyptus forests in Eastern Australia; Lowland deciduous forests in Gulf states of the U.S.A.

Local Winds

Southerly Burster (Cold Wind in Australia) impacts New South Wales and Victoria **; Pampero** (Cold Dry Wind in Argentina & Uruguay**; Berg** (Hot & Dry Wind in South Africa) brings heavy precipitation to Natal, benefiting agriculture.

COOL TEMPERATE WESTERN MARGIN (BRITISH TYPE)

Found in **Britain, North West Europe, British Columbia(USA), Southern Chile, Tasmania** and most parts of **New Zealand** (between 40° and 65° latitude in the Northern Hemisphere**)**. Also called as marine west coast climate.

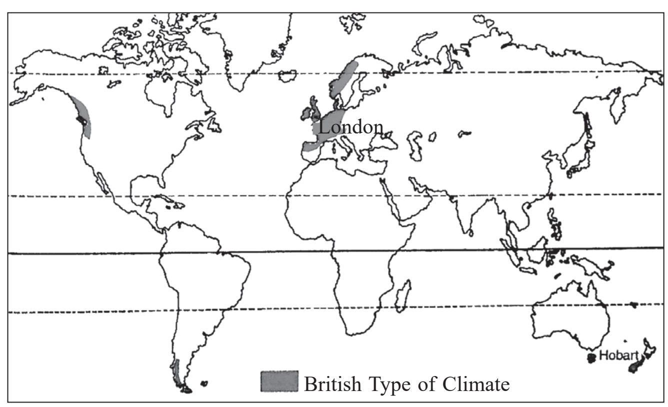


Fig. Geographical Distribution of Cool Temperate Western Margin Climate

Climate

- They are under the **permanent influence of westerlies** throughout the year;
- Regions of **frontal cyclonic activity,** typical of Britain, and are thus said to experience the British type of climate.
- **High maritime influence** on temperature and precipitation.
- **Temperature: Mild winters and cool summers (Mean annual temperature: 5 to 15^{0}C**
- **Rainfall: Throughout the year,** with a tendency towards a slight winter or autumn maximum from cyclonic sources. Precipitation varies between 50 cm – 250 cm. **[UPSC-2024]**
- **Seasons are very distinct**. **Winter** - short duration and mild (due to warming effect of **North Atlantic Drift)**; Spring is the driest; **summer is warm, sunny and long** and **autumn** is characterised by gusty winds. This conspicuous four season cycle is characteristic of temperate regions of the world.

Vegetation

- **Deciduous trees occur in pure stands.**
- Higher up the mountains deciduous trees (Shed leaves in winters to protect against snow and frost) are generally replaced by conifers.
- Valuable temperate hardwood: **Oak**, **elm**, **birch**, **beech**, **poplar**, **willows**, **alder**, **aspen, etc.**

Economic Activity

- **Market gardening, mixed farming (Rearing of animals and cultivation of crops together) Sheep rearing** etc. **[UPSC-2012]**
- **Fishing** is important in Britain, Norway, and British Columbia.
- British-type climate is suitable for crops and dairy farming. Mixed farming in north-western Europe with wheat, barley, and advanced dairy practices.

COOL TEMPERATE EASTERN MARGIN (LAURENTIAN)

Intermediate type of climate between the British and the Siberian type that is **found in only two regions: north eastern North America** (eastern Canada, north east USA and Newfoundland) and **eastern coastlands of Asia**, including eastern Siberia, North China, Manchuria, Korea and northern Japan.

- **In the southern hemisphere, this type of climate is absent.** This is because the Southern Hemisphere lacks a large, continuous landmass in the mid-latitudes similar to North America and Eurasia.

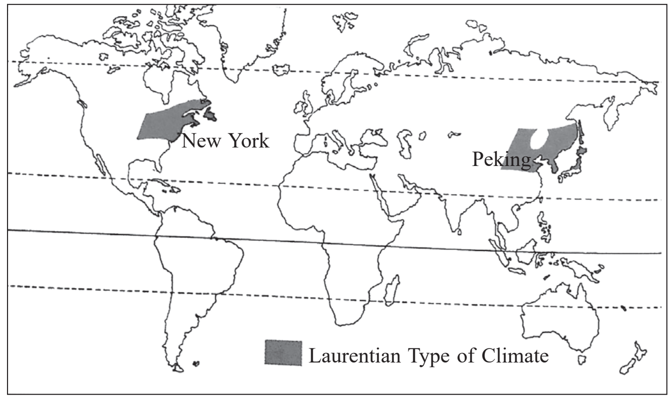


Fig. Geographical Distribution of Cool Temperate Eastern Margin Climate

Climate

- **Temperature:** Features of **both continental and maritime climate**; **cold, dry winters and warm, moist summers.**
    - Winter temperatures may be well below freezing-point and summers are as warm as the tropics.
    - **Arctic off-shore cold currents** are instrumental in cooling the summer, otherwise, it would have been even hotter.
- **Rainfall: 75 - 150** cm of rainfall distributed throughout the year with a maximum during summer.
    - **Northern Hemisphere:** Rainfall distribution is **uniform** due to **Atlantic influence and the Great Lakes**, high temperatures in summer and snowfall in winters.
    - **Asiatic regions:** Rainfall is **far less uniform;** the rainfall regime is similar to that of the tropical monsoon type in India. Japan receives adequate rainfall from both the south east monsoon in summer and North West Monsoon in winter.

Vegetation

Coniferous (north of 50 Degree N latitude) and **deciduous** (south of 50 Degree N latitude); Oak, beech, maple, and birch are principal trees.

Economic Activity

- Lumbering is an important activity, agriculture is less important due to severity and length of winter.
- Fishing, particularly in the Grand Banks of Newfoundland.

THE COOL TEMPERATE CONTINENTAL CLIMATE (SIBERIAN)

Experienced **only in the Northern hemisphere: North America** (from Alaska across Canada into Labrador), **Europe and Asia** (between 50° and 70° N of the equator).

Fig. Geographical Distribution of Cool Temperate Continental Climate

Climate

- **Temperature: Brief, warm summers** (20-25°C) and long, extremely **cold winters** (-30 to -40°C); Occasional violent cold polar winds, like **Canadian blizzards** and **Eurasian buran**.
- **Rainfall:** Relatively dry year-round, low annual precipitation mainly in the form of snow.

Vegetation

Mosses, lichens and sledges in more sheltered spots, stunted birches, dwarf willows, hardy grasses and reindeer moss are found.

- **Tundra, taiga (boreal forest), and grasslands** adapted to harsh conditions.
- Conifers with adaptations like conical shape, thick needle-shaped leaves, and podzolized soils.

Economic Life

- **Lumbering** is the primary economic activity, utilizing vast coniferous forests; Softwood logs transported downstream on rivers.
- **Paper and pulp industry** (Canada and the U.S.A.)
- Agriculture is challenging with limited crops due to extreme cold and short growing season.

ARCTIC OR POLAR OR TUNDRA CLIMATE

Found north **of the Arctic Circle** in the northern hemisphere and in the southern hemisphere in the continent of **Antarctica;** Extremely cold with long winters, devoid of tall trees or forests.

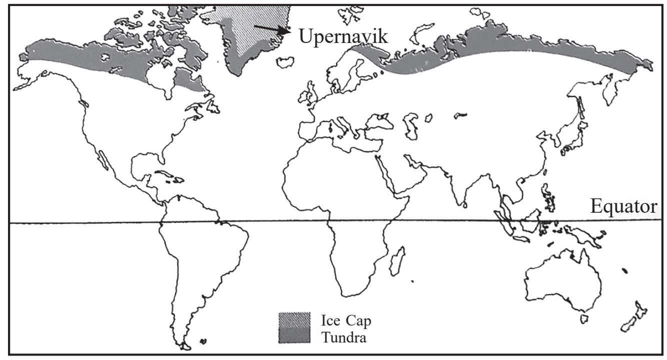


Fig. Geographical Distribution of Tundra Climate

Climate

- **Temperature:** Winters harsh, often below -37°C; summers brief with temperatures rarely exceeding 10°C.
- **Precipitation:** Generally low, with limited moisture in the form of snow and occasional freezing rain; Summer maximum precipitation in the form of rain or sleet.

Vegetation

Tundra vegetation limited to hardy, low-growing plants, mosses, and lichens.

- Permafrost restricts the growth of deep-rooted plants.
- Coastal lowlands support hardy grasses and reindeer moss.
- Brief summer bloom with the melting of snow, known as "Arctic Prairies.

Inhabitants like **Eskimos, Lapps, and Samoyeds** lead a semi-nomadic lifestyle, residing in compact igloos during winter.

7 Ocean and its Movement

3/4th or 71% of the globe is covered by the **hydrosphere** and the remaining 29% by lithosphere. Only ~3% of the water on the surface is fresh; the remaining **97%** resides in the **ocean**.

WATER DISTRIBUTION ON EARTH

Reservoir	Volume (Million Cubic km)	Percentage of the Total
Oceans	1,370	97.25%
Ice Caps and Glaciers	29	2.05%
Groundwater	9.5	0.68%
Lakes	0.125	0.01%
Soil Moisture	0.065	0.005%
Atmosphere	0.013	0.001%
Streams and Rivers	0.0017	0.0001%
Biosphere	0.0006	0.00004%

OCEANIC ZONES

Oceanic Horizontal Zones

- **Intertidal Zone**
  - **Description:** The intertidal zone is the area of the shoreline that is exposed to air at low tide and submerged at high tide.
  - **Geological Aspect:** Characterised by diverse geological features such as rocky shores, sandy beaches, and mudflats. The varying substrate supports a range of habitats.
  - **Biological Importance:** Supports a diverse array of marine life, including mollusks, crustaceans, and seaweeds, adapted to withstand both aquatic and terrestrial conditions.

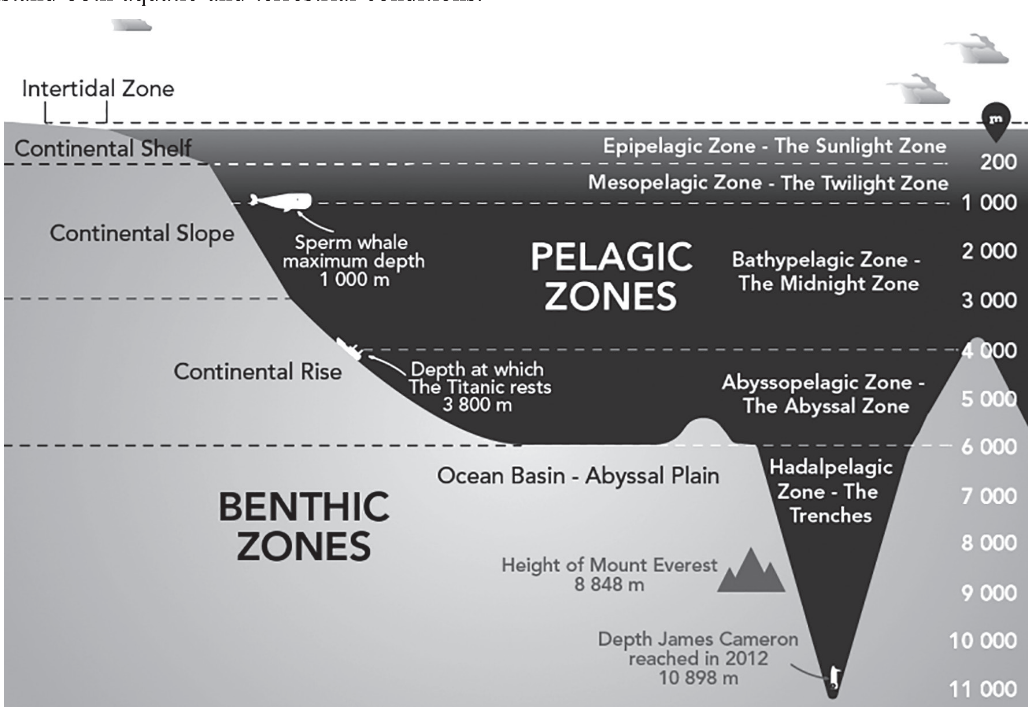


Fig. Oceanic Zones

- **Neritic Zone**
  - **Description:** This zone extends from the low tide mark to the seaward edge of the continental shelf.
  - **Geological Aspect:** Includes shallow waters over continental shelves, where geological features such as coral reefs and submerged islands are prevalent.
  - **Biological Importance:** Rich in nutrients, this zone is known for high biodiversity, including fish species, marine mammals, and coral formations. It plays a crucial role in fisheries and marine ecosystems.
- **Oceanic Zone**
  - **Description:** This zone lies beyond the continental shelf, characterised by deeper waters.
  - **Geological Aspect:** Composed of ocean basins, trenches, and mid-ocean ridges. The geology of this zone impacts ocean currents and marine life.
  - **Biological Importance:** This zone has varying biological communities adapted to different conditions based on depth.

Oceanic Vertical Zones

- **Epipelagic Zone (Sunlight Zone)**
  - **Depth:** Surface to 200 metres.
  - **Description:** The uppermost layer of the ocean where sunlight penetrates, supporting photosynthesis.
  - **Geological Aspect:** Nutrient-rich waters due to upwelling currents; geological features include underwater mountains and continental slopes.
  - **Biological Importance:** Home to a vast array of marine life, including fish, plankton, and marine mammals.
- **Mesopelagic Zone (Twilight Zone)**
  - **Depth:** 200 to 1,000 metres.
  - **Description:** Light levels diminish, making photosynthesis impossible; this zone is characterised by a gradient in temperature and pressure.
  - **Geological Aspect:** The seabed may feature slopes and oceanic ridges; nutrients are often transported downward from the epipelagic zone.
  - **Biological Importance:** Organisms in this zone have adapted to low light, with many exhibiting bioluminescence. It serves as a critical feeding ground for larger marine animals.
- **Bathypelagic Zone (Midnight Zone)**
  - **Depth:** 1,000 to 4,000 metres.
  - **Description:** Pitch dark with temperatures near freezing; high pressure exists in this environment.
  - **Geological Aspect:** Features include deep-sea trenches and abyssal plains formed by tectonic activity. Geological formations significantly influence habitat types.
  - **Biological Importance:** Home to unique species such as giant squids and deep-sea fish, adapted to extreme conditions.
- **Abyssopelagic Zone (Abyssal Zone)**
  - **Depth:** 4,000 to 6,000 metres.
  - **Description:** Extremely deep and cold waters, with little to no light.
  - **Geological Aspect:** Characterised by abyssal plains and oceanic ridges; sediment accumulation is significant due to slow processes.
  - **Biological Importance:** Despite the harsh conditions, this zone supports specialised life forms like certain types of worms and crustaceans.
- **Hadalpelagic Zone (Hadal Zone)**
  - **Depth:** More than 6,000 metres.
  - **Description:** The deepest oceanic zone, located in oceanic trenches.
  - **Geological Aspect:** Features extreme geological formations like deep-sea trenches and hydrothermal vents, formed by tectonic plate subduction.
  - **Biological Importance:** Home to extremophiles, organisms that thrive in high-pressure and low-temperature environments, often feeding on organic material that sinks from above.

RELIEF OF THE OCEAN FLOOR

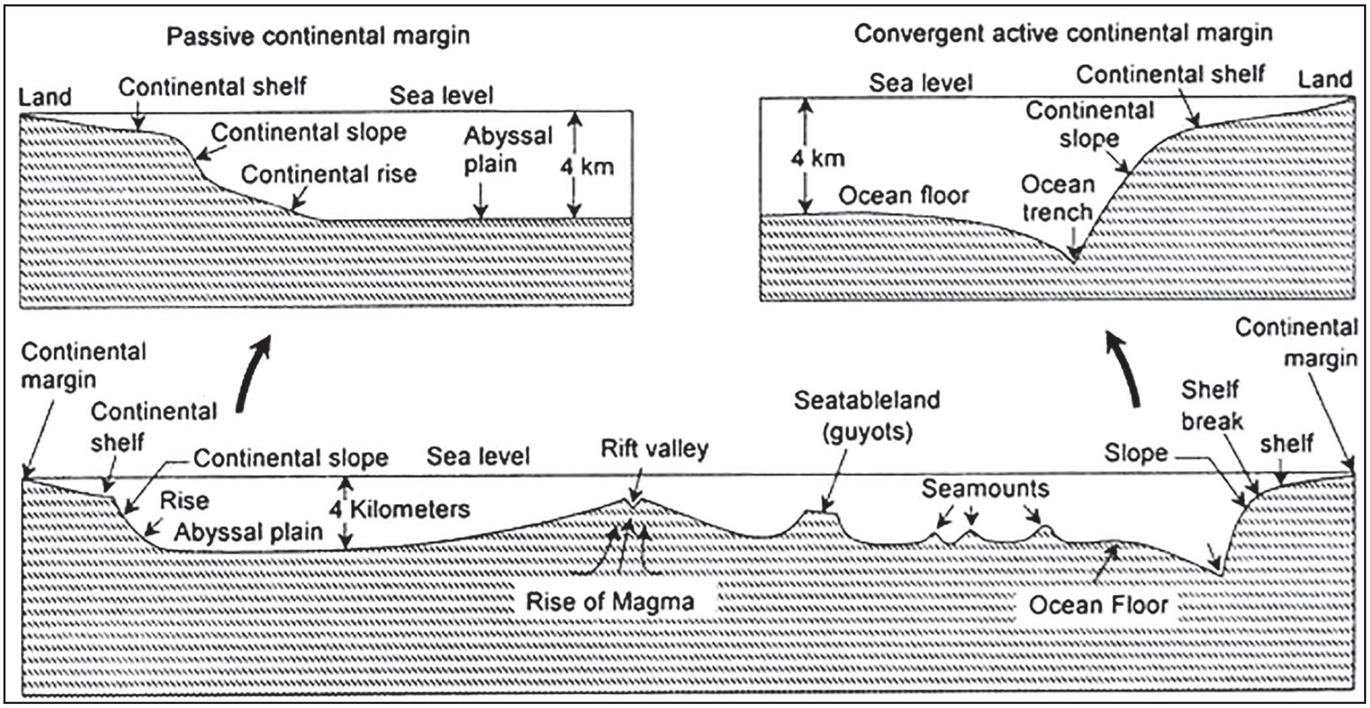


Fig. Major Relief Features

There are **major and minor relief features** on the floor of the ocean like **mountain ranges, deepest trenches, ridges, hills, sea mounts, guyots, trenches, canyons**, etc. These features are formed by **tectonic, volcanic and depositional** processes

MAJOR RELIEF FEATURES

Continental Shelf

Seaward extension of the continent from shoreline to continental edge and extends from the coast to depths of **100–200m**.

- Covers **7.5%** of the total oceanic area.
- **Shallowest part of the ocean; average gradient of 1° or even less**.
- **Ends at a very steep slope**, called the **shelf break**.
- Width of the continental shelves varies from one ocean to another; Average width is **80 km**.
- Shelves are almost **absent** or very **narrow** along the margins of **Ocean– Continent** Convergence and **Ocean–Ocean** Convergence. E.g., coasts of Chile, the west coast of Sumatra, etc.
- **Siberian shelf in the Arctic Ocean, the largest in the world**.
- It has **massive sedimentary deposits** that become sources of **fossil fuels, e.g., oil**.
- **Shelf Formation:** Tilting of land, marine erosion, submergence of a part of continental margin, relative rise in sea level, sedimentary deposition by rivers.

Continental Slope

It connects the continental shelf and the ocean basins. The slope boundary indicates the **end of the continents.**

- Gradient of the slope region varies between **2-5°.**
- **Canyons and trenches** are observed here.

Continental Rise

A major **depositional regime** in oceans made up of thick sequences of continental material that accumulate **between** the **continental slope** and **the abyssal plain**

- Formed by **sedimentation** from rivers, streams, and underwater events.
- **Gentle slope**; slope ranges from 1:50 to 1:500.

Deep Sea Plain or Abyssal Plain

Deep Sea Plains are **gently sloping** areas of the ocean basins that are covered with **fine-grained sediments like clay and silt.**

- Depths vary between **3,000m and 6,000m** and covers **nearly 40%** of the ocean floor
- A large supply of **terrigenous** and **shallow water sediments,** buries the irregular topography to form a generally flat relief.

Polymetallic Nodules:

Composition:

Polymetallic nodules, also called manganese nodules, are rock concretions found on the ocean floor. They consist of layers of metallic elements around a core, typically made up of the following:

- **Manganese (Mn):** ~30%
- **Iron (Fe):** ~15%
- **Nickel (Ni):** ~1.25%
- **Copper (Cu):** ~1.0%
- **Cobalt (Co):** ~0.25%
- **Trace Elements:** Include molybdenum, zinc, and rare earth elements.

Formation Process:

- **Slow Accretion:** Polymetallic nodules form slowly over millions of years through the precipitation of metals from seawater and pore water within ocean sediments. This accretion process involves both hydrogenous and diagenetic pathways:
  - **Hydrogenous Process:** Metals precipitate directly from seawater onto the nodules, layer by layer.
  - **Diagenetic Process:** Metals migrate from sediment pore water, combining with existing nodules or forming new ones.
- **Nodules grow extremely slowly:** They accumulate at a rate of 1 to 10 mm per million years.

Geological Features Associated with Polymetallic Nodules:

- **Abyssal Plains:** Nodules are typically found in vast expanses of deep-sea plains between 4,000 and 6,000 meters in depth. These plains provide stable, low-energy environments for nodule formation.
- **Mid-Ocean Ridges (MORs):** While nodules are often associated with abyssal plains, tectonically active regions like mid-ocean ridges can influence the distribution of polymetallic nodules. In these regions, the availability of metals (such as manganese and iron) is higher due to hydrothermal vents.
- **Sediment Layers:** Nodules rest on or are buried in soft sediment layers. The regions with fewer sediment deposits tend to have larger nodule fields.

Key Regions:

- **Clarion-Clipperton Zone (CCZ):** This area in the Pacific Ocean is one of the richest in polymetallic nodules.
- **Central Indian Ocean Basin (CIOB):** Another significant area for polymetallic nodules.

Oceanic Deeps or Trenches

Definition: Oceanic deeps or trenches are the deepest parts of the ocean, characterized by long, narrow, and steep-sided depressions in the ocean floor.

Tectonic Processes: Oceanic trenches are primarily formed by subduction, where one tectonic plate is forced beneath another. This occurs at convergent plate boundaries, typically between oceanic plates and either a continental plate and another oceanic plate.

- **Examples:**
  - **Mariana Trench:** The deepest trench in the world, reaching depths of about 10,994 meters (36,070 feet). **Challenger Deep** is the deepest point of Mariana trench.
  - **Puerto Rico Trench:** Located north of Puerto Rico, it is the deepest part of the Atlantic Ocean.
- **Long**, **narrow** and relatively **steep sided** depressions in oceanic crust
- **Tectonic Origin:** Formed by **subduction at convergent plate boundaries** (**ocean – ocean** convergence and **ocean-continent** convergence).
- **Pacific Ocean** has the **most** trenches, with the **Mariana Trench** being the deepest.

Trench Name	Subducting Plate	Overriding Plate
Mariana Trench	Pacific Plate	Mariana Plate
Tonga Trench	Pacific Plate	Indo-Australian Plate
Java Trench (Sunda Trench)	Indo-Australian Plate	Eurasian Plate
Philippine Trench	Philippine Sea Plate	Eurasian Plate
Kermadec Trench	Pacific Plate	Indo-Australian Plate
Peru-Chile Trench (Atacama Trench)	Nazca Plate	South American Plate
Cascadia Subduction Zone	Juan de Fuca Plate	North American Plate
Nicaragua Trench	Cocos Plate	Caribbean Plate
Hellenic Trench	African Plate	Eurasian Plate
Puerto Rico Trench	North American Plate	Caribbean Plate
South Sandwich Trench	South Sandwich Plate	Scotia Plate
Diamantina Trench	Indian Plate	Australian Plate
Alaska Trench	Pacific Plate	North American Plate
Izu-Ogasawara Trench	Philippine Sea Plate	Eurasian Plate
Bering Trench	Pacific Plate	North American Plate

MINOR RELIEF FEATURES

Mid-Oceanic Ridges

Mid-oceanic ridges are extensive underwater mountain chains that form the longest continuous mountain range on Earth, playing a critical role in plate tectonics and seafloor spreading.

Structure and Formation

- **Mountain Chains:** Comprising two parallel ridges separated by a central rift valley, peaks can rise above sea level, as seen in Iceland.
- **Divergent Boundaries:** Formed where tectonic plates pull apart, allowing magma to create new oceanic crust and resulting in a rift valley.
- **Tectonic Evidence:** These structures support the theory of plate tectonics by demonstrating ongoing seafloor spreading.

Minerals and Resources

- **Primary Rock Type:** Basalt, containing minerals like plagioclase, pyroxene, and olivine.
- **Hydrothermal Vents:** Rich in**:**
  - **Copper** and **Zinc** in sulphide deposits.
  - **Gold** and **Silver** concentrated in hydrothermal formations.
  - **Rare Earth Elements** found in associated sediments.

Seismic Activity

- **Frequent Earthquakes:** Occur due to tectonic movements at mid-ocean ridges.
- **Magnitude:** Generally low (4.0 to 6.0) and shallow (less than 30 km deep), primarily resulting from normal faulting due to tensional forces.

Seamount

- **Formation:** Seamounts form through volcanic activity at hotspots or divergent plate boundaries. As magma rises, it creates underwater volcanic mountains.
- **Minerals and Ores:** Rich in **ferromanganese nodules**, **cobalt-rich crusts**, and other metals like **nickel**, **copper**, and **rare earth elements**.
- **Associated Phenomena:** Volcanic activity at seamounts can cause minor earthquakes, though larger quakes are rare. They can also develop into islands if volcanic growth continues above sea level.
- **Examples:**
  - **Emperor Seamount** (Pacific Ocean)
  - **New England Seamounts** (Atlantic Ocean)

Submarine Canyons

- **Formation:** Erosion by turbidity currents or river erosion cuts long, narrow valleys into the continental shelf and slope. Landslides and mass wasting events contribute to their formation.
- **Minerals and Ores:** Deposits of **gold**, **sand**, **gravel**, and **heavy minerals** accumulate in canyon systems due to sediment transport.
- **Associated Phenomena:** Submarine landslides and tectonic activity can deepen these canyons. Earthquakes on tectonic margins may trigger such landslides.
- **Examples:**
  - **Hudson Canyon** (Atlantic Ocean, off the coast of New York)
  - **Monterey Canyon** (Pacific Ocean, off California)

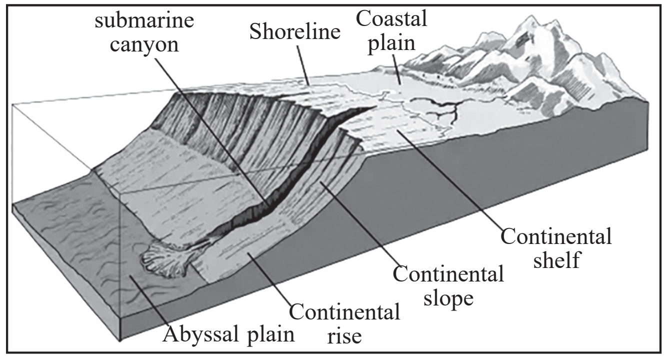


Fig. Submarine Canyon

Atoll

- **Formation:** Atolls form as volcanic islands gradually subside, allowing coral reefs to grow and surround a central lagoon. This follows Darwin's subsidence theory.
- **Minerals and Ores:** Composed of **calcium carbonate** from coral skeletons. Some atolls may contain **phosphate deposits** derived from bird guano.
- **Associated Phenomena:** Atolls are vulnerable to rising sea levels and tsunamis. Tectonic subsidence can influence their formation, while erosion and climate changes pose ongoing threats.
- **Examples:**
  - **Bikini Atoll** (Marshall Islands).
  - Lakshadweep has 12 atolls, 3 reefs, 5 submerged banks.
  - **Maldives Atolls** (Indian Ocean)

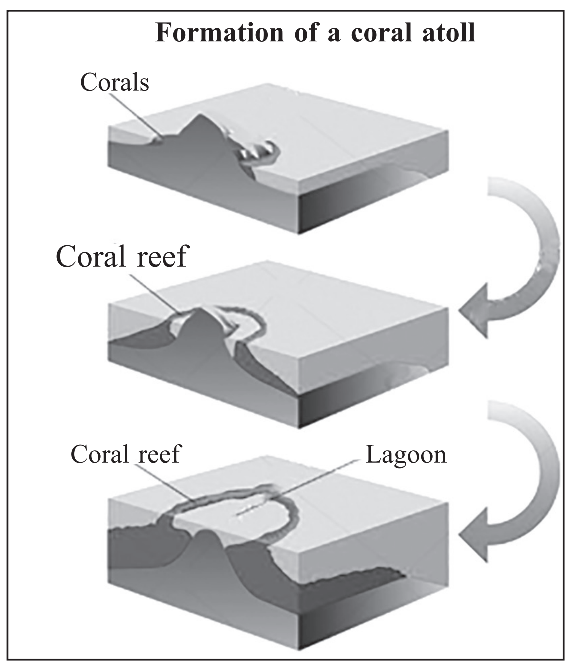
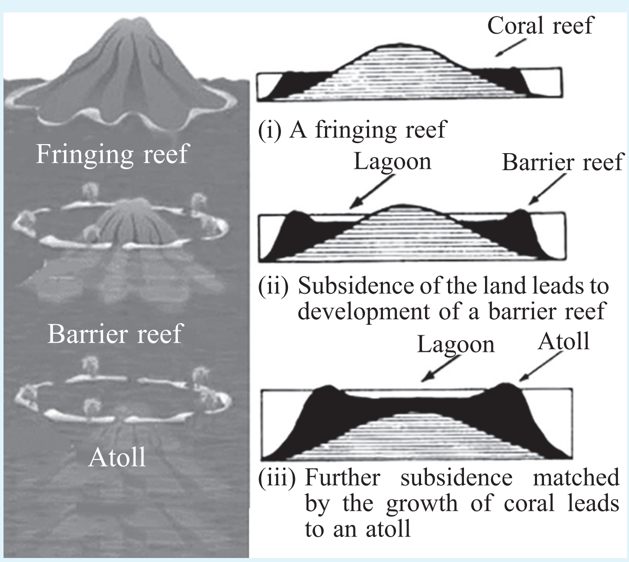


Fig. Coral Atoll

Lagoon

- **Definition:** A lagoon is a shallow body of water separated from a larger body (usually the ocean) by sandbars, barrier islands, or coral reefs.
- **Formation Mechanism:** Lagoons form when barriers such as sandbars or coral reefs restrict oceanic water from flowing freely into coastal areas. These barriers may form due to sediment deposition by waves, tides, or rivers or by coral growth in the case of coral lagoons. Lagoons can also form due to tectonic activity that traps coastal waters.
- **Types**:
  - **Coastal Lagoons:** Found along coastlines, typically in regions with low tidal ranges.
  - **Coral Lagoons:** Form within coral reefs, as seen in atolls.
- **Associated Features:**
  - **Sedimentation:** Lagoons often accumulate fine-grained sediments like silt and clay.
  - **Mineral Formation:** Salts, calcite, and other marine minerals can precipitate in these water bodies.
  - **Examples:** Chilika Lake (India), Venice Lagoon (Italy), and Lagoa dos Patos (Brazil).

Coral Reefs



- **Definition:** Coral reefs are underwater ecosystems built by colonies of tiny animals called coral polyps that secrete calcium carbonate to form their skeletons.
- **Formation Mechanism:** Corals thrive in shallow, warm, and clear waters, typically between 30° N and 30° S latitudes. Polyps grow and deposit calcium carbonate, which accumulates over time to form large reef structures. Reefs grow best on the eastern sides of continents where warm ocean currents enhance conditions for coral growth.
- **Types:**
  - **Fringing Reefs:** Directly attached to the shorelines of continents and islands.
  - **Barrier Reefs:** Separated from the mainland or island by a deep lagoon.
  - **Atolls:** Ring-shaped reefs that enclose a lagoon.
- **Biodiversity:** Coral reefs are considered the **"rainforests of the sea"** due to the rich biodiversity they support, including various marine organisms like fish, mollusks, and algae.
- **Minerals:** Corals contribute to limestone formation, which consists mainly of calcium carbonate.
- **Associated Phenomena:**
  - **Earthquakes:** Coral reefs are often located near tectonically active regions, where earthquakes can affect coral growth or cause reef subsidence.
  - **Coral Bleaching:** Due to rising ocean temperatures or changes in salinity, corals expel symbiotic algae, leading to coral bleaching.
- **Examples:**
  - **Great Barrier Reef** (Australia) – The largest coral reef system.
  - **Belize Barrier Reef** (Caribbean Sea).
  - **Maldives Atolls** (Indian Ocean).
  - **In India** - Coral reef found in Andaman and Nicobar Islands, Gulf of Kachchh and Gulf of Mannar **[UPSC-2014]**

OTHER RELIEF FEATURES

1. Volcanic Island Arcs

- **Definition:** Chains of volcanic islands formed at subduction zones.
- **Example:**
  - **Japan:** The Japanese archipelago is a prominent volcanic island arc created by the subduction of the Pacific Plate beneath the North American Plate.
  - **Indonesia:** The Sunda Arc, including Sumatra and Java, is another example resulting from the Indo-Australian Plate subducting under the Eurasian Plate.

2. **Fracture Zones**
   - **Definition:** Long, linear fault lines that intersect mid-ocean ridges, resulting from differing movements of tectonic plates.
   - **Example:**
     - **Romanche Fracture Zone:** Located in the Atlantic Ocean, this is the longest fracture zone in the world, marking a significant boundary between tectonic plates.
3. **Abyssal Hills**
   - **Definition:** Small, rounded hills scattered across abyssal plains, often formed by volcanic activity.
   - **Example:**
     - **Abyssal Hills in the North Atlantic:** These hills, found in regions like the Atlantic Ocean near the Mid-Atlantic Ridge, are formed by volcanic eruptions and are indicative of seafloor spreading.
4. **Bank**
   - **Definition:** Submerged, flat-topped elevations on the continental margins, rich in biodiversity.
   - **Banks** are shallow, submerged areas on the continental shelf that support marine life, while **Guyots** are flat-topped underwater mountains formed from eroded volcanic islands found in deeper ocean waters. Banks are primarily shaped by sediment deposition, whereas guyots result from volcanic activity and subsequent erosion.
   - **Example:**
     - **Grand Banks:** Located off the coast of Newfoundland, Canada, this area is famous for its fishing grounds and diverse marine life, stemming from its rich underwater topography.
5. **Hydrothermal Vents**
   - **Definition:** Openings in the seafloor where superheated, mineral-rich water is released due to volcanic activity.
   - **Example:**
     - **Black Smokers:** Found along the Mid-Atlantic Ridge, these vents release hot, mineral-rich water, supporting unique ecosystems that thrive without sunlight, relying instead on chemosynthesis.

TEMPERATURE OF OCEAN WATERS

Heat Sources

- **Solar Radiation:** The Sun is the dominant source of heat for the Earth's surface, including oceans. Solar energy penetrates the ocean's surface, warming the upper layers, especially the **epipelagic zone** (0-200 metres deep) where sunlight can reach.
- **Internal Earth Heat:** This is a minor component compared to solar heating. It originates from the Earth's core and mantle, where radioactive decay of isotopes generates heat. This heat affects deep ocean areas, influencing thermal gradients and contributing to the temperature of deep-sea environments.
- In deeper ocean zones, particularly in the **bathypelagic zone** (1,000-4,000 metres), organisms rely on **chemosynthesis** and internal geothermal heat rather than sunlight. Chemosynthesis relies on the oxidation of inorganic molecules, such as hydrogen sulphide (H_2S), methane (CH_4), or ammonia (NH_3), to provide the energy needed for the synthesis of organic compounds.
- **Hydrothermal vents,** often found at mid-ocean ridges, release mineral-rich, heated water, creating unique ecosystems that depend on these energy sources.

Factors Affecting Temperature of Ocean Waters

- **Latitude:** Surface water temperature decreases poleward due to decreasing insolation poleward.
- **Unequal distribution of land and water:** Oceans in the **northern hemisphere** receive **more heat** due to their contact with a larger extent of land.
- **Prevailing wind: Winds blowing** from the land **towards the oceans** result in the **upwelling** of **cold** water from below resulting in a **longitudinal variation in the temperature**; the **onshore winds** pile up warm water near the coast, **raising** the temperature.
- **Ocean currents: Warm ocean currents** raise the temperature in cold areas, while **cold currents** decrease the temperature in warm ocean areas. Eg**: Gulf stream (Warm current)** raises the temperature near the eastern coast of North America and the West Coast of Europe, **Labrador current (cold current)** lowers the temperature near the north-east coast of North America.

The process of **heating and cooling of oceanic water is slower than that of land**; **enclosed seas** in the **low latitudes** record **relatively higher temperatures than the open seas**; **enclosed seas** in the **high latitudes** have **lower temperatures than the open seas.** E.g., Red Sea has a higher temperature than the open seas.

Vertical Distribution of Temperature in Oceans

Temperature decreases with **increasing depth** of the ocean. The temperature structure of oceans over middle and low latitudes can be described as a **three-layer system from the surface to the bottom.**

- **Top Layer (Epilimnion): Layer of warm oceanic water**; about **500 m thick** with temperatures ranging between **20° and 25° C**; present **throughout the year** within the **tropical region**, but in **mid latitudes** it develops **only during summer**
  - The **epipelagic zone (or upper open ocean)** is part of the ocean where there is enough **sunlight** for algae to utilise photosynthesis.
- **Thermocline Layer (Metalimnion):** Vertical zone below the first layer; rapid decrease in temperature with depth; 500 -1,000 m thick.
  - **Seasonal Thermocline Dynamics:** Seasonal variations affect thermocline depth; Shallower thermocline in summer, deeper in winter.

- **Third Layer: Very cold and extends up to the deep ocean floor**.
    - In the **Arctic and Antarctic circles**, temperature change with depth is slight as the surface water temperatures are close to 0° C. Here, **only one layer of cold water exists**, which extends from surface to deep ocean floor.

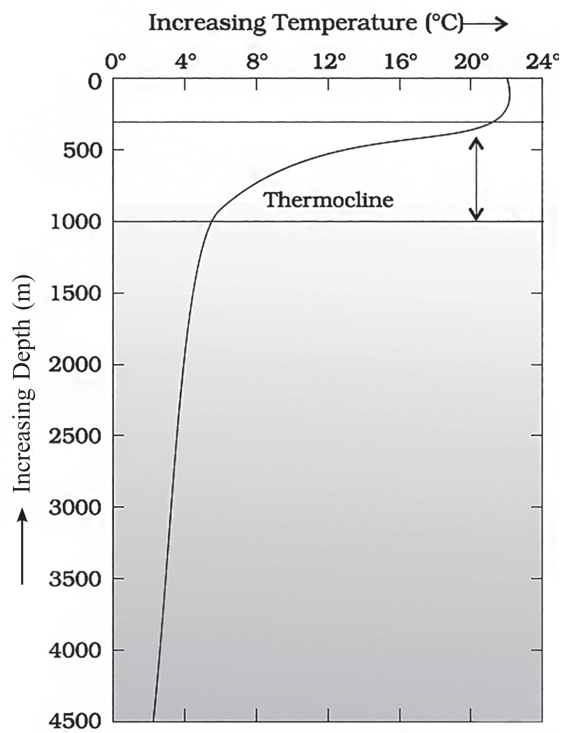


Fig. Vertical Distribution of Temperature

Ocean Mean Temperature (OMT) and Sea Surface Temperature (SST): [UPSC -2020]

- **OMT** is a more accurate predictor of the Indian summer monsoon than SST. It measures thermal energy up to the 26°C isotherm at depths ranging from 50-100 meters, capturing upper ocean thermal energy better than SST, which only measures surface temperatures.
- **SST** fluctuates more due to surface interactions but lacks representation of subsurface conditions that significantly influence monsoons.
- **Mechanism in Winter:** Ocean temperatures remain higher than land temperatures in winter because oceans retain heat longer due to their higher heat capacity.
- **Ocean Comparison:**
    - **Atlantic Ocean:** Coldest among Atlantic, Pacific, and Indian Oceans, especially in northern regions due to cold currents (e.g., Labrador Current), higher latitude coverage, and deep water formation processes.
    - **Indian Ocean:** Warmest, especially in tropical regions, with less interaction with polar waters.
    - **Pacific Ocean:** Mixed but retains warmth in tropical areas, with cooler regions in the north.

Horizontal Temperature Variations

The average surface temperature is approximately 27°C that gradually **decreases from Equator to Poles.**

- **Latitude Influence: Temperature decreases with increasing latitude** (0.5°C per latitude).
- **Hemispheric Contrast: Northern Hemisphere** records higher temperatures than southern hemisphere due to unequal distribution of land and water.
- **Tropics record the highest temperature and not the Equator,** as the Equator has clouds and witnesses rainfall due to rising air currents (convection).
- **Warm and cold currents** affect the rate of change of temperature with latitude.

SALINITY OF OCEAN WATERS

Salinity is the **total content of dissolved salts in seawater**. It is usually expressed as **parts per thousand (‰) or ppt**. The average salinity of seawater is about 35 grams per kilogram (g/kg) of seawater or **35 ppt.**

Ocean water salt composition: 77.7% sodium chloride, 10.9% magnesium chloride, 4.7% magnesium sulphate, 3.6% calcium sulphate, and 2.5% potassium sulphate.

Factors Affecting Ocean Salinity

- **Evaporation** increases, and **precipitation** decreases the salinity. Examples**:** Mediterranean Sea, Red Sea (high evaporation, high salinity). The Red Sea receives very little precipitation in any form. Also No water enters the Red Sea from rivers. **[UPSC-2024]**
- Decreases in coastal regions by the **freshwater flow from rivers** (Ganges and Brahmaputra in Bay of Bengal)
- In polar regions by the processes of **freezing (increases salinity) and melting (reduces salinity) of ice.**
- **Wind** influences salinity by **transferring water to other areas**.
- **Ocean currents:** Warm currents elevate salinity in higher latitudes; Cold currents decrease salinity near the equator. The salinity of the North Sea increases due to more saline water brought by the North Atlantic Drift.
- **Water Mixing and Enclosed Seas:** Limited freshwater mixing increases salinity. Examples - Black Sea, Caspian Sea, Red Sea, and Persian Gulf have high salinity.

Salinity, temperature, and **density** of water are **interrelated**. Any **change in temperature or density** influences the salinity of water in an area.

Highest salinity in water bodies: Lake Van in Turkey (330 ‰); Dead Sea (238 ‰); Great Salt Lake (220 ‰)

Horizontal Distribution of Salinity

- The salinity of the normal open ocean ranges between **33 ‰ and 37 ‰. In general, salinity gradually decreases towards the poles.**

- **Equatorial regions** have higher salinity due to **evaporation, but this is countered by precipitation.**
- **Subtropical high-pressure zones** experience the **highest** salinity due to high insolation (clear sky) and low precipitation due to subsiding winds.
- Polar regions and mid-latitudes have lower surface salinity.
- **High** in **land-locked Sea (Red sea)** as there is **not much mixing of water, and in hot and dry regions**, where **evaporation is high.**
- Salinity **decreases** in the **western parts** of the **northern hemisphere** because of the **influx of melted water** from the **Arctic region.**

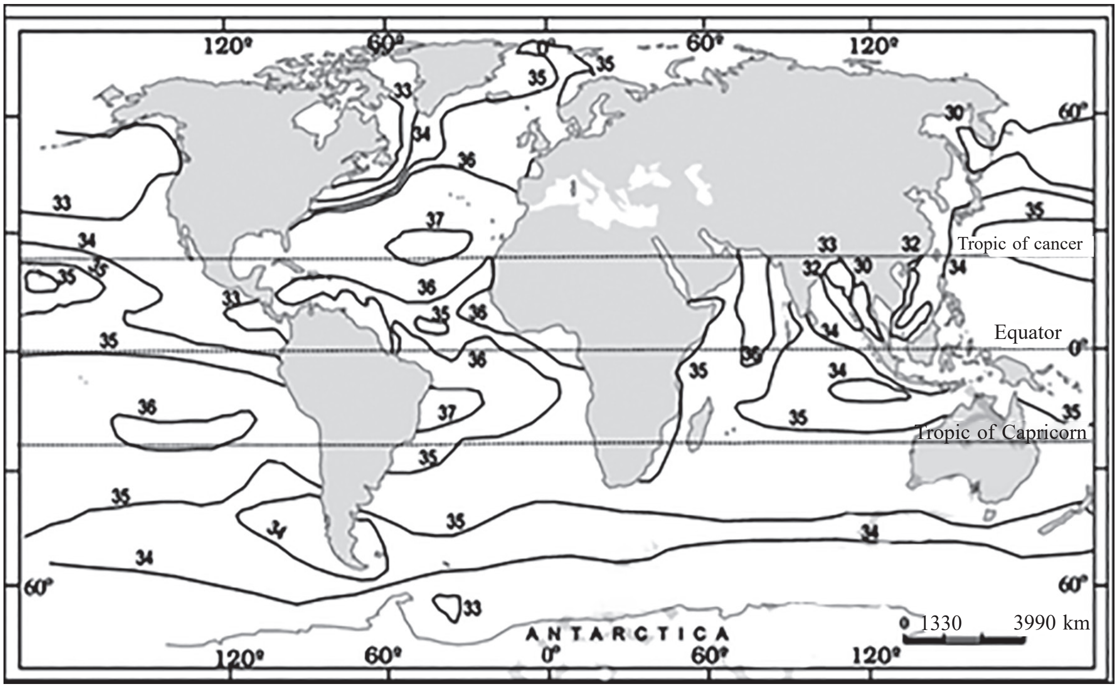


Fig. Surface Salinity of the World's Oceans

Vertical Distribution of Salinity

- Salinity **generally increases with depth** and there is a distinct zone called the **halocline** (compare this with thermocline), where salinity **increases sharply.**
- Salinity at the **surface increases with the loss of water to ice or evaporation** or **decreases with the input of fresh water**.
- Lower salinity water rests above the higher salinity dense water, leading to **stratification by salinity.**
- **Salinity** changes with depth, but the way it changes depends upon the location of the sea**.**
  - **High latitudes: Increases with depth.**
  - **Middle latitudes: Increases** up to 35 metres and then **decreases.**
  - **Equator: Surface salinity** is **lower** due to **high precipitation** and **low evaporation due to cloudiness.**

Salinity of Marginal Seas

- **North Sea**, in spite of its location in higher latitudes, records **higher salinity** due to more **saline water** brought by the **North Atlantic Drift**.
- **Baltic Sea** records **low salinity** due to the influx of **river waters** in large quantities.
- **Red Sea** has high salinity due to high evaporation and limited freshwater input.
- **Mediterranean Sea** records **higher salinity** due to **high evaporation**. Salinity is, however, very **low** in the **Black Sea** due to enormous **freshwater** influx by rivers.
- **Bay of Bengal** has **low** salinity due to the **influx of river water**. On the contrary, the **Arabian Sea** shows **higher salinity** due to high evaporation and low influx of fresh water.

Oceans Acidification **[UPSC-2012]**

- Ocean acidification is the ongoing decrease in the pH of the ocean waters caused by the absorption of excess carbon dioxide (CO_2) from the atmosphere.
- This phenomenon affects the growth and survival of calcareous phytoplankton. The growth and survival of coral reefs will be adversely affected. The survival of some animals that have phytoplanktonic larvae will be adversely affected.

OCEAN WATER CIRCULATION

The horizontal and vertical motions are common in ocean water bodies.

- **Horizontal motions: Ocean currents** and **waves**; **Vertical motions: Upwelling & downwelling and Tides**.

Waves

Waves are actually the energy, which moves across the ocean surface. Water particles only travel in a small circle as a wave passes.

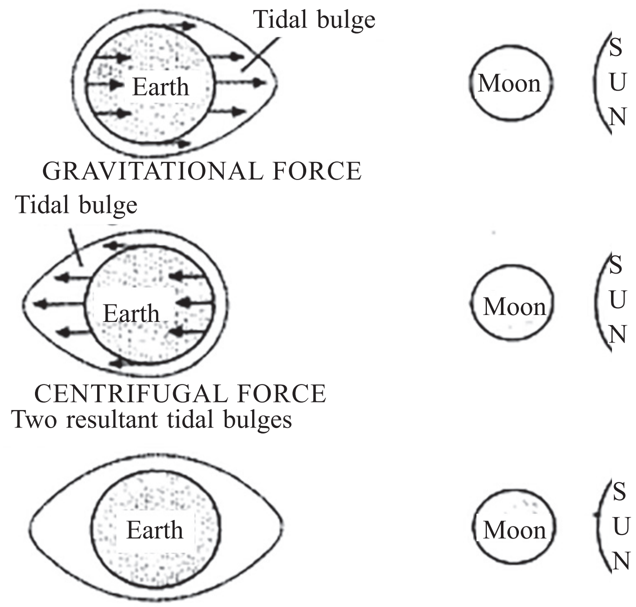
- Most of the waves are caused by the frictional force of the **wind,** which provides energy to the waves**.**
- It **slows** down as it **approaches the beach** due to the friction occurring between the water and the sea floor. When the **depth** of water is **less than half the wavelength** of the wave, the wave **breaks**.
- **The largest waves** are found in the **open oceans**.
- A wave's **size** and **shape** reveal its **origin**.
  - **Steep waves** are **young** and formed by **local winds,** whereas **slow and steady waves** are **older** and originate from **far away places**.
- **Wave height** is determined by the **strength** of the wind i.e., how long it blows and the area over which it blows in a single direction.

Characteristics of Waves

- The highest and lowest points of a wave are called the **crest and trough** respectively.
- The vertical distance from the bottom of a trough to the top of a wave crest is **wave height. Wave amplitude** is half of the wave height.
- **Wave Period:** Time interval between two successive wave crests or troughs as they pass a fixed point.
- **Wavelength:** Horizontal distance between two successive crests.
- **Wave Speed:** Rate at which the wave moves through the water.
- **Wave Frequency:** Number of waves passing a given point during a one second time interval.

Tides

- The **periodic rise and fall of ocean water twice a day** mainly due to the **attraction of the sun and the moon.**
- **Reasons for tides:** The **gravitational pull of the sun and moon** and the **centrifugal force** are responsible for creating the two major tidal bulges on the earth.
- On the **side** of the **earth facing the moon,** a **tidal bulge** occurs due to the pull of the moon, while on the **opposite side,** the **centrifugal force causes a tidal bulge**. **[UPSC 2015]**
- When the tide is **channelled between islands or into bays and estuaries,** they are called **tidal currents**.
- The vertical distance between high tide and low tide is the **tidal range.**
- Movements of water caused by **meteorological effects** (winds and atmospheric pressure changes) are called **surges**.



Gravitational and Centrifugal Forces

Fig. Forces Acting on Tides

Types of Tides Based on Frequency

1. **Semi-diurnal tide: two high tides and two low tides** each day; successive high or low tides are of the **same height**.
2. **Diurnal tide: only one high tide and one low tide** during each day; successive high or low tides are of the **same height.**
3. **Mixed tide:** Variations in height of tides, generally occur along the west coast of North America and islands of the Pacific

Tides based on Sun, Moon and Earth Positions

- **Spring tides:** When the **sun, moon** and **earth** are in a **straight line**, the **height of the tide** will be **higher** than the usual height
  - It occurs **twice a month**, once during the full moon period and again during the new moon period
  - Seven days interval between the spring tides and neap tides.
- **Neap tides:** The **sun and moon** are at **right angles** to each other and the **forces of the sun and moon** tend to **counteract** one another.
- Further, once in a month, when the **moon's orbit** is **closest to the earth** (**perigee**), unusually high and low tides occur. Two weeks later, when the **moon is farthest from Earth** (**apogee**), tidal ranges are less than their average heights.
- Similarly, when the **earth is closest to the sun** (**perihelion**), around **3rd January** each year, tidal ranges are also much greater. When the earth is **farthest from the sun** (**aphelion**), around **4th July** each year, tidal ranges are much less than average.

- **Ebb:** The **time** between the **high tide and low tide**, when the **water level is falling**.
- **Flow or Flood:** The **time** between the **low tide and high tide**, when the **tide is rising.**

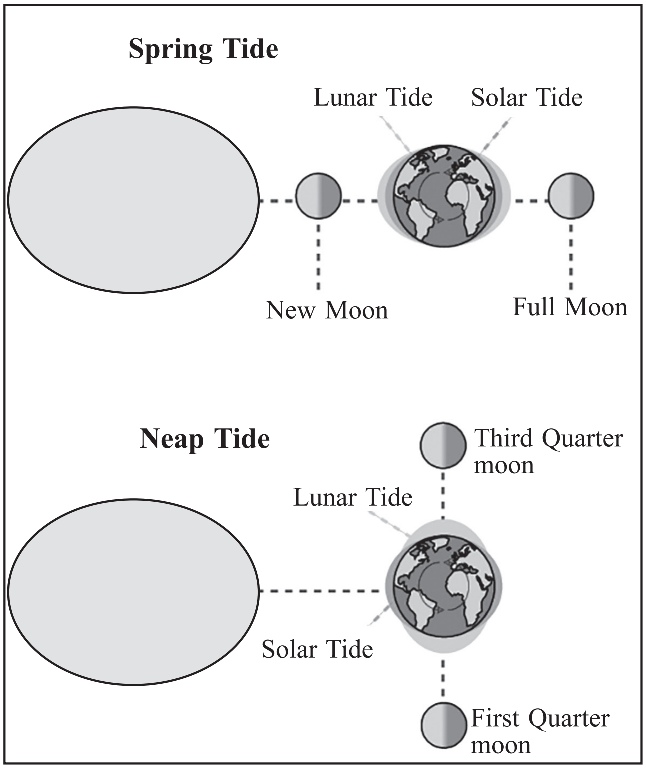


Fig. Spring Tide and Neap Tide

Significance of Tides:

Navigation; **desilting** the sediments; removing polluted water from river estuaries; **electricity generation**; makes it possible for **big ships to enter shallow harbors.**

Ocean Currents

Large masses of water flowing constantly in regular patterns **on the ocean surface** in **definite directions**.

- Usually, it is strongest near the surface.
- **Differences in water density** affect **vertical mobility** of ocean currents. **Water** with **high salinity** or colder in nature is **denser and**, hence tends to **sink.**

Factors Influencing Ocean Currents [UPSC-2012]

- **Insolation:** Heating expands water, creating a downhill gradient; Equator water is about 8 cm higher than mid-latitudes.
- **Winds** push the ocean water to move due to surface friction.
  - **Trade Winds:** North-East Trade Winds move North Equatorial Current, Florida Current; South-East Trade Winds drive South Equatorial Current, warming Brazil's eastern coast.
  - **Westerlies:** Southern Hemisphere's Westerlies drive West Wind Drift, forming Peruvian and Benguela Current.
  - **Monsoon Winds:** In Northern Indian Ocean, currents change with North-east (winter) and South-west (summer) monsoon winds.
- **Gravity:** Gravity tends to **pull the water down** the pile and create gradient variation; Influences tides and periodic sea level changes.
- **Coriolis Force** causes the water to move to the **right (clockwise)** in the **northern** and to the **left (anticlockwise)** in the **southern hemisphere, creating circular movements of water in the form of gyres.**
- **Temperature:** Warm equatorial water rises and moves poleward; Cold polar water creeps along the sea bottom towards the equator.
- **Salinity:** Higher salinity water flows below less saline water; In the Mediterranean, less saline Atlantic water flows in, compensated by denser bottom water outflow.
- **Land:** Land acts as a barrier, deflects currents, influences speed and direction; Southern Chile's tip diverts West Wind Drift as Peruvian Current northwards.
- **Underwater Topography:** Ocean floor shapes, guides and redirects currents.

Types of Ocean Currents

- **Based on Depth**
  - **Surface currents (upper 400 m of the ocean):** Constitute about **10 percent** of all the water in the ocean.
  - **Deep Water currents:** Constitute **90 percent** of the ocean water. These waters **move around the ocean basins due to variations in density and gravity.**
    - Deep waters sink into the deep ocean basins at high latitudes, where the temperatures are cold enough to cause the density to increase.
- **Based on Velocity**
  - Ocean currents can be classified as drifts, currents, and streams in the order of velocity.
  - **Drifts** are the movement of surface water of low velocity. **Example: North Atlantic drift**.
  - **Currents** are faster than drifts. **Example: Labrador current**.
  - **Streams** are larger masses of water moving in a definite direction and much greater velocity than drifts and currents. **Example: Gulf Stream.**
- **Based on Temperature**
  - **Warm Current:** Generally, they **originate near the equator** and **move towards the poles**; usually observed on the **east coast of continents in the low and middle latitudes** (true in both hemispheres). In the **northern hemisphere,** they are found on the **west coasts in high latitudes**.

- **Cold Ocean Currents:** The **cold currents** carry water **from polar or higher latitudes to tropical or lower latitudes;** usually found on the **west coast of the continents in the low and middle latitudes** (true in **both hemispheres)** and on the **east coast in the higher latitudes** in the **Northern Hemisphere**.

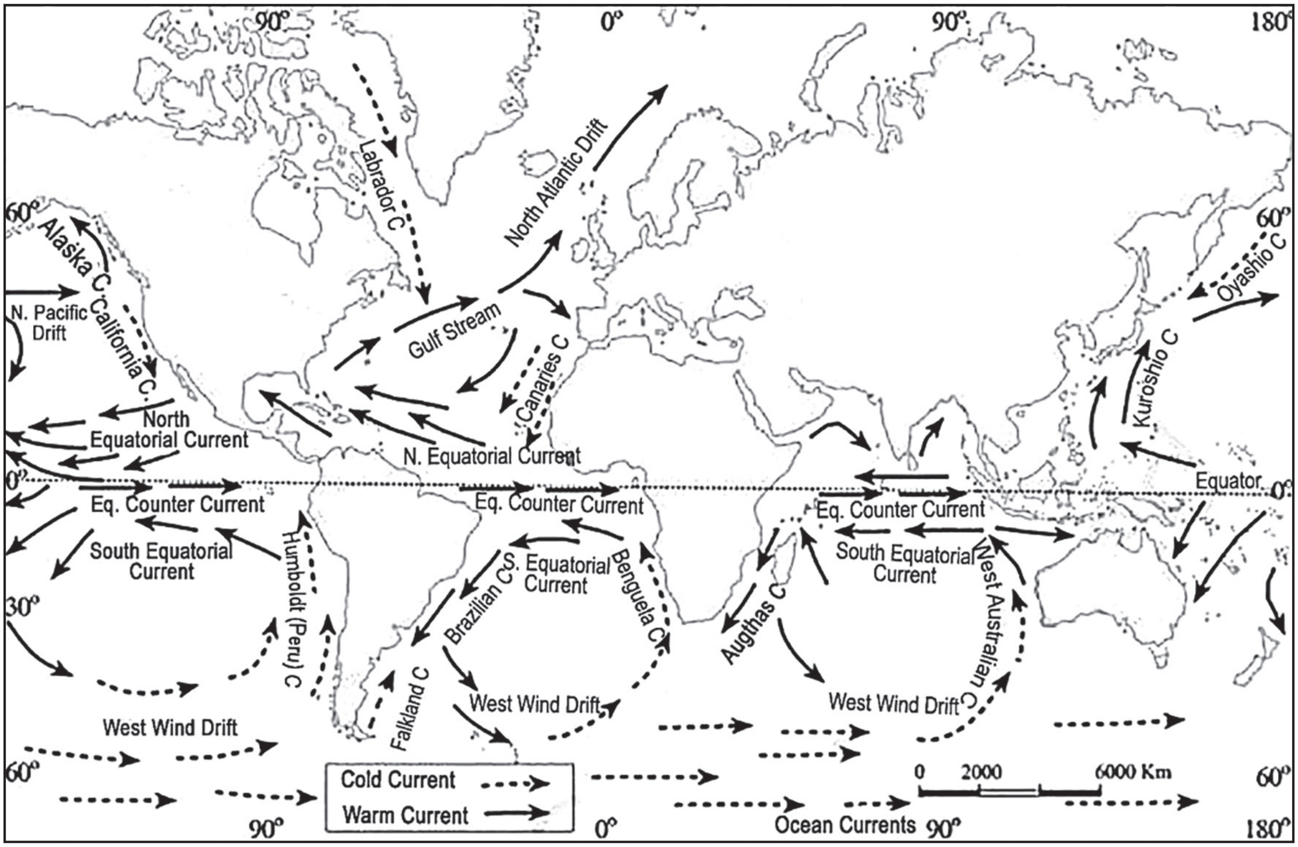


Fig. Ocean Currents of world

> **Eastward flow of equatorial counter-current:** Trade winds push the water towards the west but land masses on the west obstruct the flow. A gradient develops there and water starts moving towards the east under its influence as the influence of winds is not significant due to the presence of doldrums. **[UPSC 2015]**

Gyres

Vast circular system made up of ocean currents that spiral about a central point. Clockwise in the Northern Hemisphere & Anti clockwise in the Southern Hemisphere.

Five Major Gyres: North Pacific Subtropical Gyre, South Pacific Subtropical Gyre, North Atlantic Subtropical Gyre, South Atlantic Subtropical Gyre and Indian Ocean Subtropical Gyre.

Atlantic Ocean Currents

- **Norwegian Current(Warm):** Keeps oceans to the north of Norway free from ice.
- **Labrador Current (Cold):** Its confluence with the warm Gulf Stream creates a rich fishing ground on the northeast coast of North America (Grand Bank).

Pacific Ocean Currents

Pacific Ocean Current

- Cold Currents
  - Oyashio Current
  - California Current
  - Peru/Humbolt
  - Okhotsk Current
- Warm Currents
  - North & South Equatorial Current
  - Counter Equatorial Current
  - Kuroshio Current
  - North Pacific Current
  - East Australian Current
  - Alaska Current

Indian Ocean Currents

Warm and Stable: South Equatorial Current; Mozambique Current; Agulhas Current

Warm and Unstable: S-W Monsoon Current; N-E Monsoon Current; Somali Current

Cold and Stable: West Australian Current

Effects of Ocean Currents

- **Influences the temperature conditions** of the area
  - Coasts with **cold currents**, like **west coasts of continents in tropical and subtropical regions**, experience low temperatures with signs of aridity.
  - **West coasts of the continents in the middle and higher latitudes** are **bordered by warm waters,** which experience a distinct marine climate with **cool summers and mild winters.**
- Areas where the **warm and cold currents meet** provide the **best fishing grounds** in the world **[UPSC 2013]**. E.g., **seas around Japan** and the **eastern coast of North America**. These areas also experience **foggy weather** making it difficult for navigation.
- **Desert Formation: High aridity** due to **cold ocean currents** in west coast regions of the **tropical and subtropical continents**. E.g., **Peru Current**, also called Humboldt Current, is a cold-water current of the southeast Pacific Ocean and the reason for the **aridity of the Atacama desert.** It is the driest desert in the world.

Thermohaline Circulation (THC):

Thermohaline circulation refers to the large-scale movement of ocean water driven by differences in temperature (thermo) and salinity (haline). Together, these factors influence water density, causing denser water to sink and less dense water to rise, driving a global conveyor belt of currents that regulate Earth's climate.

Mechanism:

- **Formation:** In polar regions like the North Atlantic, cold, salty water sinks (due to high density) and initiates deep ocean currents.
- **Global Flow:** These deep currents travel toward the equator, where they rise as they warm, forming surface currents.
- **Key Role:** This system redistributes heat, maintaining temperature balance between the equator and poles.

Atlantic Meridional Overturning Circulation (AMOC):

The AMOC is a key component of THC, involving warm Gulf Stream currents flowing northward and cold deep waters returning southward. The AMOC stabilizes Europe's mild climate.

- **Impact of Disruption:** Melting polar ice caps dilute salinity, weakening the AMOC, which can lead to cooling in Europe and intensify tropical storms globally.

Examples of THC Impact:

- **El Niño-Southern Oscillation (ENSO):** Disruptions in THC can modify ENSO cycles.
- **Indian Ocean Dipole (IOD):** Influences heat distribution affecting monsoons in South Asia.

Global Implications: THC's balance is vital for weather patterns, nutrient cycling, and marine ecosystems. Its weakening, often tied to climate change, poses significant risks to biodiversity, agriculture, and human settlements. **[UPSC 2021]**

Saarthi

THE COACH

1 : 1 MENTORSHIP BEYOND THE CLASSES

- **Diagnosis** of candidates based on background, level of preparation and task completed.
- **Customized solution** based on Diagnosis.
- One to One **Mentorship.**
- Personalized schedule **planning.**
- Regular **Progress tracking.**
- **One to One classes** for Needed subjects along with online access of all the subjects.
- Topic wise **Notes Making sessions**.
- One Pager **(1 Topic 1 page)** Notes session.
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