HIGHER SECONDARY COURSE

GEOLOGY

CLASS - XI

Government of Kerala
DEPARTMENT OF EDUCATION

State Council of Educational Research and Training
(SCERT); Kerala
2020

THE NATIONAL ANTHEM

Jana-gana-mana adhinayaka, jaya he
Bharatha-bhagya-vidhata.
Punjab-Sindh-Gujarat-Maratha
Dravida-Utkala-Banga
Vindhya-Himachala-Yamuna-Ganga
Uchchala-Jaladhi-taranga
Tava subha name jage,
Tava subha asisa mage,
Gahe tava jaya gatha.
Jana-gana-mangala-dayaka jaya he
Bharatha-bhagya-vidhata.
Jaya he, jaya he, jaya he,
Jaya jaya jaya, jaya he!

PLEDGE

India is my country. All Indians are my brothers and sisters.

I love my country, and I am proud of its rich and varied heritage. I shall always strive to be worthy of it.

I shall give my parents, teachers and all elders respect, and treat everyone with courtesy.

To my country and my people, I pledge my devotion. In their well-being and prosperity alone lies my happiness.

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Dear students,

The State Council of Educational Research and Training (SCERT), Kerala presents with immense pleasure its first text book in Geology for class XI of higher secondary students. This text book is a product of combined effort of a team of higher secondary teachers in Geology, under the supervision of experts in the respective field of science.

Any informed society conscious of its complex relationship with our planet recognizes the importance of Earth science education - especially Geology at all levels. The world over, educationists have given emphasis to the centrality of Earth science in education. Therefore, Earth science has gained importance in the national strategy for science education in most of the countries.

A basic knowledge of Geology empowers the students to think globally and act locally. It will also enable them to make sound decisions on various issues related to the earth such as environmental degradation, climate change, resource scarcity etc., which are important in their lives as individuals and as citizens, apart from improving their critical thinking skills and challenging them to think about their future.

I sincerely hope that, the teachers and students in Geology of standard XI will find this text very useful for enriching their teaching and learning.

Wish you all success.

Dr. J. Prasad
Director
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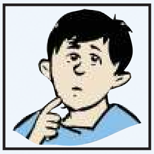
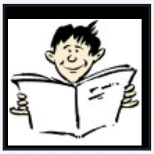


Check your progress

Let us sum up



Significant Learning Outcomes

Let us assess

1 GEOLOGY AS A DISCIPLINE

1.1. Introduction

Our home, blue with water, white with clouds, green with life - is a planet unique in our solar system and probably rare in the universe. When we had the first view of our planet from space we were startled to see how beautiful and how fantastic our home appeared, very different from the other planets of our solar system.

Practically everything we do each day is connected in some way to the Earth: to its land, oceans, atmosphere, plants, and animals. The food we eat, the water we drink, most of the materials of our homes and offices, the clothes we wear, the energy we use, and the air we breathe are all grown in, taken from, surround, or move through, the planet Earth.

It is forecasted that by 2025, eight billion people will live on Earth. If we are to continue extracting resources to maintain a high quality of life, then we, as individuals and citizens, need to know more about our planet - its processes, its resources, and its environment. Only through a study of the Earth we can understand and appreciate our complex planet.

1.2. Earth Science

Earth Science is an all-embracing term for the sciences related to the planet Earth. The term Earth Science or Geoscience is currently used for the four basic areas of science: Geology, Meteorology, Oceanography and Astronomy. Only a portion of Astronomy viz., the scientific studies of Earth's neighbours in space, forms part of this branch of science.

Geology deals with the composition of earth materials, earth structures, and earth processes and it is also concerned with the history of the organisms on the planet and how the planet has changed over time. Geologists search for fuels and minerals, study natural hazards, and work to protect the earth's environment.

Meteorology is the study of the atmosphere and how processes in the atmosphere affect Earth's weather and climate. How climate changes over time in response to the actions of people, is a topic of urgent worldwide concern.

Oceanography is the study of oceans and the subject matter includes their composition, movement, organisms and processes. The oceans cover most of our planet and provide important food resources and other commodities. Oceans are increasingly being used as energy sources. The oceans also have a major influence on the weather and climate.

Astronomy is the study of the universe. The moon drives the ocean's tidal system. Impacts of asteroids throughout the Earth's history have frequently and locally modified the Earth's surface. The energy from the sun drives our weather and climates. Study of other objects in the solar system helps us learn Earth's history. Many aspects of the Earth's early history are revealed by objects in the solar system that have not changed as much as the earth has. Therefore, knowledge of basic astronomy is essential for an understanding of the Earth. Astronomers can also use their knowledge of Earth materials, processes and Earth history to learn about other planets.

There are numerous sub-disciplines in Earth Science, reflecting diverse areas of specialization in Geography, Soil Science, etc. New developments, however, have expanded the branches of Earth Science to include a collection of studies called Environmental Sciences. These are aimed to investigate the environmental conditions that positively and adversely affect all living things on Earth.

Earth scientists use tools from Physics, Chemistry, Biology, and Mathematics in their studies of the rock record to unravel how the Earth system works, and how it evolved to its current state.

Earth Science empowers us to think globally and act locally, to make sound decisions about issues important in our lives as individuals and citizens. People who understand how Earth systems work can make informed decisions about where to buy or build a home in safe areas of the Earth's surface. They can debate and resolve issues related to clean water, urban planning and development, national security, global climate change, and the use and management of natural resources.

An informed society, conscious of its complex relationships with our planet, recognizes the importance of and insists on Earth Science education at all grade levels - elementary, secondary and higher education. When we give emphasis to Earth Science education, everyone benefits from it. If we intend to live - on and with - this planet, we truly need to understand how it works, and understand the interactions of the many components that make up the Earth. The Earth Science provides an integrated and interdisciplinary approach to a true understanding of our planet. Earth

Science education also improves critical thinking skills. It offers a historical perspective and improves our ability to predict the future. To understand Earth processes that affect us now and tomorrow, geoscientists look for evidences for what happened in the past. This connects students to the past, as well as challenges them to think about the future.

Earth Science poses questions that are exciting as well as practical to children and adults alike: Why are earthquakes frequent in the Himalayan region? Why are the marble-stones of Taj Mahal deteriorating and getting mottled? Why do landslides constitute a frequent natural disaster in the hilly regions of Western Ghats during monsoon season? Why is beach erosion more severe in some parts of the Kerala's coast and what can we do about it? Why is a river floodplain not a good location to build a house? Where do we get fresh water for our daily use? How can one help protect the environment?

Problems and issues in Earth Science are ideally suited for an inquiry based education approach - an educational process that most closely resembles the reality of scientific endeavour. Earth Science has been part of the curriculum in schools of many developed countries well over the last century. The world-over, while educationalists define science literacy they reaffirm the centrality of Earth Science in education. Earth Science should be taught in parity with physical, chemical and biological sciences as part of the country's national strategy for science literacy.

1.3. Geology

Geology is one of the branches of Earth Sciences. It is the scientific study of the whole earth - its origin, structure, the material with which it is made, the nature of processes that act on these materials, the products formed, and the history of the planet. It also includes the study of organisms that have once inhabited our planet such as dinosaurs (excluding the present day organisms) and how those have changed over time.

Geology deals mainly with the composition, structure, physical properties, and history of Earth's components, and the processes by which they are shaped. Our lives and civilization depend upon how we understand and manage our planet - Earth processes affect us all. Weather patterns influence the availability of water resources. The potential for forest fires, earthquakes, volcanic eruptions, hurricanes, and floods can kill large number of people and cause enormous damage to life and property.

Geologists typically study rocks, sediments, soils, rivers, and natural resources. Expanding technologies and growing populations increase the demand on natural resources. As we extract and use these resources, we cause an impact on Earth today, which will in turn cause an impact to those who come after us. To enhance our careful control on (stewardship of) the environment, we must proceed into the future with a sound understanding of the mechanisms of Earth systems.

1.4. Branches of Geology

The subject of geology has several clearly defined divisions. The important branches include the following:

Physical Geology : It is concerned with the study of the agents and processes which modify the Earth's surface as well as the uppermost layers of the Earth, such as weathering, erosion, sedimentation, volcanism, earthquakes and crustal deformation.

Geomorphology : It is the science of landforms such as mountains, valleys, plateaus, deltas, sand dunes, etc. It includes the study of origin and evolution of various types of landforms.

Mineralogy : The study of minerals, including their physical, chemical and optical properties.

Crystallography : The study of crystals. This forms a subdivision of Mineralogy.

Economic Geology : This branch of geology is concerned with the study of mineral resources - earth materials of economic value. These materials include metallic and nonmetallic minerals, building stones and fossil fuels.

Petrology : It is the study of rocks and consists of their description, classification and genesis.

Historical Geology : It is the study of the events in the Earth's history and includes the branches of science known as Stratigraphy and Palaeontology.

Palaeontology : This branch deals with the study of fossils. It attempts to reconstruct the history and evolution of life.

Stratigraphy : It is the branch of geology which is the study of time and space relationships of layered rocks.

Structural Geology : It deals with the study of rock structures such as fold, fault, joints, etc., and their classifications.

Engineering Geology : It deals with the application of geology in civil engineering, especially in the construction of building foundations, selection of dam sites, tunnel alignment, landslide prevention and coastal protection, etc.

Hydrogeology : It is the branch of geology dealing with the study of all aspects of groundwater.

Environmental Geology : This branch of geology is concerned with the problems of environmental pollution, waste disposal and urban development and natural hazards, such as flooding and erosion and their mitigation or prevention.

Marine Geology : The study of geological aspects of oceans and ocean basins, geological action of waves and currents.

Mining Geology : This is also an applied branch of geology and concerned with extraction of economic minerals from the Earth and their beneficiation (processing of the mined materials).

Petroloeum Geology : This branch of geology is concerned with exploration and extraction of petroleum and natural gas.

Check your progress

1. *What are the four basic areas of Earth Science?*
2. *Petrology deals with the study of rocks, whereas Stratigraphy is the study of ___________.*

Let us do

Geology is very much related to other basic branches of sciences. Earth science includes and applies knowledge from Biology, Chemistry, Physics, Ecology, and Mathematics to tackle complex interdisciplinary issues. Study the figure (Fig.1.1) given below carefully and elaborate the interrelationships of Geology with other disciplines.

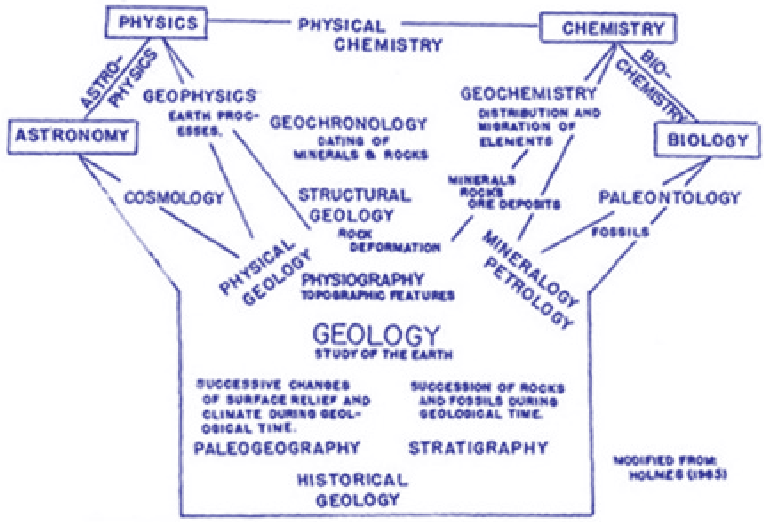


Fig. 1.1: Interrelationship of Geology with other disciplines

1.5. Geology and Human society

From the perspective of sustainable development, Geology and Geologists have a great role to play in the service of human kind. Earth Science will be beneficial to the human society only if inputs of the theoretical as well as practical knowledge will be made for the beneficial purpose of mankind, in the form of exploration for coal, petroleum, natural gas, new ore deposits, predictions of climatic changes, environmental changes, measures to safeguard from natural disasters, etc.

A sound geological knowledge helps society to move toward greater sustainability. Geologists develop new technologies to extract resources more efficiently, to reduce the pollution, for effective waste disposal methods.

Fossil fuels and uranium currently provide most of our energy resources. Coal, oil and natural gas, require tens to hundreds of millions of years to form. These will remain the dominant source of energy for some more decades of the future until energy from other sources are made available in substantial amounts.

Soil, rocks and minerals provide essential metals and other materials for agriculture, manufacturing and building. Soil develops extremely slowly from weathered rock, and the erosion of soil threatens agriculture in many parts of the country. Minerals provide the raw materials for much of our industries. Many electronic and mechanical devices have specific requirements for particular rare metals and minerals that are not adequatly available.

Natural resources are limited. Earth's natural resources provide the foundation for all the physical needs of the human society. Most of them are non renewable on human time scale and many will run critically low in the near future. Moreover Earth resources are distributed unevenly around the planet. Water resources are essential for agriculture, manufacturing, energy production and life. Geologists and engineers help to locate and effectively manage our fresh water resources.

Today we live in a time when the earth and its inhabitants face many challenges. Our climate is changing and this to a great extent is ascribed to anthropogenic causes. We also have several other challenges such as to develop new sources of energy that will have minimal impact on climate; locate new sources of metals and other mineral resources as known sources are depleted; and, determine how earth's increasing population can live and avoid serious threats such as volcanic activity, earthquakes, landslides, floods and more. These are just a few of the problem areas where solutions require a deep understanding of geology. The geological knowledge is essential for the search of new mineral resources, both on land and in ocean floors, prevention of hazardous environmental pollution, ways to tackle the consequences of climatic changes and so on.

Economic Geology is important for locating and extracting minerals and fossil fuels such as coal, oil, gold, iron, and aluminum. Locating these deposits requires efforts of able geologists to study the geologic setting and several other factors before deciding what location will produce the most mineral resources and later extract them economically. Geologists are also consulted with regard to construction projects. In some cases, such as areas with active faults, the geologists are able to predict the type of movement and the magnitude of movement likely to occur in the event of an earthquake. This helps in the design and construction of buildings and highways to make them safer in areas that experience frequent earthquakes. In areas that depend on groundwater as the only source of water geologists are able to determine how deep the wells should be drilled to recover the maximum amount of water without putting stress to the surrounding aquatic systems and creating environmental problems.

Natural hazards that result from natural processes pose risks to humans. These hazards include earthquakes, tsunamis, hurricanes, floods, droughts, landslides, volcanic eruptions, extreme weather, lightning-induced fires, coastal erosion and comet and asteroid impacts. Earth scientists are presently in a position to predict and forecast when and where natural hazards may occur.

The expertise of geologists, geophysicists and other earth scientists is required by government and private agencies concerned with agriculture and forestry, water supply and hydro-electric power generation, civil engineering, waste disposal and contaminated site remediation and conservation of natural resources.

Check your progress

1. *List out any three areas where the geological knowledge is useful in your daily life.*
2. *Mention the role of geologists in managing environmental problems.*

1.6. Major geological organizations in India

There are a number of organizations and institutions in India related directly or indirectly with the subject of Geology or Earth Sciences. The major national organizations and institutions and their salient features are listed below:

Geological Survey of India (GSI): The Geological Survey of India (GSI), established in 1851, is a government organization for conducting geological surveys and studies. GSI is the prime provider of basic Earth science information to the government. The headquarters of GSI is in Kolkata.

Oil and Natural Gas Corporation (ONGC): The Oil and Natural Gas Corporation (ONGC), conducts exploration and production activities in India of crude oil and natural gas. The headquarters is in Dehra Dun, Uttarakhand.

Central Ground Water Board (CGWB): Central Ground Water Board (CGWB), which is under the Ministry of Water Resources, Government of India, is the national apex agency entrusted with the responsibilities of providing scientific inputs for management, exploration, monitoring, assessment, augmentation and regulation of groundwater resources of the country. Its headquarters is in Faridabad, Haryana.

Mineral Exploration Corporation Limited (MECL): Mineral Exploration Corporation Limited (MECL) is functioning under Ministry of Mines, Govt. of India, for systematic exploration of minerals. The company has its corporate office in Nagpur, Maharashtra. MECL has made noteworthy contributions in development of the nation by the new recent discoveries of coal, lignite, base metals, gold, bauxite and limestone deposits.

Indian Bureau of Mines (IBM): The Indian Bureau of Mines (IBM) established in 1948, under the Ministry of Mines, is engaged in scientific development of mineral resources and protection of environment in mines other than coal, petroleum and natural gas, atomic minerals and minor minerals. The headquarters is in Nagpur, Maharashtra.

Atomic Minerals Directorate (AMD) for Exploration and Research: It is the oldest unit of the Department of Atomic Energy (DAE). Its headquarters is in Hyderabad. The principal mandate of the organization is to carry out geological exploration and discover mineral deposits required for nuclear power programme of India. Two sectional offices are located in Thiruvananthapuram and Vishakhapatnam for the investigation of beach sand and offshore deposits.

National Remote Sensing Centre (NRSC): It is an autonomous body under the Department of Space (DOS). This organization undertakes and facilitates remote sensing activities in the country. NRSC in Hyderabad has been converted into a full-fledged centre of ISRO since 2008.

Wadia Institute of Himalayan Geology (WIHG): It was established in June, 1968 as a small nucleus in the Botany Department, Delhi University. The institute was shifted to Dehra Dun during April, 1976. It is an autonomous research institute of the Department of Science and Technology, Government of India. Initially named as the Institute of Himalayan Geology, it was renamed as the Wadia Institute of Himalayan Geology in memory of its founder, the late Prof. D. N. Wadia, in appreciation of his contributions to the geology of the Himalayas.

Coal India Limited (CIL) : It is a public sector coal mining company with its headquarters in Kolkata and it is the world's largest coal mining undertaking.

Neyveli Lignite Corporation Limited (NLC) : It is a lignite mining and power generating company in India. NLC operates the largest open-pit lignite mines.

Indian Space Research Organization (ISRO): It is the primary space agency under Government of India. Its primary objective is to advance space technology. It was established in 1969 and its headquarters is in Bengaluru. The Vikram Sarabhai Space Centre (VSSC) is a major space research centre of the Indian Space Research Organization (ISRO), focusing on rocket and space vehicles for India's satellite programme. It is located in Thiruvananthapuram, Kerala.

Centre for Earth Sciences Studies (CESS): This premier research institute in Kerala was established in 1978, at Akkulam in Thiruvananthapuram. The primary objective of CESS is to promote modern scientific and technological research and focus on developmental programmes relevant to the country in general and Kerala State in particular. In January 2014 the CESS was taken over by the Government of India and is presently under the Ministry of Earth Sciences.

Centre for Water Resources Development and Management (CWRDM): Recognizing the need for catering to the research and development needs in the field of water management, the Centre for Water Resources Development and Management (CWRDM) was established by the Government of Kerala. It is situated in Kozhikode and is an autonomous research organization.

Kerala State Mining and Geology Department: It is an undertaking of the Government of Kerala that deals with geological exploration and mining within Kerala. Its headquarters is in Thiruvananthapuram and has regional offices located in all districts.

Kerala State Groundwater Department: It is a department of the Government of Kerala concerned with the exploration and exploitation of groundwater resources of the state. It has its headquarters at Thiruvananthapuram and regional offices in all the districts.

Kerala State Landuse Board: Kerala State Land Use Board was established in 1975 under the Department of Planning and Economic Affairs, Government of Kerala. It assists the state government in matters of framing policies for optimum land use and natural resource management in the state, with the basic objective of providing necessary advisory support on matters related to the optimum use of land and land resources viz., soil, water and vegetation. Its headquarters is in Thiruvananthapuram and has a regional office in Thrissur.

Let us sum up

Geology is the scientific study of the Earth. It forms one of the four basic areas that constitute Earth Sciences or Geoscience. It investigates what happened in the past and what is happening now, with reference to the planet Earth. Geology is concerned with all aspects of the Earth related to its origin, its landforms, minerals, rocks, environment, structural features found in the rocks, etc. All earth materials including water, soil, minerals, fossil fuels, etc., are discovered, exploited and managed with the help of earth scientists or geologists. The subject of Geology has several clearly defined divisions which form the various branches of Geology. It is very much related to other basic branches of sciences. As far as sustainable development is concerned, the progress of science will only be beneficial to mankind and in this aspect geology and geologists have a great role to play in the service of human kind. Geologists will help society move toward greater sustainability. In India there are a number of organizations and institutions which deal directly or indirectly with the subject of geology or Earth Sciences.

Significant Learning Outcomes

The learner can:

- describe Earth Science and geology
- explain the various branches of geology.
- recognize the role of geology in human society.
- identify the major organizations of the country related to geology.

Let us assess

1. Describe the importance of earth resources in the development of a country.
2. Explain the functions of any three major geological organizations of our country.
3. Mention five disciplines related to geology.

2 ORIGIN AND STRUCTURE OF THE EARTH

2.1. Introduction

The planet in which we live and move about is a unique and remarkable astronomical body. Geology, the science of the Earth, mainly concerns itself with the study of the Earth's constitution, structure, history and its evolution. The Earth is a member of the solar system. Solar system in turn is a member of the vast galaxy known as the Milky Way. Therefore, as an introduction to the study of geology, it is desirable to have some basic knowledge about the solar system and the vast universe in which millions and millions of stars and planets exist.

Our understanding of the universe has undergone serious revision in the last few centuries.

A **galaxy** is a vast assemblage of stars, nebulae, etc., composing an island universe separated from other such assemblages by great distances. The sun and its family of planets is part of a galaxy known as the **Milky Way Galaxy.** This galaxy has an estimated diameter of 100,000-150,000 light years. A light-year (symbol: ly), (sometimes written as lightyear) is an astronomical *unit of length* and it is equal to the distance that light travels in vacuum in one year. Light moves at a velocity of about 300,000 km each second. So in one year, it can travel about 9,500,000,000,000 km.

2.2. Solar System

The term **solar system** refers to a star and all the objects that orbit around it. Our solar system consists of the sun - our star and everything that travels around it. These include 8 planets and nearly 170 natural satellites (such as our moon); dwarf planets, countless asteroids (some with their own satellites), comets and other icy bodies and vast reaches of highly tenuous gas and dust known as interplanetary medium. It is located on the edge of a spiral arm (known as the **Orion Arm**) at one-half to two-thirds of the way (28,000 light-years) from the centre of our **Milky Way galaxy** (Fig 2.1). The whole solar system is moving around the galaxy with a period in a range of 220 to 250 million years. There are most likely billions of other solar systems in our galaxy. And there are billions of galaxies in the universe!

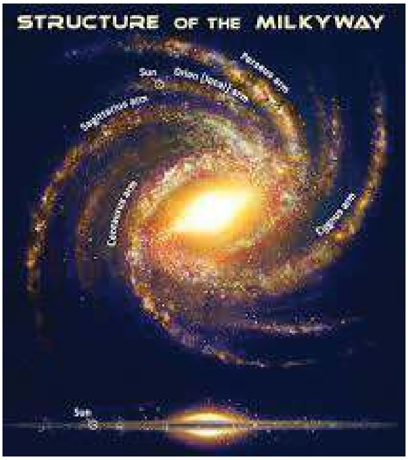


Fig. 2.1: Milky Way Galaxy and position of the Sun

The sun is the centre of our solar system. It contains almost all of the mass in our solar system and exerts a tremendous gravitational pull on planets and other bodies. Our solar system formed about 4.6 billion years ago. Two planets, Mercury and Venus, are closer to the Sun than the Earth. The four planets closest to the Sun - Mercury, Venus, Earth, and Mars - are called the **terrestrial planets** because they have solid, rocky surfaces. Two of the outer planets beyond the orbit of Mars - Jupiter and Saturn - are known as **gas giants**; the more distant Uranus and Neptune are called **ice giants**.

Until the time of Copernicus (1473–1553), it was generally believed that all celestial bodies in the universe revolved around the Earth. This concept of solar system is known as **geocentric concept**. With the invention of telescope, it was discovered by Galileo (1564–1642) that the Sun is the centre of the solar system and all planets including Earth are revolving around it. This gave rise to the **heliocentric concept**.

The orbits of the planets are ellipses with the Sun at one focus, though all except Mercury are very nearly circular (Fig. 2.2). The orbital paths of the planets are all more or less in the same plane. Planets orbit in the same direction (counter-clockwise while looking down from above the Sun's north pole); all but Venus and Uranus also rotate in that same sense.

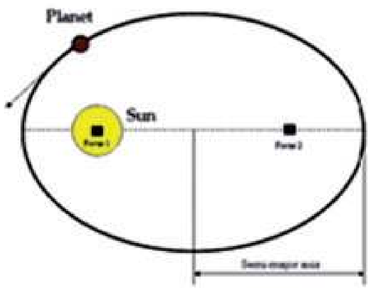


Fig. 2.2: Elliptical orbit of a planet

Most of the known dwarf planets exist in an icy zone beyond Neptune called the **Kuiper Belt**, which is also the place of origin of many comets. Many objects in our solar system have atmospheres, including planets, some dwarf planets and even a couple of moons.

The mean distance to the sun from our planet is 149.60 million kilometres. This distance is known as an **astronomical unit** (abbreviated AU), and it is used as a unit of length for measuring distances all across the solar system. One AU is roughly the average Earth–Sun distance (about 150 million km). NASA's Voyager 1 and Voyager 2 spacecrafts are the first spacecrafts to explore the outer reaches of our solar system.

2.2.1. The Sun

The Sun which occupies the centre of our solar system is a star. A star does not have a solid surface, but is a ball of hot ionized gas. The radius of the sun is 695,508 km, or about 110 times the radius of the Earth. One million Earths could fit inside the sun. The Sun has no solid surface. Its mass is approximately 330,000 times the mass of Earth and accounts for about 99.86% of the total mass of the entire solar system. Chemically, about three quarters of the Sun's mass consists of hydrogen, while the rest is mostly helium. The remainder (1.69%, which nonetheless equals 5,600 times the mass of Earth) consists of heavier elements, including oxygen, carbon, neon and iron, among others. The ionized gases are held together by gravitational attraction, producing immense pressure and temperature at its centre. Since the Sun is not a solid body, different parts of the sun rotate at different rates. At the equator, the sun spins once about every 25 days, but at its poles the sun rotates once on its axis every 36 Earth days. The surface temperature of the Sun is around 5,725 °C. The temperature at the Sun's core is about 15 million degrees Celsius.

Although the Sun is of no significance to the universe as a whole, it is earth's primary source of energy. The energy from the Sun is the driving force behind many processes taking place on Earth like winds, waves and currents, rain and climate etc. It is also responsible for the survival of varied forms of organisms of the Earth.

2.2.2. Planets

The solar system consists of eight planets (Fig. 2.3). They are Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus and Neptune.

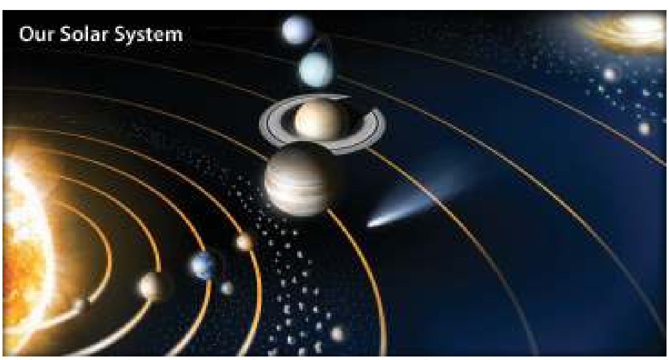


Fig. 2.3: The Sun and its planets constitute the Solar System

RELEVANT FACTS ABOUT THE PLANETS OF THE SOLAR SYSTEM

The planets are grouped into two classes as **inner planets** and **outer planets**. The first four planets – Mercury, Venus, Earth and Mars are called inner planets or terrestrial planets. The remaining planets – Jupiter, Saturn, Uranus and Neptune are known as outer planets or **Jovian planets**.

Mercury is the planet nearest to the Sun and it is also the smallest planet in our solar system - only slightly larger than the Earth's moon. Because Mercury is so close to the Sun, it is hard to directly observe from Earth except during dawn or twilight. Mercury orbits around the Sun every 88 days. Its orbital speed is faster than that of any other planet. One Mercury solar day equals 175.97 Earth days. Venus is the hottest planet in the solar system. Its surface temperature is estimated as 465^{o}C. Since the duration of rotation and that of revolution of this planet are almost the same (see the table 2.1) one day of Venus is slightly lengthier than its one full year. Neptune is the farthest planet and Jupiter is the largest.

Table 2.1: Some relevant facts about planets

Sl. No.	Name of Planet	Average Distance from Sun in Million km.	Equatorial Diameter in km.	Density. kg/m^3	Time for one Revolution	Time for one Rotation (hours)	Mean Temperature (^{o}C)	No. of Satellites
1.	Mercury	57.9	4,879	5427	88 days	1407 .6	167	0
2.	Venus	108.2	12,104	5243	224 days	-5832.5	464	0
3.	Earth	149.6	12,756	5514	365¼ days	23 .9	15	1
4.	Mars	227.9	6,792	3933	109 years	24.6	-65	2
5.	Jupiter	778.6	1,42,984	1326	11.9 years	9.9	- 110	67
6.	Saturn	1433.5	1,20,536	687	29.5 years	10.7	- 140	62
7.	Uranus	2872.5	51,118	1271	84 years	-17.2	- 195	27
8.	Neptune	4495.1	49,528	1638	164.9 years	16.1	- 200	14

2.2.3. Asteroids

Asteroids are smaller celestial bodies which revolve around the Sun. Most of them have their orbits in between those of Mars and Jupiter. They are made up of rocky materials and have varying sizes and shapes. The largest one, 'Ceres', is about 1000 km. in diametre. Recently Ceres is included among the group of dwarf planets along with Pluto and some others. The discovery of this celestial body was made on January 1st, 1900.

Most of the known asteroids, numbering over 50,000, have only about 1km diametre. Scientists generally believe that asteroids are fragmental remains of some pre-existed planet that has been shattered by some unknown process.

2.2.4. Comets

Comets are smaller celestial bodies revolving around the sun in highly elliptical and elongated orbits (Fig. 2.4). The majority of them spend most of their time in the outer reaches of the solar system, occasionally coming very close to the sun.

Fig. 2.4: Comet

When a comet comes closer to the sun, its contents such as ice particles, carbon dioxide etc. get evaporated. The comets have a rocky nucleus and a long luminous tail made up of gases, ice and dust particles, directed away from the sun. The gases form a halo around the nucleus which may be visible from the Earth when a comet comes closer to the sun. There is a well known comet the Halley's Comet, named after Edmund Halley a famous astronomer of the eighteenth century. This comet appears in the neighbourhood of the earth once in 76 years.

THE OORT CLOUD

In 1950, the Dutch astronomer Jan Oort proposed that certain comets come from a vast, extremely distant, spherical shell composed of icy bodies surrounding the solar system. This giant swarm of objects is now named as the **Oort cloud**, occupying space at a distance between 5,000 and 100,000 astronomical units from the Sun. Some of the comets belonging to the Oort cloud have very large, eccentric orbits and take thousands of years to circle the Sun. In recorded history, they are observed in the inner solar system only once. In contrast, short-period comets take less than 200 years to orbit the Sun and they travel approximately in the plane in which most of the planets orbit. These comets are presumed to come from a disc-shaped region beyond Neptune, called the **Kuiper Belt**, named in honour of astronomer Gerard Kuiper. The Kuiper Belt extends from about 30 to 55 AU from the Sun and is probably populated with hundreds of thousands of icy bodies larger than 100 km across and an estimated trillion or more comets.

Let us do

Prepare a model of solar system, using an appropriate scale (for eg. 1 metre = 2AU) in a convenient location of your school compound.

2.2.5. Meteors and Meteorites

Most of you are familiar with the event of a sudden and bright streak of light moving across a moonless night sky and disappearing after a few seconds without leaving a trail behind. This phenomenon is caused by the members of the solar system known as **meteors**.

Meteors are small celestial bodies which enter the earth's atmosphere from interplanetary spaces and burn by friction with the particles of the earth's atmosphere, producing a streak of light across the sky. The heating resulting from friction causes the burning of the body of the meteor within the atmosphere. Meteors are rock fragments from space which travel at great speeds of several km/second. Thousands of meteors enter the earth's atmosphere every day. Sometimes there are meteor showers that originate from "the debris" of the tails of the comets. Incompletely burnt meteors reaching the surface of the earth are called **meteorites**.

The impact of huge meteorites produces impact craters on the surfaces of the earth. A well known impact crater is the Meteor Crater (Barringer Crater) of Arizona Desert in U.S.A (Fig. 2.5). The crater is about 1.2 kilometre across and 200 metre deep. An Indian example of impact crater is the Lonar Crater (a saline soda lake) with a diametre of 1.8 km, located at Lonar in Buldana district, Maharashtra. It was created by a meteor impact on Deccan lava flows, during the Pleistocene Epoch.

There are three types of meteorites:

a) Stony meteorites,   b) Iron meteorites and c)   Stony - iron meteorites

Fig. 2.5: Meteor Crater (Barringer Crater) of Arizona, USA

There are two reported meteorite finds from Kerala. One from Cranganore (Kodungalloor) which fell in 1917 at 10°12’N, 76°16’E, weighing about 1460 g and another one from Kuttipuram (10°50’N, 76°2’E) collected in 1914 and weighing about 45 kg. Both of these are chondrites or stony meteorites.

This grouping is based on the composition of the meteorite. Stony meteorite mainly consists of silicates. The iron meteorite is made up of iron alloyed with nickel and other metals. Stony iron meteorites consist of a mixture of silicates and iron. Most meteorites are of stony variety. Only very few are a mixture of stone and iron.

Meteorites are valuable to science because they are the only objects that come to us from outside the earth and therefore are especially valuable as they give clues regarding the age of the solar system. They also give information about certain chemical aspects of the solar system.

2.3. Origin of the Universe -The Big Bang Hypothesis

Today, from our tiny homeplanet- Earth, our scientists are using their ingenuity, and probing the depths of the Universe and trying to unravel its mysteries. The origin of the universe is a most complex topic, only a very brief discussion of which is given below.

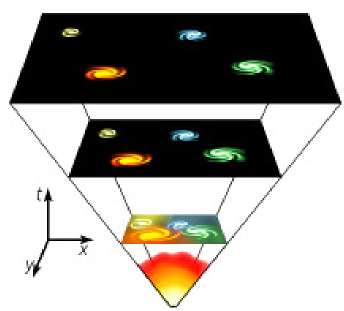


Fig 2.6: Concept of an expanding universe

The universe contains all the matter and energy that exists now, that existed in the past, and that will exist in the future. The universe also includes all of space and time. Edwin Hubble combined his measurements of the distances to galaxies with other astronomers' measurements of redshift. **Redshift** is a shift of element lines toward the red end of the spectrum. Redshift occurs when the source of light is moving away from the observer. Hubble noticed a relationship, which is now called Hubble's law: *The farther away a galaxy is, the faster it is moving away from us.* The farther away a galaxy is, the more its light is redshifted, and the faster it is moving away from us. In other words, the universe is expanding! You'll notice that the galaxies that are farther away in distance are travelling at higher velocities.

Imagine a balloon covered with tiny dots (Fig. 2.6). Let us say that each dot represents a galaxy. When you inflate the balloon, the dots slowly move away from each other because the rubber stretches in the space between them. If it was a giant balloon and you were standing on one of the dots, you would see the other dots moving away from you. Not only that, but dots farther away from you on the balloon would move away faster than dots nearby. Note that the distance between galaxies gets bigger as you go forward in time, but the size of each galaxy stays about the same.

The discovery that the universe is expanding also told astronomers something about how the universe might have formed. Before this discovery, there were many ideas about the universe, most of them thinking of the universe as constant. Once scientists learned that the universe is expanding, the next logical thought is that at one time it had to have been smaller. The current expansion of the universe suggests that in the past the universe was squeezed into a very small volume.

The **Big Bang** is the name of a widely held scientific theory of the evolution of the universe. To understand this theory, start by picturing the universe expanding steadily. Then, reverse the direction of time, like pressing the "rewind" button on a video player. Now the universe is contracting, getting smaller and smaller. If you go far enough back in time, you will reach a point when the universe was squeezed into a very small volume.

According to the Big Bang theory, the universe emerged from a highly compressed primitive state with extremely high temperature and density with no stars, atoms, form or structure - called a "**singularity**". Initially, the universe was concentrated at a single point. The theory states that the universe expanded rapidly with a tremendous explosion, from its highly compressed primordial state, which resulted in a significant decrease in density and temperature.

The Big Bang started somewhere about 13.7 billion years ago. In the first few moments after the Big Bang, the universe was extremely hot and dense. As the universe expanded, it became less dense and it cooled. After only a few seconds, the universe had cooled enough that protons, neutrons, and electrons could form. After a few minutes, the nuclei of atoms formed. The first neutral atoms with neutrons, protons, and electrons, did not form until about 380,000 years after the big bang. The matter in the early universe was not smoothly distributed across space. Some parts of the universe were denser than others. These clumps of matter were held close together by gravity. Eventually, these clumps became the protogalaxies and within them the earliest stars. Stars are nuclear furnaces in which heavier elements such as carbon, oxygen, silicon and iron are formed. Massive stars exploding as supernovae create even heavier elements. Such explosions send material into space ready to be incorporated into future generations of stars and planets and other structures that we see in the universe today.

Both time and space were created in Big Bang event.The Big Bang might also have been the beginning of time. If the Big Bang was the beginning of time, then there was no universe before the Big Bang, since there was no concept of "before" without time. Other ideas state that the Big Bang was not the beginning of time; instead, some believe that there was a different universe before and it may have been very different from the one we know today.

Now, some of you may be curious to know the answers to the questions: What is the rate of expansion of our universe? Will the universe expand and its size grow forever?

Many scientists believe that, the expansion of the universe cannot continue forever, but the process of expansion will stop some day in the remote future. When the expansion stops, it will begin to contract due the gravitational force between the galaxies and matter present in the universe. This gravitational collapse can be called as the 'Big Crunch'. At the end of the Big Crunch, singularity may again take place. And this may lead to the next Big Bang! In short our universe will oscillate between alternate phases of expansion and contraction.

2.4. Origin of the Earth

How was this planet born? Where did it come from? These questions agitated the minds of scientists, and escaped satisfactory explanations for a long time. Even today the answers to those questions remain not fully satisfactory (Fig. 2.7).

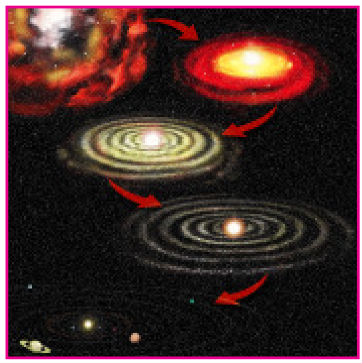


Fig. 2.7: Origin of the Earth

Regarding the origin of earth, several views appeared during the last 250 years. Most of these are given only the status of *hypotheses* rather than that of *theories*.

Let us learn in brief two important early hypotheses that attempted to explain the origin of earth.

2.4.1. The Nebular Hypothesis

Early attempts to explain the origin of this system led to the Nebular Hypothesis. This was originally proposed by a German Philosopher, Immanuel Kant in 1755 and later in 1796, the French astronomer/ mathematician Pierre Simon de Laplace modified and elaborated it.

According to the Nebular Hypothesis, the solar system evolved from a cloud of dispersed particles- a large, primordial **nebula**. This term, derived from Latin (meaning "mist" or "cloud"), refers to any of the various tenuous clouds of gas and dust that occur in interstellar space (that part

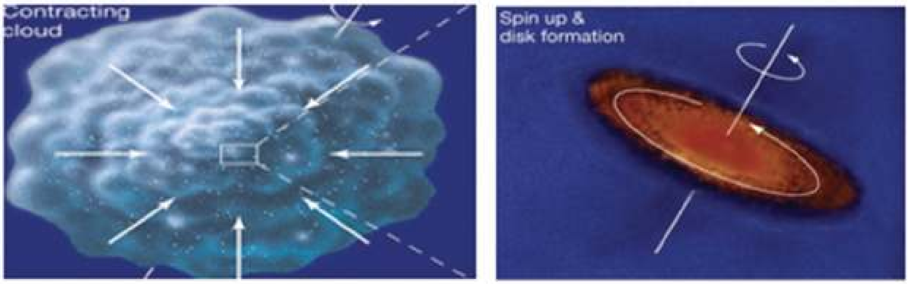


Fig. 2.8: (a), (b) - Nebular Hypothesis

of the space in between stars). According to the nebular hypothesis, part of an interstellar cloud of dust and gas underwent gravitational collapse (contraction) to form a primeval solar nebula (Fig. 2.8a). After contraction, it began to spin and transformed into a disc (Fig. 2.8b).

Clumps of interstellar matter were left behind in the midplane of the solar disc as it contracted towards its centre gradually coalesced, through a process of accretion, to form grains, pebbles, boulders, and still larger masses measuring a few kilometres to several hundred kilometres across. These larger building blocks then combined under the force of gravity to form protoplanets, which were the precursors of most of the current planets of the solar system. Later these protoplanets accreted more materials, and assumed the size and shape of planets as we know them today. (Fig. 2.9 a and 2.9 b).

Fig. 2.9: (a) Evolving solar system

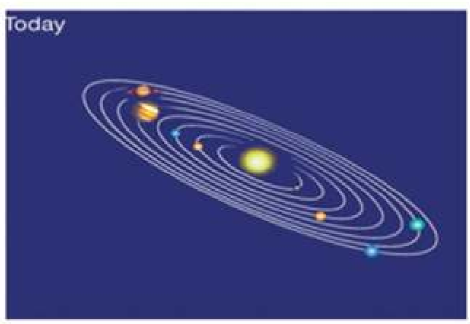


Fig. 2.9: (b) Present solar system

The asteroids and some other smaller celestial bodies are fragments left by the shattering of one or more of other planets so formed in the process. The remaining central mass of the nebula later formed the Sun.

2.4.2. Planetesimal Hypothesis

This hypothesis was proposed by the U.S. Geologist Chamberlin, and a U.S. Astronomer Moulton, in 1905. Planetesimals are one of a class of bodies that are theorized to have coalesced to form Earth and the other planets after condensing from concentrations of diffuse matter early in the history of the solar system. According to the planetesimal hypothesis, a star once passed near the Sun, pulling away from it matter that later condensed and formed the planets. This hypothesis postulates that due to an event of near approach of a passing star, very large tidal waves were created upon the surface of the Sun. Due to the extreme gravitational pull of the passing star, a portion of Sun's mass that formed a tidal swell was pulled far out into the space.

This ejected mass chilled out immediately resulting in the formation of innumerable small solid particles. These small particles, named as planetesimals, continued to revolve around the Sun in various nearly circular orbits. During the revolution, these swarms of planetesimals mutually collided and coalesced to form the planets. Therefore, the planets have been in solid form all the time during their growth, according to this hypothesis. This hypothesis explains the occurrence and occasional fall of meteorites. The Planetesimal Hypothesis could also give a satisfactory explanation for the known design (plane of rotation of planets) and other features (similar rotational directions of planets) of the solar system.

2.5. Shape and Size of the Earth

Until the 17th century, it was believed that the earth was a perfect sphere. Later scientists discovered that the Earth has a shape of an **oblate ellipsoid**. (If you slightly press down a sphere it will assume the shape of an oblate ellipsoid).

The Earth's polar axis is slightly shorter than its equatorial axis. This is attributed to its rotation about its polar axis and consequent effect of the resulting centrifugal forces (Fig. 2.10). The equatorial radius of the earth is 6378 km while its polar radius is 6357 km. Note that the equatorial diameter of the Earth is 42 kilometre longer than its polar diametre.

Elevation of a point on the Earth's surface is expressed with reference to **mean sea level**. It was once believed that the sea was in balance with the earth's gravity and formed a mathematically regular figure. The mean sea level is usually described as the arithmetic mean of hourly water elevations caused by tidal effect (of the gravitational forces from the Moon and Sun) observed over a specific 19-year cycle. Since the sea

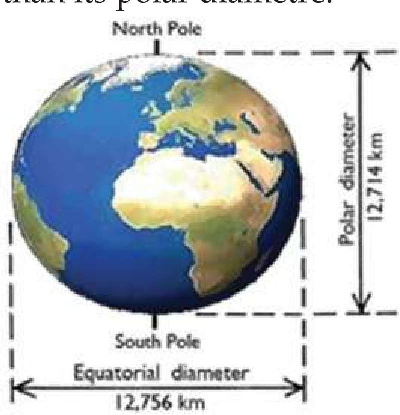


Fig. 2.10: Oblate ellipsoidal shape of the Earth

surface conforms to the earth's gravitational field, mean sea level also has slight hills and valleys that are similar to the land surface but much smoother. Modern studies have indicated that the actual shape of the earth is not truly that of a mathematically true oblate ellipsoid. Scientists have noticed the fact that while some parts of the earth's surface are higher than the surface of a mathematically true oblate ellipsoid other regions are below that surface (Fig. 2.11). The true form or shape of the earth is today described by the scientific term '**geoid**'. If we cut numerous canals from one side of the continent to the other in different directions and allow the ocean water to occupy the canals, the surface formed by connecting the water surfaces of the canals will give the true form described by the term geoid.

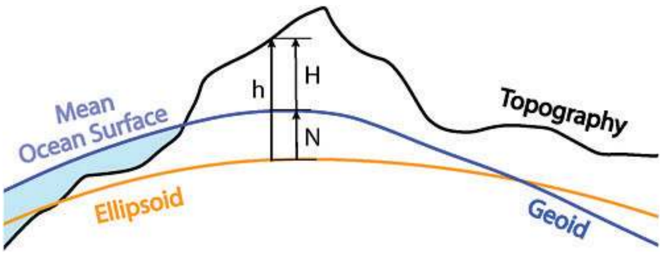


Fig. 2.11: Relationship between ellipsoidal surface, mean sea level and geoidal surface

2.6. Concept of Geologic Time

One of the most important modern developments in Earth Science was the determination of the age of the solar system and its family of planets and satellites. Scientists generally agree on the point that our earth is about 4500 million (4.5 billion) years old. The term '**geologic time**' is given for the entire duration of time since the formation of the earth to the present day.

2.6.1. The Geologic Time Scale

According to the present scientific estimate our earth is about 4.54 ± 0.05 billion years (4.54×10^9 years ± 1%) old. This age is based on evidence from radiometric age dating of meteorite material and the ages of the oldest - known rocks samples of the Earth.

The **geologic time scale** is a system of chronological measurement used by earth scientists to relate the timing and relationships between events that have occurred during the Earth's history. However, that segment of Earth history that is represented by and recorded in rock strata extends only from about 3.9 billion years ago (corresponding to the age of the oldest known rocks) to the present day. It is, in effect, that segment of Earth history that is represented by and recorded in rock strata.

Table 2.2: Geological Time Scale (with their duration in millions of years)

Eon	Era	Period	Epoch
Phanerozoic 542 to present	Cenozoic (65 my to present)	Quaternary (2.6 - present)	Holocene (0.1 to present)
			Pleistocene (2.6-0.1)
		Tertiary (66 – 2.6)	Pliocene (5.3- 2.6)
			Miocene (23- 5.3)
			Oligocene (34-23)
			Eocene (56-34)
			Palaeocene (66-56)
	Mesozoic	Cretaceous (145 - 66)	
		Jurassic (201 - 145)	
		Triassic (247 - 201)	
	Palaeozoic	Permian (299 - 247)	
		Carboniferous (359 -299)	
		Devonian (419 -359)	
		Silurian (445 - 419)	
		Ordovician (485 - 445)	
		Cambrian (541 - 485)	
Proterozoic (2500 - to 542)	Neoproterozoic (1000 - 541)		
	Mesoproterozoic (1600- 1000)		
	Paleoproterozoic (2500 - 1600)		
Archaean (4000 to 2500)	Neoarchaean (2800 - 2500)		
	Mesoarchaean (3200- 2800)		
	Paleoarchaean (3600 -3200)		
	Eoarchaean (4000 - 3600)		
Hadean (about 4600 – 4000)			

Dates given are in millions of years (my)

The geologic time, as it is known today, is subdivided into a number of named time units. The term **geologic time scale** is applied for the time scale consisting of various named divisions of the geologic time (Table 2.2). The time span *right from the birth of the earth* up to the present day is divided into many units - larger and smaller time units. The major division of this duration of time is given below:

(1) **Eons :** The Geological time from the birth of the Earth to the present is divided into four grand divisions called eons. The oldest eon is (1) **Hadean Eon** (starting from 4600 million years to about 4000 million years), (2) **Archaean Eon** (starting from 4000 million years to 2500 million years) (3) **Proterozoic Eon** (starting from 2500 million years to about 541 million years) and the youngest (4) **Phanerozoic Eon** (starting from 541 million years to present).

(2) **Eras:** Eras are the subdivisions of eons. *There are no subdivisions for the Hadean Eon.* Archean Eon is subdivided into four eras (the oldest being **Eoarchean Era**, followed by **Paleoarchean Era**, **Mesoarchean Era** and the youngest **Neoarchean Era**).

The Proterozoic Eon is similarly subdivided into three eras (namely the **Paleoproterozoic Era**, the **Mesoproterozoic Era** and the youngest **Neoproterozoic Era**).

Phanerozoic Eon is divided into three eras (the oldest one being the **Palaeozoic Era**, followed by the **Mesozoic Era** and the youngest, the **Cenozoic Era**).

The term **Precambrian** (**Pre-Cambrian**) is generally used to describe the large span of time in earth's history before the current Phanerozoic Eon.

(3) **Periods:** Some eras are further subdivided into smaller time units called periods. Thus the Phanerozoic Eon consists of eleven periods. They are in order : the Cambrian Period (the oldest period of the Palaeozoic Era), the Ordovician Period, the Silurian Period, the Devonian Period, the Carboniferous Period (the Mississippian and the Pennsylvanian) , the Permian Period (the youngest period of the Paleozoic Era), the Triassic Period (the oldest of the Mesozoic Era), the Jurassic Period, the Cretaceous (the youngest period of the Mesozoic Era), the Tertiary Period (the oldest of the Cenozoic Era), and the Quaternary Period (the youngest period of the Cenozoic Era).

(4) **Epochs:** An epoch is a subdivision of the periods of the geologic time scale. We are currently living in the Holocene Epoch of the Quaternary Period.

Check your progress

1. *What is the peculiar shape of the Earth?*
   How does it affect the Earth's circumference and radius?
2. *What is meant by Geologic Time?*
3. *Which is the latest epoch of the Geologic Time Scale?*
4. *What do you mean by the 'Big Bang' ?*

2.7. Internal Structure of the Earth

If we could make a journey to the centre of the earth we would have to travel about 6,400 km. Along the way to earth's centrally located core we would pass layers of rock that can be classified in two different ways, either by their *chemical composition* or their *physical behaviour*. According to the chemical composition of the rocks, earth's interior can be differentiated into three layers - crust, mantle, and core. When considering the rocks of earth's interior in terms of their physical behaviour, six layers can be differentiated from the surface to the core. The characteristics that distinguish these six different layers are based on the relative strength of a given layer in response to stress and irrespective of whether it is solid or liquid.

The chemical composition and physical behaviour of rock inside the earth relate to each other because the chemical composition of a rock is one of the factors that determine its physical behaviour. However, the physical behaviour of rock also depends on the pressure and temperature it is subjected to at its depth within the earth. As depth inside the earth increases, the pressure and temperature increase. Some layers in the earth are harder or softer than adjacent layers, *even though they have the same composition*, because they are at different pressures and temperatures. Fig 2.12 represents the interior of the earth showing all the inner layers.

(1) Crust

Our tour to the centre of the earth starts at the surface with earth's crust. Crust is the outermost division of the solid earth. Although all the three types of rocks, namely igneous, metamorphic and sedimentary, are found here, the first two constitute volumetrically dominant portion of the crust. The thickness of the crust is variable from region to region and is not uniform everywhere. Beneath the oceans, the crust is generally 5 km to 10 km thick whereas, on continental areas it has an average thickness of about 35 km. In regions of major mountains, such as the Himalayas, the thickness

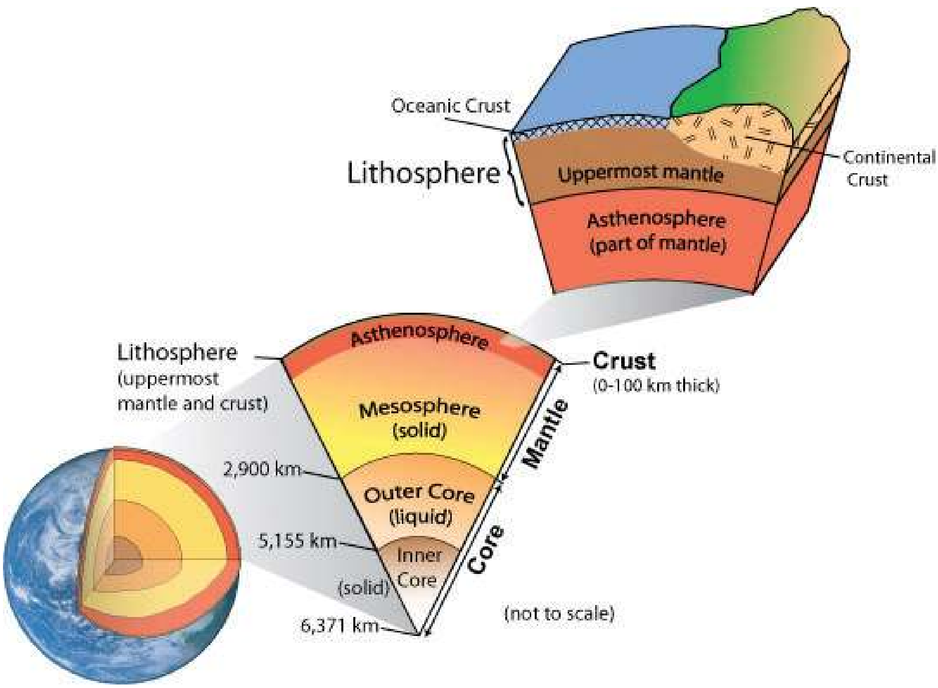


Fig. 2.12: Interior of the Earth showing all inner layers

of the crust is estimated to exceed 70 km. A prominent seismic discontinuity, known as Mohorovicic discontinuity or simply 'Moho' is considered as the boundary separating the overlying crust from the underlying mantle, which is the second interior division. Generally speaking, the crust is predominantly silicon oxide and aluminum oxide. Continental crust is thicker and less dense than oceanic crust. Earth's crust varies in thickness from less than 5 km (under mid-ocean ridges) to more than 70 km (beneath the highest mountain range).

The concept of Sial and Sima: The rocks of the crust composed predominantly of silicates of aluminium have relatively lower density ranging from 2.7 – 2.8 g/cm^{3}. These rocks, in bulk composition are similar to the rocks called granite. These rocks have the minerals feldspars (an aluminosilicate mineral series) and quartz (crystalline silica) as their dominant minerals. Because of their relatively lower density compared to other common rocks of the crust, these tend to be concentrated in the upper portion of the crust. The upper layer of the Earth's crust is the continental portions, and these are predominantly composed of granitic rocks. The name sial (taking the first two letters of the words **silica** and **aluminium** - which are the dominant elements of granitic rocks) is therefore given to this portion (continental portion) of the crust. The term felsic, (derived from the words feldspars and silica), is also used for this portion of the crust (the continental crust) which is made up mostly by rocks enriched in silicates of aluminium. Sial is absent in the oceanic part of the crust.

The crustal portion that underlies the sial is often exposed in the ocean basins where they are not blanketed by marine sediments. The ocean floors are mainly composed of the volcanic rock called **basalt**. These rocks are composed predominantly of **silica** and **magnesium**. This lower layer of the crust has relatively higher density (2.8 to 3.3 g/cm^3) than the sial due its relatively greater content of iron and magnesium, and decreased amounts of aluminium. Therefore, the term **sima** (taking the letters **si** from the word silica and **ma** from magnesium) has been given to this portion of the crust i.e., the 'oceanic crust'. It is also called the basaltic layer of the crust. Because it is the lower portion of the crust this portion of the crust is also known as the **'basal crust'** or **'basal layer'**.

The boundary of the sial and sima (known as the Conrad discontinuity) is not a clearcut one and it has been arbitrarily set at a mean density of 2.8 g/cm^3. Sima behaves like a very viscous liquid, the sial floats on the sima, in what is called isostatic equilibrium. Mountainous portions of continents (sial) extend deep down into the sima, much like roots of floating icebergs on an ocean. These divisions of the Earth's interior (sial and sima) were first proposed by Eduard Suess in the 19th century, and still frequently appear in geologic writings.

(2) Mantle

Mantle is the middle division of the earth (recognized on the basis of chemical composition). It extends from the bottom of the crust or Mohorovicic discontinuity down to a depth of nearly 2900 km from the earth's surface. In terms of volume, the mantle is the largest of earth's three chemical layers. Mantle occupies about 83% of the earth by volume and about 68% by mass.

The mantle has an **ultramafic composition** - it contains more iron, magnesium, less aluminum and somewhat less silicon than the crust. It is assumed that the rocks of upper mantle are dominantly composed of the silicate minerals olivine and pyroxenes. The lower boundary of the mantle is marked by a discontinuity known as Guttenberg-Weichert Discontinuity.

(3) Core

Our final stop in our journey, is the core, which is the innermost part of the earth. It starts at 2900 km below the surface and extends up to the very centre of the earth. Core is mostly iron and nickel. The radius of the core is about 3,500 km. It constitutes around 17% by volume and 34% of the mass of the earth. The pressure and temperature reaches up to 6000^{o} C.

When we consider the layers of the Earth's interior in terms of their physical behaviour, six layers can be differentiated from the surface to the core:

(1) Lithosphere: Starting at the surface, the first layer is the lithosphere. We humans, and the other creatures that live on earth, occupy the surface of the lithosphere. The lithosphere is entirely solid except where there are zones of magma beneath volcanoes or in places undergoing magma intrusion. The volume of molten rock in the lithosphere is a tiny fraction, less than 0.1%, of the volume of the entire lithosphere.

The lithosphere itself has two parts. The top part is the crust. The bottom part is the upper portion of the mantle – the **lithospheric mantle**. The two components of the lithosphere, in combination, form a relatively strong, rigid layer of rock that covers the earth. Earth's **tectonic plates**, (which you will learn in unit 11) all of which are in motion relative to each other, make up the lithosphere.

(2) Asthenosphere: Beneath the lithosphere is a relatively weak and ductile layer of the mantle called the asthenosphere. Although the asthenosphere is solid, not liquid, it flows at geological rates, up to several centimetres per year. In other words, the asthenosphere behaves more plastically than the rigid lithosphere above it.

The chemical composition of the asthenosphere is about the same as the chemical composition of the overlying lithospheric mantle. Why, then, is the asthenosphere soft and the lithosphere rigid? It is because at the depth of the asthenosphere, temperatures are very close to the melting point of the rock, weakening the rock. In fact, it is thought likely, from indirect evidence, that there is a small percentage of molten rock in the tiny spaces between the mineral grains of the asthenosphere, which contributes to the soft nature of the rock. However, the solid minerals of the asthenosphere are extensively in contact with each other, forming a material that is solid overall despite the possible presence of a small amount of partial melt.

The asthenosphere is the primary source of most magma. Because the asthenosphere is close to its melting point and may contain everywhere a small proportion of partly molten rock, it does not take much to cause magma to form and separate from the asthenosphere. Melting of the asthenosphere can be caused by addition of fluid, particularly water, or by a decrease in pressure.

(3) Upper mesosphere: Beneath the asthenosphere is the rest of the mantle, the mesosphere. The mesosphere makes up most of the volume of the mantle. It is entirely solid. The temperature and pressure of the rock in the mesosphere keep it from breaking; therefore, *no earthquakes originate from the mesosphere.*

The upper mesosphere is a transition zone in which the rock rapidly becomes denser with depth in response to the increasing lithostatic pressure.

(4) Lower mesosphere: The lower mesosphere starts at a depth of 660 km from earth's surface. At that depth there is an abrupt increase in density. This increase is caused by changes in the crystal structures of the most abundant minerals in the rock. These minerals change from less dense crystal structures above the boundary to more dense crystal structures below the boundary. The lower mesosphere undergoes little density change from its top boundary at 660 km to its base at 2900 km where it meets the outer core.

(5) Outer core: The bottom of the mesosphere is the boundary with the earth's core. The core is about twice as dense as the crust, and about 1.5 times as dense as the mantle. The outer core is liquid, as was discovered when it was first observed that S-waves (seismic or earthquake waves) will not pass through it.

(6) Inner core: The inner core is solid. The inner and outer cores are made of the same iron-rich, metallic composition. The temperature of the inner core is not very much greater than the temperature of the outer core. However, lithostatic pressure keeps increasing with depth and the inner core has the great weight of the rest of the earth pressing in on it. The pressure on the inner core is high enough to keep it in the solid state.

The following table 2.3 summarizes the physical layers of the earth.

Table 2.3 Physical layers of the Earth

	Physical behaviour	Thickness
1. Lithosphere	Rigid, brittle at shallow depths	5 to 200 km
2. Asthenosphere	Ductile	100 to 300 km
3. Upper Mesosphere	Rigid, not brittle, rapid increase in density with depth	300 to 400 km
4. Lower Mesosphere	Denser and more rigid than upper mesosphere	2,300 km
5. Outer Core	Liquid	2,300 km
6. Inner Core	Rigid, not brittle	1,200 km

Check your progress

1. *What are the different layers of the Earth?*
2. *Differentiate between outer core and inner core.*

Let us do

1. *Construct a three dimensional model showing the internal structure of the Earth.*
2. *Prepare a table as given below, showing the chemical and physical characteristics of the various layers of the Earth.*

	Crust	*Mantle*	*Core*
Chemical Characteristics			
Physical Characteristics			

2.8. The basic components of the Earth System

Earth system science is a new concept that treats the Earth as an integrated system and seeks a deeper understanding of the physical, chemical, biological and human interactions that determine the past, current and future states of the Earth. It provides a physical basis for understanding the world in which we live and upon which humankind seeks to achieve sustainability.

The Earth System has two primary components: the **geosphere** and the **biosphere**. The geosphere has four subcomponents: **lithosphere** (solid Earth), **atmosphere** (gaseous envelope), **hydrosphere** (liquid water), and **cryosphere** (frozen water). Each of these subcomponents can be further subdivided into *elements*: for example, the oceans are elements of the hydrosphere. The biosphere (living organisms) contains several phyla organized into five kingdoms of life forms. (Human beings belong to the Kingdom Animalia and are but one species of the estimated 20 million to 100 million species in the biosphere).

2.8.1. Lithosphere

Lithosphere is the outer rocky covering of the earth. The term lithosphere is used for a division of the Earth's interior comprising the crust and the upper part of the mantle. Lithosphere is composed of three types of rocks (igneous, sedimentary and metamorphic) and its products.

In modern texts and in Earth system science, the term **geosphere** refers to the *solid parts of the Earth* and is used along with **atmosphere**, **hydrosphere**, and **biosphere** to describe the major basic components of the systems of the Earth. *In that context, sometimes the term **geosphere** is used instead of the term lithosphere*. However, the *lithosphere only refers to the uppermost layers of the solid Earth (oceanic and continental crustal rocks and uppermost mantle).*

2.8.2. Atmosphere

The Earth is surrounded by a blanket of air called the atmosphere, which is a mixture of gases. Nitrogen, oxygen, carbon dioxide, and other gases are all parts of this mixture. Earth's atmosphere changes constantly as these gases are added and removed. For example, animals remove oxygen when they breathe in and add carbon dioxide when they breathe out. Plants take in carbon dioxide and add oxygen to the atmosphere when they produce food. Gases can be added to and removed from the atmosphere in ways other than through living organisms. A volcanic eruption adds gases. A vehicle both adds and removes gases.

The atmosphere also insulates Earth's surface by slowing down the rate at which heat from the sun is lost and it keeps Earth at temperatures at which living things can survive.

Composition of the Atmosphere

This gaseous composition of the atmosphere is usually expressed by percentage volume i.e., relative part of the total mixture. For example, 78.08 % of the atmosphere is made of the gas diatomic nitrogen (N_2), 20.95 % is composed of diatomic oxygen (O_2), and 0.93% is made up of argon (Ar). These three gases together make up 99.9% of the atmosphere. Nitrogen, which makes up the largest portion of air, is relatively inactive chemically. Much smaller amounts of water vapour (0 to 4% -highly variable in time and location), carbon dioxide (0.0395 % and presently rising), methane (0.00018 % and presently rising), and others are also present.

The atmosphere also contains solid material in addition to the gases noted above. This solid material is very small, between 0.1 and 25 thousandths of a millimetre, or micrometer and is known as **particulates**. These tiny, solid particles include dust which is mainly soil, salt, ash from fires, volcanic ash, solid products of combustion, pollen, and tiny liquid droplets called aerosols. In addition to gases and solids, liquids also exist in the atmosphere. The most common one of these is water in each of its

Let us do

Prepare a large pie diagram showing the relative percentage of the composition of the atmosphere.

three phases (solid, liquid, and gas), which has been essential for the development of life on the planet.

The gases of the atmosphere extend from the surface of Earth to heights of thousands of kilometres, eventually merging with the solar wind—a stream of charged particles that flows outward from the outermost regions of the sun. The composition of the atmosphere is more or less constant with height to an altitude of about 100 km, with particular exceptions being water vapour and ozone.

Air has weight and can exert pressure. Earth's atmosphere is pulled toward Earth's surface by gravity. As a result of the pull of gravity, the atmosphere is denser near Earth's surface. Almost the entire mass of Earth's atmospheric gases is located within 30 km of our planet's surface. Fewer gas molecules are found at altitudes above 30 km; therefore, less pressure at these altitudes pushes downward on atmospheric gases. Air is a powerful force on Earth exerting pressure on all organisms. Barometers are used to measure the air pressure. The typical pressure at sea level is 1013.25 millibars.

Vertical structure of the atmosphere (Layers of the Atmosphere)

The atmosphere begins at sea level (and in some places on land that are just below sea level) and extends outward some 10,000 km into space. The Earth's atmosphere can be divided into several layers. How the layers are defined can vary depending upon what properties are taken into consideration. We can define these layers based on many different properties of the atmosphere. Layers defined by different types of properties can overlap and the boundaries between layers are not sharply delineated.

Earth's atmosphere consists of two major vertical zones:

(1) **The homosphere** : This extends to an altitude of about 100 km. In this zone turbulent mixing dominates the molecular diffusion of gases and the composition of the atmosphere tends to be independent of height. Therefore the chemical composition of the atmosphere in the homosphere is highly uniform. The term homosphere is applied for this zone because of this fact.

(2) **The heterosphere :** This zone is located above 100 km from the Earth's surface. In this zone various atmospheric gases are separated by molecular mass, with the lighter gases being concentrated in the highest layers. Above 1,000 km, helium and hydrogen are the dominant species. Diatomic nitrogen (N_2), a relatively heavy gas, drops off rapidly with height and exists in only trace amounts at 500 km and above.

The transition zone, located at a height of around 100 km between the homosphere and heterosphere, is called the **turbopause**.

Based on temperature changes that occur at different distances above the Earth's surface, the homosphere, or **lower atmosphere**, is subdivided into four distint layers, and another three small intermediate layers that serve as *transition regions* from one layer to the next.

Figure 2.13 shows the vertical layers of Earth's atmosphere.

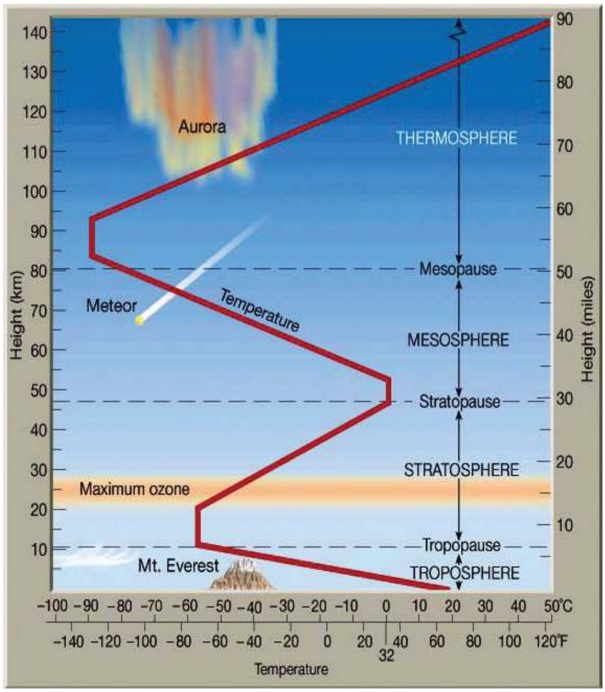


Fig.2.13: Layers of the Earth's atmosphere

(1) The troposphere

The troposphere is the inner or lowest layer of the atmosphere. Therefore, it is closest to the earth's surface and it is the layer that we live in. The troposphere is an extremely dynamic and ever changing system. Every day, the light, clouds, and heat energy in the troposphere go through a million variations. These changes affect daily life in thousands of subtle and direct ways and, for generations, humans have been fascinated by the troposphere's daily changes, which is known as weather. The behaviour of the gases in this layer is controlled by convection. This process involves the turbulent; overturning motions resulting from buoyancy of near-surface air that is warmed by the Sun. Because of convection, troposphere is a layer where temperature generally decreases with height. The name 'troposphere' comes from a Greek word *tropos* for "change" reflecting the fact that turbulent mixing plays an important role in this part of the atmosphere. And mixing is exactly what happens within the troposphere, as warm air rises to form clouds, rain falls, and winds stir the lands below. This mixing of air leads to the phenomenon of weather.

Troposphere extends only to a height of about 18 to 20 kilometres at the equator. Troposphere is thicker at the equator and thinner at the pole (where it may extend to only 7 km in winter).

The troposphere is the region where nearly all water vapour exists and essentially all weather occurs. The chemical composition of the troposphere is essentially uniform, with the notable exception of water vapour.

As light from the Sun reaches the ground, a portion of the solar energy reaching the troposphere is absorbed and converted into thermal energy and the latter spreads through the atmosphere by conduction and convection. The result is that the troposphere is warmest near the ground.

Typically, the higher you go in the troposphere, the colder it gets. Many of you may have experienced the fact that it is cooler on mountain tops than in the valleys. The rate at which the temperature decreases through the troposphere is called the *environmental lapse rate (ELR)*. In the troposphere, the average environmental lapse rate is about 6.5 °C per kilometre of elevation gain and at the top of the troposphere, the temperature is about -60°C. The region of the atmosphere where the lapse rate changes from positive (in the troposphere) to negative (in the stratosphere), is defined as the **tropopause**.

The troposphere contains most of the atmosphere's mass and 99% of the atomspheric water vapour and 75% atmospheric gases. It has abundant water vapour to propel the water cycle/and contains about 90% of the molecules in the atmosphere.

(2) The stratosphere

The stratosphere extends from the top of the troposphere (average value 14.5 km) to an altitude of about 50 kilometres above Earth's surface. In this layer of the atmosphere, *convective motions of air are weak or absent*; *here air flow is mostly horizontal*. The temperature in this layer increases with altitude. Stratosphere has almost no weather. The lower stratosphere is cold at about -60°C. High-altitude weather balloons can reach into the lower part of the stratosphere. In the stratosphere, there is a gradual temperature rise to about -3°C resulting from the absorption of ultraviolet light by ozone (the "ozone layer"). In the lower stratosphere, temperature increases with height. Temperatures as high as 0 °C (32 °F) are observed near the top of the stratosphere. This is because of thermodynamic stability with little turbulence and vertical mixing. The warm temperatures and very dry air of this zone makes it almost cloud-free. When clouds do occur, these may be found up to a height of 30 km in the stratosphere and are called nacreous, or mother-of-pearl, clouds because of their striking iridescence. These clouds appear to be composed of both ice and supercooled water. These clouds form up to heights of 30 km.

In the upper stratospheric regions, absorption of ultraviolet light from the Sun dissociates or breaks down molecular diatomic oxygen (O_2); recombination of the resulting single oxygen atoms with O_2 molecules into ozone (O_3) creates the shielding ozone layer in the stratosphere. Natural stratospheric ozone is produced mainly in the tropical and middle latitudes. Ozone absorbs most of the dangerous ultraviolet light that comes from the Sun to the Earth. This protects us, on the surface, from this harmful radiation, but it also serves another purpose. The ozone converts the energy of the ultraviolet light into thermal energy, heating

WEATHER AND CLIMATE

Most of you may not have a full understanding about the relationship between ***weather*** and ***climate.*** It can be explained in terms of your checking account. The monthly balance for twelve months of a year would represent climate while the daily inputs and outflows of funds represent weather. Your daily balances might vary a great deal from day to day while your monthly balances, which are an average of your daily balances, would be more consistent. In the same manner, you know from your own experience that weather changes much more rapidly than climate. One day it might be warm and close to 40°C and the next day, cold and below 30°C. Climate also changes, but on a much longer time scale.

Daily changes in the troposphere are known as weather. Long term, average conditions are referred to as climate. Weather is more extreme than climate, meaning that daily ranges of temperature, precipitation, pressure, and wind are greater than the long-term extremes of climate. Since climate refers to long-term average conditions, it is more moderate. Almost all land-dwelling life forms are found in the bottom 5 kilometres of the atmosphere. At higher altitudes, the thin atmosphere and harsh conditions are inhospitable to most living organisms. Mt. Everest, at 8,848 m in elevation, extends about halfway into the troposphere.

the stratosphere. Regions of nearly complete ozone depletion, which have occurred in the Antarctic during the spring, are associated with nacreous clouds, chlorofluorocarbons (CFCs), and other man-made pollutants.

The stratosphere continues up to an altitude of about 45- 50 km and the **stratopause** is the transition region between it and the overlying mesosphere. Here, the atmospheric pressure is only 1 millibar. In this thin region, the temperature stops changing again. With the ozone layer heating it from below, the mesosphere is warmer at lower altitudes and cools at higher altitudes. This decreasing temperature with height continues throughout the mesosphere up to an altitude of about 80 km.

(3) The mesosphere

The atmospheric layer above the stratosphere is the mesosphere. It begins 50 kilometres above Earth's surface and extends to 80 kilometres. Temperature decreases rapidly upward and the mesosphere is the coldest layer of the atmosphere, and at the top its temperatures have been measured as low as –120°C.

Mesosphere is the region of the atmosphere where planetary and other debris entering the atmosphere begins to burn up. It thus protects Earth's surface from most meteoroids. They burn up as they fall toward Earth through this layer of the atmosphere (This is why the Earth's surface isn't pocked with meteor craters, like the moon's surface).

The **mesopause** separates the mesosphere from the overlying thermosphere, and it again has roughly the same temperature throughout the layer. This is the coldest layer. Although the air is thin, it is still thick enough to burn up meteors.

OZONE

A single molecule of oxygen (O_2) contains two oxygen atoms. But add another oxygen atom, and you have ozone. O_3 is a molecule of ozone that is made up of three oxygen atoms. In the stratosphere, ozone protects us, absorbing much of the sun's harmful ultraviolet radiation. But carried in the air we breathe at ground level (the troposphere), ozone is a poison that burns and corrodes living and non-living things. Small amounts of ozone develop naturally, especially during lightning storms, but industrial chemicals and automobile exhausts into the atmosphere, cook them with heat and sunlight, and ozone levels can rise dangerously high. Ozone is the main component of "photochemical smog."

(4) The thermosphere and ionosphere

The thermosphere is the layer of the Earth's atmosphere directly above the mesosphere and directly below the exosphere. The thermosphere begins about 85 kilometres above the Earth. At these high altitudes, the residual atmospheric gases sort into strata according to molecular mass (see turbosphere). Thermospheric temperatures increase with altitude due to absorption of highly energetic solar radiation. Temperatures are highly dependent on solar activity, and can rise to 2,000 °C (3,630 °F). Radiation causes the atmosphere particles in this layer to become electrically charged. The thermosphere extends outward into space, up to **thermopause**. Above about 100 km, the chemical composition of the atmosphere changes with altitude. This layer is known as the **upper atmosphere** or **heterosphere.** The **thermosphere,** the lowest layer of the heterosphere, extends outward several thousand kilometers with no real boundary between the upper atmosphere and space. It is the hottest region of the Earth's atmosphere. In this extremely thin atmosphere (with highly diluted gas in this layer) temperature can reach 2,500 °C during the day. Even though the temperature is so high, one would not feel warm in the thermosphere, because it is so near vacuum that there is not enough contact with the few atoms of gas to transfer much heat.The thermosphere is heated mostly by absorbing more ultraviolet radiation from the Sun. At an altitude of about 700 km. the temperature stops changing as we go higher, and the remaining atmosphere above this altitude is called the **thermopause**. Beyond this, the exosphere describes the thinnest remainder of atmospheric particles with large mean free path, mostly hydrogen and helium. As a limit for the exosphere this boundary is also called exobase. The exact altitude of thermopause varies by the energy inputs of location, time of day, solar flux, season, etc. and can be between 500–1000 km high at a given place and time because of these. Both the space shuttle and the International Space Station orbit in the middle-to-upper part of exosphere.

Within the thermosphere is a region known as the ionosphere. The ionosphere is not, technically, a separate layer of the atmosphere. It is a portion of the thermosphere where charged particles (ions) are abundant. These ions result from the removal of electrons from atmospheric gases by ultraviolet radiation reaching there from the sun. The ionosphere extends from about 80 to 300 km in altitude, and it is an electrically conducting region. This layer makes long-distance radio communication possible as it is capable of reflecting radio signals back to Earth. Auroras (northern and southern lights) also occur in thermosphere (Fig. 2.14).

Auroral displays consisting of attractive colours are the visible result of collisions between molecules in the atmosphere and incoming particles in the solar wind trapped by and traveling along magnetic field lines towards Earth's poles.

Fig. 2.14: Auroral lights

(5) The Exosphere

Beyond the thermosphere is the exosphere. It is the uppermost layer of the atmosphere, ranging from an altitude of about 700 km above sea level to about half way to the Moon, where the atmosphere thins out and merges with **interplanetary space**. The upper part of this layer is the beginning of true space. It is mainly composed of hydrogen, helium and some heavier molecules such as nitrogen, oxygen and carbon dioxide closer to its lower layers. The atoms and molecules are so far apart that they can travel hundreds of kilometres without colliding with one another, so the atmosphere no longer behaves like a gas. This tenuous portion of the Earth's atmosphere extends outward until it interacts with the solar wind. Solar storms compress the exosphere. When the sun is tranquil, this layer extends further outward. Its top ranges from 1,000 kilometers 10,000 kilometres above the surface, where it merges with interplanetary space.

The Greenhouse Effect

Sunlight that penetrates Earth's atmosphere heats the surface of the Earth. The Earth's surface radiates heat back to the atmosphere, where some of the heat escapes into space. The remainder of the heat is absorbed by greenhouse gases, which warm the air. Heat is then radiated back toward the surface of the Earth. This process, in which gases trap heat near the Earth, is known as greenhouse effect. Without the greenhouse effect, the Earth would be too cold for life to exist.

The gases in our atmosphere that trap and radiate heat are called **greenhouse gases**. None of the greenhouse gases have a high concentration in Earth's atmosphere. The most abundant greenhouse gases are carbon dioxide, methane, and nitrous oxide and together with water vapour they act like shields that protect the earth's surface. The quantities of carbon dioxide and methane in the atmosphere vary considerably as a result of natural and industrial processes, and the amount of water varies because of natural processes.

2.8.3. Hydrosphere

It is the term used for the total body of water of the earth. Earth's hydrosphere is a discontinuous layer of water at or near the planet's surface. In other words, all the natural waters occurring on or below the surface of the earth is known as Hydrosphere. Thus the term includes the oceans, seas, lakes, rivers, snow, ice, underground water and atmospheric water. In this sphere water is present in solid, liquid and gaseous forms i.e., ice, liquid water and vapour forms.

About 97% of the water of the hydrosphere is concentrated in oceans and seas as saline water. The remaining water is distributed in streams, lakes, glaciers, underground water systems and atmosphere. In terms of percentage, atmospheric water vapour is negligible, but the transport of water evaporated from the oceans onto land surfaces is an integral part of the hydrologic cycle that renews and sustains life.

The Hydrologic Cycle

After a short rain, you might have noticed a smoke like phenomena slowly rising upwards from warm road surface. What is the reason behind this process?

Here when the rain water falls on warm road, it changes its state to gaseous form through evaporation. This process is an important part of a major natural phenomenon called the **water cycle** or **hydrologic cycle** (Fig. 2.15).

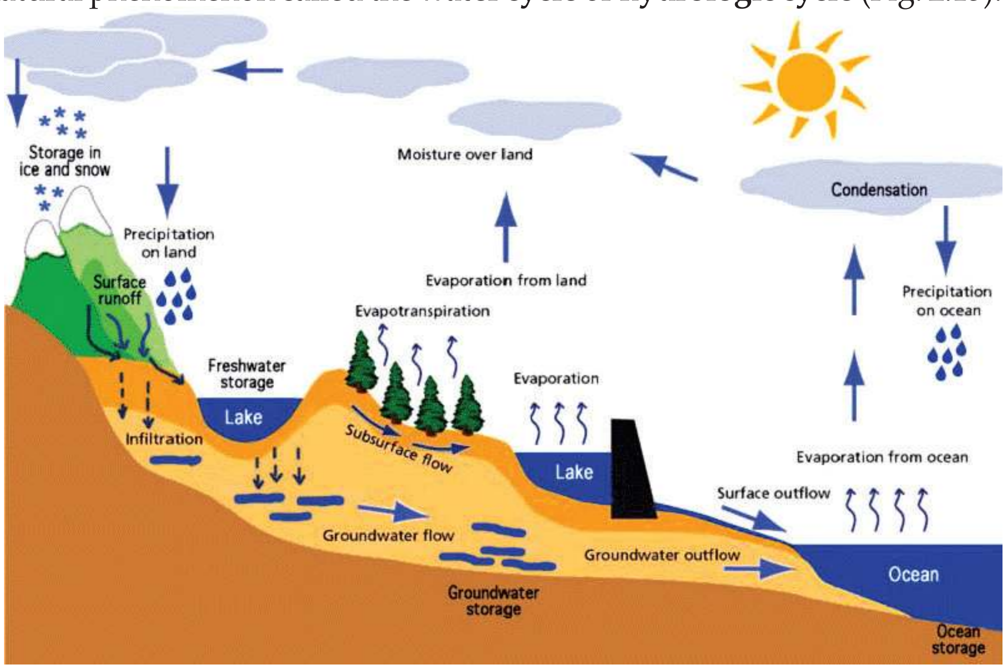


Fig. 2.15: Hydrologic cycle or Water cycle

The endless circulation of water through the different geospheres in solid, liquid and gaseous forms is called ***water cycle***. The hydrologic cycle or water cycle is composed of various processes, viz. 1) Precipitation, 2) Surface run-off, 3) Infiltration, 4) Base flow, 5) Evaporation, 6) Transpiration and 7) Condensation. These processes operate throughout the entire hydrosphere, which extends from about 15 km into the atmosphere to roughly 5 km into the crust.

Water reaches onto the surface of the earth in the form of precipitation. Rain and snow are the common types of precipitation.

After reaching the surface a part of the rain water is absorbed by the ground. This is called infiltration. The remaining water flows along the slopes towards oceans and lakes in the form of streams. The infiltrated water reaches the pore spaces of rocks and enriches the groundwater level. A portion of the infiltrated water flows through subsurface rock towards the oceans as **base flow**. This water is also absorbed by plants and trees, which is later evaporated through their leaves. This process is called ***Transpiration***.

Evaporation also takes place from rivers, lakes, oceans etc. The evaporated water then reaches the atmosphere and forms clouds. When the temperature in the troposphere drops sufficiently the cloud condenses and precipitation takes place.

The hydrologic cycle involves the transfer of water from the oceans through the atmosphere to the continents and back to the oceans over and beneath the land surface. About one-third of the solar energy that reaches Earth's surface is expended on evaporating ocean water. The resulting atmospheric moisture and humidity condense into clouds, rain, snow and dew. Moisture is a crucial factor in determining weather. It is the driving force behind storms and is responsible for separating electrical charge, which is the cause of lightning and thus of natural wildland fires, which have an important role in some ecosystems. Moisture wets the land, replenishes subterranean aquifers, chemically weathers the rocks, erodes the landscape, nourishes life, and fills the rivers, which carry dissolved chemicals and sediments back into the oceans.

2.8.4. Cryosphere

The temperature of some regions of the earth's surface are so cold that water in regions exist in solid state- ice or snow. Such regions of the Earth together constitute a component of the earth system called 'cryosphere' and these include the glaciated and ice covered regions.

Check your progress

1. *Why are ozone, water vapour and dust particles important to life on Earth?*
2. *Why is the troposphere called the 'weather sphere'?*
3. *What are the major gases present in the atmosphere?*
4. *What is the significance of the hydrologic cycle?*

2.9. Biosphere

Earth's biosphere can also be termed the **zone of life** on Earth. The term "biosphere" was coined by geologist Eduard Suess in 1875. Generally, the biosphere is defined as '*the global ecological system integrating all living beings and their relationships, including their interaction with the elements of the lithosphere, hydrosphere, and atmosphere*'.

Every part of the Earth, from the polar ice caps to the equator, features life of some kind. The actual thickness of the biosphere on earth is difficult to measure. Among larger animals, some birds (such as Rüppell's vulture) are know to fly at altitudes exceeding 11 km and some varieties of fish live underwater at depths exceeding 8 km., in deep sea trenches. The extent and range of microscopic organisms is still greater. Single-celled life forms have been found in the deepest part of the Mariana Trench, Challenger Deep, at depths of 11,034 metres. And microbes have been extracted from cores drilled more than 5 km into the Earth's crust in Sweden.

Our biosphere is divided into a number of biomes, inhabited by fairly similar flora and fauna. On land, biomes are separated primarily by latitude. Terrestrial biomes lying within the Arctic and Antarctic Circles are relatively barren of plant and animal life, while most of the more populous biomes lie near the equator.

All living beings of the earth including plants, animals and micro organisms constitute the Biosphere.

Let us sum up

The Earth is a unique and remarkable planet in solar system. The solar system consists of the sun, eight planets and their satellites, asteroids, comets and meteoroids. The solar system, in turn, is a member of the vast universe, which is believed to have formed from singularity by a 'big bang' about 13.7 billion years ago. There are several views regarding the origin of the Earth. The Geologic Time Scale refers to the entire duration of time since the formation of the Earth about 4.5 billion years ago.

The Earth is an oblate ellipsoid which causes slight differences in its equatorial and polar radii and circumferences. The true shape of the Earth is today described as a 'geoid'. The Earth is found to have a concentric layered structure distinguished on the basis of physical and chemical properties from its crust to the core.

The Earth system science treats the Earth as an integrated system that consists of a solid lithosphere, gaseous atmosphere, liquid hydrosphere and frozen water in the form of cryosphere. Biosphere is the zone of life on the Earth. The endless circulation of water through different spheres of the earth is called the hydrologic cycle.

Significant Learning Outcomes

The learner can:

- illustrate the earth's position in the solar system and get an awareness about the different members of the solar system.
- explain origin of the earth.
- describe the dimension of the earth, concept of geological time, internal structure of the Earth and identify the various major components of the earth system and their mutual relationships.

Let us assess

1. Define an astronomical unit? How many kilometres are one AU?
2. How does the earth's atmosphere act as a green house?
3. In which layer of the atmosphere temperature increases with altitude?
4. List out the characteristics of the different layers of the earth's interior.
5. At what depth does the earth's mantle begin?
6. What is nebular hypothesis?
7. What are the different Geologic time units?
8. What do you mean by the terms lithosphere and asthenosphere?

3 EARTH PROCESSES

3.1. Introduction

Our home, the earth, is a dynamic planet. It is undergoing continuous change. Even though you may not be always aware of it, changes take place everywhere. Nothing about it is static and none of its features will endure forever. Materials of the solid earth are constantly undergoing changes of form, position and makeup. Rocks with the same chemical composition may vary in form and organization of their materials. The movement of molten rock material to the earth's surface and transportation of sediments by the rivers are familiar examples of changes in position. The changes affect all the three earth spheres (*atmosphere, hydrosphere and geosphere*) and they are manifested in various ways. Clouds collect and disperse, winds change direction and velocity, tides rise and fall, ocean waves vary in frequency and wavelength. Some changes such as volcanic eruption and earthquakes are rapid, while others such as the development of mountains, migration of shorelines, global sea level changes etc. are slow by human standards.

3.2. Earth as a System

A system is defined as a collection of interacting objects. A system is any assemblage or combination of interacting components. An example is the human body, which is a system composed of a number of organs that interact to produce a living body. Each system can be further subdivided into subsystems. In the case of a human body, we can recognize subsystems such as skeletal system, digestive system, nervous system and so on.

The earth system is a complex functioning system that is composed of a number of subsystems. The major components of the earth system are the fundamental sphere of solid materials - the geosphere, the "water sphere" - the hydrosphere, the gaseous envelope surrounding the earth - the atmosphere and the biosphere, comprised of all living organisms. These seemingly separate systems of the earth are all part of an integrated whole system. In other words, the earth system is composed of numerous larger and smaller systems and works as a single unit. The term "Earth system" includes Earth's interacting physical, chemical and biological processes. To understand any component of the earth, we first study its physical and chemical properties and the energy sources that drive it. Then we look at the interactions of the processes with all the other components of the planet.

The Earth system also includes human society. Our social and economic systems are now embedded within the Earth system. In many cases, the human systems are now the main drivers of change in the Earth system. Global change refers to planetary-scale changes in the Earth system. The earth itself is a component of a much larger system -the solar system, which consists of the Sun and the associated celestial objects bound to it by gravity. Though earth has relatively little interaction with the other planets, the sun and the earth's moon indeed do.

All systems consist of three basic elements:

- a functioning set of components,
- a flow of energy which powers them, and
- a process for the internal regulation of their functioning called 'feedback'.

The Earth system diagram (Fig. 3.1) shows arrows representing flow of energy and mass which connect and intertwine the four spheres. At the top, solar energy drives many of the environmental processes operating in the four spheres. The earth's internal heat engine and the gravitational attraction of the moon are additional sources of energy to power earth systems. There is a constant cycling of energy and mass between the hydrosphere, geosphere, atmosphere, and biosphere as indicated by the arrows.

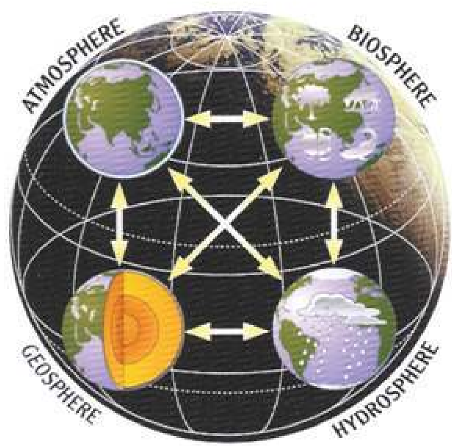


Fig. 3.1: Earth system diagram

The Earth system around us today is the result of millions of years of evolutionary processes, tending toward a stable equilibrium. At times, assaults from within and outside have stressed the system, forcing changes to take place.

Systems are driven by the flow of energy and matter. The earth's subsystems - the geosphere, hydrosphere, atmosphere and biosphere - are powered by the sun. Wind is powered by uneven solar heating of the atmosphere, ocean waves are driven by the wind, currents move in response to wind or temperature differences, and so on. The earth receives a continuous inf1ux of solar energy, and will continue to receive this energy for some more billion years.

Matter, unlike energy, can be recycled. We mine iron ore, smelt the ore to make metal, and use the metal to manufacture a car. When the car is old and worn out, you can melt it back down and make a new car. The process could be repeated over and over, indefinitely. Several material cycles are fundamental to our study of earth systems. These include the hydrological cycle, the rock cycle and some others. During the course of these cycles, matter is always conserved; however, matter continuously and commonly changes form.

Universality of changes

Earth is continuously changing. Earth's geosphere changes through geological, hydrological, physical, chemical and biological processes that are explained by the universal laws. These changes can be small or large, continuous or sporadic and gradual or catastrophic.

Recognition and description of change requires observations. However, not all changes are observable, but are nonetheless taking place. Changes occur everywhere, some of which have been neither observed nor described. Man cannot identify some of the changes without some kind of observation, using instruments or his senses alone. By observing a process causing a specific change at one time, you can establish a basis for deducing the cause of a change from a similar effect observed at another time. Such reasoning is made on the basis of the principle of uniformity of process.

The present knowledge in earth science is derived from observations and assumptions made relying on the principle of uniformity of process. When you observe a particular earth change and link it to a natural process, you establish a cause and effect relationship. Once such relationship is established, it is assumed that similar effects were resulted from similar causes throughout the earth's history.

You may also note the fact that a large variety of changes may be produced by a single event, as for example in a volcanic eruption. A volcanic eruption may be able to destroy an island, as in the case of the eruption of Krakatoa (a volcanic island situated in the Sunda Strait between the islands of Java and Sumatra in Indonesia) in 1883, it can also cause the birth of an island, as in the case of the volcanic island Surtsey, off the southern coast of Iceland, created in 1963. Interpretations based on one of these events would necessarily present an incomplete picture of what can occur.

Let us do

Try to note some changes you recognize that affect the Earth on regional or global scale. Now list them with their characteristics in the given table.

Kind of change	*Examples*	*Characteristics*
Changes within your surroundings (Local in effect or operation)		
Regional and global changes		

The ability to detect change depends on the degree of sensitivity of a detecting mechanism. Not being able to observe change does not mean that it is not taking place. Man has developed a variety of sophisticated instruments for detecting and measuring changes that are beyond the capacity of his sense organs. In order to study his environment, man must make measurements at many scales.

3.3. The Interface Concept

Where do changes take place?

Let us focus our attention on where changes take place. On careful observation, you will discover the fact that changes take place across interfaces, between or among substances with different properties. How rapidly the changes occur determines the degree of discontinuity or the sharpness of the interface. The nature of the transition zone is an important part of the interface concept. Well-known examples of interfaces you may come across in the study of the Earth, include places where different materials meet, such as oceans and atmosphere, ocean and land, land and atmosphere, sand grain and water etc; you can identify and name many more such interfaces.

- When you dissolve a crystal of sodium chloride in water, where was the boundary or interface between the salt (the earth material) and water?

  Answer: ………………………..

- Did a change take place at the boundary where the salt and water meet?

  Answer: Yes. The salt ……………

- What portion of the salt dissolved first?

  Answer: That portion where the water and salt were in direct contact.

- What will be the nature of the interface of the salt crystal and water after the salt has been placed in quiet water (let us say for five minutes)?

  Answer: The interface is fuzzy or diffuse forming a gradual transition zone.

Although many boundaries or interfaces are abrupt, distinct and readily discernible, others lack clearly identifiable interfaces. But there still exists interface - but they are of gradational nature and are not always easy to determine exactly where the interfaces are. Diffuse interfaces are more common. When studying earth processes, we encounter examples of both abrupt and gradational interfaces. The abruptness of any interface depends on the scale at which it is being observed. For example a seemingly smooth surface will appear very rough when viewed under a microscope.

Suppose you place a clear and coloured ice cube in water. The boundaries or interfaces between the coloured cube and water can be readily identified (unlike in the case of salt crystal in water). This illustrates the fact that although interfaces between different materials are not always visible, they still exist.

Can you determine the exact interface in the figure 3.2? Is it transitional or abrupt?

Most organisms exist at the interface where the geosphere, hydrosphere and atmosphere meet. Most of the biosphere exists within this thin zone across the interface, a few metres down or a few kilometres up from the solid surface of the earth. In the hydrosphere, much of

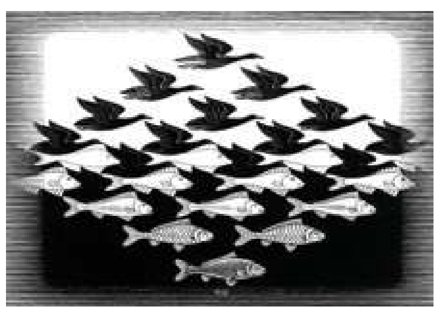


Fig. 3.2: Figure illustrating the interface separating the fields of fishes and birds

the life is attracted to the interface. Life is especially varied and abundant where land, sea and air come together. Countless other interfaces of a smaller scale exist within this large scale interface.

Basic to the interface concept is that an interface is the transition zone between two materials and / or systems. *The interface is the zone of maximum transition from a medium with one set of characteristics to a medium with observably or measurably different characteristics.*

Interfaces exist throughout the universe. They occur at all scales, from the subatomic to the universal. Their physical significance is that, no matter how abrupt or diffuse, they are the boundaries of systems of a given content and characteristic. The universality of change in earth materials results from the continuous redistribution of energy across interfaces.

The dynamic significance of interfaces is that changes in the system are brought about by energy flow across those boundaries. Energy in a system tends to dissipate, and a gain in energy occurs only if more energy is supplied to the system. For example a lava flow will cool as its energy flows outward into the air and adjacent rocks but it will not gain more energy and re-melt unless heat is added to it from another source.

Now, let us answer the question: Are all changes predictable? Some changes are patterned. Examples: Daily changes in light and darkness, seasonal changes of many types, temperature, speed and direction of wind etc; when a pattern of change is recognized, the change is predictable. In such cases, the change and its causes are completely understood. Most earth processes are exceedingly complex because they involve so many variables that man has seldom been able to delineate them all completely and accurately. A change is thus rarely understood completely. The more valuable predictions involve the two elements in the framework of change - time and space. Attempting to predict the probability of a change is more difficult. The ease of predictability depends on the number of variables involved and to our understanding of the probability that a given change will occur. What is a variable? A variable is anything that changes value. We can take time as a variable in our investigation and the result will provide the rate of change. When a great number of variables are involved, change may not follow a discernible pattern.

Though man may not consciously perceive change, either because its rate is imperceptibly slow or because his frame of reference does not include many of the aspects of change, change is now, was in the past, and will continue to take place.

3.4. Classification of Earth Processes

The major earth processes are traditionally grouped into two types: (1) External processes and (2) Internal processes. The land surface constantly responds to external and internal processes and forces that shape the Earth.

External Earth processes are those that are restricted to the surface or exterior of the earth, while **Internal Earth processes** are the processes taking place below the earth's surface, beyond our observation. These earth processes are also known respectively as **exogenous** and **endogenous processes.**

Landforms are the result of the interactions among the geosphere, atmosphere and hydrosphere. The branch of geology called geomorphology is the study of the nature and origin of landforms, particularly of the formative processes resulting from internal and external earth processes.

A. External Earth Processes

I. Degradation or Denudation

Degradation is the geologic process by means of which various parts of the surface of the earth are worn away and its general level is lowered. The process of degradation consists of two sub processes, namely (a) Weathering and (b) Erosion.

(a) Weathering

Geologists use the term 'weathering' for the sum total of all the processes acting at or near the earth's surface, whereby rock undergoes physical disintegration and chemical decomposition. Weathering involves physical, chemical and biological processes. Weathering is a static process and the translocation of disintegrated or altered material occurs within the immediate vicinity of the rock exposure. In other words, there is little or no transport of the resulting products in weathering.

The term bedrock is a general term for the rock, usually solid, that underlies soils or other unconsolidated, superficial material in any locality. The process of weathering converts the bedrock into regolith and soil. Geologists use the term regolith (Greek rhegos = blanket + lithos = stone) for the entire layer or mantle of fragmental and loose, incoherent or unconsolidated rock material, of whatever origin (residual or transported), and of very varied character, that nearly everywhere forms the surface of the land and overlies or covers the more coherent bedrock underneath. It includes rock debris (weathered in place) of all kinds, volcanic ash, alluvium or other kinds of sedimentary and vegetable accumulations and soils.

Laterite is a typical product of weathering seen in our state (Fig. 3.3) Weathering thus can be considered as the preliminary process of preparation of rock material involving disintegration or alteration of rocks for the next grand process - erosion. Remember that weathering is a static process while erosion is a dynamic process.

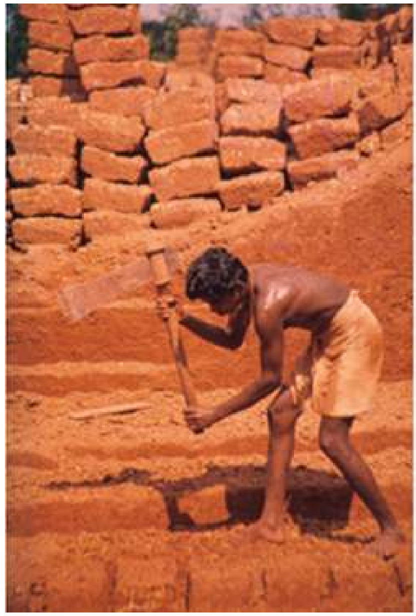


Fig. 3.3: Laterite - A product of weathering

(b) Erosion

Erosion is the detachment of earth material from the earth's surface. Once detached, agents like water or wind transport the material to a new location. The most familiar form of erosion is that done by water. As noted earlier, unlike weathering, erosion is a dynamic process and includes the transportation of the disintegrated rock materials away from the site of their origin. The natural agents of erosion are gravity, water (in the form of rain drops, flowing surface water, waves, subsurface or groundwater), glaciers (streams of moving ice), and wind. Gravity pulls down weathered materials from their place of origin to lower elevations and these will be ultimately carried to the sea through the action of running water (streams), glaciers and wind. These agents are sometimes grouped into two categories as shown hereunder:

Passive agent of erosion	Gravity
Active agents of erosion	Flowing water, waves, rain drops, glaciers and wind.

The pedestal rocks seen in the deserts are the effect of erosion by wind and valleys are the effect of erosion by flowing water (Fig. 3.4).

(a) (b)

Fig. 3.4: (a) Pedestal rock seen in deserts, the effect of erosion by wind; and (b) river valleys, the effect of erosion by flowing water.

The rate of movement of earth materials can be so slow that it is imperceptible to the human eye, or at tremendous speeds, covering or destroying all in its path (e.g., landslide and flood waters).

The term denudation is also used for the sum total of long-term processes that cause the wearing away of the earth's surface, leading to a reduction in elevation and relief of landforms and landscapes. Therefore, this term is sometimes used as a synonym of the term 'degradation'. The meaning of the term is the 'removal of covering' or 'make bare' and in geology it is used for the removal of rock material from the surface of the earth through the combined process of long continued weathering and erosion and the consequent laying bare of underlying fresh rocks.

II. Aggradation or Deposition (Sedimentation)

The process called deposition takes place when water, wind and glaciers lay down grains of material that have been eroded and transported from one locality to another geographical location. In Geology, the term sediment, is used as a general term for the materials transported by various agents of erosion, such as water, wind, glacier, waves or gravity, and deposited on the land surface. In due course, under favourable conditions, sediments may be converted into cohesive sedimentary rocks.

The rock materials eroded and transported will not travel continuously for ever; it will come to rest temporarily in different localities or permanently in some other places. The geological process of deposition or sedimentation is the laying down of sediment carried by any agent of erosion.

The rock materials such as pebbles, sand, silt or clay particles may be transported from one place to another by agents of erosion mechanically, or if these rock materials are soluble, they are carried in the form of solution. Deposition of mechanically transported sediments occurs when the energy causing the transportation of sediments becomes insufficient to move them any further.

The deposition of sediments locally build up the land surface by the formation of sedimentary layers one over the other. The term aggradation is used in geology for the increase in land elevation or raising of any land surface as a result of the continuous deposition of layers of sediments.

The process of degradation (a general lowering of the earth's surface by the combined action of weathering and erosion) and aggradation together constitute the process of **gradation**. It simply means leveling or bringing of a land surface or area to a uniform or nearly uniform grade or slope through the combined action of weathering and erosion (degradation) and by the complementary process of deposition (aggradation).

Gradation is the process whereby higher areas are worn down and depressions or low-lying areas are filled up leading to the formation of a featureless landform or even plain.

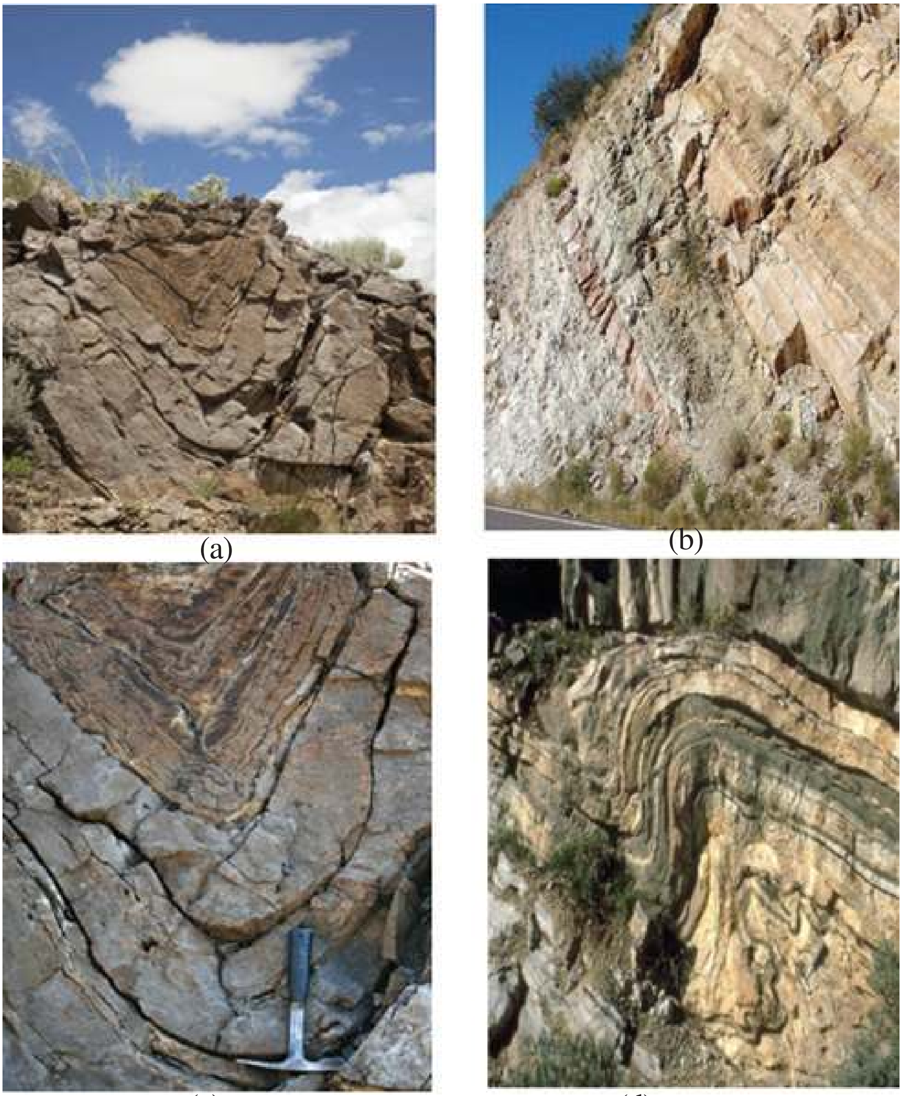
B. Internal Earth Processes

There are three different types of geological processes of internal origin. These are:

I. Diastrophism (Earth Movements)

Diastrophism is a general term for all movements of the crust produced by earth forces, including the formation of ocean basins, continents, plateaus and mountain ranges. The uplift and depression of land areas and sea floors; and mountain building activities also constitute a part of diastrophic process.

Diastrophism is an internal geological process of deformation of the earth's crust by natural processes. It moves, elevates or builds up portions of the earth's crust. The term **tectonism** is increasingly used as an alternate term for diastrophism. Carefully observe the images shown below (Fig. 3.5) and comment on the characteristic structures of the layers of rocks and the probable reasons for their appearance and origin.



(a) (b) (c) (d)

Fig. 3.5 (a, b, c, d): Tilted and folded rock layers resulting from diastrophism.

We can recognize two kinds of diastrophic processes.

(a) **Orogeny or orogenic processes** - which involves mountain building through severe deformation of rocks along narrow belts of the earth's crust, and

(b) **Epeirogeny or epeirogenic processes** - involves broad regional uplifting or warping of extensive portions of the earth's crust, such as the stable interior portions of continents generally called craton. Epeirogeny takes place over broad, nonlinear areas and the process is relatively slow, and results in relatively mild deformation of the crustal layers.

II. Magmatism (Magmatic activity or Igneous activity)

The processes of development, movement and solidification of magma, giving rise to igneous rocks is termed magmatism. This includes the intrusion of magmas (the process of emplacement in pre-existing rocks) and the extrusion of lavas (process of emitting lava and other associated volcanic fragments onto the earth's surface).

III. Metamorphism

Metamorphism is an internal process of transformation of pre-existing rocks into new types by the action of heat, pressure, and chemically active migrating fluids. It involves mineralogical, textural (distinct arrangement of minerals) and structural adjustments of solid rocks to physical and chemical conditions which have been imposed at depth far below the surface zones of weathering.

Check your progress

1. *Why is magmatism described as an internal process?*
2. *What is the importance of system concept in understanding the earth processes ?*
3. *What do you mean by exogenous processes?*

3.5. Weathering

Weathering is the breakdown and alteration of rocks and minerals at or near the earth's surface into products that are more stable with the conditions found in this environment. The process of weathering which takes place along the interface separating the geosphere from atmosphere and hydrosphere, could be considered as an interface phenomenon.

Although you are familiar with the word 'weathering', you may not be fully aware of its geological implications. Many rocks now at the earth's surface were formed deep below the surface of the earth i.e., where the conditions of the environment (especially the temperatures, pressures and chemical conditions) were entirely different from those of the earth's surface. When these rocks are brought to the earth's surface by geological processes, the components of the rock will be in disequilibrium or unstable with the surface conditions. Weathering is the response of rocks to their new environment existing at the earth's surface. The rate of weathering depends on the composition of earth materials and their response to varying surface environment.

Weathering involves physical disintegration and chemical decomposition of rock and produces an in situ mantle of waste. This process changes rocks from a hard state, to become much softer (weaker) and smaller, making them suitable for more easy erosion. Weathering can be considered as the preparation phase for next phase of erosion and transportation of earth materials. Weathering of rock-forming minerals can create new products from pre-existing rocks. The weathering is a prerequisite for the formation of soils. Under favourable conditions fertile soils develop from weathered materials. Under some conditions, weathering also leads to the formation of some economic deposits (such as bauxite - an ore of aluminium).

Weathering processes are not restricted to natural materials alone. The response of any material to its environment at the earth's surface should be considered as a weathering process. Man-made structures exposed at the earth's surface also show signs of weathering. Deterioration of bricks and stones in buildings, loosening of mortar in brick walls, cracking of sidewalks in cold regions, peeling-off of paints of buildings, rusting of iron and steel materials, fading of inscriptions of tombstones, staining and tarnishing of metals etc., are some of the common and familiar examples of process of weathering. Scientists are working to find solutions to impede such unwanted changes brought about by weathering. For example, iron is now pre-weathered or pre-rusted to give it a protective external coating of iron oxide to prevent further oxidation of the metal beneath (recall the significance of interfaces). Aluminium and chromium are examples of metals that develop a protective oxide layer naturally.

Two principal types of weathering are generally recognized:

(1) **Physical weathering**, also called **mechanical weathering**, or **disintegration** - involves the breaking down of rock materials into smaller pieces. Physical weathering involves no change in the chemistry of the material being altered.

(2) **Chemical weathering** (**Decomposition**) involves the chemical decay (decomposition, dissolution etc.) of rocks by chemical processes. In this case, a chemical change occurs and new products are created from the material that is undergoing weathering.

3.5.1. Physical Weathering

We have described physical weathering as an external geological process of rocks breaking apart, but the chemical composition of the rock remains the same. The result of physical weathering is to simply make smaller pieces out of larger ones. In doing so, physical weathering makes it easier for surface materials to chemically decompose to be eroded. In physical weathering, some of the forces originate within the rock or mineral, while others are applied externally.

The smaller we subdivide a material, the more surface area is exposed and heat transfer or chemical reactions happen at a faster rate. In nature, when a large block of rock is broken into smaller pieces, additional surface area is created for chemical weathering to act. The following graph (Fig. 3.6) shows the increase in surface area when a cube of 1 cm on each edge is cut into four, eight and sixty four equal parts.

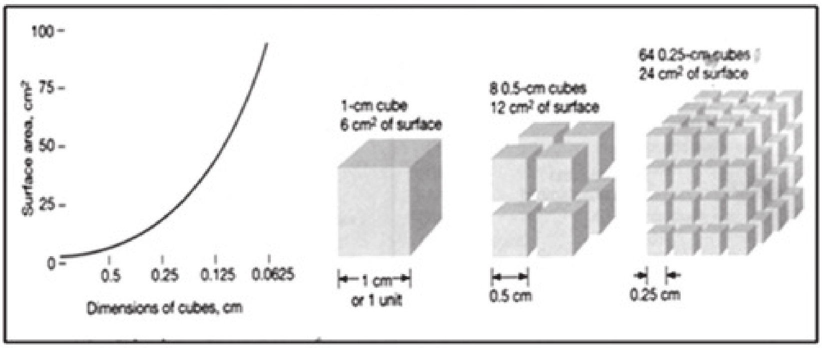


Fig. 3.6: Graph illustrating the effect of disintegration on surface area.

Types of physical weathering

(a) Weathering associated with unloading due to pressure release

Unloading is the process of removal of overlying rock materials and associated release of pressure by the process of denudation, occurring above deeply buried rock masses. Now analyze the given figures (Fig. 3.7 A and B) and find out what kind of changes take place?

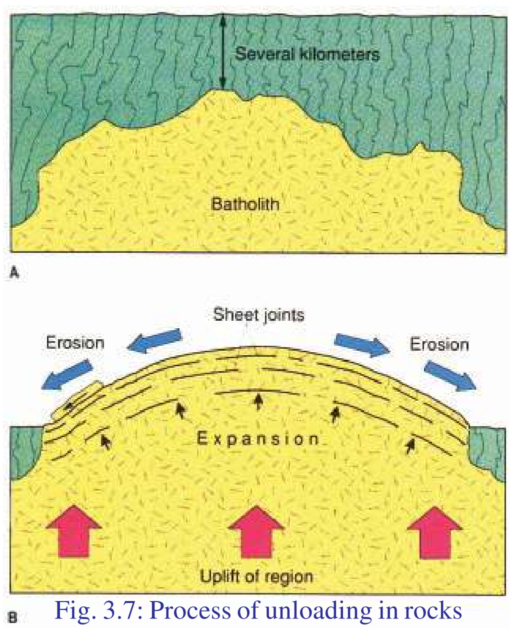


Fig. 3.7: Process of unloading in rocks

When a rock body that had formed deep below the earth's surface is gradually exposed by the erosion of overlying rock, "unloading" occurs and the rock breaks along "sheeting joints" as stored pressure is released. Unloading can cause physical weathering and may occur when the overlying portions of rocks are eroded or rocks are removed from a quarry.

The majority of igneous and metamorphic rocks were formed deep under the earth's surface at much higher pressures and temperatures. Erosion and consequent uplift brings these rocks towards the surface gradually, and as result they become subjected to lesser and lesser pressure. This unloading of pressure causes the rocks to expand vertically or normal to the ground surface. This expansion leads to the development of almost horizontal fractures (cracks) or fractures that are parallel to the ground surface. Increasing number of fractures develop in the rock, as the rock approaches the earth's surface. Over a period of time, the outer layers of the rock break away in sheets by the process of exfoliation.

Exfoliation

Observe the nature of surface of the rocks in the given diagrams (Fig. 3.8). What processes are responsible for the splitting of sheet like layers on it? The process of unloading caused the granite mass shown in the figure to "exfoliate" or break into sheets. Large plutons (bodies of igneous rock formed far below the surface) or metamorphic bodies split into sheets that are parallel to the earth's surface or to the mountain face, a process known as exfoliation. It is also known as sheeting, if the expansion from unloading occurs in granite to form rock slabs. During the processes of weathering, the earliest fracture in an igneous or metamorphic rock results from the process of unloading.

(b) Weathering due to thermal expansion and contraction of rocks

The geologic effects of the sun's rays on the surficial materials, specifically, the effects of changes of temperature resulting in mechanical weathering

Fig. 3.8: Separation of sheet like layers on rock.

of rocks, is termed **insolation**. The physical breakdown of rock by their expansion and contraction due to diurnal (taking place daily) temperature changes is termed **insolation weathering.**

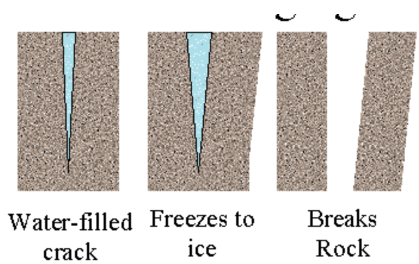
Rocks are poor conductors of heat. As a result of the physical inability of rocks to conduct heat, the exterior portions of the rock expand more than its interior. The repeated heating by day and cooling by night cause the outer layers of the rock to expand and contract alternately, while its interior remains unaffected. The resulting differential expansion and contraction produce stresses within the rock sufficient to cause layers of rock to rupture off.

In insolation weathering, the colors of mineral grains composing rock are also a factor to be taken into account. Because of their greater absorptive properties darker colored grains will expand much more than the lighter ones. Therefore, in a rock with many different coloured grains, rupturing can occur along boundaries separating mineral grains differing in colour. Likewise, the rates of expansion of different minerals with increasing temperature are not identical and this fact also contributes to the granular **disintegration** (separation of mineral grains).

In desert regions surface materials get exceedingly hot during the day and expand by a small amount. During the night the temperature drops significantly making it very cold and so the rocks contract. The expansion upon heating and contraction during cooling weakens rock ultimately breaking it apart.

(c) Frost wedging (Frost Shattering)

During freezing, from liquid to solid state, there is a 9% increase in the volume of water. In cold temperate regions, polar regions and high mountain tops, where the water occupies the fractures, joints and



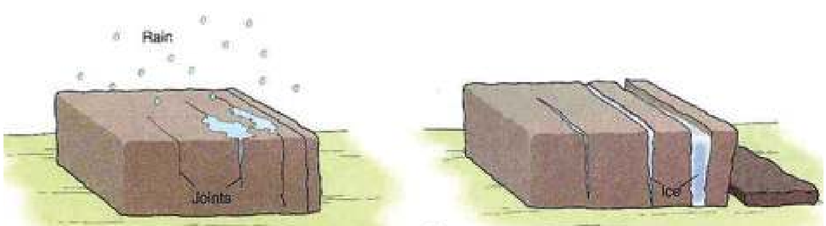


Fig. 3.9: Frost wedging

cracks in rocks, the relatively large volumetric change associated with freezing produces sufficient rupturing effect in rocks. Freezing of water in such regions exerts pressure on the sides of the crack and pushes the crack further apart and also force the fracture to propagate into further depth. Repeated daily freezing and thawing enlarges the crack, until the rock breaks apart or shatters producing smaller pieces. The process is called **frost wedging** and plays a major role in weathering of rocks in regions where the daily temperatures fluctuate between above and below the freezing point of water. Fig. 3.9 depicts the stages of frost wedging.

3.5.2. Chemical Weathering

The weathering of rocks by chemical processes is called chemical weathering. While physical weathering alters the size and shape of rocks, chemical weathering alters the composition of the minerals of a rock. In chemical weathering, the chemical constituents of rocks are changed, reorganized, or redistributed. That is why the term decomposition is used as a synonym of this process.

The minerals in rocks formed deep beneath the surface will be in equilibrium with the environment of high temperature, high pressure, little or no water and absence of oxygen, attending their formation and are quite stable at that environment. At the earth's surface, these minerals are chemically unstable and weather most quickly because they are farther from their "zone of stability", or the conditions under which they had formed (In contrast, minerals which form at lower temperatures and pressures are most stable at the Earth's surface). The minerals which are no longer in equilibrium with their environmental conditions (of low temperature, low pressure conditions, abundance of water and oxygen), when exposed at the surface are susceptible to chemical weathering. The colour variation in broken rocks, which are exposed at the surface, is an indication of chemical weathering (Fig. 3.10).

Fig. 3.10: The colour variation notable in this broken boulder is a proof of chemical weathering

Water is the most important agent of chemical weathering. Most chemical weathering takes place in a water film that adheres to mineral surfaces (recall the concept of interface). Although pure water is nonreactive, the small amounts of dissolved materials (such as oxygen or carbon dioxide) make it chemically reactive and thus make it an effective agent of chemical weathering. Rainwater is naturally slightly acidic because carbon dioxide from the air is dissolved in it. Some minerals in rocks may react with the rainwater, causing the rock to be chemically weathered.

Some varieties of rocks are easily weathered by chemical weathering. For example, limestone and chalk are made up of a mineral called calcite (which is chemically calcium carbonate). Rainwater with dissolved carbon dioxide is slightly acidic. When this water falls on limestone or chalk, a chemical reaction takes place and new substances are produced by the reaction. Some of these substances are soluble in water and are removed from the zone of weathering by the movement of water.

When fossil fuels such as coal, oil and natural gas are burned, carbon dioxide and sulphur dioxide escape into the atmosphere and increase the concentration of these gases to an abnormal level locally. During rainfall these gases dissolve in the rainwater and when this happens, we call the rain as 'acid rain'. Acid rain is a powerful agent of chemical weathering in modern times in industrialized areas of the world. Acid rain causes severe damage to buildings and statues made from rocks such as limestones and marble.

Chemical weathering tends to weaken or soften rocks, and thereby make them easier to break. It is already noted that physical weathering creates additional surface area in rocks and thereby favour chemical attack. Therefore, in weathering process, disintegration and decomposition work together and mutually assist in attacking rocks exposed at the Earth's surface.

There are many processes that can chemically alter and weather rocks. Some of the most important ones are briefly described below:

(a) Dissolution (or solution)

Dissolution is the process by which minerals in the rocks dissolve directly in natural water. Several common minerals such as halite (NaCl) dissolve in water. Limestone and marble are made up of the mineral calcite and are soluble in acidic water as noted earlier. Marble tombstones and carvings are particularly susceptible to chemical weathering by the process of dissolution (Fig. 3.11).

(a)

(b)

Fig. 3.11: Chemical weathering by dissolution

(b) Oxidation

In weathering, oxidation takes place when oxygen dissolved in water reacts with the minerals of rocks. Oxygen dissolved in water combines with atoms of metallic elements in minerals. When rocks containing iron-rich minerals are oxidized by the action of water, a yellow to reddish-brown crust will gradually appear on the rock surface. The red or brown colour commonly seen in the weathered zones of rocks and soils can thus be attributed to the process of oxidation.

Can you explain the reason for the reddish colour of the soil shown in the picture (Fig. 3.12)?

Fig. 3.12: Development of reddish colour of soil

During chemical weathering oxygen combines with iron-bearing silicate minerals producing one or more iron oxide minerals (limonite, hematite, goethite). Iron oxides are red, orange, yellow or brown in color and these impart the characteristic colour to the products of weathering.

(c) Hydrolysis

Hydrolysis is a chemical weathering process affecting silicate and carbonate minerals. Pure water ionizes slightly and reacts with silicate minerals. This reaction theoretically results in complete dissolution of the original mineral, if enough water is available. In reality, pure water rarely acts as a H+ donor. Carbon dioxide, though, dissolves readily in water forming a weak acid and H+ donor.

Carbonic acid is consumed by silicate weathering, resulting in more alkaline solutions because of the bicarbonate. Aluminosilicates (for example, feldspars), when subjected to the hydrolysis reaction produce secondary minerals rather than simply releasing cations.

Hydrolysis takes place when acid rain reacts with rock-forming minerals such as feldspars to produce clay and salts that are removed in solution. The only common rock-forming mineral that is not affected by hydrolysis is quartz, which is a chemically resistant mineral. This is why quartz and clay are two of the most common minerals in sedimentary rocks.

(d) Hydration

It is a process whereby minerals in the rock absorb water and expand, creating stress which causes the weakening of rocks. Hydration of the mineral hematite leads to the formation of another iron bearing mineral called limonite.

(e) Carbonation

During rain, carbon dioxide of the atmosphere dissolves in water as it falls through the air. In addition as the rainwater infiltrates through the soil, it acquires more amounts of carbon-dioxide that is released by decaying organic matter of the upper horizons of the soil. Solution of carbon-dioxide in rainwater, as already noted, leads to the formation of carbonic acid - a weak acid. The chemical weathering caused by naturally formed carbonic acid is termed carbonation.

In regions where extensive limestone rocks occur, dissolution of limestones by the action of groundwater gives rise to underground caves.

Let us do

Blow air through a glass tube or drinking straw into a small beaker of distilled water containing a piece of blue litmus paper (or an appropriate acid indicator). As the breath bubbles through the water, the litmus paper gradually turns red, indicating the acidic nature of the water. The CO_2 of the exhaled air combines with water to form carbonic acid (H_2CO_3).

(f) Spheroidal weathering

During chemical weathering of rocks within the earth's surface, the corners of joint blocks in the rocks weather relatively at a faster rate, than their edges and faces. The interior remains immune as long as the surrounding material is intact. Because of this, corners become rounded and the blocks of rocks weather to form roughly spherical shapes - resulting in what are termed 'core boulders'. The process is known as 'spheroidal weathering'. When spheroidal boulders are brought to the surface, successive outer layers peel off from the boulder like layers of an onion. Therefore, this type of weathering is sometimes termed as onion skin weathering (Fig. 3.13).

Fig. 3.13: Spheroidal weathering or onion-skin weathering.

Check your progress

1. *How does mechanical weathering add to the effectiveness of chemical weathering?*
2. *If two identical rocks are weathered -one mechanically and the other chemically, how do the products of weathering for the two rocks differ?*
3. *What are the ways by which water acts as an agent of chemical weathering?*

3.5.3. Biological Weathering

Different forms of weathering caused by the activities of living organisms (plants and animals) are collectively termed biological weathering. It includes both the processes of disintegration and decomposition, often in combination.

Tree roots can grow into fractures in a rock and pry the rock apart, causing mechanical fracturing. Moss and fungus can also grow on a rock surface. In this case, their roots will produce a weak acid that dissolves the rock and causes chemical alteration of rocks. However, weathering processes caused by living organisms take place through mechanical and chemical processes, and therefore many consider that the third type of weathering (biological weathering) is unnecessary. In fact, all the processes of weathering, viz., physical, chemical and biological, are interconnected and act simultaneously.

Root wedging

You may have seen weeds growing through cracks in pavements. If you have gone for a walk in the countryside, you may even have seen bushes or trees growing from cracks in rocks or unused buildings. In nature, tree roots are probably the most significant agents of biological weathering. The roots of plants and trees grow through joints or cracks in the rock, in order to find moisture. As the tree grows, these exert an expansive force tending to widen the existing opening and the roots gradually wedge or prise apart rocks on both sides of the fracture (Fig. 3.14). It is a very slow process. This is a common problem for home owners where trees grow too close to a house. Tree roots can force their way into the foundation, breaking it apart, and allow water to seep into the basement of the buildings.


Fig. 3.14: Root wedging, a type of biological weathering

Insects like earth-worm, snail etc. and burrowing animals like rodents (such as rats, groundhogs, wolves, prairie dogs, ground squirrels, muskrats, moles etc.) loosen the soil cover and create suitable conditions for the various external agencies to have their own action on the underlying rocks that lead to rock weathering (Fig. 3.15). Many animals, such as some forms of molluscs, bore into rocks for protection either by scraping away the grains or secreting acid to dissolve the rock.

(a) (b)

Fig. 3.15: Rodents as agents of biological weathering

Lichens are a symbiotic combination of algae and fungi. They frequently exist where other plants cannot thrive. Lichens also play a role in the biological weathering of rocks (Fig. 3.16) by giving off organic acids causing chemical weathering of rocks.

Fig. 3.16: Circular patterns seen in rock outcrops due to growth of lichens that play a role in biological weathering of the rocks

Several organisms can assist in breaking down rock into sediment or soil. Today, man is also an important agent of biological weathering. Human processes such as pollution, which can be a large factor in acid rain, along with the acts of other living organisms, can cause chemical weathering to occur at faster rates.

Human being can even cause biological weathering just by walking, quarrying and construction activities. Over time, paths in the countryside become damaged because of all the boots and shoes wearing them away.

Let us do

Make a collection of un-weathered and weathered rock samples from your neighbourhood. A close study of the samples will show you that the surfaces of most weathered rocks are quite different from their interiors. The most noticeable differences will be in colour and texture. Weathering usually *masks the true characteristics of a rock. Compare the sample of fresh rock with those showing various stages of weathering (crumbled pieces of rock and soil) and prepare a list of changes produced by weathering.*

Factors Influencing Weathering

Several factors control the type of weathering and the rate at which rock weathers. These include: (1) Rock characteristics, (2) Climate, (3) Topography (Relief), (4) Vegetation cover, (5) Rate of local erosion, (6) Man's activities and (7) Time.

3.6. Products of Weathering: Regolith and Soil

3.6.1. Regolith

You have learned that weathering causes rocks to disintegrate and decompose and produce a mantle of rock fragments of varied sizes and composition from underlying bedrock. These materials are collectively known as the regolith. These range in size from large boulders to clay sized particles less than 0.004 millimetres in diameter.

3.6.2. Soil

All of us are most familiar with the word 'soil'. What is a soil? A popular definition of soil is that "Soil is a layer of unconsolidated material on the earth's surface in which plants grow". The branch of science dealing with the study of soil is called **pedology**. In pedology, two types of weathering are recognized. The weathering processes leading to the formation of a weathered mantle over fresh bedrocks are termed **geochemical weathering** whereas further weathering of regolith leading to the conversion of the resulting materials, commonly called soil, is called **pedochemical weathering**. The process of pedochemical weathering requires the presence of organic matter (humus) and interaction of various types of microorganisms of the humus with the regolithic material or the transported sediments. The resulting soil is capable of supporting plant life and is vital to life on earth.

We can define the term soil as the unconsolidated mineral or organic material on the immediate surface of the earth that serves as a natural medium for the growth of land plants.

Soils can be broadly grouped into two types: **residual soils** (i.e., those derived from underlying bedrock) and **transported soils** (those derived from the rock materials transported and deposited in the localities by agents such as water, wind, etc.). Residual soils develop from weathered materials derived from rocks lying underneath. The laterite cover in major portions of Kerala and the soils developed over it should be considered as residual soils. The characteristic feature of residual soil is the presence of transitional or gradational variation from the overlying humus rich fertile soil to the underlying partially weathered bedrock.

Transported soils, unlike the residual soils, develop in a locality over the materials transported and deposited by agents such as water, wind, glacier and gravity. The term **colluvium** is applied for the materials formed along the bases of the hillslopes by the combined action of erosion by rain drops, water and gravity. The material deposited by streams is known as **alluvium**. Those transported and deposited by wind are termed as **aeolian sediments**. The soils developed over these transported materials can be further described by corresponding adjectival terms such as colluvial-, alluvial-, aeolian- and so on.

Colluvial soils generally occur along the valley bottoms. Alluvial soils are found bordering the major river channels in river valleys and all along the coastal and other lowland regions of our state.

The nature of the soils developed in any region depends on several factors. These include: a) nature of the parent material (the nature of the bedrock which forms the source of the soils as well as nature of transported and deposited material from which the soil is developed), b) climate, c) the nature of the associated landscape, relief or topography, and d) time and several other factors.

Soil Profile and Soil Horizons

The vertical section of a soil column is known as soil profile. In such a section layers in the soil, distinguished on the basis of color, soil texture,

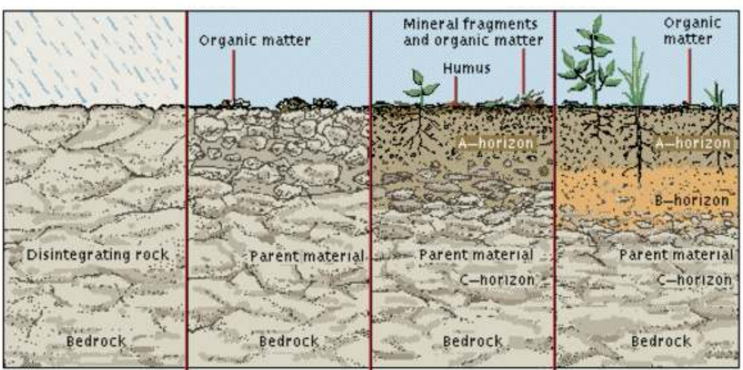


Fig. 3.17: Diagram showing the development of soil horizons and soil profile

soil structure, and other visible properties, are called **soil horizons**. Each of these horizons has different physical and chemical properties, which result from various soil forming processes such as weathering, introduction of humus and migration or movement of chemical constituents into or away from the horizon (Fig. 3.17). Soil horizons are typically found and well developed in residual soils rather than in soils derived from transported sediments.

A typical soil profile (in residual soils) shows four distinct horizons (Fig. 3.18). The uppermost layer is called **A-horizon**. This layer contains organic matter mixed with mineral particles. Decomposing organic material from plants and animals mixes with the top layer of accumulated soil minerals. This is also known as the **topsoil** and in most places it is enriched in organic matter and therefore accounts for its dark colour. The term **O-horizon** is given for this topmost layer which is mostly made up organic materials, and often brown or black. In areas of severe erosion this horizon may be absent. Percolating water dissolves and removes some mineral constituents from the A-horizon. The process of removal of soil materials through solution or by other means from soil horizons by percolating water is technically called **leaching**.

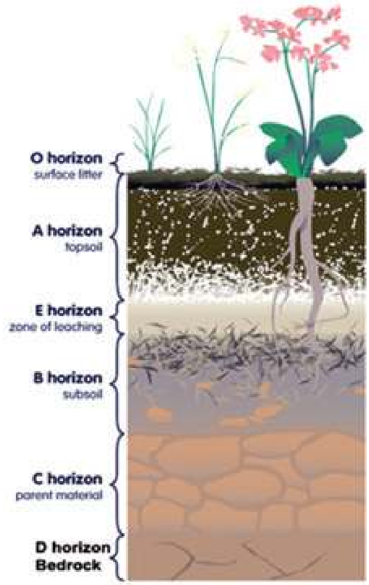


Fig. 3.18: Typical soil profile

Below the A-horizon is the **B-horizon**. It is also known as the **subsoil**. Some constituents removed from the A-horizon through leaching accumulate or get deposited within this horizon and the term **E-horizon** is given for this layer, which is composed of light-colored materials resulting from leaching of clay, calcium, magnesium, and iron to the lower horizons. A-horizon and E-horizon make up the **zone of leaching.** This **horizon is** enriched in clay, iron oxides, silica, carbonate, or other materials leached from overlying horizons and is also known as the **zone of accumulation.**

The **C-horizon** is located below the B-horizon. It consists of partially weathered bedrock and thereby indicates that the weathering and soil forming processes have not effectively reached that depth.

The term **D-horizon** is applied for the horizon of solid parent rock (un-weathered rock or fresh parent material). It is characterized by total or nearly total absence of weathering and soil formation. However, you should note that this horizon has potential for future degradation, decomposition and soil development after several hundreds of years. In some schemes of classification the term **R-horizon** is also given for the unweathered parent rock.

A mature soil profile with A, B, and C horizons, takes several hundreds of years to develop. Weathering and soil formation are extremely slow processes. Therefore soils constitute very valuable natural resources. These are extremely slowly renewable and once lost will be lost forever. This is the reason why we give great importance to soil conservation measures.

The thickness of the soil existing in a locality is a measure of the balance of input (weathering of bedrock) and output (erosion). Normal rate of erosion keeps the soil profile stable under the current climate. Human activities can significantly accelerate erosion resulting in the excessive soil loss by **accelerated soil erosion**.

Check your progress

1. *The mantle of rock fragments occurring above the weathered rock surface is called _______ .*
2. *Which horizon of soil is rich in organic content?*
3. *Can you give an example of residual soil?*

Let us sum up

Earth is a complex system of interacting realms of rock, water, air, and life. The corresponding four major subsystems of Earth are the lithosphere, hydrosphere, atmosphere, and biosphere. Humans are part of the biosphere, and their activities have important impacts on all four spheres.

The concept of a natural system provides a framework for understanding how the earth works and how it is changing. The essence of earth's geologic system is the flow of energy and movement of matter through various sub systems of the earth. As a result, materials on and in the earth are changed. Predicting and understanding these changes is an important reason for using a system approach in the study of the earth processes.

All earth processes are the result of energy flowing and mass cycling within and between Earth systems. The land surface responds to the internal and external earth processes. External processes such as weathering, erosion, transportation and deposition are the result of interaction among the various subsystems of the earth. These interactions take place along the interfaces separating the lithosphere from hydrosphere and atmosphere.

Significant Learning Outcomes

The learner can:

- explain the concept of - universality of change or the fact that everything around you is undergoing change.
- recognize changes and realize the fact that you live on a dynamic earth and thereby gain a better understanding of your environment and able to place yourself in the picture of environmental changes caused by man.
- get some insight about the forces that bring about the changes on or below the earth's surface and the energy required for those changes, and explain.
- recognize what happens to rocks and minerals as they weather, and explain how the products of weathering differ from the rocks from which they have formed.

Let us assess

1. The following terms are related to two types of weathering processes. Name the types of weathering and classify them accordingly.

   (sheeting, solution, carbonation, frost wedging, hydration, exfoliation, hydrolysis, spheroidal weathering, oxidation)

2. Differentiate between

   (a) Residual soil and transported soil.
   (b) Passive and active agents of erosion.
   (c) External and internal earth processes.

3. What do you mean by interface concept? How is it related with the process of weathering?

4. Complete the given table related to weathering.

Weathering process	**Name of weathering**	**Type of weathering**
Splitting of rocks by growth of plant roots	Root wedging	
Breaking of rocks similar to the peeling off of layers in an onion		Chemical weathering
	Frost wedging	Physical weathering

5. Degradation + Aggradation = Gradation. Examine the expression and justify it.

6. Weathering is caused by the activities of living organisms. Evaluate this statement by giving examples.

7. Describe the significance of weathering in sustaining life on earth.

8. Heat speeds up chemical reaction. Then why does chemical weathering proceed slowly in a hot desert?

4 SLOPE PROCESSES

4.1. Introduction

Have you ever noticed the fact that most of the Earth's surface is not perfectly horizontal and flat? If you carefully observe the earth's surface you will come to realize that sloping surfaces are more common in natural surfaces than other types of surfaces. Now, let us answer the question: What is a slope? A slope is an inclined surface of any part of the earth's surface (e.g., valley side slope, beach slope, etc). Some slopes are steep, others are gentle. Hill slopes are an important part of the terrestrial landscape. Landscapes are composed of *a mosaic of slope, varying in areal extent and in degree of inclination.* The geometric form of a slope depends on the various geologic processes acting on it. In profile when viewed in cross section, a natural slope may be concave, convex, straight / rectilinear or combinations of one or more of these geometric forms.

Most slopes on the surface of the Earth are mantled with unconsolidated regolith, (the product of weathering) with its associated soils. Generally regolith serves as parent material for soil above and grades downward into unaltered bedrock as we have discussed in unit 3.

4.2. Slope Processes

Slopes, specifically hill side slopes, have a direct and indirect influence on a number of human activities. The steepness of slopes primarily determines their suitability for agriculture, human settlement and for various other uses. Under the natural conditions, water, sediments, and rocks tend to move down the slope. Valley side slopes and hill slopes in certain condition constitute a potential site of hazards to humans, if the materials of the slope rapidly move down-slope. In any locality, the present topography and soil thickness reflect a sensitive balance between the processes of weathering, erosion, and deposition. Human activities can upset the balance and cause loss of the fertile soil from cultivated lands, excessive erosion of lands and enhancement of sediment load in streams and triggering of catastrophic and disastrous landslides. Therefore, all of us should be aware of the basics of geologic processes that are active along natural slopes.

A variety of natural processes move earth material down-slope. The part of surface runoff flowing over the land surfaces, taking the form of thin sheets (i.e., not concentrated into channels larger than rills), towards a stream channel is termed **overland flow**. As most portions of runoff here is in the form of a thin sheet of flowing water over relatively smooth soil or rock surfaces, it is also called **sheet flow.** This type of water flow significantly contributes to the overall process of erosion of thousands of soil particles down-slope during heavy rains.

4.2.1. Splash Erosion

This kind of erosion is caused by the impact of rain drops striking the ground surface (rain splash). Splash erosion generally takes place in two steps. As initial precipitation is absorbed by the ground surface, it fills the pore spaces (inter-granular air-filled spaces between grains), loosening the soil particles and moving them apart. The impact of subsequent rain drops hitting the surface splash (knock into the air) and sends sand and other types of particles of the soil away from the point of impact (Fig. 4.1).

Fig. 4.1: Impact of rain drop

You can judge the distance travelled by particles as a result of splash erosion, by observing the underside of leaves of plants in a garden, after a heavy shower. Upward jumping grains get attached themselves to the underside of the leaves. You will wonder how far the grains travel upward as a result of rain splash.

Rain splash is a micro scale process that can be quite effective in moving material on slopes (Fig. 4.2). A moving object possesses kinetic energy (e.g., a car on a highway). This energy is released when the object hits something (highway crash). Each rain drop has kinetic energy which is released to splash soil particles upon hitting the ground. On an average, the travel distance of a particle landing on the down-slope side is greater than the opposite slope or upslope, resulting in net downward motion of the soil. Each drop splashes a little bit, but billions of drops can cause significant erosion. The impact of rain droplets on the soil surface often detaches individual grains of soil moving them some distance from their source. On flat surfaces, the effect of rain drop impact is to redistribute the material without any net transport in a particular direction. However, on a slope, the influence of gravity and slope encourage more material to be redistributed down-slope rather than upslope. When slopes become 25° or greater, almost all the redistribution occurs in a down-slope direction. This process is particularly important on steep slopes devoid of vegetation. Thick vegetation protects soils from direct hits of rain drops. Soils are resistant to erosion when they have high organic content and reasonable amount of clay to develop aggregated structure. Tillage breaks down the structure and reduces the resistance to erosion and also the infiltration capacity.

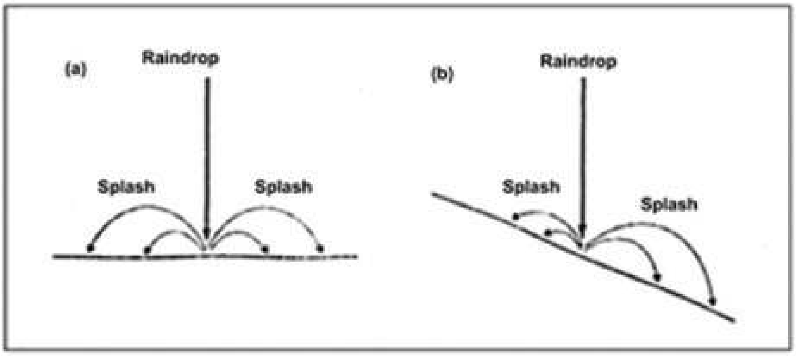


Fig. 4.2: Rain splash and Splash erosion

4.2.2. Overland flow and Sheet erosion

Erosion by overland flow occurs on non-vegetated land surfaces. Surface runoff begins when the rainfall intensity exceeds the infiltration capacity of the soil or other surface earth materials. On relatively flat surfaces, runoff across the ground surface (*overland flow*) will be unconfined (not restricted within a channel) and occurs as a continuous layer of water. This type of surface flow of water is termed **sheet flow** and the erosion associated with it is correspondingly termed **sheet erosion**. Considerable transport of surface materials on slopes occurs through this type of surface runoff. The erosive potential of sheet flow is usually quite limited because this type of flow is shallow and non-turbulent and cannot readily entrain surface particles. Sheet erosion occurs with rain splash also, and it is indeed difficult to separate the two. Both are governed by the same factors; vegetation, slope gradient, and resistance of soil to erosion.

Sheet erosion is the detachment of soil particles by raindrop impact and their removal down-slope by water flowing overland as a thin sheet (instead of as definite channels or rills). A uniform layer of fine particles is removed from the entire surface of a sloping area. This may result in an extensive loss of fertile topsoil. Sheet erosion commonly occurs on recently ploughed fields or on other sites having poorly consolidated soil material with scant vegetative cover. The effects of sheet erosion often go unnoticed because only thin layers of soil are removed. Significant degradation is perceived only after several years.

However, overland flow of water will not persist indefinitely in the down-slope direction. The presence of surface irregularities quickly transforms sheet flow into small channels called *rills*. Rills are formed by the minute streams of water cutting separate flow channels. The flow of water is concentrated in rills, and efficiency and intensity of erosion increases as a result of increased velocity and turbulence. Erosion caused in this fashion is known as **rill erosion**. Rills then coalesce into larger channels (gullies**)**. Generally, when the depth of a rill exceeds about 0.3 m, it is called **gully**. **Gully erosion** produces incisions up to 10 m deep and 1000 m long. Gullies occupy relatively small area, but they have major localized erosional effects. Rills and larger channels concentrate the movement of water causing an increase in flow velocity and turbulence. Higher flow velocities and turbulence lead to a greater potential for entrainment of earth materials and subsequent transport of rock materials.

The term rill erosion is applied for the erosion caused by flowing water concentrating into innumerable, closely-spaced small channels along slopes. Left unchecked, rills can cut vertically and horizontally and when the adjacent ones join together, gullies are formed. Gullies are steep-sided trenches formed by the coalescence of many rills. Once formed along hill slopes, they are difficult to stop.

Colluvium

The general name applied for the loose, unconsolidated earth materials that accumulate at the base of hillslopes by the processes of sheet erosion, splash erosion and slow continuous down-slope movements (called *creep*) of rock particles or a variable combination of these processes is **colluvium**. Colluvium is generally a heterogeneous mixture of earth materials ranging from silt (a particle smaller than very fine sand and larger than a coarse clay particle and having diameter ranging from 1/256 mm to 1/16 mm) to larger rock fragments of various sizes. Colluvium generally includes angular fragments, not sorted according to size, and may contain large pieces of bedrock. The slope or dip of colluvial accumulation will be toward the slope. **Colluviation** refers to the process of building up of colluvium at the base of a hillslope.

Check your progress

1. *What do you mean by the term sheet erosion?*
2. *Where can you expect the effect of splash erosion in nature?*
3. *Can you list the necessary conditions of the land surface that favour sheet erosion?*
4. *What is the difference between a rill and a gully?*
5. *Describe the term colluvium.*

4.2.3. Mass Wasting or Mass Movements

Rock materials of the surface of the earth constantly tend to move down-slope, in response to gravity. **Mass wasting** is the process of down-slope movement of rock debris and soil mainly under the influence of gravity. This process may be slow and gradual or swift or very rapid.

The term "mass" here implies a somewhat coherent or consistent grouping or accumulation of sediment/rock. "Wasting" means that a cliff or mountain slope is diminishing in size, or wasting away. This can occur suddenly with tremendous destructive force, or very slowly with only a gradual alteration of Earth's surface over a period of many years. Given enough time and repetition, the different types of mass wasting can play significant role in reducing a high mountain to a mound of low rolling hill, or in widening a narrow canyon into a broad stream valley.

Mass wasting is a process of erosion and here the agent involved is gravity**.** You have already learnt in unit 3 that, among the various agents of erosion, gravity is considered as a passive agent and therefore it requires no medium for its erosive action. However, mass wasting processes take place due chiefly to the force of gravity and usually in combination with some triggering mechanism such as an earthquake, heavy rainfall or rapid erosion of the base of a slope.

In a strict sense, in mass wasting, the earth materials (which may be soil, soil mixed water, rock fragments, a mixture of soil and rock fragments, soil and associated vegetation, ice, or a combination of any of these materials) move down-slope by the force of gravity *without the aid of a transporting medium* (such as water, ice or wind). Recall that we have noted earlier that gravity is considered as a *passive agent* of erosion. Still, as we shall see soon, water plays a key role in some forms of mass wasting. The water contributes to reduce the strength and compactness of the rock materials but is not involved as a geomorphic agent. Rapid forms of mass wasting involving huge amount of earth materials causing damage to life and property are considered as one kind of *natural hazard*.

The 'angle of repose' (Fig. 4.3) describes the natural angle at which a granular material, such as sand or gravel, will rest without slipping. It is therefore, the maximum slope angle that unconsolidated materials can maintain. Know-how of this property for different materials plays an important part in the construction of cuttings and building embankments when deciding what angle the sloping surface withstands without other measures to be taken to prevent down slope movement of materials. The downhill movement of soil and loose unconsolidated sediments is due to the force of gravity and is resisted by friction. The forces of gravity and friction are in balance at the *angle of repose*.

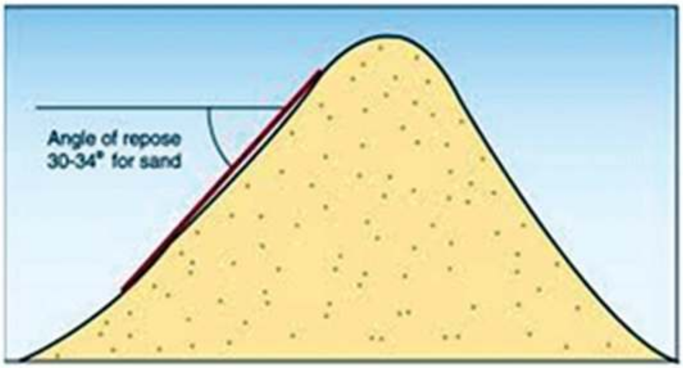


Fig. 4.3: Diagram depicting angle of repose for sand

Hillslopes have direct and indirect influences on a number of human activities. The steepness and structural stability of hillslopes determines their suitability for agriculture, forestry, and human settlement. Hillslopes can also become a hazard to humans if their materials move rapidly through the process of mass wasting. This movement can be very slow and barely perceptible or can be devastatingly rapid and apparent within minutes.

The rapidity of slope movement depends mainly on steepness of slope. Some natural slopes are very gentle, while others are extremely steep and therefore the nature of mass wasting also varies. On the basis of the nature of movement involved, mass wasting processes are classified into various types such as Creep, Falls, Topples, Slides and Flows.

Creep

Creep is the slowest form of mass movements. The process of creep along slopes cannot be monitored in a short interval of time and is undetectable by the eye. The evidences of creep along the slope include the leaning of electric poles, fences, bending of trees, etc., down the slope (Fig. 4.4). The

Fig. 4.4. Evidences of creep along the slope include the bending of trees and leaning fences down the slope

slow down-slope movement of soil and regolith is termed **soil-creep** or **solifluction.**

Falls

Falls are included in the category of rapid mass movements. Falls are abrupt movements of masses of geologic materials, such as rocks and boulders that become detached from steep slopes or cliffs. Separation of rock units occurs along discontinuities (such as *fractures*, *joints* and *bedding planes*) and movement occurs by free-fall, bouncing, or rolling of rock masses to from deposits known as '*talus*' or '*scree*' (Fig. 4.5). Falls are further subdivided into rock fall, debris fall, etc., based upon the *type of rock materials involved*.

Fig. 4.5: Rock-fall along steep slopes adjoining cliffs

Topples

Toppling movements are characterized by the forward rotation of a rock unit or rock units about some pivotal point, located below or low in the unit, under the action of gravity and forces exerted by adjacent units or by fluids in cracks (Fig. 4.6).

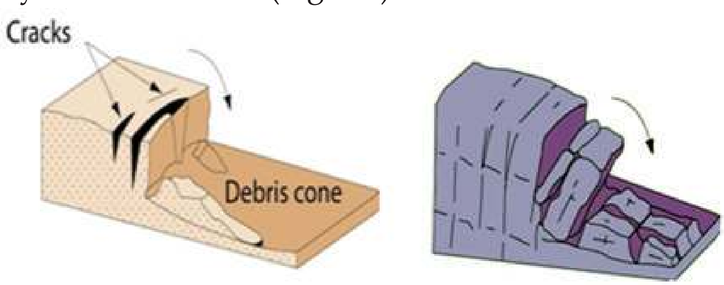


Fig. 4.6: Developmental stages of toppling movements

Flows

In flows, particles or earth materials move around and mix while undergoing movements and behave partly as a viscous fluid. Rather than moving down-slope as a coherent mass as in the case of a slump or fall, the material *flows* downhill as a chaotic mixture. Flows are further differentiated based upon the type of rock materials involved, such as **debris flows**, **mud flows, earth flows,** etc. In slides and slumps a well defined *surface of discontinuity* separates the moving mass from the underlying bedrock or other material whereas in flows no such discontinuities exist and the velocity gradient of the flowing mass gradually diminishes downward.

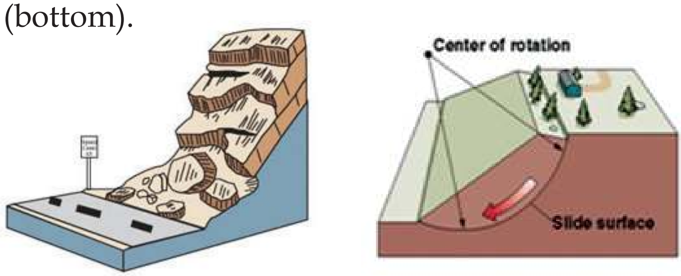
In addition to the above types of mass movement, another type of mass movement or ground failure, called **subsidence**, is also noteworthy. **Subsidence** is the direct sinking or lowering of a mass of earth material below the surrounding ground level. Such processes can occur, both on slopes or on flat ground.

Slides

Slides are the down-slope movement of a coherent block of earth material. The movement takes place along a clear-cut or distinct *surface of detachment* that separates underlying stationary material from the moving mass of rock material above. Slides can be either (a) **Translational slides** or (b) **Rotational slides** (Fig. 4.7).

Different kinds of slides are recognized based on the type of rock materials involved (such as rock slide, earth slide etc.).

Slumps are **rotational slides** moving along curved surfaces. In other words, these have spoon-shaped *surfaces of failure* or *surface of detachment*. Movement of material takes place as a coherent mass. Materials are often clay-rich (cohesive unit) and the movement may be either slow to rapid. Slumped units display clear scarp face at head (top) and end in earth flows at toe (bottom).



(a) (b)

Fig. 4.7: Diagrammatic representation of (a) translational and (b) rotational slides

Landslide

The term "landslide" describes a wide variety of processes that result in the downward and outward movement of slope-forming materials including bedrock, regolith, soil, artificial fill, or a combination of these. The materials may move by *falling, toppling, sliding, spreading*, or *flowing*.

The various types of landslides are named on the basis of: (1) the kinds of material involved and (2) the mode of movement. Such a classification of landslides is shown in the table given below (Table 4.1).

Table 4.1: Classification of Landslides

Type of movement		Type of material		
		Bedrock	**Predominantly coarse**	**Predominantly fine**
Falls		Rock fall	Debris fall	Earth fall
Topples		Rock topple	Debris topple	Earth topple
Slides	Rotational	Rock slide	Debris slide	Earth slide
	Translational			
Lateral spreads		Rock spread	Debris spread	Earth spread
Flows		Rock flow (Deep creep)	Debris flow	Earth flow
Complex movement		Combination of two or more principal types of movement		

Avalanches

Another type of mass movement that occurs along mountain slopes especially in cold countries and at high mountain altitudes covered with snow is known as **avalanche**. The term avalanche refers to a form of mass movement where the downward moving mass of material comprises mostly of snow and ice. Avalanches can be triggered by slight disturbances at the toe of mountains or when the overburden of snow and ice increases in weight and the angle of repose is exceeded. Avalanches can be really destructive as they devastate all forms of plant and animal life along their flow path.

Check your progress

1) *What is the maximum slope angle that unconsolidated materials attain?*
2) *Since Creep is an imperceptibly slow process, what evidence might indicate that this phenomenon is affecting the slopes?*
3) *What is the difference between translational and rotational slides?*
4) *What is the name given to the rapid down-slope movement of snow and ice?*

LANDSLIDE IN KERALA

The highland regions of our state Kerala experience several types of landslides, of which debris flows are the most common. They are called 'Urul Pottal' in the local vernacular. The characteristic pattern of this phenomenon is the swift and sudden downslope movement of highly water saturated overburden containing a varied assemblage of debris material ranging in size from soil particles to boulders, destroying and carrying with it everything that is lying in its path. The western flanks of Western Ghats scarps that run the entire extent of the mountain system is the most prone physiographic unit for landslides in our state. These scarp faces are characterized by thin soil (regolith) cover modified heavily by anthropogenic activity. The highlands of the region experience an annual average rainfall as high as 500 cm from the South-West, North-East and Pre-Monsoon showers. Heavy rainfall for prolonged period in the high ranges result in landslides. Recent instances of landslides in Kerala are reported from Idukki, Amboori in Thiruvananthapuram, Kothamangalam, foothills of the Western Ghats in Kozhikode and Kannur districts, etc. Figure 4.9 shows a landslide in a high-range bus route of Idukki district and Figure 4.10 shows the after effects of the Kothamangalam landslide.

Fig. 4.9: A landslide in a high-range bus route of Idukki district

Fig. 4.10: After-effects of the Kothamangalam landslide

Let us sum up

Most of the Earth's land surfaces are not horizontal, but sloping at various degrees. The geological processes that are significant along slopes are splash erosion, overland flow and mass wasting. These influence the morphological changes that take place along slopes that are covered with loose materials and unprotected by vegetation. Mass movements are subdivided into various categories chiefly on the basis of rapidness of the down-slope movement and the materials involved in it.

Significant Learning Outcomes

The learner can:

- explain the significance of slope processes on the Earth.
- recognize and categorize various types of slope processes.
- explain the role played by man in changing slopes and thereby intiate slope processes.

Let us assess

1. What factors, other than gravity, are important in triggering mass movements?
2. What type of mass movement occurs when rock fragments or rocks fall freely through the air?
3. What factor commonly triggers mass movements?
4. Distinguish between fall, slide and flow.
5. Say whether the following statements are true or false.
   a) Avalanches generally occur in cold countries and at high mountain altitudes covered with snow.
   b) Landslides are the slowest types of mass wasting.
   c) Slumps fall in the category of translational slides.
   d) Solifluction is the slow down-slope movement of soil and regolith.

5 GROUNDWATER

5.1. Introduction

More than 70 % of the earth's surface is covered with water. 98% of this is salt water. Fresh water accounts for only the remaining 2 percent. 87 percent of the fresh water resources of the world are locked up in extensive icecaps of the polar regions and in large number of glaciers of mountainous regions, 12 percent below the earth's surface as groundwater and the remaining 1 percent in world's rivers and lakes (Fig. 5.1). According to the experts, only around half of the total quantity of the groundwater is extractable for our use. This means that groundwater is a valuable resource that should be used with utmost care to keep life on the Earth as it forms the largest source of fresh water supply.

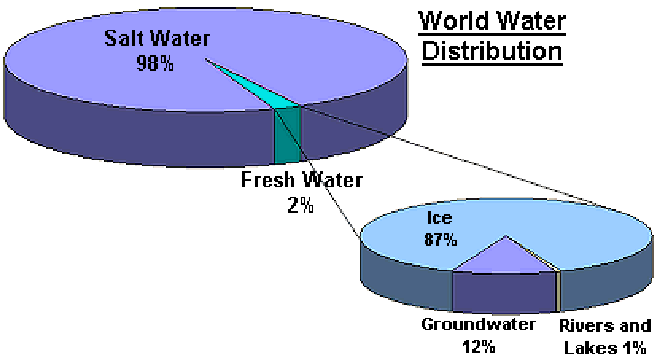


Fig. 5.1: Diagram showing the distribution of water on earth

When most people think about a water source, they think of lakes, rivers and streams; in other words the various surface water bodies rather than the subsurface water. The term groundwater is applied to the water that occurs beneath the land surface. Although groundwater estimates vary, scientists unanimously agree that there is lot of water under the earth's surface.

Groundwater is the portion of water of the hydrologic cycle that accumulates below the ground. It exists in spaces between grains of sediments and rock, or in cracks and crevices of rocks. Different types of rocks and sediments and other loose earth materials contain different amounts of water.

There has been considerable increase in the development and utilization of groundwater in various fields during the last few centuries in many parts of the world. The indiscriminate exploitation of groundwater has resulted in water scarcity in many parts of India and many other countries. In addition, the industrial discharges and domestic waste disposal are greatly polluting groundwater and the water resources in general. Chemical and biological pollution of varied nature deteriorates the quality of groundwater in many regions.

5.2. Sources of Groundwater

During rainfall and snowfall, the water falls on the surface of the earth. What happens to this water?

A part of precipitation that reaches the surface is infiltrated down to the ground.

- **Meteoric water** is the water added to ground from precipitation in the form of rain and snow. It constitutes the major source of groundwater. Fluctuation of water level in the wells in different seasons indicates the balance between the input from meteoric sources and output of groundwater locally.
- **Juvenile water** is the portion of groundwater derived from molten rocky matter or magma. Input from magmatic sources to the groundwater resources of the earth is believed to take place from time to time. The term juvenile indicates that such inputs of water represents newly added portion that subsequently take active part in the water cycle.
- **Connate water**: Some water is generally entrapped in sedimentary rocks during their formation and remains there for several years. This type of water may be salty or fresh depending on the environment of deposition of sediments. It is called **connate water** or **fossil water** and such water also forms a significant part of groundwater resources of the earth.

5.3. Porosity and Permeability

When rain falls on the ground surface, how does the water move further downwards? Most rocks contain innumerable pore spaces (inter-granular spaces) or various kinds of openings (joints, fractures, fault surface etc.). It is through these openings that the water percolates into the ground. of pore spaces. The storage of groundwater in subsurface zones and its movement through the rock formations are chiefly determined by two factors namely *porosity* and *permeability*.

5.3.1. Porosity

The amount of openings present in rocks is commonly referred to as the ***porosity*** of the rock. It is the ratio of the volume of voids in a rock or soil to the total volume of the rock or soil. Porosity represents the total amount of water a rock material can store and it depends on the total *volume* of open spaces in the rock. Porosity is defined as the *ratio of the total volume of the pore spaces to the total volume of rock*, and therefore it is generally expressed as a percentage. For example, when we say that a rock (e.g., sandstone) has a porosity of 30 percent, we mean that 100 cc of that sandstone actually consists 70 percent solid (grains) portion and the remaining 30 percent is the vacant or void (inter-granular) spaces.

Porosity of any rock depends on various factors. These include (a) the shape of the grains, (b) the packing of the grains (c) the degree of sorting of the grains composing the rock or other earth materials, (d) the amount of cementing materials, etc.

A rock composed of well rounded grains of uniform size will have greater porosity than one in which the grains are well rounded but vary in size. This is because smaller grains will occupy the inter-granular spaces between larger grains and thereby reduce the effective porosity. A rock consisting of grains of uniform and well sorted materials has high porosity whereas a rock with assorted grains with irregular arrangement decreases in porosity. The amount of cementing materials deposited between grains is yet another factor influencing the overall porosity of rock material. A poorly cemented rock, therefore will have greater porosity whereas, a well cemented rock will have lower porosity.

In general, most of the sedimentary rocks exhibit relatively higher values of porosity while most igneous and metamorphic rocks devoid of fractures and fissures possess relatively lower degree of porosity. The following table 5.1 gives a list of common rocks with their porosity values.

On the basis of the degree of porosity, rocks can be grouped into two broad categories:

(a) **Porous**: Rocks with higher degree of porosity, e.g., Limestone, sandstone, clay, laterite.

(b) **Non-porous**: Rocks with lower degree of porosity e.g., Granite, marble, basalt (all igneous and metamorphic rocks).

Table 5.1: Range of values of porosities in rocks

Rock / Earth materials	Porosity %
Clay	45 - 55
Sands	35 - 40
Alluvium	20 - 30
Sandstone	10 - 20
Shale	1 - 10
Granite	1.5
Slate	1.5
Limestone	0.6 - 17
Basalt	0.6 - 1.3
Marble	0.1 - 0.2

5.3.2. Permeability

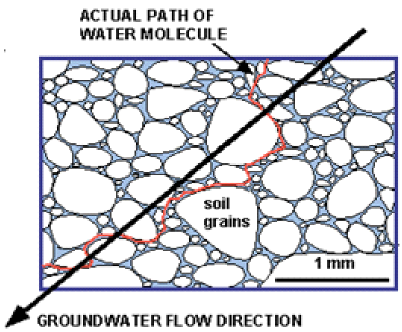
Porosity itself does not ensure the storage of underground water in rocks. Water moves through rocks only if the pore spaces are interconnected. *The term permeability denotes the degree of interconnections between neighbouring pore spaces in a rock.* While porosity determines the amount of water that a rock material can ***store***, permeability is the ability of a rock to ***transmit water*** through it or yield water.

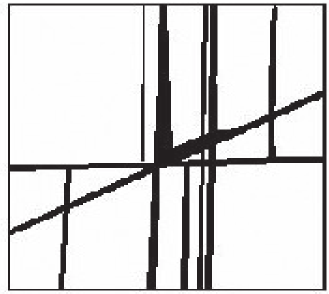
If the size of the openings in rocks is relatively larger water flows more readily through it. Therefore, the size of pore spaces is an important factor influencing permeability. Based on the degree of permeability, we can classify rocks broadly into two groups, namely permeable and impermeable rocks, as shown below in the Table 5.2.

Table 5.2: Classification of rocks based on degree of permeability

Permeable Rocks	Impermeable Rocks
Sandstone	Shale
Laterite	Clay
Sands and gravels	Limestone
Soil	Granite
Fractured igneous and	Marble
metamorphic rocks	Basalt

In an area of permeable rocks, there will be more infiltration of surface water. On the contrary if the rocks of a region are impermeable, there will





Fractured bedrock

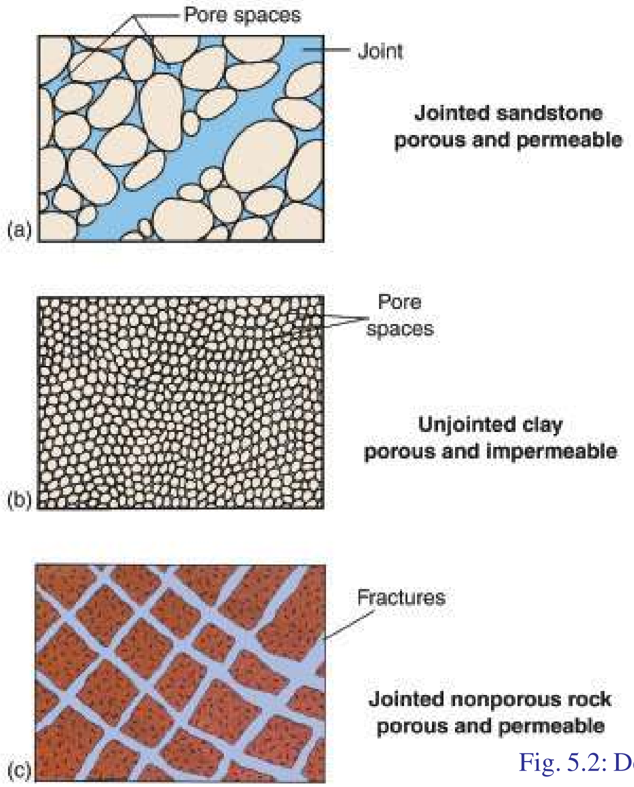


Fig. 5.2: Depiction of porosity and permeability.

be relatively less infiltration and more run off. Fig.5.2 depicts porosity and permeability.

5.4. Zonal Distribution of Groundwater

In most places of the earth, if you dig a well, the well will first pass through a zone where the inter-granular pore spaces are *partly filled with water and partly filled with air*. Then on further deepening, it will pass through a zone where all the pore spaces are *completely filled with water*. This is illustrated in the figure 5.3 given below.

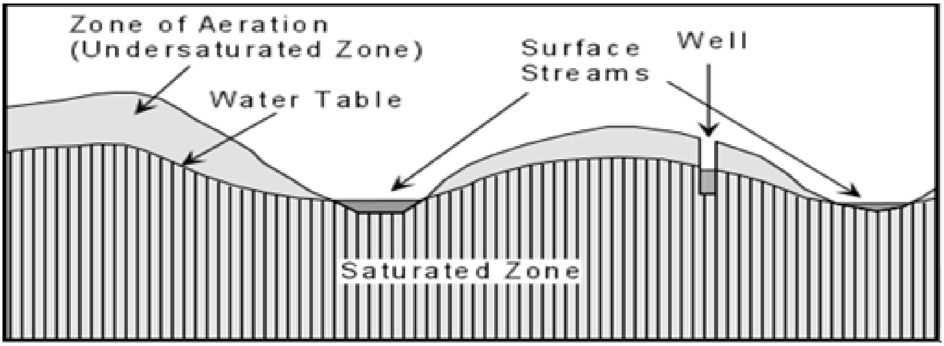


Fig. 5.3: Zones of underground water

Now, let us learn a little more about the occurrence of groundwater.

On the basis of the distribution of groundwater, we can identify two well defined zones, in most places of the Earth.

1. **Zone of aeration or unsaturated zone**: Zone where the pore spaces in rocks are *partly* filled with water and partly with air. It is also termed as **vadose zone**. This zone extends from the ground surface downwards to the zone of saturation. Within the zone of aeration, the net movement of water is vertically downwards.

2. **Zone of saturation**: It is the zone where all the pore spaces in rocks are *completely* filled with water. The water in this zone is termed as **phreatic water** or **groundwater** and will be under hydrostatic pressure. In this zone the net movement of water will be in a lateral direction. In the broadest sense, the term groundwater is given to all water occurring below the ground surface; more commonly that part of the subsurface water in the saturated zone.

The upper surface of the zone of saturation is called the **water table**. It represents the topmost level of groundwater in an unconfined aquifer.

In ordinary wells, the level of the standing body of water will coincide with or indicate the uppermost level of the water table. Thus the surface obtained by connecting water levels of a number of wells in a locality will give some idea about the level and shape of water table in that area. The depth of water table from the ground surface in an area is influenced by several factors. Most important among these factors are the topography, lithology and amount of rainfall or other forms of precipitations. It generally follows the outline of the topography and continuously adjusts itself towards the equilibrium condition with water moving from higher point to the lower point.

The level of the water table in a locality over an extensive region is not stationary. It fluctuates up and down with variation of the input of the meteoric water. Generally, during rainy season the level of the water table will attain the higher elevation while in hot summer seasons and drought conditions it will reach lowest levels. The zone of upward and downward migration of the water table defines the **zone of intermittent saturation**.

In some regions, wells will be fed with water from isolated units of large or small zones of saturation situated within the zone of aeration. The water table associated with such water bearing bodies is called **perched water table** (Fig. 5.4). It always stands at higher elevations than the main water table.

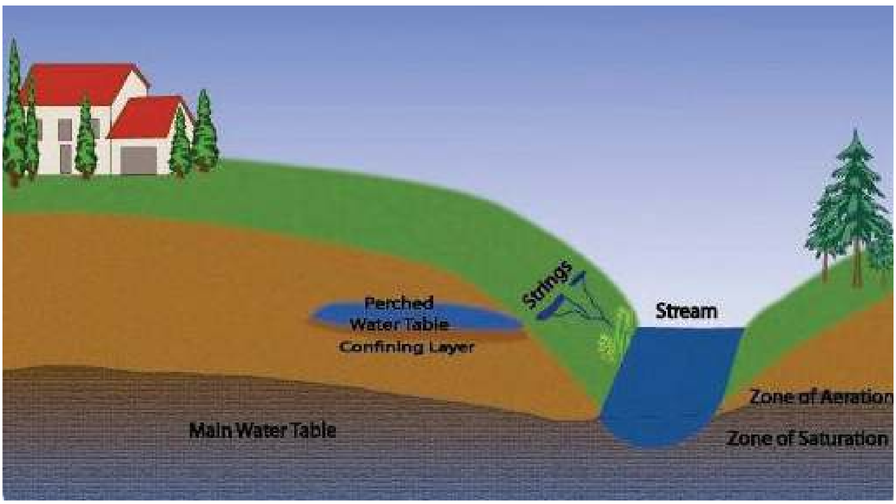


Fig. 5.4: Occurrence of perched water table above the main water table

Check your progress

1. *Where does the groundwater occur in nature?*
2. *Why are sedimentary rocks more porous than igneous rocks?*
3. *Which one of the given statements is correct? Give justification for your answer.*
   - (a) *All porous rocks are not permeable*
   - (b) *All permeable rocks are porous*
   - (c) *All permeable rocks are not porous*
4. *Name the zone below the ground where the pore spaces are completely filled with water.*

5.5. Water Bearing Formations

Rock types show wide variations in their capacities to store and yield water. On this basis, the following types of rocks are recognized.

1. **Aquifer**: An aquifer is a rock unit which holds and transmits water freely through it. Such rocks are considered as natural underground reservoirs. Aquifers are porous and permeable rocks, e.g., sandstone, alluvium.
2. **Aquiclude**: An aquiclude is a rock unit which can store water but is incapable of yielding it. Aquicludes contain water, but does not allow it to flow through it. The rock units forming aquicludes are porous but non permeable, e.g., clay.
3. **Aquifuge**: An aquifuge is a formation which neither stores nor transmits water. It is a non porous and impermeable formation, e.g., massive igneous and metamorphic rocks, like granite, massive basalt, gneiss.

5.6. Groundwater in Unconfined and Confined Conditions

When an ***aquifer*** is open to the atmosphere, the associated groundwater will be affected only by the atmospheric pressure. In such aquifers the upper surface is a water table which is free to fluctuate. In such conditions, the groundwater of the locality is said to be in **unconfined condition**. As mentioned earlier, the level of the water in the wells located in an unconfined aquifer denotes the level of ***water table*** in the area (Fig. 5.5).

The groundwater occurring in rock units (aquifers) which are bounded above and below by impermeable rock units or units with a lower permeability than that of the aquifer is said to be in **confined condition**.

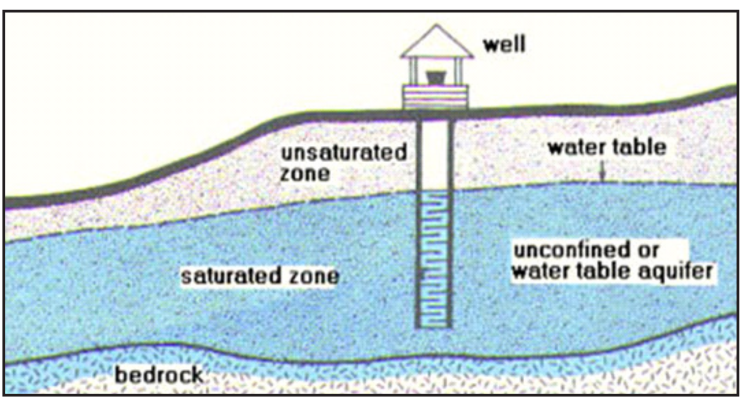


Fig. 5.5: Unconfined aquifer and ordinary well

Generally the groundwater in confined aquifers will be under pressure. This pressure of water is always greater than the atmosphere pressure. Such an aquifer is called an *artesian aquifer*. Wells receiving water from such aquifers is described as *artesian wells* (Fig. 5.6).

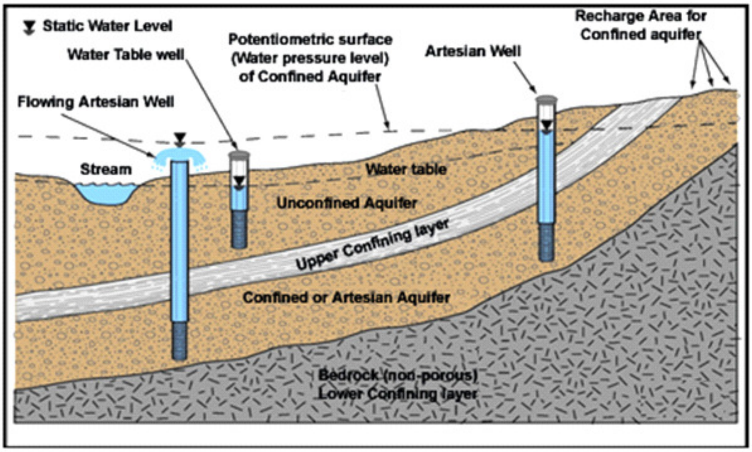


Fig. 5.6: Confined aquifer and artesian well

Groundwater either flows to the surface or gushes out from an artesian well (Fig. 5.7). Artesian condition was first observed and studied in Artois – a locality in France, in 1750. Artesian wells are found in various parts in India. In Kerala also the occurrences of artesian conditions are reported from Muhamma in Alappuzha district.

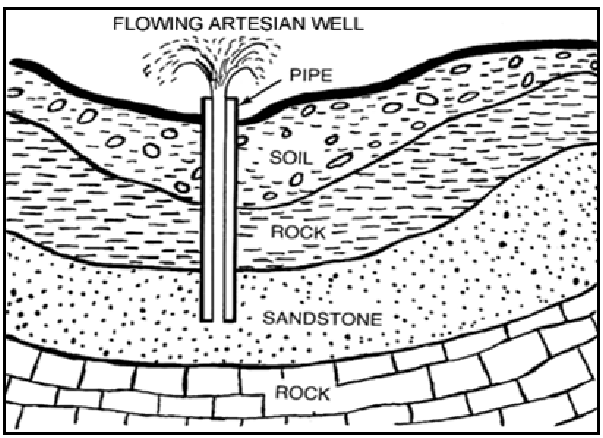


Fig. 5.7: Schematic representation of an artesian well

Now, carefully study the figures 5.5, 5.6 and 5.7 shown above and answer the questions.

1. Groundwater will not freely flow out to the ground surface from all artesian wells. Why?
2. Find out the conditions required for the occurrence of artesian wells in nature.
3. What is the difference between a water-table well and an artesian well?

5.7. Types of Wells

A **well** is a simple hole drilled vertically in the ground to collect groundwater. Many methods exist to construct a well depending upon its purpose, geologic conditions and economic factors.

1. **Dug well/Gravity well**: It is a hole dug into an aquifer with shallow depth and large diameter. Depth ranges up to 20 m or more and diameter ranges from 1 m to 10 metres. It is commonly known as open well.
2. **Tube well**: It is a type of well in which a long 100–200 mm wide stainless steel tube or PVC pipe is bored into an underground aquifer. The lower end of the tube is fitted with a strainer, and a pump at the top lifts water for irrigation or domestic use. The required depth of the well depends on the depth of the water table.
3. **Bore Well**: These are wells drilled with hand operated or power driven earth augers. The diameter is limited to 20 cm and depth is more than 30 metres. Bore wells generally tap water from the intermediate and deep sources of groundwater.

5.8. Groundwater Discharge and Cone of Depression

Wells are artificial means of groundwater discharge distinct from the natural discharges like springs and seepages. When wells are pumped there will be a lowering of water table. This lowering of water table due to pumping is called **drawdown**. The discharge of excessive quantity of water from a well by pumping ultimately leads to a localized lowering of water table. This results in the formation of a ***cone of depression***. It is a funnel shaped, nearly inverted, conical depression, formed in the water table. Large-scale pumping of groundwater from numerous closely spaced wells, at rates in excess of the replenishment of the associated aquifer, will ultimately lead to considerable lowering of water table in an extensive region. Fig. 5.8 depicts the diagrammatic representation of drawdown and cone of depression.

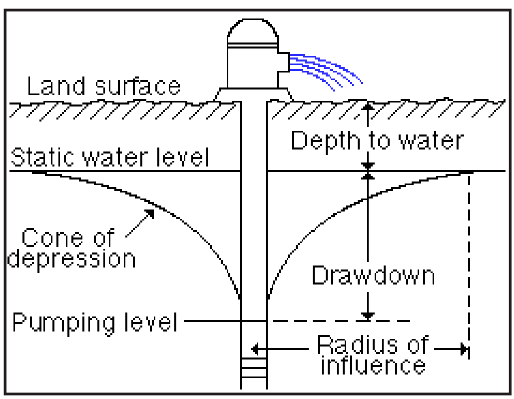


Fig. 5.8: Diagrammatic section showing drawdown and cone depression

If groundwater is pumped from two closely spaced pumping wells then there will be mutual interference between the wells and the resulting cones of depression will be a combined effect and the lowering of water table will be drastic under these conditions. Fig. 5.9 shows groundwater drawdown with time due to continued pumping and the resulting cone of depression. The maximum distance up to which the effect of cone of depression is felt is called the **radius of influence**. Water levels of all wells located within this radius will be lowered and the degree of lowering of the water table will be almost proportional to the distance from the well which is located at the centre of the cone of depression.

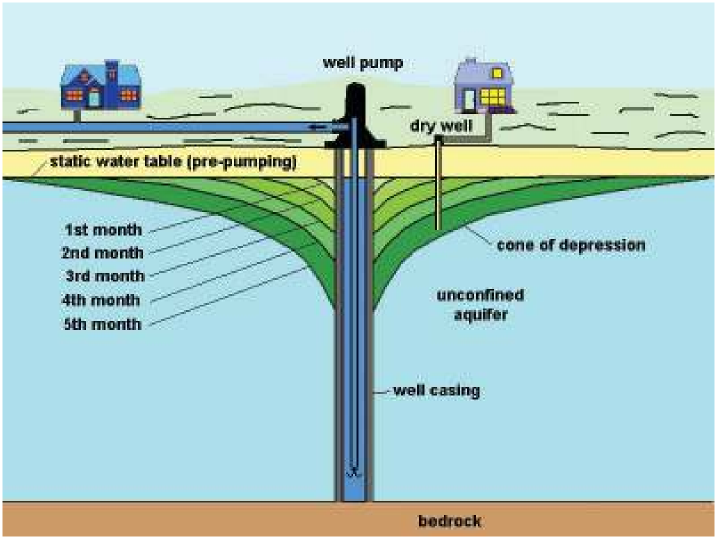


Fig. 5.9: Diagrammatic section showing groundwater drawdown with time and the resulting cones of depression

In highly permeable rocks, the cone of depression is relatively wider with more gentle slopes while in less permeable rocks, it is relatively narrow with steeper slopes.

5.9. Groundwater Recharge

The use of groundwater for various purposes such as agricultural, domestic and industrial needs, increased many fold during the preceding decades. In some regions the annual extraction exceeded the annual recharge from various sources. This has led to scarcity of groundwater resources in those regions and has resulted in consequent crop failure, salt water intrusion in coastal aquifers, land subsidence and other problems. The only solution to mitigate the problem of groundwater scarcity is recharge of the shrinking groundwater reservoirs (aquifers) by various artificial means.

In natural conditions, recharge of groundwater in a region takes place through various sources such as from rainfall, melting of snow, inflow from rivers and lakes. The methods of artificial recharge of groundwater include the following:

- Reducing surface run off of rain water and collection of water in ditches and furrows and allowing the water so collected to percolate down to the underlying aquifers.
- Rainwater harvesting also significantly contribute water to local aquifers.
- Pumping down of surface water brought from neighbouring areas (injection recharge).
- Reducing the loss through evaporation by adopting the methods of afforestation and other methods.

Check your progress

1. *What are the various types of wells you have noticed in your area and write their differences?*
2. *Vegetation tends to*

   (a) Increase the runoff from the catchment.

   (b) Decrease the runoff from the catchment.

   (c) Does not affect the run off.

   (d) None of these.
3. *What is the reason for the formation of a cone of depression? Describe how it will affect the nearby wells?*

Let us do

Conduct a field visit to the well sites in your nearby areas and try to answer the following questions and prepare a report on it.

1. *What is the depth of the local water table in that region?*
2. *Why does the water table fluctuate in different seasons of a year?*
3. *What kinds of wells are chiefly made there to extract water?*
4. *Describe the various kinds of artificial recharge methods adopted if any in that locality.*

5.10. Springs

When the water table intersects the surface of the earth, groundwater flows out to the ground surface. This phenomenon occurs in certain areas of the earth. A **spring** is a natural discharge of groundwater at the land surface (Fig. 5.10).

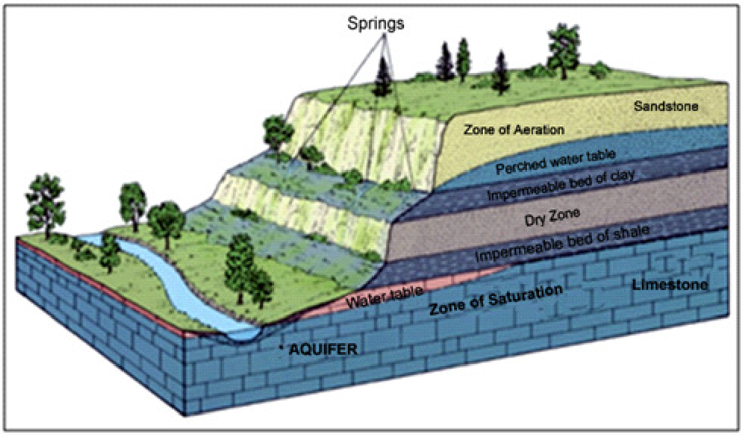


Fig. 5.10: Development of springs

Hot springs are the discharge or eruption of hot water from an underground source (Fig. 5.11). A hot spring is a spring that is produced by the emergence of geothermally heated groundwater from the Earth's crust. The water issuing from a hot spring is heated by geothermal heat, i.e., heat from the Earth's mantle. Geothermal hot springs are found in many locations all over the crust of the earth. In active volcanic zones such as Yellowstone National Park, water may be heated by coming into contact with magma (molten rock).

Fig. 5.11: Hot spring in Yellowstone National Park, U.S.A.

Geyser is a special type of spring from which hot water and steam is erupted to the surface mostly at regular intervals. Here the water rises up to a height that varies from a few meters to 100 meters or so. Both hot springs and geysers are generally observed in neighbourhood regions of volcanic activity. The groundwater occurring in deep underground horizons in these regions are heated up due to the proximity with magma. The "Old Faithful" Geyser in Yellowstone National park of U.S.A. is the best example for Geyser (Fig. 5.12). Many geysers erupt water sprouts at specific time intervals.

Fig. 5.12: Old Faithful Geyser in Yellowstone National Park, U.S.A.

5.11. Geological Work of Groundwater

You have already learnt in unit 2 that water in various forms constitutes an important geological agent. In this section let us briefly study the geological work of groundwater.

Erosion caused by groundwater is in the form of chemical action -solution of soluble constituents of a rock. In the case of groundwater, mechanical process of erosion is absolutely insignificant. Therefore, not all kinds of rocks are susceptible to the erosive action of groundwater. The soluble rocks and minerals are dissolved by groundwater when it moves underground through various openings through the rocks. In nature, only certain kinds of sedimentary rocks such as those containing carbonates (various types of limestones, dolomite, marble etc.), sulphates (gypsum) and chlorides (rock salt and other saline deposits) are prone to erosive action of groundwater. When underground water circulates through soluble rocks, it tends to dissolve the materials where it comes into contact with the rocks and enlarges the fractures and other types of channel ways through which it passes, giving rise to chambers of varying dimensions. The degree of dissolution of carbonate rocks by groundwater depends on various factors, such as its carbon-dioxide content, temperature and pressure.

Groundwater transports the dissolved materials derived from the rocks in solution and deposits them in favourable places under suitable conditions.

5.11.1. Erosional Features

A variety of landforms are produced by the erosional and depositional work of groundwater. The most common erosional features associated with the geological work of groundwater are briefly described below:

a) Sinkholes

Sinkholes are depressions or large solution cavities, usually cylindrical or funnel shaped and found on land surfaces underlain by limestone rock. Sinkhole is initiated to develop with the formation of a small fracture. It gets enlarged with the passage of time due to continuous solution activity and removal of materials. Some of these sinkholes are several metres in diameter. Number of sinkholes are found in limestone terrains and are formed by natural causes viz., dissolution of the limestone by underground water.

b) Caves and Caverns

Caverns are large interconnected subterranean cavities found in areas of carbonate rocks. Those caverns having openings to the ground surface are called caves. **Solutional caves** are the most frequently occurring caves and such caves form in rock that is soluble, such as limestone, but can also form in other rocks, including chalk, dolomite, marble, salt, and gypsum. They considerably vary in size and sometimes become exceptionally large in dimension like the Mammoth Cave of U.S.A. (Fig. 5.13) The nature of caves and caverns formed are influenced by the associated fracture, fissure systems and bedding planes of the rocks. Caves and caverns that have resulted from the geological action of groundwater occur in many countries that they become quite famous.

5.11.2. Depositional Features

In limestone caverns lying above the local water table, the water containing dissolved calcium carbonate may drip down from the roof.

THE 'MAMMOTH CAVE'

Caves and caverns that have resulted from the geological action of ground water occur in many countries. The 'Mammoth Cave' of Kentucky in U.S.A. is the most famous example. It is the longest cave system known in the world having a total length of about 500 kms.

Fig. 5.13: The 'Mammoth Cave' of Kentucky in U.S.A.

Fig. 5.14 given below depicts the magnificent interior of the Mammoth limestone cave with features like stalactites and stalagmites.

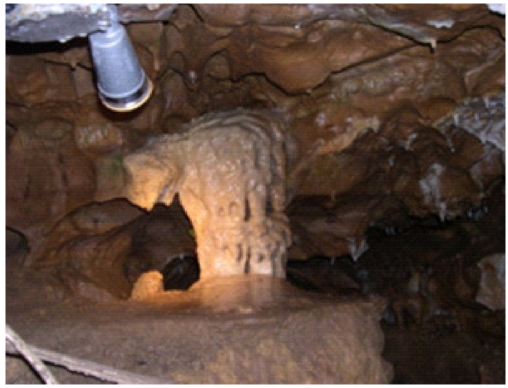
Fig. 5.14: The magnificent interior of the 'Mammoth Cave'

When this water evaporates, the dissolved calcium carbonate is deposited there. In course of time, with subsequent deposition of calcium carbonate, a column of calcium carbonate develops, hanging downward from the roof the cavern. Such depositional features, composed of carbonate, are called **stalactites.**

The water droplets enriched with calcium carbonate dripping down over the floor of the cavern, from the terminus of a downward growing stalactite column, when evaporated, its calcium carbonate get deposited. Gradually, a column of calcium carbonate starts to grow upward from the floor of the cavern. It is called a **stalagmite**. Stalagmites are more massive than stalactites as the water splatters over the surface before its evaporation.

These opposing stalactites and stalagmites are several meters tall and may join to form **vertical columns or pillars** during their subsequent growth. Figure 5.15(a) depicts the stalactites and stalagmites in a limestone cavern. The figure 5.15 (b) shows vertical column developed by the meeting of a stalactite and stalagmite.

(a)



(b)

Fig. 5.15: Stalactite and stalagmite and a vertical column

Travertine and Siliceous Cinter

Calcium carbonate dissolved in groundwater gets ultimately deposited around the mouth of springs in limestone terrains when it is discharged through them. These deposits seen around the springs are known as travertine. When the deposited mineral composition is Silicon dioxide (silica) the deposits are called Siliceous Cinter.

Karst Topography

The term Karst is given for an area of irregular topography formed mostly in limestone regions with many sinkholes and cave-cavern systems,

Fig. 5.16: Typical Karst topography developed in a limestone terrain

beneath the land surface. Karst regions usually lack surface drainage streams. The distinctive type of landscape that results from the erosional as well as depositional work of groundwater is known as **Karst Topography** (Fig. 5.16). This topography is well developed in the plateau regions of northwestern Italy and Yugoslavia. This type of topography occurs in many parts of the world.

Let us sum up

Groundwater makes only 1.8 percent of the total water resource of the earth. The groundwater occurs on the earth in various zones and the knowledge of these zones are important for all of us for making wells and taking suitable recharge measures in an area.

Groundwater is not stagnant or motionless. It forms the integral and dynamic part of the hydrologic system, accomplishing a lot of geological work as discussed in this unit. The erosional and depositional work of groundwater is very active in regions underlain by soluble rocks, particularly the limestone rocks. In such areas, it produces an entirely different topography with its erosional as well as depositional features. In the case of groundwater the erosion always occurs in the zone of saturation and deposition occurs in the zone of aeration.

Significant Learning Outcomes

The learner can:

- become aware of the significance of water for life.
- identify the sources of groundwater.
- explain the water bearing properties of rocks.
- explain groundwater discharge and the impact of over-draft of groundwater.
- realize the need and importance of recharging and take part in the activities.
- explain the geological action of groundwater and related landforms.

Let us assess

1. Suggest some measures for improving the availability of ground water in your area.
2. Groundwater is one of the important agents of land modification. Explain the important landforms formed by the activity of ground water.
3. Groundwater is a valuable resource. Justify the statement.
4. What are the characteristic features found in a karst topography?
5. Make a comparison between the following kinds of rocks.
   - A highly porous rock
   - A highly porous and permeable rock
   - A non porous rock.

   What conclusion do you make regarding the water bearing capacities of the above rocks?
6. Where do springs form, with respect to the water table?

6 STREAMS

6.1. Introduction

You have already studied diverse agents of erosion and among them running water - in the form of streams, is the most important agent that modifies the dominant portion of the Earth's land surface. Streams are important for several reasons:

- Streams carry most of the water that goes from the land to the sea, and thus are important parts of the water cycle.
- Streams carry enormous amounts of sediment to lower elevations, and thus are one of the main transporting agents in the production of sedimentary rocks.
- Stream flow accounts for 85-90% of total sediment transport to the ocean basins.
- Streams carry dissolved ions, the products of chemical weathering, into the oceans and thus make the sea water salty.
- Streams are a major part of the erosional process, working in conjunction with weathering and mass wasting, and result in a variety of degradational landforms.
- Streams are a major source of water, waste disposal, and transportation for the world's human population. Larger streams produce floodplains with fertile soils and most ancient civilizations were developed along fertile stream valleys (e.g., the Indus Valley Civilization).
- When stream channels fill with water, the excess water flows onto the land as floods. These form one of the common natural disasters.

6.2. Sheet flow and Channel flow

During rainfall a portion of the rainwater reaching the ground surface infiltrates into the soil and the remaining water flows over the ground surface. The water that flows over the land is termed runoff**.** Initially, the runoff will be in the form of a thin sheet of water moving in the down slope direction, similar to the flow of water over the gently sloping flat surface of a roof. Sheet flow will not persist for long and as natural surfaces are usually not perfectly flat; the irregularities of the ground surface will rapidly transform sheet flow into flow concentrated along small channels – called **rills**. The rills formed initially are very small and they are sometimes described as **shoe-string rills**. Adjacent rills coalesce together to form larger and larger ones – such as the **gullies** and still larger channels – variously described under terms such as **brooks, creeks, nullahs** and so on. These are all grouped under the term **channels** and the concentrated flow of running water along a channel is therefore termed **channel flow**. Stream channels are variable in terms of their width, depth, and surface appearance. In terms of their width, the naturally formed channels range from the smallest ones called rills, passing over through those types over which one can jump or stride over, to the widest ones – a few kilometres wide such as those of Amazon River of South America – the widest river in the world which has a width of 325 km. where it opens up into the ocean. The river Nile of Africa, with a total length of 6,650 km. is the longest river in the world.

We can define the term **stream** as a body of water that carries rock particles and dissolved ions and flows down-slope, under the influence of gravity, along a natural channel shaped by it. Larger streams are called **rivers**. As noted earlier, streams may vary in width from a few centimetres to several tens of kilometres.

The highland or the mountainous region from where a stream originates is termed its **head** or **source region.** From this region, the stream flows down-slope, enlarging gradually in size, and ultimately emptying into a sea, a body of standing water (such as a lake), or another stream. (Not all streams empty their waters into a sea, an ocean or a lake. In arid regions streams associated with the so called **interior drainage** end up in a centrally located topographic depression. Examples are the streams of the Sahara region of Africa and the desert regions of Central Australia, Central Asia and North America). The place where a stream enters a sea, or a lake or another stream is called its **mouth**. The portion of the stream channel located nearer to its source is called its **higher reaches** while that which is closer to its mouth is correspondingly called its **lower reaches** (a reach is any length of a stream between any two specified points).

A stream, for example A, joining and discharging its water to another stream B, is described as a **tributary stream** of the stream B. Tributary streams are generally smaller streams that flow into larger streams. Similarly, a stream C, which branches off from another stream D, is called a **distributary** of the stream D. The point at which a stream joins another stream, a lake or sea is called the **confluence.**

STREAM DISCHARGE

All streams flow along channels created and continuously being modified by their own geological action. The amount of water passing through a stream channel across an observation point, per unit time, is termed its discharge. To determine the discharge we need to know velocity and the area of the cross section of stream's channel. The latter will be equal to width (w) x depth (d). The equation for the calculation of discharge is "Discharge (Q) = Velocity (v) x Area of cross section of the channel (A)" It is expressed as m^3/s (volume of water flowing past a certain point per unit of time). The ability of a stream to erode and transport materials depends largely on its velocity. The factors that influence the velocity of any stream include: (1) its gradient or slope (how steep or flat its bed), (2) shape of the channel (i.e., crooked vs straight), (3) size of the channel (i.e., wide vs narrow and deep vs shallow) and (4) roughness of the channel (i.e., smooth vs rough).

Discharge of streams varies with time (varying with season) and place of observation. In times of flooding, discharge is higher than during normal periods. The discharge of streams normally increases towards its mouth.

Velocity of a stream defines how quickly water is moving through the stream or it is a measure of the swiftness of the water flow. It is the distance stream water travels in unit time. Some streams are slow while others are very fast. The highest water velocities in a stream are found confined to the middle of the stream channel in straight stream courses. In stream bends, the velocity is highest in the outer convex side. A stream's velocity depends on position in the stream channel, irregularities in the stream channel, and stream gradient. Friction slows water along channel edges. Friction is greater in wider, shallower streams and less in narrower, deeper streams. The deepest part of the channel is called the thalweg, which meanders with the curve of the stream. Actual flow around stream curves follows spiral paths. Velocity is the key factor that determines a stream's ability to erode, transport, and deposit sediments.

Stream flow can be either laminar (streamlined), in which all water molecules travel along parallel paths, or turbulent, in which individual particles take irregular paths. In the latter case, although there is a net forward movement, it is achieved by a series of chaotic or erratic movement involving downward, upward and side-way movement of water. Any increase in stream velocity - beyond what is known as critical velocity - causes turbulence and the intensity of turbulence increases proportionally. Turbulent eddies scour the channel bed, and keep sediments in suspension.

In curved channels (stream bends), the maximum velocity occurs along the outside of the curve and therefore the stream channel is preferentially scoured and deepened on the convex side. On the inner side of a stream curve where the velocity is lower, deposition of sediments takes place (Fig.6.1) . Cross-sectional shape of stream channels varies with the location and generally as the discharge increases downstream the stream channel become deeper and wider.

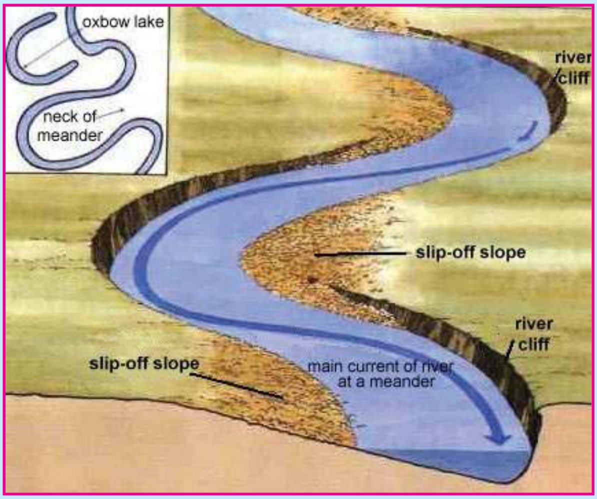


Fig.6.1 Erosion and deposition in stream bends

6.3. Sources of Stream Water

A stream receives its supply of water from various sources. These include:

1. Direct supply from precipitation that does not infiltrate into the ground, and from melting of snow and glacial ice.
2. Supply received from groundwater outflowing along lines where the water table intersects the surface, forming springs. The water from rain and snowmelt – that forms the **run off** component of the hydrologic cycle, is the main source of water for most streams of the world.

6.4. Classification of Streams

On the basis of consistency of water flow in the stream channels and the connectivity of stream water with groundwater, streams are commonly classified as follows:

(a) **Perennial streams**: These are streams that carry water throughout the year. Channels of such streams are in direct contact with water table. The Himalayan rivers viz., the Ganga and its tributaries, the Brahmaputra, the Indus, etc are all perennial streams.

(b) **Intermittent (seasonal) streams**: Those streams that carry water during most part of the year and dry up or stop flowing during summer seasons, but the streams are still in direct contact with water table. Some of the streams of Peninsular India and those of Kerala are considered to be intermittent streams.

(c) **Ephemeral streams**: These are streams that contain water only during the rainy season or periods of snow melting. The channels of such streams are well above the water table. Some of the river systems of the Thar Desert fall under this category.

We have already noted that the condition favouring the existence of a perennial stream is the proximity of the water table in that locality. In other words, *perennial streams are possible only where the stream channel coincides with the water table of that locality*. On the basis of gaining water from or losing water to the underlying water table, streams/reaches can be classified into two types, namely, effluent stream and influent stream. A stream that receives the supply of water from the local groundwater is termed an **effluent stream** while the one from which water is continuously drained and lost and where it becomes groundwater is an **influent stream** (Fig. 6.2).

In influent streams water will be continuously losing to the underlying aquifer while in effluent streams the stream will be gaining water from the local aquifer.

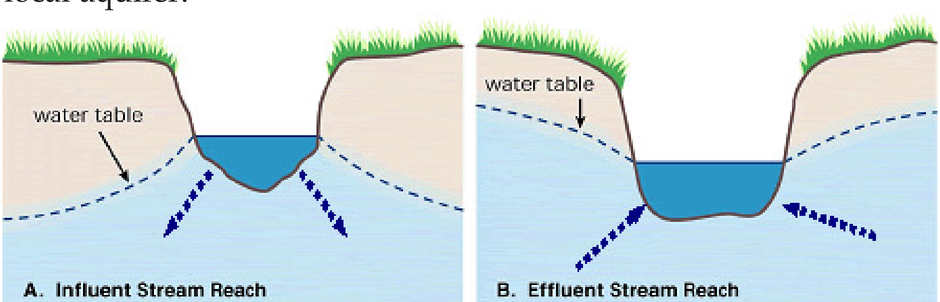


Fig. 6.2: Influent and Effluent streams

Based on the nature of the **stream course**, stream reaches can be classified into any one of the following:

(a) **Straight**: streams with a single thread that is straight.

(b) **Meandering**: streams with a single thread, but the channels have many curves (Fig. 6.3).

(c) **Braided**: streams having multiple threads with many sand bars that migrate frequently (Fig. 6.4). Islands of sand bars are very characteristic of braided streams (Fig. 6.5).

Fig. 6.3: A meandering stream

Fig. 6.4: A braided stream

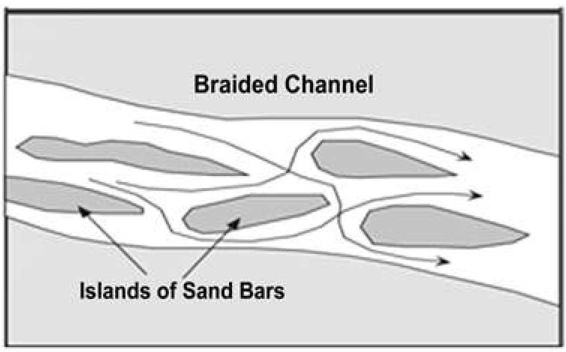


Fig. 6.5: Schematic diagram of a braided stream showing islands of sand bars

Check your progress

1. *Which process describes water seeping into the ground?*
2. *What type of streams carry water throughout the year?*
3. *What are the sources of stream water?*
4. *What kind of a stream is called an effluent stream?*

6.5. Drainage Basin

Drainage basin, also called **catchment area**, or **watershed,** is the area from which all precipitation flows commonly to a single stream. In other words, the entire area drained by a stream and its associated tributaries is known as its **drainage basin**. For example, the total area drained by the Bharathapuzha constitutes its drainage basin, whereas that part of the Bharathapuzha Basin drained by the Kunthipuzha River is the Kunthipuzha's drainage basin - a sub-basin of Bharathapuzha. The terms **watershed** or **catchment area** are also used as synonyms of the term drainage basin. The term **drainage area** is the actual areal extent of a drainage basin. For example the drainage area of Bharathapuzha is 6,186 km^2. Figure 6.6 depicts the schematic of a drainage basin.

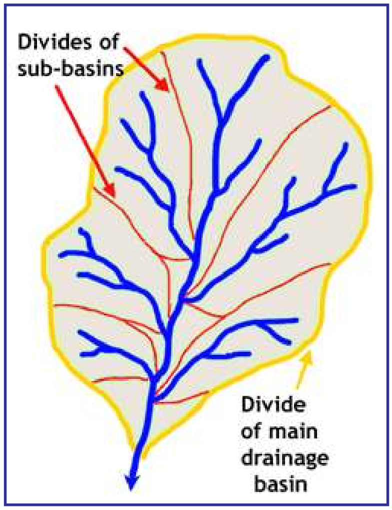


Fig. 6.6: Schematic diagram of a drainage basin

It need not be stated that a drainage basin consists of several smaller and larger streams. The main stream of a drainage basin is termed as the **trunk stream** or **master stream**. The higher land above the valley sides that separates adjacent valleys is termed **interfluve or inter-stream area** or **drainage divide** (Fig. 6.7). Fig. 6.8 shows the relations of the boundary of the main drainage basin and the boundaries of secondary drainage basins.

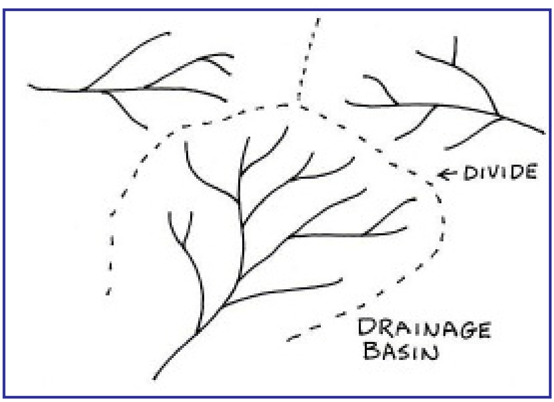


Fig. 6.7: Schematic diagram of drainage basins showing the drainage divides

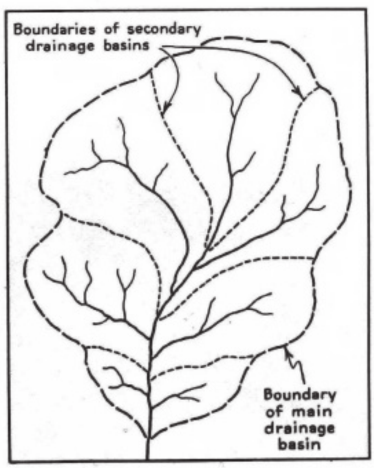


Fig. 6.8: Schematic diagram of a drainage basin showing the relation of main drainage basin boundary and secondary drainage basin boundaries

Generally, the trunk stream and its associated major tributaries alone will be perennial streams whereas smaller tributaries of the stream will be intermittent streams. The **fingertip tributaries** which are mostly located at the peripheral portion of a drainage basin will be ephemeral streams (Fig. 6.9). The fingertip stream of the main stream in the figure is enlarged and shown in the second figure. The enlarged portion shows countless streamlets. If you carefully study an ordinary map of any region or state or country, commonly the main stream (trunk stream) and its major tributaries – which are perennial streams, alone will be found marked.

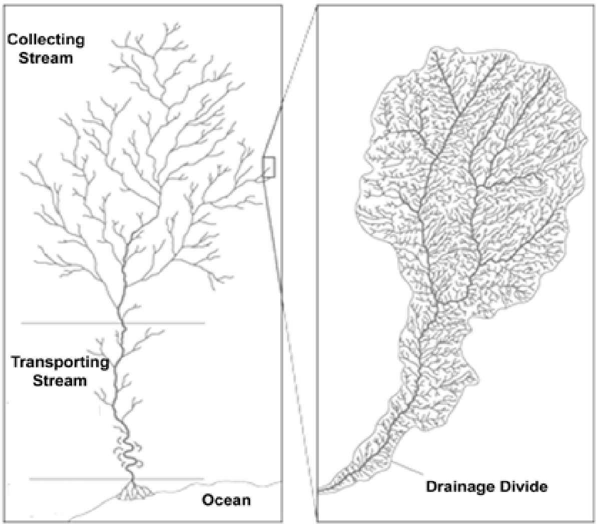


Fig. 6.9: Schematic diagram of stream segments showing collecting stream with fingertip streams, the transporting stream and the dispersing stream

The boundary of a drainage basin, which is a line of separation between run off that descends into two adjoining drainage basins is called the **drainage divide**. Continents usually have high mountain ranges that act as divides between drainage basins that drain into completely different oceans. This type of drainage divide is called **continental divide**. The Western Ghat Mountain constitutes the continental divide in peninsular India.

Irrespective of their size and extent, drainage basins constitute ideal and scientifically appropriate geomorphic units for sustainable watershed management planning (land use management and planning), estimation of groundwater resources, and monitoring and evaluation of pollution of surface and sub-surface water resources, in modern times.

6.6. Drainage Patterns

Streams of any drainage basin tend to develop along zones where rock type and structure are most easily eroded. Thus various types of drainage patterns develop in a region and these drainage patterns reflect the structure of the rocks occurring in that region. The following are the important types of drainage patterns (Fig. 6.10).

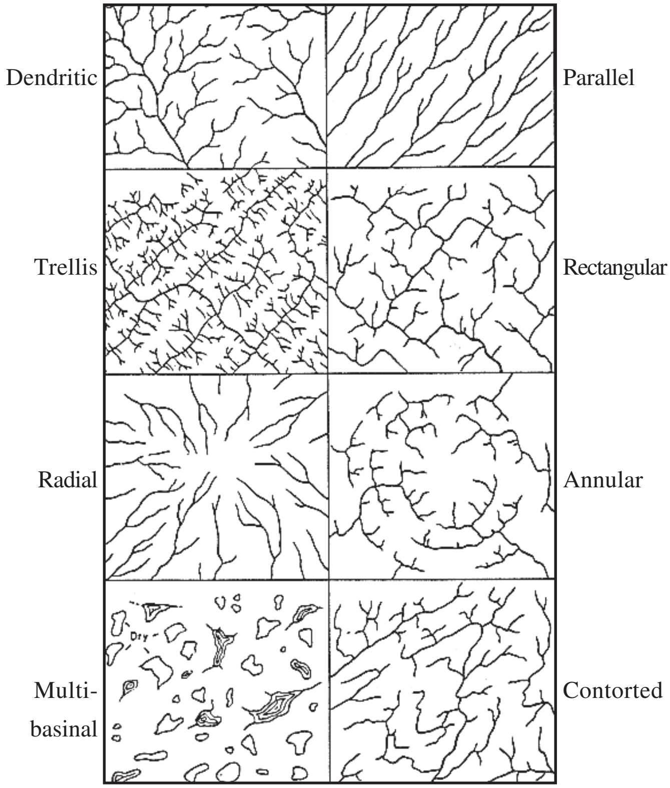


Fig. 6.10: Different types of drainage patterns

(a) **Dendritic drainage pattern**: This type of drainage pattern resembles the branches of a tree (*dendritic* means tree-like). This is the most common drainage pattern in nature. This type of drainage pattern develops on gently sloping land surfaces where the underlying rock is of uniform resistance to erosion everywhere.

(b) **Radial drainage pattern**: This type of drainage pattern forms when streams flow in all directions away from a centrally located higher region (such as a large more or less conical hill where elevation drops from a central high area to surrounding low areas).

(c) **Rectangular drainage pattern**: As the name indicates this pattern is characterized by tributaries joining larger streams at almost right angles (90°). Streams show sudden right-angle bends, where linear zones of weakness, such as joints or faults cause the streams to cut down along the weak areas in the rock.

(d) **Trellis drainage pattern**: Trellis drainage pattern forms where streams flow along a number of straight valleys that are separated by parallel ridges or mountains and short tributary streams flow down the mountains into the main streams which flow through the intervening valleys, together forming a pattern resembling a trellis (A trellis is a structure, or lattice of interwoven or intersecting pieces of wood, bamboo or metal that is normally made to support and display climbing plants, especially shrubs in gardens).

(e) **Parallel drainage pattern**: A drainage pattern in which the streams and their tributaries are regularly spaced and flow parallel or sub-parallel to one another over a considerable area is described as parallel drainage pattern.

(f) **Annular drainage pattern**: Annular drainage pattern is a drainage pattern, in which streams follow along roughly circular or concentric path, more or less resembling a ring-like pattern, in plan.

Lastly, the term **deranged drainage pattern** refers to areas that have not yet developed a good drainage pattern. In this case the flow directions are irregular and there may be many swampy areas.

6.7. Stream Ordering

The concept of stream order describes the hierarchy of a stream in the drainage net. This concept is based on the type and number of tributaries that make up a channel network. Stream orders provide a way to rank and identify relative sizes of channels in a drainage basin. Smaller order numbers are given to smaller, headwater streams that are typically found in the upper reaches of a watershed. Higher order streams are given larger numbers and are commonly found in the lowlands.

In stream ordering, the Strahler method is the most commonly used (Fig. 6.11). First-order streams are the furthest upstream channels that have no tributaries. When two first-order streams unite, they form a second order stream. In the same way, when two second-order streams unite a third-order stream is created, and so on. Where two streams of different orders join, for example a first and third-order, the combined stream retains the order of the higher order stream contributing to it.

The main assumption behind this ordering system is that when two similar order streams join to create the next higher order stream, mean discharge capacity is doubled. *The bigger the stream order, the more water flows through it.*

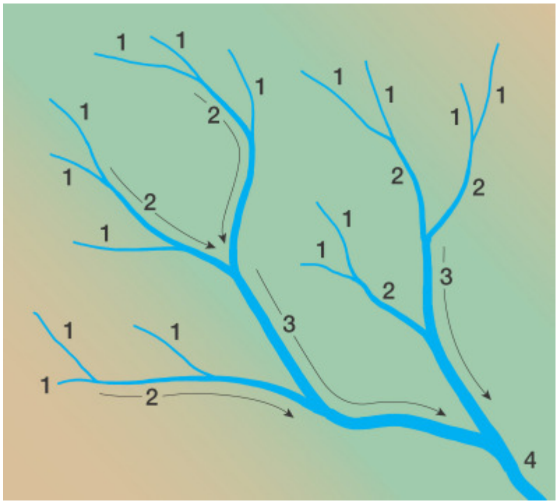


Fig. 6.11: Strahler's method of stream numbering

Check your progress

1. *What do you call the entire region that is drained by a stream and all the tributaries that flow into it?*
2. *What is meant by a drainage divide?*
3. *What do you call the type of stream drainage pattern that resembles the branching pattern of the veins in a leaf?*
4. *Regions of which kinds of rocks commonly show dendritic drainage pattern?*
5. *In which type of regions can we expect a radial drainage pattern?*

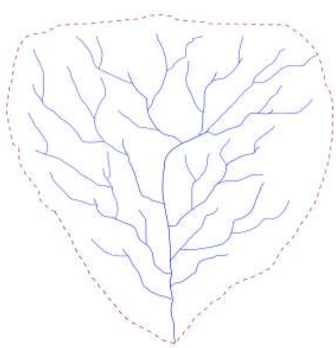
Let us do

Examine the drainage network map shown in the figure and perform the tasks mentioned below.

Task 1: *In the figure, label the drainage boundary on this map. Label the tributary outlet for the watershed.*

Task 2: *Compare the map with the drainage patterns you have already learnt in this chapter and name the pattern.*

Question 1: *Is this drainage network best described as "dendritic" (i.e., like veins on a leaf), rectangular, or parallel?*



Task 3: *Determine the stream order of the watershed system at the point where the stream exits the drainage basin.*

Task 4: *Using the "Strahler stream ordering method" determine and label the stream order numbers for each tributary in the watershed.*

6.8. Geological Work of Running Water

Landforms created by running water have done more to shape our earth than any other process. Let us now study how streams modify the land surface by the process of erosion and deposition.

Streams are the most important sub-aerial agents of gradation. During the life span of a stream, it and its associated tributaries are capable of greatly modifying the topography of its drainage basin. The geological activity of streams can be discussed under three heads, viz., (1) erosion (the wearing away of land by running water), (2) transportation (transfer of materials from one place to another, generally from a higher region to a lower region), and (3) deposition (the placement of material carried by running water).

The process of modification of the drainage basin or a region is brought about by running water and by the processes associated with it. The term **fluvial process** is generally applied for the geological activities carried out by streams, in association with a variety of other processes. The term **fluvial denudation** (and also **fluvial erosion** or **fluvial degradation**) is applied for the *combined action* of channel erosion (erosion caused by flowing water along channels), overland flow (erosion by sheet flow or overland flow), mass wasting (erosion by gravity) and weathering – resulting in the modification of land surfaces. Remember that the term *fluvial* means "*stream-related*". The word "*fluvius*" (in Latin) means river.

Fluvial processes produce one set of landforms by erosion and another by deposition. The former set is also described as **erosional**, **degradational** or **destructive fluvial landforms** while the latter category constitutes **depositional, aggradational** or **constructive fluvial landforms**. We shall discuss the various fluvial degradational and fluvial aggradational landforms in the following sections.

6.8.1. Fluvial Erosion

The adjective **fluvial** denotes streams and is used in earth science to refer to the *processes associated with streams and the deposits and landforms created by* *them*. You have already learnt that the process of fluvial erosion involves a complex group of processes such as channel erosion, overland flow, splash erosion, mass wasting and weathering.

Stream erosion can be defined as the progressive removal of rock materials from the floor and sides of the stream channel. The process of erosion by stream involves the following:

a) Hydraulic action
b) Abrasion (Corrasion)
c) Attrition
d) Corrosion (Solution).

(a) Hydraulic action

Hydraulic action is a form of erosion that is mostly caused by the force inherent in moving water to dislodge and transport rock particles. (Hydraulic action also occurs where the sea waves crash against rocks and cliffs). If you place a hose over a heap of sand grains and allow water from the hose to flow over it the water will erode the sand grains along with its flow. This is hydraulic action. This type of erosion also occurs where a stream tumbles over a waterfall and crashes onto the rocks below. Weakly consolidated bedrocks and various kinds of uncemented or poorly consolidated rock materials are prone to hydraulic action. The products of hydraulic action of a stream vary in size from large boulders to fine silt and clay.

(b) Abrasion /Corrasion

Abrasion or corrasion is the process of *mechanical* erosion of the rocks of the Earth's surface caused when rock materials are transported across it by running water (as well as waves, glaciers, wind or gravitational movement, down slope). The process involves the wearing, grinding, or rubbing or bumping action of the rocks of the channel floor and channel sides with other rock fragments (such as sand and pebbles) transported by a stream. The resultant effect on the rock is called **abrasion**. (It is similar to smoothening of walls by a painter using sand paper). The grains and rock fragments moving along with stream water collectively constitute the tools of erosion, in corrasion.

Through the process of corrasion, streams are capable of eroding and smoothening even the hardest rocks lying in its path. Corrasion is largely responsible for the ability of the streams to deepen their channels and creating narrow, deep stream valleys – known as **gorges** and **canyons**.

(c) Attrition


Fig. 6.12: A dried up stream channel with pebbles and cobbles showing effect of attrition.

The mutual wear and tear suffered by the transported materials themselves while in transport, whereby they are broken down, smoothened and rounded is called **attrition**. By this process the big boulders are gradually reduced in size. Due to mutual collisions the irregularities and angularities of the particles are worn out. These become spherical in shape and rounded and polished at the surface (Fig. 6.12).

(d) Corrosion/ Solution

The wearing down of surface of the bedrocks by the solvent and chemical action of natural water is referred to as **corrosion/ solution**. Under natural conditions, chemically pure water does not exist. The extent of corrosion depends much on the composition of rocks and also on the composition of flowing water. Limestone, gypsum and rock salt are easily soluble in water and therefore easily prone to corrosion.

6.8.2. Stream Transportation

The stream load

The material (other than water) transported by a stream is described as its **load**. The amount of material transported past a point during a specified time interval in a stream will be directly proportional to the velocity and the gradient of the stream.

Generally, the load carried by a stream consists of the following three types:

a) Suspended load,
b) Bed load, and
c) Dissolved load.

(a) Suspended load

It is the visible cloud of sediments a stream carries and is made up of fine sand, silt and clay sediments that are light enough to be transported in the stream water in a state of suspension. This load normally remains lifted up in the stream water and are not allowed to touch the base of the channel, due to the eddies caused by turbulence in the flow. The intensity of turbulence in stream water is directly related with the velocity of stream flow. Therefore, any reduction in velocity of stream will accompany settling or deposition of a portion of the suspended load it carries. Most streams carry the major part of their load in suspension. The visible cloud of sediment suspended in the water, during flood times, is the most obvious evidence of a stream's suspended load. Streams are able to transport larger and larger particles in suspension, with increase in velocity and accompanying turbulence during a flood.

(b) Bed load

Bed load is that part of a stream's load transported along its bottom or bed of its channel. This part of load is made up of particles too large or too heavy to be carried in suspension. The quantity and the nature of bed load increases directly with the energy of the stream – that in turn depends on its velocity. The mechanical erosive action of a stream (corrasion and attrition) and the intensity of modification of stream channel depend on the nature and amount of bed load.

Bed load in streams is transported in two ways, the first being **traction**, which involves mostly forward movement through rolling and sliding of particles along the stream bed. The second is **saltation**, a bouncing-like movement. Saltation occurs when particles are temporarily lifted up by eddies and suspended in the stream for a short time during which time they travel a short distance and afterwards fall back onto the bed. Upon impact these particles discharge others to saltate (Fig. 6.13).

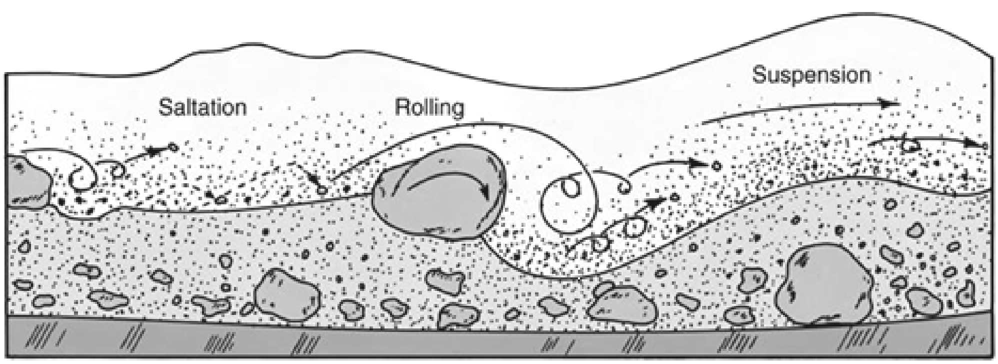


Fig. 6.13: Methods of transport of bedload by streams

Therefore, most of the ***work of streams*** is accomplished during floods in the form of bed scouring (erosion), sediment transport (bed and suspended loads) and sediment deposition.

(c) Dissolved load

The portion of the load carried by a stream as ions in solution is termed its **dissolved load**. The dissolved load in streams comes primarily from groundwater seepage into the stream and also come from the solution (corrosion) of soluble rock materials that line the stream channel.

The figure 6.14 given below represents the characteristics of various processes of transport of load by streams or rivers.

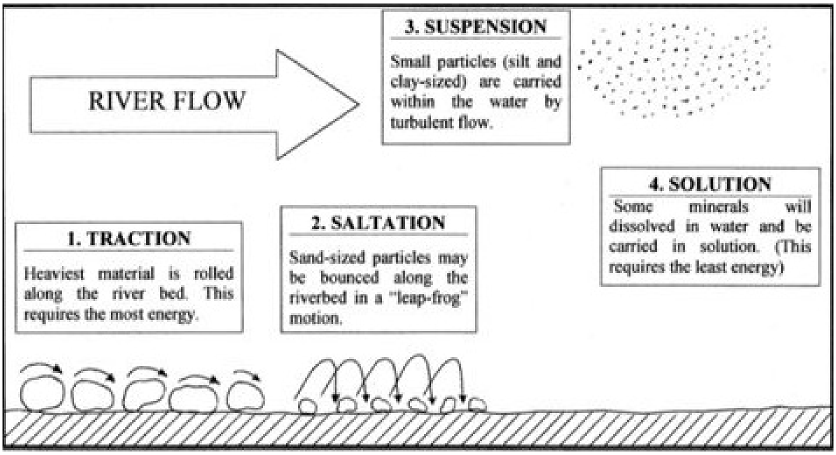


Fig. 6.14: Characteristics of the processes of transport of sediment load by streams and rivers

The amount of material that a stream carries in solution varies with climate and the geologic setting of the region. It is estimated that streams supply almost 4 billion metric tons of dissolved substances to the oceans each year.

Unlike the two types of stream loads noted earlier, the dissolved load of a stream is totally unaffected by any fluctuation in stream velocity. This means that unlike other types of loads, this portion of a stream's load will be transported to the stream's ultimate destination – i.e., ocean or sea.

Check your progress

1. *How does hydraulic action differ from sream abrasion?*
2. *What is meant by capacity of a stream?*
3. *What are the three types of stream load?*

COMPETENCE AND CAPACITY

The ability of a stream to transport its load is determined by two factors: the stream's competence and its capacity.

Stream competence refers to the heaviest particles a stream can carry. It depends on stream velocity. Faster the current, heavier the particles that can be transported by the stream. As stream velocity and discharge increase so do competence and capacity. But it is not a linear relationship (e.g., doubling velocity and discharge do not simply double the competence and capacity). Competence varies as approximately the sixth power of velocity. For example, doubling the velocity results in a 64 times increase in the competence.

The capacity of a stream is the maximum amount of load it is able to carry. It depends on both the discharge and the velocity (since velocity affects the competence and therefore the range of particle sizes that may be transported). Capacity varies as the discharge squared or cubed. So tripling the discharge results in a 9 to 27 times increase in the capacity.

Therefore, most of the work of streams is accomplished during floods when stream velocity and discharge (and therefore competence and capacity) are many times their level during normal flow condition. Note the fact that velocity of flow and discharge (quantity of water flowing) are the two factors that control the quantity and nature of total load (i.e., the capacity of the stream) being transported by a stream.

6.8.3. Stream Deposition

The complementary process of erosion involving settling out, placement or laying down of rock materials transported by a stream is **fluvial deposition**.

A stream’s load is deposited, eroded, and re-deposited many times in a stream channel, with variations associated either with discharge (flood) or velocity (change of slope).

The factors that determine deposition of a stream load are: (1) Reduction in velocity and (2) Reduction in discharge or volume of water. The requirements favouring stream deposition satisfy wherever natural conditions lead to reduction in velocity or reduction in discharge, along the course of a stream. Therefore, in regions where a swift-flowing stream from a mountain enters a foothill zone located in front (where reduction of slope in the long profile of a stream occurs) significant deposition takes place. Similarly, where a stream enters a body of standing body of water (a lake or sea) we can expect large scale deposition of stream load.

Similarly where a swift flowing, sediment-laden, tributary stream enters a slow moving trunk stream, a major portion of its load will be forced to be deposited immediately downstream from its confluence with the master stream.

Variation in discharge along a stream occurs when a stream enters an arid or semi-arid region where stream water is reduced in volume by excessive infiltration and it becomes 'overloaded' and consequently deposits a portion of its load.

Alluvium is a general term for sediment deposited by a stream. The term **fluvial deposit** is also used as a synonym of **alluvium**. As alluvium is transported by water, it is a type of unconsolidated, sedimentary accumulation generally showing sorting and layering. In contrast, colluvium, is the soil or other rock materials transported by mass wasting and associated slope processes. Colluvial materials are unsorted, unstratified, and have a heterogeneous mixture of sizes.

6.9. Landforms of Fluvial Erosion

Streams are regarded as one of the most important agents doing the erosion efficiently. The erosion of stream produces many features. The significant erosional landforms of streams are: (a) Stream valleys, (b) Potholes and (c) Waterfalls.

6.9.1. Stream Valleys

A stream valley can be defined as an elongated depression in the land surface between hills or mountains, formed by erosion of a stream. Stream valley includes valley bottom as well as valley sides.

We have noted earlier that a stream develops initially from rills joining together and forming gullies which in turn combine together to form smaller and larger streams. During the channel flow, a stream shapes and reshapes its channel and associated valleys. Streams and stream processes can be explored from three different perspectives: (1) Vertical, (2) Lateral, and (3) Longitudinal, (Fig. 6.15) and correspondingly the evolution and transformation of a stream valley can be described in terms of the following

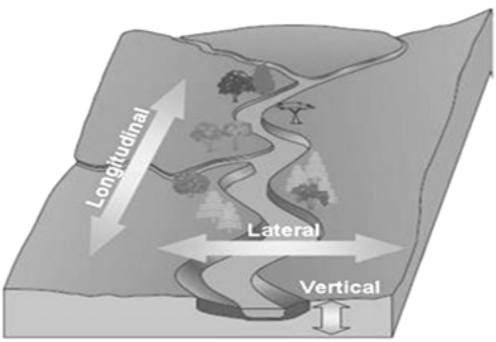


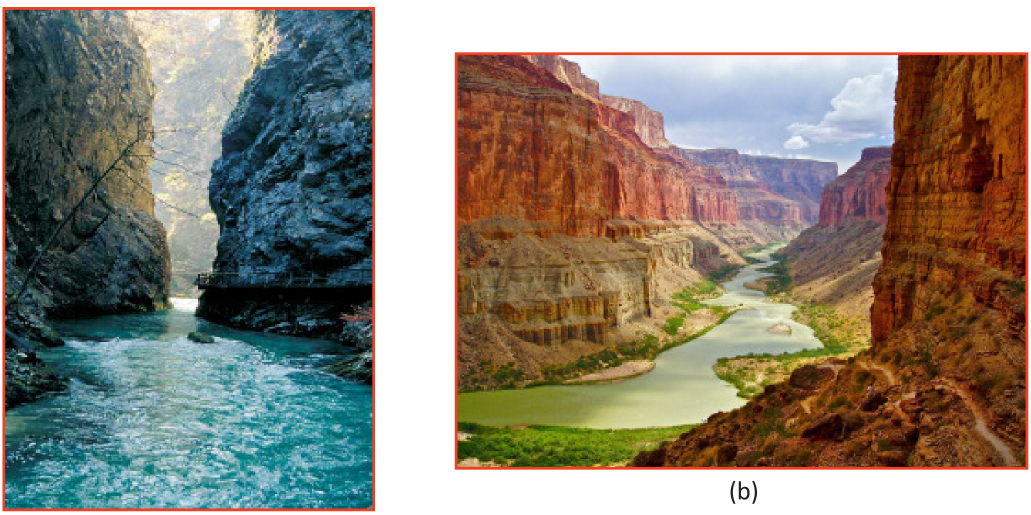
Fig. 6.15: Three different perspectives of studying streams and stream processes

processes: (a) Valley deepening (b) Valley widening and (c) Valley lengthening.

a) Valley Deepening

Valley deepening is achieved by down-cutting of the stream bed or stream floor. Recall that corrasion is largely responsible for the ability of the streams to deepen their channels and associated valleys. In the early stages of valley development almost the entire energy of the stream will be used for down-cutting of its channel. Down-cutting will not proceed indefinitely. There is a lower limit, technically known as the **base level of fluvial erosion**. We can define the term base level of stream erosion as the lowest level to which a land surface can be eroded by a stream. It is an imaginary surface extending underneath the continents from sea level (except in special circumstances, which will be discussed in another section).

Continuous down-cutting of a stream channel gives rise to a deep and narrow valley, with steep or vertical walls known as **gorges** or **canyons** (Fig. 6.16).



(a) (b)

Fig. 6.16: (a) Gorge and (b) Canyon

b) Valley Widening

As the down-cutting process progresses and the stream channel approaches the base level, the process of valley widening begins. The valley widening is achieved by the combined action of the processes, such as (1) Weathering and (2) Slope processes (down-slope erosion by overland flow, splash erosion, and mass wasting). Fig. 6.17 depicts a schematic diagram of the process of valley widening.

Down-cutting will expose fresh rock surfaces, which will in turn be attacked by various weathering processes (the preparation of rock materials for the next process of erosion). The operation of various slope processes continuously supplies rock materials from both sides of the stream valley to the stream channel, and the stream transports the materials downstream. As you can imagine, the result will be widening of associated stream valleys.

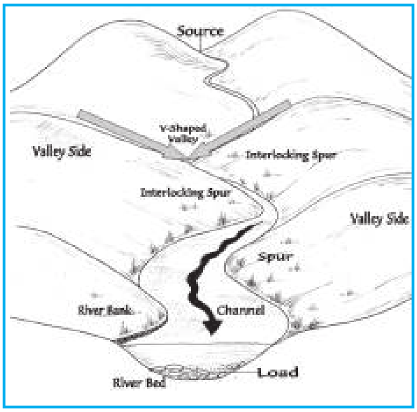


Fig. 6.17: Schematic diagram of the process of valley widening

Lateral Planation

The process of reduction of the land in inter-stream areas to a plane by the lateral erosion of streams is called **lateral planation**. This is achieved by horizontal or lateral migration of a stream channel against its banks. A stream reach will start the process of lateral cutting and creation of a planation surface immediately after achieving a graded condition. Through this process the valley wall will laterally retreat by the development of meanders. The process of lateral planation plays a significant role in widening the valleys of streams along with other slope processes.

c) Valley lengthening

Valley lengthening usually takes place by the process of headward erosion. The presence of resistant rocks influences the lengthening process.

Thus in short, stream valleys grow, with the passage of time, by the processes of deepening, widening and lengthening.

6.9.2. Potholes

These are circular or cylindrical depressions formed in stream channels which are devoid of any alluvial cover (rocky stream beds). Potholes are generally found in the upper reaches of streams, where the streams traverse bedrocks and possess higher energy. Potholes range in size from a few centimetres to many metres in diameter as well as in depth (Fig. 6.18).

Fig. 6.18: Potholes developed in stream channels

6.9.3. Waterfalls

Running water in the form of streams always erodes rocks, but some rocks are more resistant than others. So, a waterfall occurs where a sudden change in erodibility of rock types or a steepening of a gradient occurs along a stream course. The stream plunges down over the resistant rock bed as a waterfall (Fig. 6.19). The height of waterfalls greatly varies and ranges from a few to many metres. In due course of time a waterfall gradually migrates in the headward direction. A depression formed by excessive erosion in front of a waterfall, where the plunging water strikes the stream channel, is termed a **plunge pool**. A series of successive miniature waterfalls in a stream course are referred to as **rapids** and **cascades**.

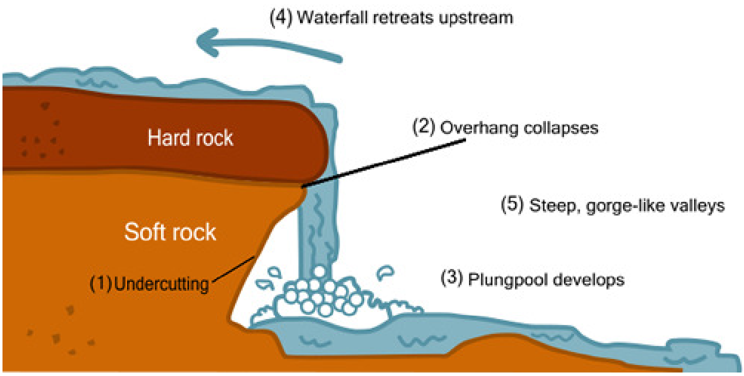


Fig. 6.19: Waterfall

Kunchikal falls of Karnataka, where Varahi River cascades down in the form of a waterfall and having a total height of 455 metres, is the highest waterfall in India. Meenmutty Waterfalls, a three-tiered waterfall of Wayanad District of Kerala, with a height of 300 metres, is considered to be the highest one in Kerala.

Check your progress

1. *What are the erosional processes that actively change a stream valley?*
2. *Name a feature that is formed by differential erosion of the bed rocks by a stream.*
3. *What is the term applied for the cylindrical depressions found excavated along the rock beds of a stream channel?*

6.10. Fluvial Depositional Landforms

Many different depositional features are formed by fluvial action. Some of the common landforms of this category are briefly described in this section. Deposition, in many forms, occurs in streams throughout their courses. However, small scale depositional features are ignored in the following discussion. The most important landforms produced by stream deposition are described below:

6.10.1. Alluvial Fans

When a steep mountain stream enters a flat valley, there is a sudden decrease in gradient in stream channel. This means that there is reduction in stream velocity, and consequent reduction in energy. Consequently, a major share of the sediments transported by the stream will suddenly get deposited in front of the valley. These deposits generally resemble an open Japanese fan, when viewed from above, and are therefore known as **alluvial fans** (Fig. 6.20). Deposits of this type with significant height and steepness of slope are termed **alluvial cones**.

Fig. 6.20: Alluvial Fan

6.10.2. Piedmont Alluvial Plain

A plain is a level or gently sloping flat or a slightly undulating land surface of considerable areal extent. Some plains originate on the surface of the Earth by aggradational processes while others by degradational processes. An aggradational plain formed in front of a mountain chain and resulting by lateral coalescence of a number of adjacent alluvial fans is called a piedmont alluvial plain. The best known alluvial plain of this type is the Indo-Gangetic Plains that border the Himalayan Mountains in North India.

6.10.3. Stream Channel Deposits

A stream deposit consisting of sand or gravel deposited in the center of the channel is called a bar deposit. These form when the stream's velocity or discharge decreases and its bedload is dropped. Bar deposits are generally found associated with braided streams.

6.10.4. Floodplain Deposits

Floodplain can be defined as a flat land area adjacent to a stream, composed of unconsolidated alluvium. It is that portion of a stream valley which is readily submerged under water during floods. Floodplains are produced by the process of *lateral planation* of a stream and by overbank deposition; therefore floodplains are absent in other portions of a stream course (Fig. 6.21).

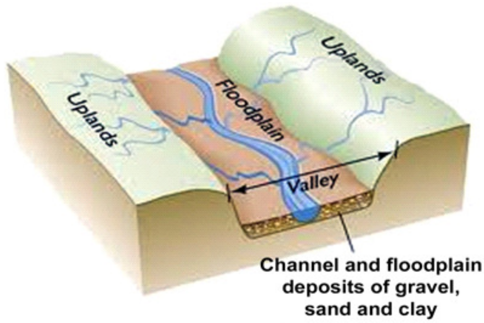


Fig. 6.21: Floodplain of a stream and associated features

Flood plains are extremely fertile tracts as these seasonally acquire layer over layer alluvial silt and clay. Because of this reason, floodplains formed ideal choice for early settlements throughout the world- although there were occasional threats of hazards of floods.

6.10.5. Depositional Features Associated with Stream Meandering

The broad sweeping curves found along the course of a stream channel are called **meanders** (Fig. 6.22). The process of development of such channels is called **meandering.**

Fig. 6.22: A stream meander

Meanders are developed mostly in the middle and lower reaches of larger streams (i.e., in alluvial valleys). The formation of meanders involves both the processes of erosion as well as deposition (Fig. 6.23).

In stream bends, the water flowing along the convex side will cause erosion of alluvium while that of the concave side results in deposition. This is because of the relative difference in stream velocity in the respective sides of the stream bend. The net result is that, with the passage of time, the outer curves of the stream are progressively eroded and the inner curves are little by little built up (as shown in various stages from A to

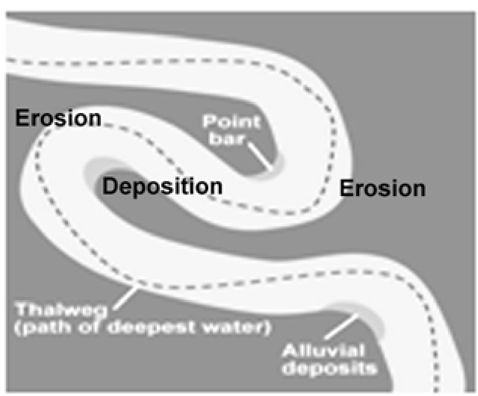


Fig. 6.23: Formation of meanders involving both the processes of erosion as well as deposition

D in the Fig. 6.24). The depositional features, made up of sand and gravel, accumulating on the inside stream bend (concave sides) are known as **point bars**.

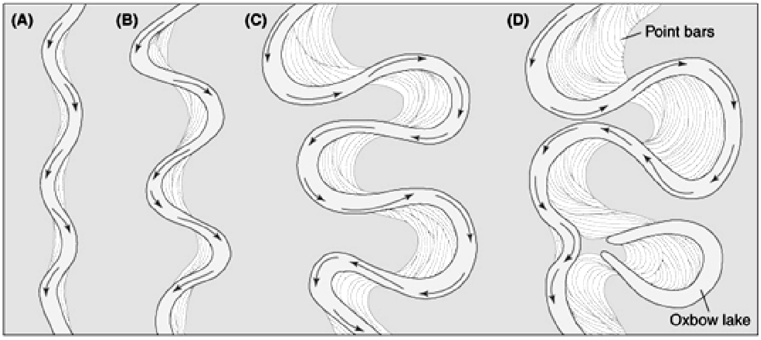


Fig. 6.24: Growth of meanders and development of oxbow lakes

(a) Oxbow Lake

During times of flood, in stream reaches with meanders, when the stream acquires greater discharge, it cuts across a meander loop, shortening and straightening its course. The event results in leaving an isolated loop of stream channel on the side completely detached (free-standing body of water or stream segments). These isolated horse-shoe or crescent-shaped water bodies, exclusively formed in stream flood plains, are termed **oxbow lakes**.

(b) Natural Levees

Natural levees are narrow ridges of alluvium, formed along both sides of relatively wider stream channels. During floods, when a stream overflows its banks, the interaction between swift flowing portion of deep water of the central channel and slow moving shallow water of the adjoining flood plains results in deposition of stream load along linear zones of interaction. Successive floods over many years build up ridges or **natural levees** (Fig. 6.25) on both sides of the stream channel. In many parts of the world these provide protective grounds for men and animals during flood. These fluvial depositional features are described as 'natural' to distinguish such artificial embankments constructed

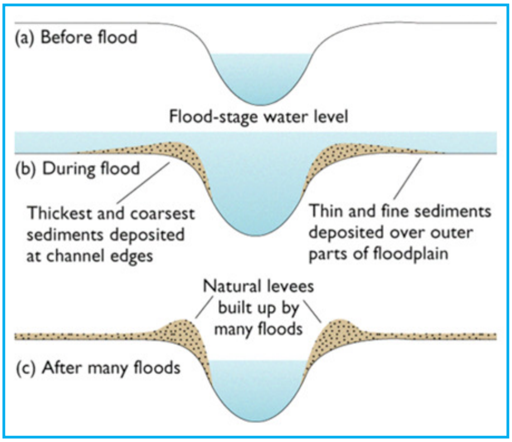


Fig. 6.25: Development of natural levees

on both sides of streams for preventing flood waters inundating and damaging neighbouring urban settlements.

(c) Delta

A **delta** is a fluvial landform that is roughly triangular in shape formed at the mouth of a stream where it enters a sea (Fig. 6.26). When a stream enters a standing body of water such as a lake or ocean, there is a gradual reduction in its velocity and consequently deposition of its load takes place. Much of its load, except the dissolved ones, are progressively deposited with increasing reduction in its velocity. The coarser and heavier materials are laid down first and the finer and lighter materials are carried further out.

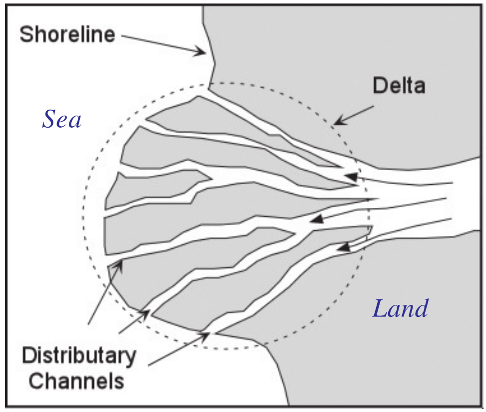


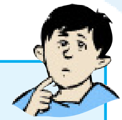
Fig. 6.26: Delta

When a stream enters its delta, the main channel often divides and subdivides into several smaller ever changing channels (distributaries). Unlike tributaries, which carry water into the main channel, distributaries carry water away from it. The name **delta** is given to these fluvial landforms in allusion to their triangular shape resembling the Greek letter delta **(Δ)**. However, except the Nile delta, not all deltas have this idealized shape. Differences in the shapes of shorelines and variations in the strength of waves and currents result in variation in shape of deltas from the ideal triangular form. River mouths lacking deltas are known as **estuaries**. All the river mouths of our state Kerala are of this type.

Examples of major deltas of the world include the Nile delta, Indus delta, Mississipi River delta, Ganges delta, Brahmaputra delta (Sunderbans), etc.

Let us do

1. *Prepare an album showing the various erosional and depositional landforms found associated with fluvial action.*
2. *Trace the course of a river from its head to mouth using 'Google Earth map' and find out the various features formed by the geological activity of streams.*



Check your progress

1. *Where do you expect the development of distributaries in a stream channel?*
2. *How are meanders developed?*
3. *What are natural levees?*

6.11. The Concept of Base Level

You are now aware that streams can erode the land and make landforms of various types like valleys, canyons etc. Can you say up to what level a stream can erode?

Base level is a key concept in the study of stream erosion. *The base level of erosion of a stream is defined as the lowest level up to which the stream can lower its channel*. As a stream flows down and erodes its channel, it is constantly attempting to lower the channel bottom to its base level. Generally, the sea level is considered as the **ultimate base level of fluvial erosion.**

For tributaries the level at which the tributary joins the master stream constitutes the base level of erosion for the particular tributary. Therefore, it follows that a tributary can lower its channel *only if* the level of its confluence with the main stream is lowered by erosion taking place in the stream valley into which it flows. These types of base levels are termed **local base levels**. Likewise, construction of a dam and associated reservoirs create a local base level in a drainage basin which will be effective in controlling down cutting of the stream valley beyond the dam site. Because of this reason, higher reaches of a stream beyond the dam will be temporarily (geologically speaking) prevented from further down cutting of its channel. The surface of a lake water likewise forms the local base level for an inflowing stream, as its energy becomes totally insufficient to downcut and its velocity becomes nearly zero when it enters that standing body of water. A variety of local base levels are possible in a drainage basin and all these are temporary base levels in the geological sense. However, even the ultimate base level is not a stationary one as world-wide changes of mean sea level influence it. All the streams erode towards the sea level which is also known as the **ultimate base level**. If a stream is dammed, a new base level (the level of the reservoir) replaces the ultimate base level. As a result, deposition of sediments consequent to reduction in velocity of the stream takes place.

A stream flowing into a lake cannot erode deeper than the lake because it would then have to flow uphill into the lake. Eventually, the outflow channel from the lake may erode away the local base level and the lake will vanish.

The top of the waterfall also acts as a local base level. The channel below the waterfall undercuts the resistant rock, causing the waterfall to retreat upstream. Eventually, the waterfall will completely erode away.

Creation of local base levels consequent to dam construction and subsequent silting up of the reservoirs reducing the expected life-span of the intended reservoir is a serious problem in dams built in mountainous areas.

THE LONG PROFILE AND GRADED PROFILE

The long profile of a stream shows how the gradient of a stream changes as it flows from its source to its mouth. The long profile of a stream is a graph drawn along the course of a stream from the source to the mouth. The study of streams' long profiles shows that they have a concave shape, with a steeper upper reach and a gentler, or flatter lower reach towards its base level. A sketch of a long profile of a stream would look something like that as shown in the figure 6.27.

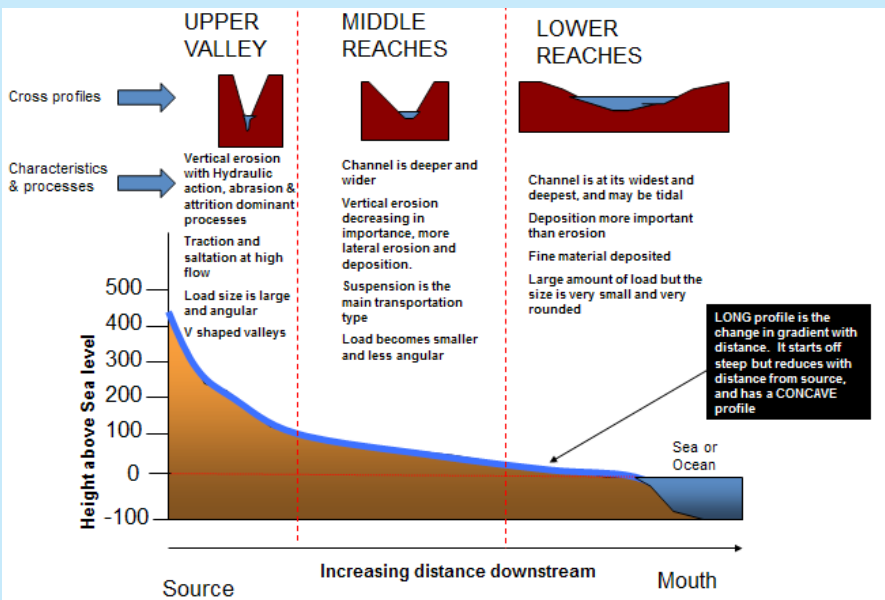


Fig. 6.27: Sketch of the long profile of a stream

A point of significant or abrupt change in the gradient in a long profile of a stream is termed a **knick-point**. These generally mark the location of relatively more resistant rocks along the course of a stream. Waterfalls and rapids occur at such locations (knick-points).

You should carefully note the associated changes of the cross profile (transverse section) of a stream valley in its upper, middle and lower reaches in the diagram shown above.

When the deposition and erosion are balanced throughout the long profile of a stream, i.e., in dynamic equilibrium condition, when inputs (the amount of rock materials received) and outputs (the amount of rock materials removed in transportation) are balanced, the long profile of streams would become a smooth, concave upward profile. At this stage, all the irregularities of the stream channel would be eliminated. A stream that has reached such a stage is said to have achieved a 'graded condition' and the corresponding long profile is termed 'graded profile'. It would take a long time for a stream's long profile to become a graded profile. Therefore, the idea of a graded profile is, essentially, theoretical one, as it doesn't really occur in nature.

6.12. Stages in the Evolution of Stream Valleys

We can identify three major stages in the development of stream valleys. These can be named as: (1) Youthful stage, (2) Mature stage and 3) Old stage (Fig. 6.28).

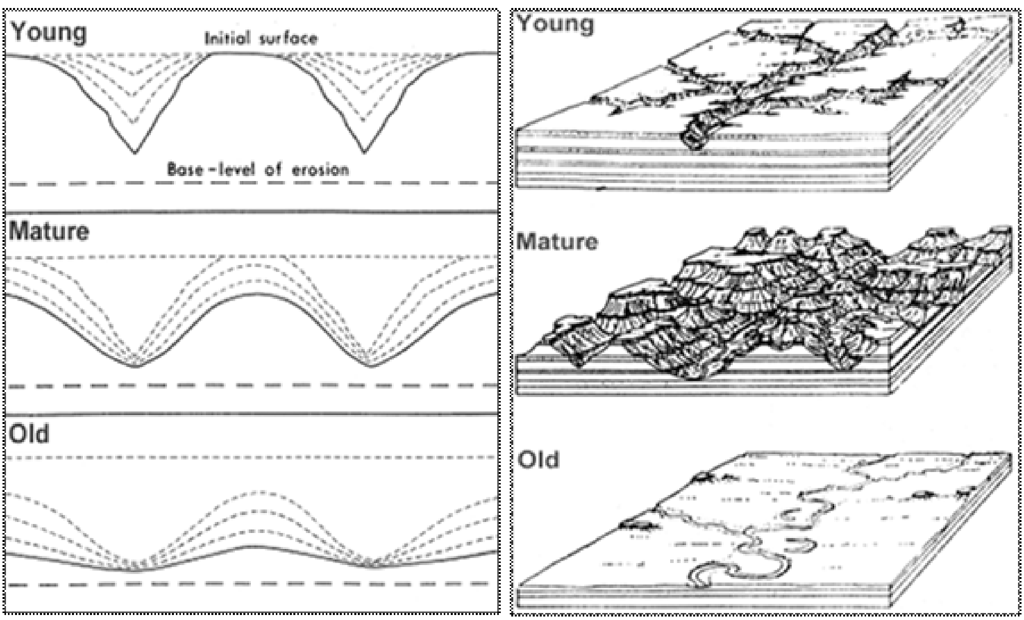


Fig. 6.28: Youth, mature and old stages in the evolution of stream valleys

6.12.1. The Youthful Stage

At this stage, a stream will be flowing through valleys with characteristically vertical or nearly vertical sides (canyons or gorges) and the stream will be moving in turbulence and torrents often with roaring noise and with very high velocity. All the energy of the stream will be used up in downcutting of the channel floor, and therefore these valleys will be devoid of any significant features indicative of aggradation. The associated channels will be either rocky with numerous potholes or consist of coarser rock fragments such as boulders, cobbles etc. and the long profile of youthful valleys will be characterized by the presence of irregularities in the form of waterfalls, rapids and cascades. The stream reaches of mountainous regions, such as our Western Ghats, display the features of youthful stage of valley development.

6.12.2. The Mature Stage

Immediately after the youthful stage, the stream valleys undergo progressive widening of their valleys. We have already learnt that this is achieved by the combined action of various slope processes and channel erosion. Thus the cross sections of the initially valleys which were initially nearly vertical and steep sided, gradually get transformed into a V-shaped cross section.

Stream valleys associated with stream reaches that have attained a graded condition, will be described as attained a mature stage. Stream channels of mature stream valleys will commence the process of meandering and associated lateral planation - the processes that create wider valleys. The mature stream valleys in advanced stage will be characterized by a wide plain with meanders, oxbow lakes, and natural levees.

6.12.3. The Old Stage

During the old age stage, a stream valley will be acquiring the widest flood plain possible. The intervening divides will be slowly reduced by a variety of slope processes and the channel floor will be almost at or close to the controlling regional base level. Increased number of oxbow lakes and meander bends will be common features at this stage.

Check your progress

1. *What is the lowest elevation that any stream can erode its channel?*
2. *Give examples of various types of base levels along a stream course.*
3. *What are the characteristic features developed in youth, mature and old stages in the development of stream valleys?*

STAGES OF EVOLUTION OF REGIONS OF FLUVIAL DENUDATION

We have already noted the fact that much of the continental surfaces are acted upon by the fluvial processes rather than by processes associated with any other agent (wind, glacier etc). A large number of careful studies of landscapes associated with fluvial action have shown that such regions evolve from an initial stage and pass through a series of sequential stages and finally reach an ultimate stage. The concept of the initial stage is not a simple one. It is largely hypothetical. However, if we collect a large number of photographs of landscapes associated with fluvial action, these can be arranged in a logical sequence of increasing intensity of land dissection and such a sequence will give some idea about the general course of evolution of a region undergoing fluvial degradation. During the course of our study we have noted that the transverse sections of the stream valleys are initially steep and vertical (canyon or gorge like) but during the course of their further evolution they are transformed into V-shaped and subsequently into U-shaped forms. Likewise, we have also learnt that during the evolution of stream valleys the long profile of a stream will be gradually modified, removing all irregularities (waterfalls, rapids, etc) into a smooth concave curve steeper at the source and gentler towards the mouth.

Along with the transformations taking place in the stream valleys, the associated landscapes will also undergo significant transformations. Geologists subdivide the course of evolution of regions undergoing fluvial degradation into three stages: (1) Youthful, (2) Mature, and (3) Old age. During the maturity, the relief of the landscape will be the maximum. If you assume that there are no interruptions in the course of landscape evolution which will take several millions of years, the last one will terminate with the ultimate stage we have noted earlier. The common types of interruptions include, changes of base level (which may be either positive or negative), regional climatic change (which will affect the amount of precipitation), tectonic disturbances affecting the region and so on. The ultimate stage, which is also a theoretical concept, will be characterized by a landscape reduced down to the regional base level and the resulting surface of degradation is termed a peneplain. A peneplain is a gently undulating, almost featureless plain, that in principle, would be produced by fluvial erosion, which in the course of geologic time, would reduce the land almost to base level (sea level), leaving so little gradient that essentially no more erosion could occur. The peneplain concept was named in 1889 by William M. Davis. When this stage is attained any isolated remnants of hard rocks, found projecting above the general surface of the peneplains are called monadnocks.

A specific landform associated with a region that passes through various stages of fluvial dissection, without any interruption is generally described as monocyclic. However, such landforms are rare in nature and in fact most of the regions undergoing fluvial dissection are polycyclic consisting of landforms produced and modified by more than one cycles, i.e., the landscape associated with an incomplete cycle will constitute an initial stage during the commencement of the next cycle of erosion. Geologists can identify the details regarding such polycyclic landforms by careful studies of fluvial landscapes.

Let us sum up

If the amount of water falling on the ground is greater than the infiltration rate of the surface, runoff or overland flow will occur. Runoff specifically refers to the water leaving an area of drainage and flowing across the land surface to points of lower elevation. Accumulating water causes a thin layer of water to form. This water layer begins to move down slope because of gravity. Flowing water accumulates into larger depressions on the ground surface. Depressions fill up and overflow forming small rills. Rills join to form larger streams and rivers.

Surface bodies of water flowing in channels of their own are called streams. Streams and rivers flow until they eventually empty into lakes or oceans. Streams are very important features on the surface of the earth. The entire area drained by a stream is known as drainage basin.

Geological work of streams takes place through the three main processes namely erosion, transportation and deposition. In between the life span of a stream, several erosional and depositional landforms (fluvial landforms) are created. Streams play an important role in the modification of earth's surface.

Stream erosion involves the following methods: Hydraulic action, Abrasion/Corrasion, Attrition and Corrosion/solution. Many erosional landforms produced by the stream include stream valley, gorges / canyons, potholes, waterfalls, etc. Streams carry materials in three ways as suspended load, bed load and dissolved load.

Stream deposits are mainly known as fluvial deposits. Major stream depositional landforms are deltas. Other landforms include meandering, oxbow lake, etc.

Stream has three stages of evolution viz., Youth, Mature and Old age. The lowest level up to which a stream can erode is known as the Base level of erosion.

Significant Learning Outcomes

The learner can:

- identify that streams are one of the main agents that change the morphology of the earth's surface.
- explain the different geological landforms created by streams and rivers.
- explain the geological activity of streams.
- distinguish between the erosional and depositional features formed by streams.

Let us assess

1. Complete the table of fluvial process.

Landform	Process	Stage
Valley	....	Youthful
....	Deposition	Old stage

2. Name the following:
   a) Triangular shaped deposits found at the mouth of the stream.
   b) Circular or cylindrical depressions found excavated along the rock beds of a stream.
   c) The streams that contain water only during rainy season.
   d) The process of lifting and moving of loose particles by the force of flowing water.

3. No delta is formed at the stream mouths of Kerala. Why?
4. How does a stream modify the existing topography of a region?
5. Stream valleys in mountainous regions are deep, compared to their lower reaches. Why?
6. List out the various fluvial erosional and depositional landforms.
7. Match the following.

A	B	C
Gorges	Circular shape	Deep and narrow valleys
Delta	V shape	Depressions on channels
Pot holes	Triangular shape	Fluvial deposits at the stream mouth

8. Briefly describe the three ways by which streams transport sediments.

7 WIND

7.1. Introduction

Moving air masses are known as winds. You have already learnt in unit 3 that, wind is one of the active agents of erosion. The geological action (erosion, transportation and deposition) of wind is prominently visible in arid and semi arid regions and along some sea shores, which are regions unprotected by vegetation favouring the free play of wind.

Winds form due to non-uniform heating of the surface of the earth leading to local differences in atmospheric pressure. The pressure differences thus created make the air to move from regions of higher pressure to those of lower pressure, in the form of winds. Under favourable conditions, such movements of air in the form of winds are capable of producing significant changes of the land surfaces. The geologic processes associated with wind action as well as its products and the landforms created are generally described in geology using the adjectival term **aeolian** (also spelled **eolian**), after the Greek God *Aeolus*, keeper of wind.

7.2. Geological Activity of Wind

The geological action of wind, as in the case of other geological agents, such as running water, glaciers and so on, consists primarily of erosion, transportation and deposition of rock materials on the surface of the earth. During these processes, a variety of landforms are produced. These landforms, which are grouped under the term **aeolian landforms**, as you will learn in subsequent sections, are unique and distinct from those formed by the action of other geological agents.

7.2.1. Wind Erosion

We are all familiar with the blowing away of dust particles by wind wherever loose rock materials are found exposed and unprotected by a cover of some sort of vegetation. Wind, as an agent of erosion, is relatively less effective globally than running water (mostly streams). However, in arid and semi arid regions, it does play an important role, in eroding and transporting earth materials. Strong winds blowing over ground covered with loose materials such as dry soils or in the deserts, are capable of transporting enormous amounts of loose rock materials (sand, silt and clay particles) from one place to another.

The erosional processes associated with wind action or aeolian erosion consists of the following processes.

a) Deflation

b) Abrasion

c) Attrition

Let us learn more about these aeolian processes.

(a) Deflation

The process of removal of loose, fine-grained particles by the turbulent eddy action of wind is termed deflation. When moving with sufficient velocity over dry and loose sands or bare ground or dust, wind can remove or sweep away huge quantities of loose materials from the earth's surface. Deflation is the main process of wind erosion in desert regions. Arid regions have little or no soil moisture to hold rock and mineral fragments. Deserts or arid regions are areas where rainfall is less than 250 mm per year while semi arid regions receive 250 to 500 millimeters of rainfall per year.

In extensive regions of deserts that experience intense and sustained erosion by the process of deflation, the altitudes of the ground surface gradually decrease with time. These kinds of lowering produce landforms such as *deflation hollows*, *deflation basins*, *blowouts*, etc.

(b) Abrasion

The process of mechanical wearing down of rock surfaces by the grinding or sand blasting actions of wind-borne particles is termed aeolian abrasion. Wind becomes a powerful agent of erosion when it is naturally loaded with coarse or fine sand particles. The difference between the process of deflation and aeolian abrasion is that in the former process there are no tools involved and erosion is done by the inherent energy of the wind itself while in the latter the erosion is achieved by the tools carried by the wind.

In general, during the times of desert winds, the rock particles, forming the tools for abrasion, are found concentrated mostly within 50 cm above the desert surface. As in the case of a sand paper, the frequently blowing winds that are armed with sand grains bring about wear and tear of the exposed desert rocks. The efficiency of the process of aeolian abrasion is dependent chiefly on factors such as the velocity of the blowing wind, the resistance of the attacked rocks and the nature of rock particles (size and shape) forming the tools, as well as the frequency of collision (i.e., the frequency of winds).

(c) Attrition

In wind action, the sand grains and other rock particles lifted up from the ground from different places are transported to considerable distances from their source regions. During such journeys, because of turbulence within the moving mass of air, the particles do not move in straight and parallel paths. The grains carried by winds continuously collide with one another and rub each other during their transit. These kinds of repeated collisions of grains cause their continuous wear and tear. This process is called **attrition**. Apart from bringing about a reduction in size of the particles, the process of attrition removes irregularities of the surfaces of grains and ultimately makes them rounded or nearly spherical in shapes.

7.2.2. Aeolian Transportation

The mode of transportation of rock particles in wind action are (a) suspension, (b) saltation, and (c) traction.

(a) Suspension

The relatively lighter clay and silt particles are lifted from the ground by eddies of the turbulent wind and carried high up into the atmosphere and may travel for long distances. Normally, fine particles, once taken in suspension and raised up, are not allowed to immediately settle down on to the ground, because the intensity of air turbulence rapidly increases with altitude.

(b) Saltation

It is the net forward movement of the particles by successive leaps or jumps (just as some particles of the bed load of streams). Saltating grains of sand, driven by wind, are highly effective abrasives in eroding rock surfaces. Some evidences of the effects of saltating grains are provided by fence posts and telephone poles of the desert and arid regions that abraded near the

Fig. 7.1: Bedrock cliffs with notch along the base as evidences of the process of saltation by wind

ground level, and by bedrock cliffs with a small notch along their base (Fig. 7.1).

(c) Traction

Coarser rock particles larger than sand grains (pebbles and cobbles) may be moved forward by the process of rolling or dragging along the ground. Such movement of the particle along the ground is known as traction.

Check your progress

1. *What is meant by aeolian process?*
2. *In which locations on the earth's surface, does wind act as a means of erosion, transportation and deposition of rock materials?*
3. *In which method of sediment transport by wind, grains hop and bounce along in small jumps?*

7.2.3. Erosional features formed by wind

The common features associated with wind erosion are briefly described below.

(a) Deflation hollows

You have already noted the fact that deflation is the main process of wind erosion in desert and semi arid regions. Continuous deflation ultimately lowers extensive areas of the ground surface of the desert, and creates topographic depressions of varied dimensions. Relatively smaller depressions thus formed are called **deflation hollows** while the larger ones are known as **deflation basins**. **Blowouts** are the smallest type of deflation basins scooped out in soft unconsolidated deposits. The deflation basins range from a few meters to several kilometres in diameter.

Water table acts as the ***base level of deflation process or wind action***. Once the bottom of the deflation basin encounters the local water table, **oasis** is formed, and such a condition favours the growth of localized and scattered spots of vegetation in arid and semi-arid regions. An **oasis** is an isolated

Fig. 7.2: Oasis in a desert

area of vegetation in a desert, typically surrounding a spring or similar water source (Fig. 7.2).

(b) Mushroom Rocks

The term mushroom rocks are applied for isolated rocks in which their basal portions have been partially undercut by the abrasion carried out by windblown sands (Fig. 7.3). They are also known as pedestal rocks. Mushroom rocks are rock masses of varied sizes but all of them remotely resemble mushrooms and are characterized with slender supporting rock stems.

Fig. 7.3: Typical mushroom rock

(c) Ventifacts

The abrasion of wind develops one or more flat and polished surfaces on rock fragments. Ventifacts are stones of any size that have been abraded, shaped or faceted by wind-blown sediment. The term 'ventifact' is derived from the Latin word meaning 'wind-made' (Fig. 7.4).

Fig. 7.4: Ventifact

(d) Desert Pavement

Desert surfaces that are covered only with angular, interlocking fragments of pebbles, gravel, or boulders are called desert pavements. Desert pavement forms on level or gently sloping desert regions. They are products of deflation in regions composed of a heterogeneous mixture of loose rock materials with varied sizes and shapes. The finer rock particles are selectively removed during the course of time, leaving behind the larger ones (Fig. 7.5).

Check your progress

1. *Deflation is the removal of fine sediment by wind. What are the characteristic features developed by wind deflation?*
2. *Removal of fine sediment by deflation may also leave behind a surface of boulders, cobbles and pebbles. What is it called?*
3. *What is the name given to a rock fragment or stone that gets abraded by wind and becomes polished and faceted?*

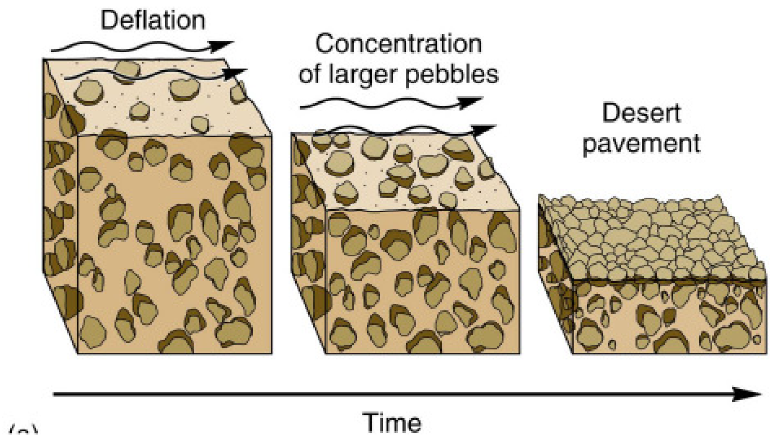


Fig. 7.5: Diagrammatic representation of the process of formation of desert pavement by deflation

7.2.4. Aeolian Deposition

Whenever wind velocity is reduced, the wind loses its ability to transport sand and dust, and then deposits the material carried by it. Various types of landforms are formed by aeolian deposition, depending on the size of the particles carried, the presence or absence of vegetation in the region, the constancy of wind direction, and the amount of material available for movement by wind.

The important types of wind deposits are **loess** and **sand dunes**. Various forms of aeolian deposits and their associated landforms are briefly described further below.

(a) Loess

The finest particles of dust, travelling by suspension in wind, are transported to considerable distances from their sources and ultimately get deposited. When these settle down, sheet or blanket-like aeolian deposits (consisting exclusively of very fine particles like silt and clay) are produced. These aeolian deposits are typically unconsolidated, unstratified and porous. These are known as ***loess***. The thickness of such deposits may vary from a few centimeters to several tens of meters. Soils developed on loess are rich in nutrients and suitable for several types of crops.

Extensive deposits of loess occur in some parts of China, Europe and America. The Yellow River of China gets its name from its characteristic yellow colour resulting from a large supply of suspended sediments derived from loess.

(b) Sand Dunes

Sand dunes are conical or asymmetrical mounds or ridges of sand deposits created by the action of wind. Sand dunes form when there is (i) a ready supply of sand, (ii) a steady wind, and (iii) some kind of obstacle such as vegetation, rocks, or fences, or even a pre-existing sand heap to trap some of the wind-blown sand. Sand dunes form when moving air slows down on the downwind side of any of those obstacles mentioned above. The sand grains drop out and form a tiny mound that grows into a dune in due course of time (Fig. 7.6).

A typical dune is characterized with a gentle (5-15^o) **windward face** or up-wind face and a steep (usually up to 30^o) **leeward face** or down-wind face. The latter face is also known as the **slip face** (Fig. 7.6). Some dunes are only a few meters in height but others reach tremendous sizes. Dunes may cover large areas in arid regions and reach heights up to 500m.

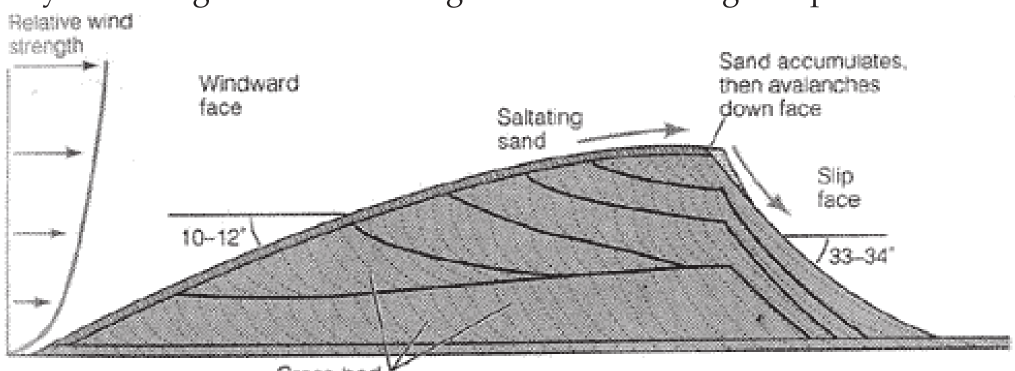


Fig. 7.6: Morphology of a dune

Dunes are not stationary features, they migrate by erosion of sand by wind (saltation) on the gentle upwind slope, and deposition and sliding on the slip face (Fig. 7.7). Coastal sand dunes are common in different parts of the world. These are natural structures which protect the coastal environment by absorbing energy from wind, tide and wave action.

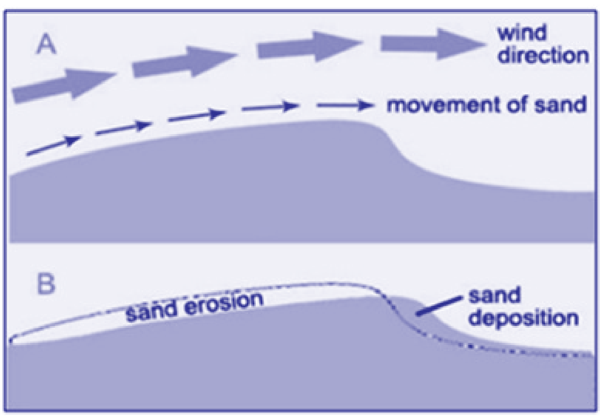


Fig. 7.7: Process of migration of a dune

Types of Dunes

Geologists have recognized different types of dunes based on their geometric shape. The principal types of dunes are barchans, longitudinal dunes, transverse dunes, parabolic dunes, etc.

(i) Barchans

Crescent-shaped dunes with the points of the crescents pointing in the downwind direction, and a curved slip face on the downwind side of the dune, are called barchans. Note that the convex side of these dunes will be directed towards the windward side and the tapering horns of the crescent point towards the direction of flow of wind - in other words, they are concave in direction opposite to that of the blowing wind (leeward side) (Fig. 7.8). Barchans grow to heights as great as 30m and widths up to 350 m. The figure 7.9 shows a typical barchan dune *in plan*. They form in areas where there is a hard ground surface, a moderate supply of sand, and a constant wind direction.

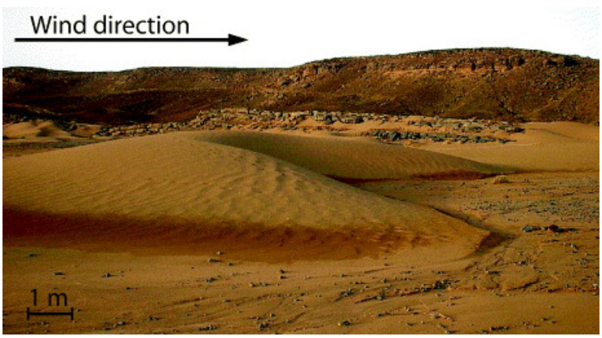


Fig. 7.8: Barchan dune in a desert field

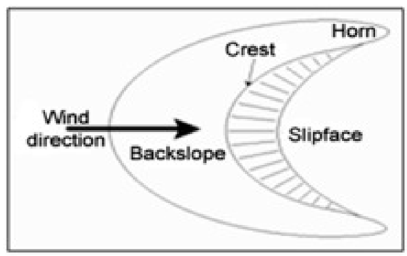


Fig. 7.9: Plan view of a typical barchan dune

(ii) Parabolic Dunes

In plan view, parabolic dunes are U-shaped or V-shaped sand dunes with convex noses trailed by elongated arms. Their horns point towards the upwind direction, i.e. towards the direction of the source of the blowing wind (Fig. 7.10). They commonly form in the coastal tracts covered with vegetation where there is a constant wind direction, and an abundant sand supply.

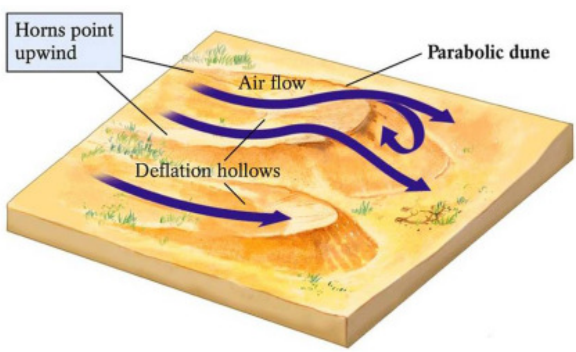


Fig. 7.10: Parabolic dunes

(iii) Longitudinal Dunes

Longitudinal dunes are long, straight dunes which are parallel to the wind direction. They form in areas where the sand supply is moderate and winds usually blow from the same general direction (Fig. 7.11).

(iv) Transverse Dunes

Transverse dunes are dunes that form perpendicular to the prevailing wind (Fig. 7.12). These form where sediment supply is abundant and the wind blows in constant direction**.**

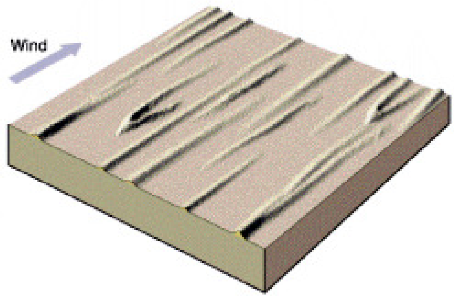


Fig. 7.11: Longitudinal dune

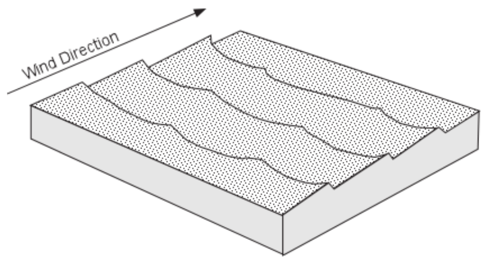


Fig. 7.12: Transverse dune

Check your progress

1. *Distinguish between longitudinal dunes and transverse dunes.*
2. *Where does the sand come from that forms a sand dune?*
3. *How rapidly does a sand dune move or migrate?*

Let us do

1. *Prepare a list of places where wind acts as a powerful geological agent?*
2. *Make a chart showing various erosional and depositional landforms developed by aeolian action.*

Let us sum up

Moving mass of air is known as wind. It is an important geological agent. Wind action is prominent in arid regions without vegetation and in coastal plains. Winds have created distinct landforms -notably differing from those created by other geological agents.
Geological activity of wind is mainly through erosion, transportation and deposition. Deflation, abrasion and attrition are the different modes of wind erosion. Wind transports its load mainly by three different processes: suspension, saltation and traction.

Erosional features formed by wind are: mushroom rocks/pedestal rocks, deflation basins, deflation hollows, blowouts, ventifacts, etc. The common aeolian depositional landforms are sand dunes, loess, etc. There are different types of sand dunes. Barchans, longitudinal dunes, transverse dunes and parabolic dunes are some of the varieties.

Significant Learning Outcomes

The learner can:

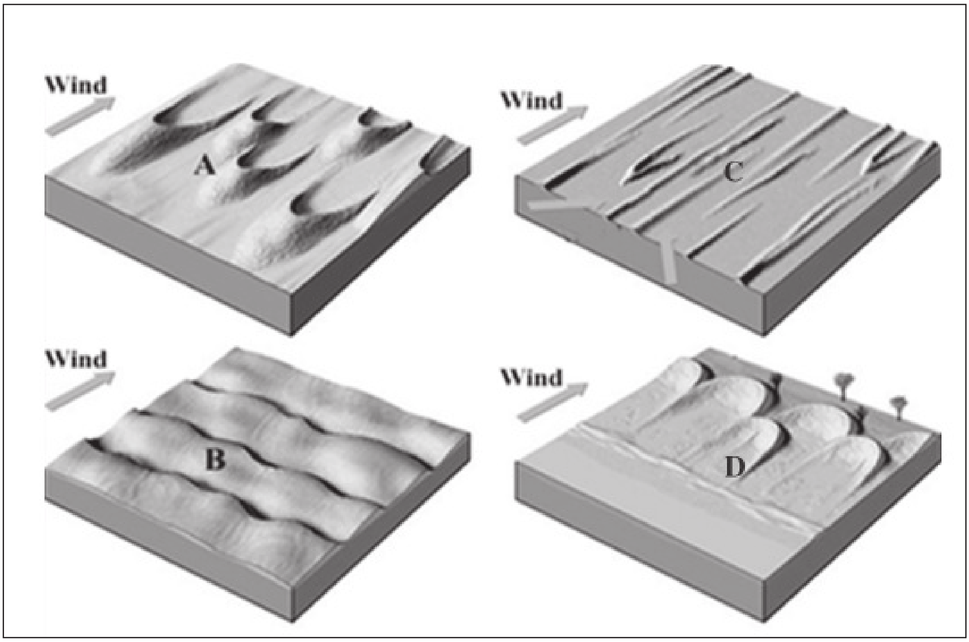
- describe the factors that control and explain the processes of wind erosion, transportation, and deposition.
- identify major aeolian landforms and their development in arid regions.
- distinguish between erosional and depositional features formed by wind.
- explain that wind always modifies the land.

Let us assess

1. Describe the various kinds of aeolian deposits.
2. What are the factors that control the shape of a sand dune?
3. Complete the table given below.

Type of dune	Shape / Characteristics	Direction in relation to wind
	Crescent shaped	
Transverse dunes		
	Elongated, ridges	
		Points to windward direction

4. Differentiate between the following.
   (1) Blowout and Oasis
   (2) Mushroom rocks and ventifacts
   (3) Loess and sand dunes
5. What is the main type of weathering in deserts?
   a) chemical weathering b) weathering by organic acids
   c) physical weathering d) weathering by water
6. Analyze the given figure and identify the dunes A to D.



8 GLACIERS

8.1. Introduction

You know that some places on Earth are so cold that water of those regions exists in solid form - ice or snow. Scientists consider these places of our planet, together to constitute what is known as the '**cryosphere**' of our Earth. The word 'cryosphere' comes from the Greek word 'kryos', meaning 'cold'. Glaciers are important components of the cryosphere.

A glacier is a large, long-lasting mass of ice, formed on land by the compaction and recrystallization of snow, and showing evidence of present or past motion. In other words, solid masses of ice capable of movement, under the influence of gravity are considered as glaciers. Today, about 11% of the Earth's land area is covered by ice. Widespread occurrence of glaciers on Earth during a particular period of time in geological past is termed **glacial period** or **ice age**. There are numerous geological records that indicate the occurrences of several ice ages during the history of the Earth. The concept of '**Snowball Earth**' describes the coldest global climate imaginable - a planet covered by glacial ice from pole to pole. Scientists believe that our planet was covered by ice from pole to pole, at least twice, for long periods, in the geological past.

Glaciology is the branch of geology that deals with the study of glaciers.

8.2. Distribution of Glaciers

Glaciers are found chiefly in (1) the Polar and sub-Polar regions and (2) at mountainous zones of very high elevations, such as the Himalayan Mountains or Alps Mountains. Glaciers are found in widely scattered mountainous regions of North America and South America, Europe, Asia, Africa and Australia.

The Himalayas, 'the abode of snow' has many glaciers distributed throughout its higher elevations. One of the largest occurrences of snow or ice outside the Polar Regions occurs in this mountain range. It is estimated that 33,200 km^2 of this is covered with ice (18%). The glaciers of the Himalayan Mountains are the major sources of fresh water and all the rivers of northern India are nourished by the melt waters of the Himalayas.

8.3. Formation of Glacial Ice

The glaciers form from snow. Snow is precipitation made up of ice crystals. Snow crystals form in nature when cold temperatures and high humidity levels combine in the atmosphere. As long as air temperature remains below the freezing point, snow crystals will rain down to the ground. Newly fallen individual masses of snow exhibit feathery hexagonal habit and a mass of newly formed snow layer on the ground surface will possess high porosity and will contain mostly air (up to 90 percent) by volume. The density of snow generally ranges from about 0.05 to 0.30 grams per cubic centimeter. The snow falling in glaciated regions, gradually thickens and after considerable time the individual snow crystals undergo partial melting and get transformed into granular grains (Fig. 8.1). Ice at the pointed ends of the delicate hexagonal snow crystals, melts and migrates towards the centre forming a granule of recrystallized ice. Thus, the snow layer originally composed of delicate hexagonal snow crystals, gradually changes to an aggregate of spherical grains. This process also leads to a reduction in porosity. This intermediate stage in the *transformation of snow to glacial ice* is known as '**firn**' or '**névé**'. Névé is a young, granular type of snow which has been partially melted, refrozen and compacted, yet precedes the form of ice. Firn is partially compacted névé, a type of snow that has been left over from past seasons and has been recrystallized into a substance denser than névé. It is ice that is at an

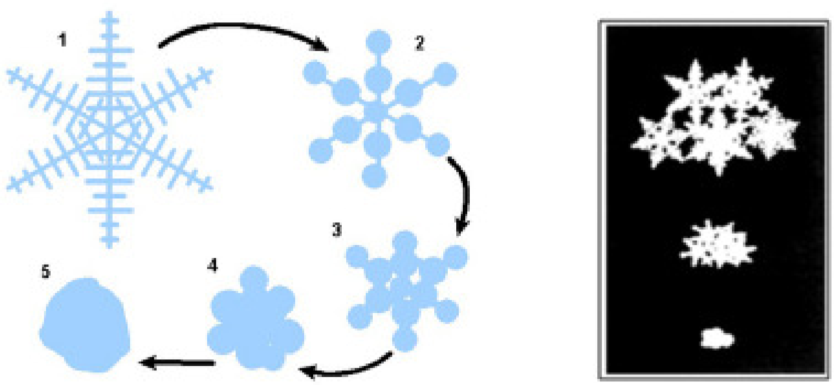


Fig. 8.1: Stages of conversion of snow crystal to granular snow

intermediate stage between snow and glacial ice. Firn looks like wet sugar, but has a hardness that makes it extremely resistant to shoveling. At this stage the material will have a density slightly more than 0.5 grams per cubic centimeter. Further compaction as a result of melting of individual grains and accompanying recrystallization transforms névé or firn to **glacial ice**. Note that, during this transformation, in addition to a reduction in porosity, a proportional increase in density of the material also occurs. Glacial ice has a density of about 0.85 grams per cubic centimetre. The transformation of névé into glacial ice may take more than two to ten decades.

We can define **glacial ice** as a type of rock, composed solely of crystals of the ice. As this ice is naturally occurring, homogeneous material possessing a definite chemical composition, it should be considered as a member of the mineral kingdom. Snow layer and firn can be considered as a kind of sedimentary rock. But the subsequent transformation to glacial ice involves recrystallization. Fig. 8.2 depicts the cross section of a glacier showing the vertical distribution of snow, névé and glacial ice.

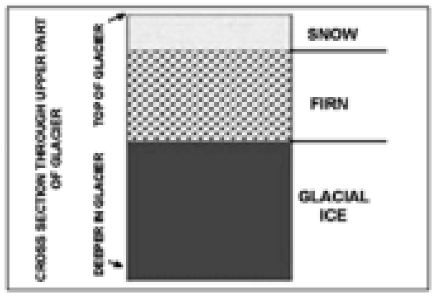


Fig. 8.2: Cross section of a glacier showing vertical distribution of snow, firn or névé and glacial ice

Glaciers can only form at latitudes or elevations above the snow line, which is the elevation above which snow can form and remain present year round. The term **snow line** refers to the level of a glacier covered region above which snow is permanently found *throughout* the year. It marks the base of the permanent ice cover on the mountains. The area situated at a level above the snow line is called ***snow field***. At present, the snow line lies at sea level in polar latitude and rises up to 6000 m in tropical areas.

8.4. Zone of Accumulation and Zone of Ablation

Glaciers have a dynamic existence. Several elements contribute to glacier formation and growth. Snow falls in the zone of accumulation, usually the part of the glacier with the highest elevation beyond the snow line, adding to the glacier's mass. As the snow slowly accumulates and turns to glacial ice, the glacier increases in thickness, forcing down-slope movement. Further down, the glacier is in the ablation zone, where most of the melting and evaporation occur. Between these two areas a balance is reached, where snowfall equals snowmelt. In this condition, the glacier will be in equilibrium. Whenever this equilibrium is disturbed, either by increased snowfall or by excessive melting, the lower terminus of a glacier either retreats or advances at more than its normal pace.

In glacial geology, the word **ablation** is used as the antonym of the word **accumulation**. Ablation can be defined as the collective processes that remove snow, ice or water from a glacier or snowfield. Loss by ablation involves melting, evaporation, sublimation, calving (glacier calving or iceberg calving), or erosive removal of snow by wind (deflation). **Sublimation** is the transition of a substance directly from the solid to the gaseous phase without passing through an intermediate liquid phase. **Calving** is the breaking off of chunks of ice at the edge of a glacier where it meets a sea or a large body of standing water. It involves a sudden release and breaking away of a mass of ice from the terminus of a glacier. The floating masses of glacial ice that have broken or calved from the seaward end of either a glacier or an ice shelf are called **icebergs**. Thousands of floating icebergs of various sizes are found in the oceans surrounding Antarctica, in the seas of the Arctic and sub-Arctic, and in lakes fed by glaciers. Very large floating and drifting icebergs of open oceans are a danger to ships, such as the sinking and loss of the Titanic that was hit by an iceberg in 1912.

8.5. Movement of Glaciers

A mass of ice in nature becomes a glacier only when it moves or is capable of motion. In general, the movement of a glacier will begin when the total thickness of a glacier exceeds 20 metres. Down-slope movement of glaciers under the force of gravity involves two different processes, namely, (1) **internal flow** or **creep**, in which the ice crystals slide over each other like cards in a deck of playing cards, and (2) **basal sliding**, a process of down slope movement of glacier across its bed aided by the lubricating action of the melt water produced below the glacier. The rate of glacial flow will be maximum in the middle and upper part of the glacier.

We can recognize two vertical zones in a moving glacier. The upper portion of a moving glacier behaves as a **brittle** material and the glacial ice in this zone *yields by the development of fractures* during glacial motion. In contrast, its lower portion behaves as a **ductile** or **plastic** material and during glacial motion deforms by the **internal flowage**. Because of this fact, fractures that form in the upper zone of a moving glacier (known as **crevasses**), will be found to extend only up to a depth of 50 metre, the top of the underlying **zone of flowage**. Fig. 8.3 depicts the longitudinal section of a glacier showing the zones of accumulation and ablation and related features.

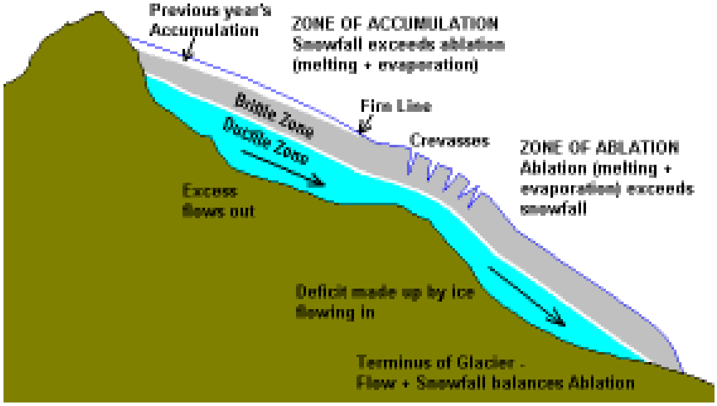
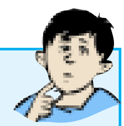


Fig. 8.3: Zone of accumulation and the zone of ablation in a glacier



Check your progress

1. *What are the factors influencing the motion of ice sheets?*
2. *The collective process that results in loss of ice and snow from a glacier is called ______ .*
3. *If the glacier flows over water, blocks of ice may calve off to form _____ .*
4. *What are the two mechanisms involved in the downslope movement of glaciers?*

8.6. Types of Glaciers

There are numerous classification schemes of glaciers but basically, three types of glaciers can be recognized in nature, namely, 1) **Mountain glaciers or Alpine glaciers,** 2) **Continental glaciers or ice sheets, and** 3) **Ice shelves.**

8.6.1. Mountain Glaciers (Alpine Glaciers)

Glaciers that form in high mountains – known as **mountain glaciers**, are generally small and are confined to distinct valleys. They are also known as **Alpine glaciers** because these are found confined to the high mountain ranges such as the Alps. Maximum widths of mountain glaciers may be a

GLACIAL CREVASSES

Elongated open cracks in glacial ice, usually nearly vertical, and subject to change at any moment are known as glacial crevasses. Crevasses form due to extensional changes in velocity or gradient. They can be oriented to the glacier in a transverse, longitudinal or oblique manner and occur in marginal, central or terminal positions on the ice. Bergschrund is an irregular crevasse, usually running across an ice slope in the accumulation area, where the active glacier ice pulls away from ice adhering to the steep mountain side (Fig. 8.4) This is generally the largest crevasse in a glacier that occupies a mountain valley.

The presence of crevasses aids the process of calving. In general, glacial crevasses cannot exceed 50 metres deep (lower limit of the zone of brittle fracture) as they are closed by plastic flow of glacial ice below that depth.

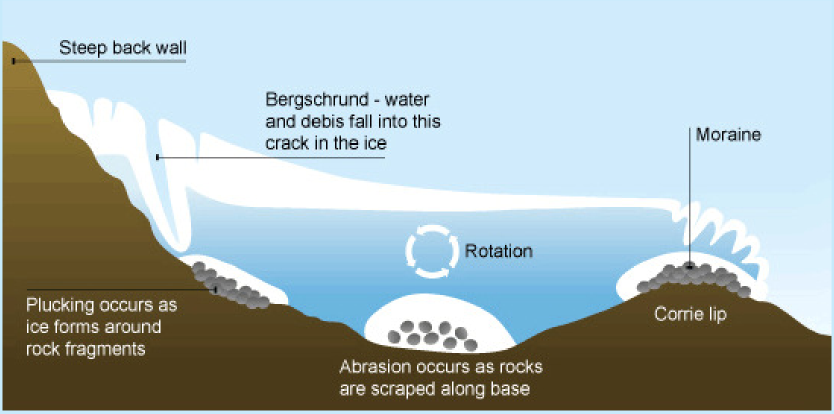


Fig. 8.4: Bergschrund

few hundred metres and thicknesses a few tens of metres. Most of you are probably aware of the fact that the Himalayan Mountains of our country gets its name from its association with glacial ice and snow at its peaks and valleys.

8.6.2. Continental Glaciers (Ice Sheets)

These are the largest types of glaciers found on earth. In areal extent some of these attain continental dimensions. Continental glaciers form in high latitudes and are generally much larger and thicker than alpine glaciers and are not confined to specific valleys. These glaciers may cover several million square kilometres and may reach many kilometres thick. Because these glaciers cover the land almost completely, the continental glaciers carry a much smaller amount of material on their surface than the valley

TYPES OF MOUNTAIN GLACIERS

The following categories of mountain glaciers can be recognized:

a) Cirque glaciers: These are the smallest type of glaciers among mountain glaciers and occupy hollows or bowl shaped depressions on mountain sides.

b) Valley glaciers: When a cirque glacier grows, it will spread into a neighbouring mountain valley and flow down and give rise to a valley glacier. Further down slope movement of these glaciers are controlled by existing topography of the locality. Note that valley glaciers never carve out their own valleys; they only occupy and modify pre-existing stream valleys. Commonly, valley glaciers are fed by several cirque glaciers. The lengths of valley glaciers are many times their widths. (In some schemes of glacial classifications the term 'valley glaciers' is used as a synonym of Alpine or Mountain glaciers.)

c) Fjord glaciers: The valley glaciers that extend down into a sea, occupying narrow, steep-sided, and unusually deep valleys into the coast line are called fjord glaciers (fiord glaciers). When these glaciers retreat, their valleys will be invaded and filled with sea water and these are called fjords (Fig. 8.5). Fjords provide access to the ships to inland parts of the land. Fjords are commonly found along sea coasts of continents which were glaciated during the last glacial period - such as those of Scotland, Norway, Alaska and several other regions.

Fig. 8.5: Fjord

d) Piedmont glacier: A glacier extending down a mountain valley and covering a gentle slope in front of a mountain range is termed piedmont glacier. (The term 'piedmont' means mountain foot lowland).

e) Ice caps: Ice caps are formed in mountain zones when all the valley glaciers that occupy neighbouring valleys grow in size. Ice caps bury the divide separating the adjacent valleys and more or less cover the entire mountain range.

glaciers (if any at all) but their vast size and thickness means that they do much more erosion at their bases. These glaciers bury even mountain ranges of the region where they occur. Ice sheets or continental glaciers occur in Greenland and Antarctica and these two comprise about 95 percent of total glacial ice on earth. One estimate shows that if these ice sheets melt completely, the sea level would rise world-wide above the present level to a height of about 66 metres. The thickness of the Greenland ice sheet exceeds 3 km in some localities. The ice sheets of Antarctica constitute a polar ice sheet as it is located at the Earth's South Pole. Movement of continental glaciers is not unidirectional (as in valley glaciers) but radial and outward from their zones of accumulations. Mountain peaks that project out prominently above the general surface of a continental glacier are called **nunataks**.

The direction of movement of continental glaciers is different from that of the mountain glaciers. These do not usually move *downhill* with respect to the land beneath them, but rather from areas of thicker to thinner margins. In many cases this is actually uphill with respect to the ground! The thicker zones correspond to the zone of accumulation and their thinner zones to the zone of ablation (Fig. 8.6).

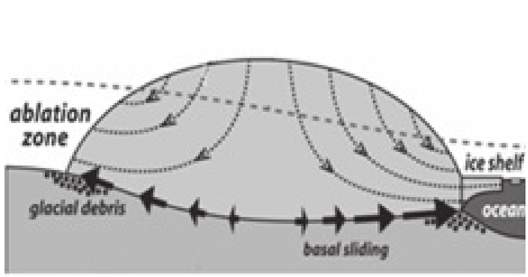
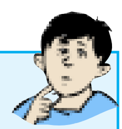


Fig. 8.6: Direction of movement of continental glaciers

8.6.3. Ice Shelves

Extensive sheets of glacial ice found floating on water forming a seaward continuation of a land glacier is called an **ice shelf.** Some of these extend hundreds of kilometres away from the land and reach thicknesses exceeding one kilometre.



Check your progress

1. *In which regions are glaciers found on the earth's surface at present?*
2. *What is the other term given for continental glaciers?*

8.7. Geological Work of Glaciers

Like all other geological agents, glaciers also act as agents of erosion of land surface, transporting the eroded materials and finally depositing the materials in various locations. During these processes they give rise to a variety of unique landforms, characteristic of glacial action. They create new landforms as well as modify the pre-existing ones.

8.7.1. Glacial Erosion

Erosive work by glaciers is accomplished chiefly through the processes of *glacial plucking* and *abrasion*.

a) Glacial Plucking

Glacial plucking is the mechanical removal of pieces of rock, or particle detachment from bedrock surfaces that are in contact with moving glacier. In this process, basal ice freezes in cracks of underlying rocks. As the main body of the glacial ice moves rock fragments are pulled off from the parent rock and plucked out. Blocks of rocks are separated from the underlying rock masses by the repeated freezing and thawing of water in cracks, joints, and fractures of rocks and the resulting pieces are frozen into the moving glacial ice and subsequently transported. The basal portion of glaciers will be carrying enormous quantities of glacially plucked, mostly angular rock fragments, of varied sizes and shapes. These act as tools for the *process of abrasion*.

b) Glacial Abrasion

Abrasion, in geology, is the process of mechanical scraping of a rock surface by friction between rocks and moving particles during their transport by glacier or any other agent of erosion (such as moving water or wind). Rock fragments, from varied sources that are incorporated within a glacier will be distributed throughout the mass of a glacier. Those at the basal portion and its flanks act as tools for the process of abrasion of rocks with which it will come into contact. During the movement of a glacier, these fragments are dragged over the rock surfaces and these grind, rub, scrape, polish, and stroke rocks and bring about significant erosion of earth materials. The intensity of glacial abrasion depends on the hardness, concentration, velocity of glacial motion as well as on the thickness of the glacier.

As a result of abrasion, rocks of the once glaciated regions exhibit grooves and striations of various sorts. Linear depressions, centimeters to kilometres in length, produced by the removal of rock material by the abrasive action of a glacier are called **glacial grooves**. The less prominent **glacial striations** (Fig. 8.7) are scratches cut into bedrock by glacial abrasion. Small, curved (crescent-shaped) or wedge-shaped fractures that generally range from 1 to 5 centimetres, formed by the pressure and impact of boulders moved along by irregular rolling or sliding around on hard, brittle rocks (such as granite) of glaciated regions are called **chatter marks** (Fig. 8.8). (These resemble "chatter" of a carpenter's chisel slipping along the surface of a piece of wood, and thereby the name). Chatter marks are commonly arranged in nested series, with the orientation of the fractures at right angles to the direction of ice movement.

Fig. 8.7: Glacial striations

Fig. 8.8: Chatter marks

The glacial abrasion generally produces a fine clay-sized rock flour and this gives a light, cloudy appearance to the melt-water streams emerging from the terminus of a glacier and waters of such streams are described as **glacial milk**. In regions from where glaciers have retreated, the trends of these *glacial marks* afford valuable indications about the direction of glacier movements in the past.

8.7.2. Landforms formed by Glacial erosion

Now let us learn about some of the common landforms created by the process of glacial erosion.

a) Cirque (Corries)

Cirques are often the starting point of a mountain glacier or Alpine glacier. This is known also under the name **corrie**. A cirque may be defined as a semicircular or half bowl shaped depression present at the valley head in a glaciated mountain. They are arm-chair like depressions (Fig. 8.9). Cirques are invariably bounded on *three* sides by steep walls. Generally, they range in diameter from a few metres to a few kilometres.

Cirques result from a combination of frost wedging, glacial plucking and abrasion. After the disappearance of glaciers, the depression of cirques will be sometimes occupied by a small circular lake. Such lakes are called tarns (Fig. 8.10).

Fig. 8.9: Cirque glacier

Fig. 8.10: Cirque lake or tarn

b) Arête

An arête is a knife-edge like ridge, formed when two neighbouring cirques (corries) erode back to back and meet (Fig. 8.11). As each glacier erodes either side of the ridge, the edge becomes steeper and the ridge becomes narrower.

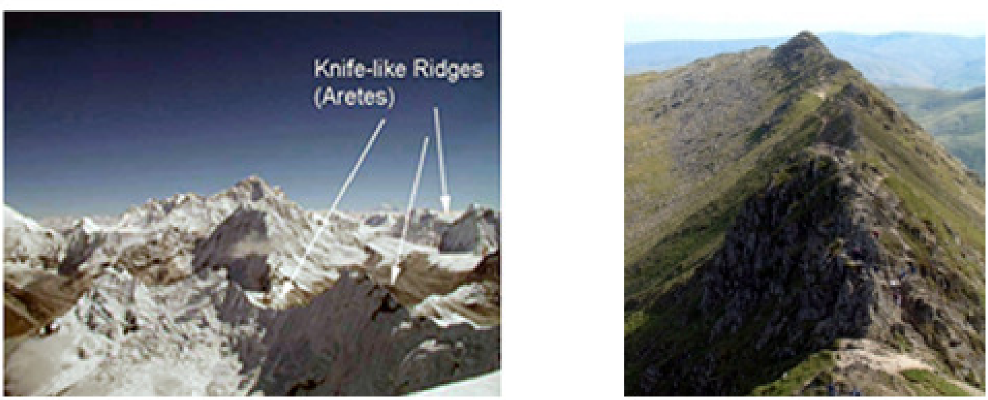


Fig. 8.11: Aretes

c) Horn or Pyramidal peak

Horns are mountain peaks or pinnacles, progressively thinned by glacial erosion from three or more glacial cirques. These are also known as **pyramidal peaks** (Fig. 8.12) and are formed in mountainous areas where three or more cirques (corries) and arêtes meet and where the valley glaciers carved away the peak of a mountain, creating a sharply pointed summit. Matterhorn in Alps is the best known example.

Fig. 8.12: Horns or Pyramidal peaks

d) Col

Glacial erosion of two cirques located on both sides of a mountain results in a mountain pass, known as a **col** (Fig. 8.13). The term is exclusively used in the description of topography of glaciated regions. Cols, like gaps, offer convenient and short communication routes or passage ways permitting movement of men and animals across mountain chains.

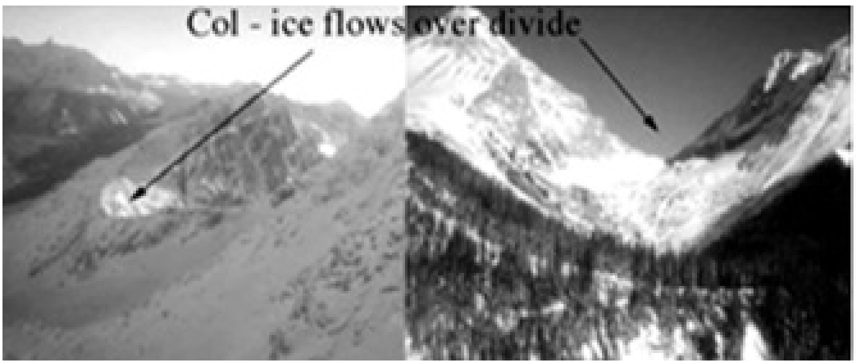


Fig. 8.13: Cols or Mountain passes

e) Glacial Valley (Glacial Trough)

You have already learnt that glaciers never create their own valleys but they occupy valleys of the mountainous regions created by fluvial action and in due course of time they only modify them by erosion. The most notable feature of stream valleys of mountainous regions is that they are characteristically *V- shaped* (i.e., they have V-shaped transverse sections).

A **glacial trough** is a mountain valley reshaped or modified by glacial action into a valley with a flat floor and steep sides. Glaciers (valley glaciers) that occupy valleys of mountainous regions modify these, in due course of time, into valleys with a U-shaped transverse section (cross section) (Fig. 8.14). Such glacial valleys or glacial troughs have broad bottoms and steeper sides, in contrast to the ordinary stream valleys of the region (Fig. 8.15).

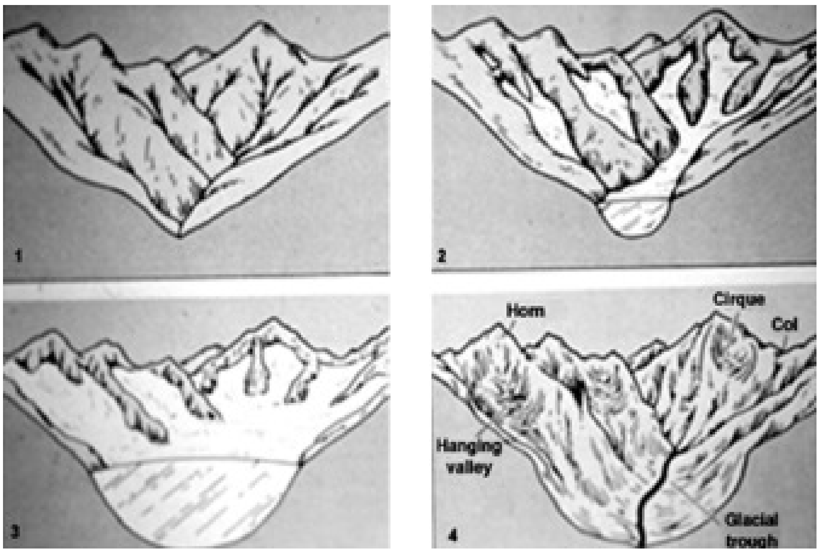


Fig. 8.14: Developmental stages of glacial valley or trough

Fig. 8.15: U shaped glacial valley

f) Hanging Valley

Where a glacier occupying a small tributary valley meets the larger valley, the tributary valley usually does not have the ability to erode the valley floor to the level of the floor of the main valley. This is because the intensity of glacial action in tributary valleys will be relatively lesser than that in the main valley. It is largely because of the lesser thickness of the tributary glacier in comparison with that of the trunk glacier. When the glacial ice melts or retreats, the floor of the tributary valleys hang above the floor of the main valley (or stand at a higher elevation than that of the main valley) and such valleys are called **hanging valleys** (Fig. 8.16). When stream flows through such valleys they will meet their trunk valleys with a waterfall.

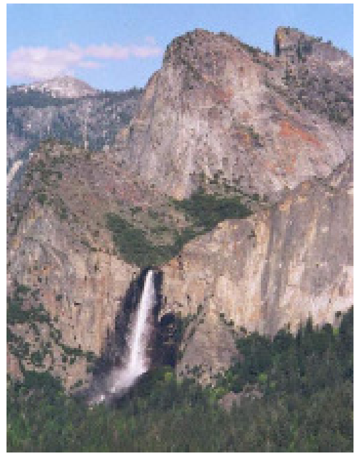


Fig. 8.16: Hanging valleys

OTHER GLACIAL EROSIONAL LANDFORMS

a) Fjords

Fjord glaciers are valley glaciers that extend down into a sea, occupying narrow, steep-sided, and unusually deep valleys into the coast line and when these glaciers retreat, their valleys will be invaded and filled with sea water thereby forming fjords (fiords).

b) Roche Moutonnée (sheep rock)

A symmetric erosional form produced by passage of a glacier as a result of abrasion on the 'stoss' (direction in which ice advances) side of the rock (which will be a smooth surface) and plucking on the 'lee' (down-ice) side (resulting in a steep and jagged face), is termed roche moutonnée (Fig. 8.17). These erosional features are seen on scales of less than a metre to several hundred metres.

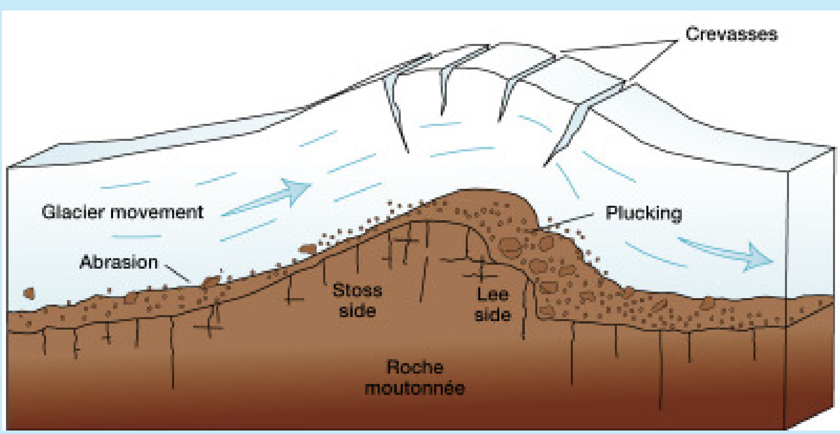


Fig. 8.17: Roche moutonnée or sheep rock

8.7.3. Glacial Transport

There are various sources that supply rock materials to a glacier. In addition to the materials eroded by glaciers (through the processes of glacial plucking and glacial abrasion) various other sources also supply materials to the total load carried by a glacier. In the case of mountain glaciers, the dominant share of the load carried by a glacier is supplied by the valley walls on either side of the glaciers. Rock materials of various sizes reach the surface of a valley glacier as a result of the operation of various **slope processes**. You have already learnt about the different types of slope processes in unit 3. Avalanches are frequent occurrences in glaciated mountainous regions and these supply huge volumes of heterogeneous materials to the valley glaciers. This is only one example and if you are able to recall the major ideas of the section on slope processes of unit 3, you will understand the full significance of the role of several other slope processes in supplying rock materials to a glacier for further downward transport.

Unlike a stream, a glacier is capable of carrying rock materials not only along its bottom or basal portion, but also on its surface and within its entire body. At any one time, in comparison with streams, the load being transported by a valley glacier will be highly heterogeneous, and several times greater in terms of both its volume and mass.

The general term **moraine** is applied for the rock material in transit and this term is also used to describe the rock materials ultimately deposited by a glacier. Based on their location in relation to the body of the glacier the following categories of moraines are recognized: (1) **Superglacial moraine** (morainic materials occurring on the surface or top of a valley glacier), (2) **Englacial moraine** (those occurring within a glacier) and (3) **Subglacial moraine** (morainic materials carried and moving along the basal portion of a glacier). It should be noted that when a glacier reaches the zone of ablation, as a result of melting of the upper portions of the glaciers, some englacial morainic materials will become part of the superglacial moraines. Similarly, during seasons of heavy snow fall, the superglacial moraines will be blanketed by a layer of snow and thus they become a part of englacial moraine.

Superglacial moraines are further classified into the following types:

a) Lateral moraines

These are thin or thick streaks or ridges of rock debris that generally extends all along the sides of a glacier or where the ice meets the valley walls.

b) Medial moraines

Where two mountain glaciers converge or when two tributary glaciers merge their lateral moraines unite to form a dark band of rock fragments traceable along the medial portion of the resulting glacier. These are known as medial moraines (Fig. 8.18).

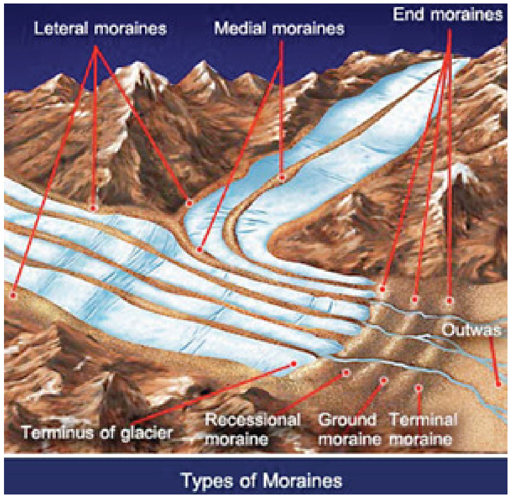
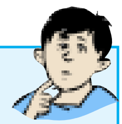


Fig. 8.18: Different types of moraines



Check your progress

1. *What is the name applied to erosion caused by the frictional force of the ice moving over bedrock, like sandpaper?*
2. *What is the shape of a valley before it gets eroded by glaciers and what types of valleys are produced by glacier erosion?*
3. *A bowl-shaped depression formed by glacial erosion on mountain sides located at the head of a valley glacier is known as ________.*
4. *After the ice melts, the former location of a cirque may contain a small lake called a ________.*
5. *________ is a narrow ridge of rock that separates two adjacent cirques.*

8.7.4. Glacial Deposition

Glaciers carry enormous quantities of heterogeneous materials and when they melt, these materials get deposited. In contrast to the processes of deposition associated with streams, the materials deposited directly from the glaciers will not be sorted according to their size. In streams the settling process of grains is directly related to the velocity of flow and larger and larger particles settle first followed by smaller and smaller ones with progressive reduction in velocity. No such sorting is observable in the case of glacial deposition and the process results in the dumping of a heterogeneous, assorted and jumbled mass of rock fragments ranging in size from finest clay particles, silt, pebbles, cobbles and boulders derived by various means.

Glacial Drift

The term glacial drift is used as a general term for all materials transported and deposited directly by or from the glacial ice, or by water running off from the terminus of a glacier undergoing melting (melt-water streams). There are two categories of glacial drifts, namely: (a) Till or unstratified drift and (b) Fluvio-glacial or stratified drift.

a) Till

Till is also called unstratified drift or boulder clay, and is the most common form of glacial deposit. Till consists of unsorted mixture of glacial sediments ranging in size from boulders to clay.

b) Fluvio-glacial, Glacio-fluvial or Stratified Drift

All those accumulations of glacial origin where melt-waters have played a prominent part in their deposition are called fluvio-glacial, glacio-fluvial or stratified drifts. As they are transported by melt-water streams these deposits frequently exhibit the typical characteristics of alluvial deposits. However these are often less sorted in terms of their particle size.

Landforms of Glacial deposition

Glacial deposits form a variety of characteristic landforms in regions from where both mountain glaciers and continental glaciers have retreated during the recent past. These are listed and briefly described further below.

(a) Morainic Landforms

i) **Ground Moraine:** A gently rolling ground surface underlain by till deposited beneath a glacier and usually bordered by terminal moraines (described below) is called ground moraine.

ii) **Terminal Moraine or End Moraine**: A ridge formed by the accumulation of glacial deposits at the point marking the *furthest advance* of an ablating glacier.

iii) **Recessional Moraine**: End moraines created during occasional stabilization of the ice front during retreat – associated with temporary standstills of the glacial terminus.

(b) Drumlins

A drumlin is a streamlined oval and asymmetric hill (resembling an inverted spoon) formed during the advancement of thick glaciers (ice sheets), by reworking of older glacial sediments (poorly sorted till) located below (Fig. 8.19). Note that the side profile of a roche moutonnée (an erosional feature) is opposite to that of a drumlin (a depositional feature). In a drumlin, the steep side is facing the approaching glacier, rather than trailing it. These glacially deposited landforms may extend over several kilometres. They are typically groups, clusters or swarms and produce drumlin fields and the associated topography is sometimes described as 'basket of eggs topography' (Fig. 8.20).

Fig. 8.19: Drumlin

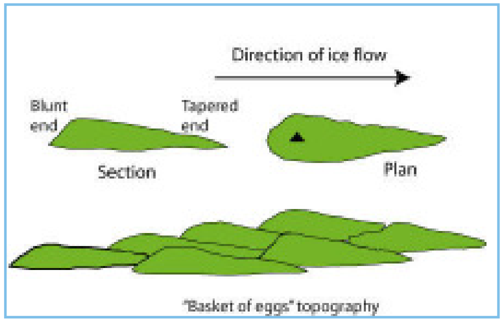


Fig. 8.20: "Basket of Eggs" topography

(c) Esker

The term "esker" is given for a sinuously curving, narrow ridge of stratified glacial sediments deposited by melt-water streams formed in water filled tunnels beneath, above and within the ice (Fig. 8.21). Eskers are one of several types of landforms associated with de-glaciation. Eskers have been reported from all over the mid-latitudes, and are particularly, common in Ireland, Britain, Scandinavia, Canada, Alaska, the northeastern U.S. and Patagonia. The most extensive esker formations in the world are found in Canada where some of these are up to 800 kilometres long but most of these are not continuous ridges. Due to their long winding shape (Fig. 8.22), many roads are built on top of eskers.

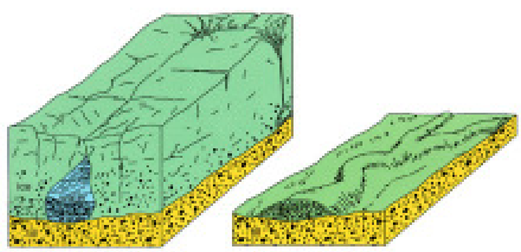


Fig. 8.21: Formation of an esker

Fig. 8.22: An esker with its characteristic long winding shape

(d) Erratics

Huge rock boulders carried and transported within a glacier and deposited several kilometres away from their source as the glacier melts are called

erratics. These erratic rock boulders vary in size from small boulders to boulders of enormous sizes. Moreover the rock types forming the erratic boulders significantly differ from that of the underlying country rocks. Example, a volcanic erratic boulder located over a region of sedimentary rocks.

OTHER GLACIAL DEPOSITIONAL LANDFORMS

Kame

A kame is a depositional feature of glaciation which is a mound-like hill of poorly to well-sorted drift (mostly sand and gravel). Kames form when melt water and the sediment it carries collect in a depression on the top of the glacier. Kames form near the snout or terminus of the glacier, where most of the ice is melting. If lots of kames form in the same area, it is called a kame field. A kame terrace is produced when a melt-water stream deposits its sediments between the ice mass and the valley wall (Fig. 8.23).

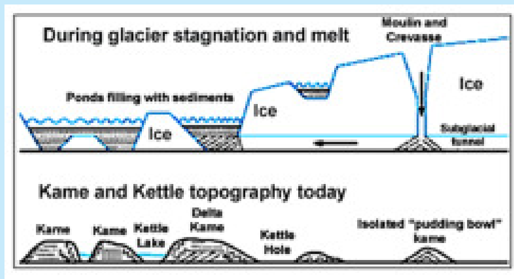
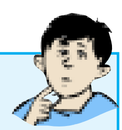


Fig. 8.23: Formation of kame and related topography

Outwash Plain

An outwash plain is a plain formed of glacial sediments deposited by melt-water outwash in front of the terminus of a glacier (ice sheet). Such plains often contain braided streams and kettle lakes (locations where blocks of ice have melted, leaving a depression that fills with water). Outwashes are the most extensive of the fluvio-glacial deposits. These provide a considerable source of windblown material. Those associated with valley glaciers and found confined within valley walls, the outwash deposit is known as a valley train.



Check your progress

1. *Any material deposited directly by glaciers can be referred to as________.*
2. *Glaciers carry huge boulders of rock to locations far away from their origin. These boulders are different from those of all the surrounding rocks, and are called _________.*
3. *Ice sheets may form a type of till deposit along their bases consisting of rounded hills like inverted teaspoons, and are called ________.*

8.8. Glacial Periods and Ice Ages

Glaciation is the modification of the land surface by the action of glaciers. The geological periods during which large scale glaciations have occurred are called **ice ages**. At the peak of glaciation about a third of the earth's land surface was glaciated (in contrast to the 10% of the land surface presently under glaciers). Pleistocene glaciations were the last ice ages that the earth had experienced. In the Pleistocene epoch, many parts of northern Europe and northern parts of North America were covered by glaciers.

World wide climatic changes during the glacial age distinctively altered landscapes in areas far from the glacial boundaries. Glaciations have occurred so recently in North America and Europe, that weathering, mass wasting and stream erosion have not had time to alter the landscape. Thus the evidences of glacial erosion and deposition are still present on different parts of the earth's surface.

Let us do

1. *Prepare a seminar paper on glaciation that experienced the earth surface during the geological past.*
2. *Construct models showing various glacial landforms using clay, gypsum, paper pulp, plaster of paris or any other material.*

Let us sum up

Moving mass of ice is known as glacier. The activity of glaciers is more prominent in polar regions and areas of high altitudes. Cirque glaciers, Valley glaciers, Piedmont glaciers, Continental glaciers are examples of different types of glaciers.

Glaciers act as agents of erosion of land surface and transport the materials eroded and finally act as agents of deposition. Several erosional and depositional landforms are produced by glaciers. Valleys carved out by glaciers are U-shaped. The planet earth has experienced several periods of glaciations over its surface.

Significant Learning Outcomes

The learner can:

- identify that glaciers are one of the important geological agents.
- distinguish erosional and depositional features produced by the activity of glaciers.
- explain the significance of ice ages.

Let us assess

1. Complete the table given below.

Name	Shape	Characteristics
Drumlins		
	Pyramidal	
		Depressions formed by glacial erosion

3. Compare and contrast between the following landforms.
   (1) Arête and Horns
   (2) Drumlins and Eskers
   (3) Till and Drift
   (4) Moraines and Drumlins
   (5) Valley glaciers and ice sheets
3. How does global warming affect glaciers?
4. Match the following

Cirque	Covers plains and foothills of mountains
Valley glacier	Largest glacier covering the whole continent
Piedmont glacier	Small depressions
Continental glacier	Occupies valleys

5. What is a glacier? Describe its formation, motion and work.

9 OCEANS

9.1. Introduction

Most of you who have carefully studied globes in lower classes, might have noticed the fact that more than 70 percent of the surface of the earth is covered with water in the form of oceans and also that the land surface is concentrated mainly in the northern hemisphere and the water body forming oceans in the southern hemisphere (refer unit 5). Unlike Earth's major land masses (continents), the oceans are all connected with one another. This makes for a unique water world known as the **World Ocean**. The World Ocean forms a connected body of salty water that covers over major portion of the Earth's surface. Because of this fact, many people refer to the planet Earth as "**the watery planet**". It forms the most important part of the hydrosphere of our planet. Seen from space, our planet's surface appears to be dominated by the blue color because the oceans dominate the planet's surface.

The oceans and seas cover an area of about 361 million square kilometres of the surface of our planet and it is customarily divided into several principal oceans and smaller seas. There is one ocean – the World Ocean, with many ocean basins. Five oceanic divisions (basins) are usually recognized: The **Pacific**, **Atlantic**, **Indian**, **Arctic**, and **Southern**; the last two are sometimes considered as parts of the first three. The term '**sea**' is used in the names of smaller; partly landlocked sections of the ocean, for example the Lakshadweep Sea.

A **coastline** or **seashore** is the area where land meets the sea or the ocean. However, coastline cannot be determined precisely because of the dynamic nature of tides. The term "**coastal zone**" can be used instead, which is a spatial zone where interaction of the sea and land processes occurs. The term **coast** is generally applied for a strip of land of indefinite length and width that extends from the seashore inland to the first major change in terrain features.

Any indentation in a shoreline, a recess or inlet in the shore of a sea (or lake) is an **embayment**. An embayment between two capes or headlands is called a **bay**. Bays are larger than a **cove** (A cove is a circular or oval coastal inlet forming a small sheltered recess with a narrow entrance, generally located inside a larger embayment). Bays generally have calmer waters than the surrounding seas and therefore afford safe shelter for anchorage to small crafts. A large bay may be called a **gulf** (the terms, sea, sound, or bight are sometimes used as synonyms in some parts of the world). The term gulf can be considered as a relatively large portion of ocean or sea, partly enclosed by land.

Let us do

1. *Identify the major ocean basins, seas, bays and gulfs from a map showing the world ocean.*

9.2. Ocean Water

The ocean is an integral part of the water cycle and is connected to all of the earth's water reservoirs via evaporation and precipitation processes. The oceans contain nearly 97% of our planet's available water. The other 3% is found in the atmosphere, on the Earth's terrestrial surface, and in the Earth's lithosphere in various forms. The average depth of the extensive bodies of sea water is about 3.8 kilometres. Maximum depths can exceed 10 kilometres in a number of areas known as oceanic trenches.

Composition of the ocean water

Many substances are dissolved in sea water, the most abundant being sodium (Na^+) and chloride (Cl^-) ions, which occur in the form of dissolved common salt. Sea water is not uniformly saline. **Salinity** is expressed by the amount of salt found in 1,000 grams of water. Therefore, if we have 1 gram of salt in 1,000 grams of water, the salinity is 1 part per thousand, or 1 ppt (parts per thousand). Average salinity of sea water is about 3.5% (35 g/L). This means that every kilogram (roughly, one litre by volume) of sea water has approximately 35 grams of dissolved salts in it. Rainfall, evaporation, river runoff, and ice formation cause regional variation in salinity. Salinity of freshwater is usually less than 0.5 ppt. Water between 0.5 ppt and 17 ppt is called **brackish**. Estuaries (where fresh river water meets saline ocean water) are examples of brackish waters. Sea water is denser than fresh water or pure water (density 1.0 g/ml) because of the presence of dissolved salts. The density of surface sea water ranges from about 1.020 to 1.029 g/cm^3, depending on the temperature and salinity. Its freezing point is slightly lower than that of fresh water. The freezing point of sea water decreases as salt concentration increases. At typical salinity it freezes at about 2°C.

Did you ever wonder why the oceans are filled with salt water instead of fresh water? The salts in sea water come from the erosion of lands, volcanic emissions, chemical reactions taking place at the seafloor, and atmospheric deposition. Over millions of years, rain, rivers, and streams have washed over rocks containing sodium and chlorine and carried these elements into the sea. In addition to the input from land, sodium has been leaching out of the ocean floor since the ocean had formed millions of years ago. The presence of chlorides results from the out-gassing of chloride (as hydrochloric acid) with other gases from Earth's interior via volcanoes and hydrothermal (hot water) vents. The sodium and chloride ions in course of time became the most abundant constituents of sea salt. Geologists believe that the salinity of the oceans of our planet remained more or less stable for billions of years. This is because the rate of output (removal of salts by various chemical and tectonic processes) and input remained almost the same, throughout major part of the Earth's history.

PRESSURE AND DENSITY OF OCEAN WATER

Even though we do not feel it, 1 kg per square cm of pressure is pushing down on our bodies as we rest at sea level. Our body compensates for this weight by pushing out with the same force. Since water is much heavier than air, this pressure increases as we go deep into the water. Assuming the density of sea water to be 1025 kg/m^3 (in fact it is slightly variable, as noted earlier), pressure increases by 1 atmosphere (atm) with each 10 m of depth. At a depth of 10 m the pressure will be 1.99209 atm (total pressure i.e., pressure due to the water plus the 1 atm ambient air pressure at sea level), and at 100 m it will be 10.9204 atm. To travel into such higher-pressure environment we have to make some adjustments. Humans can travel only up to a depth where the pressure is three or four atmospheres, unaided by any external protective devices. To go further deep, submarines or other protective gadgets are required.

Two major factors that determine the density of ocean water are salinity (the amount of salt dissolved in the water) and temperature. The more salt that is dissolved in the water, the greater will be its density. Temperature also affects density: colder the water, the greater will be its density. This is because temperature affects volume but not mass. Colder water takes up less space than warmer water (except when it freezes). So, cold water has greater density than warm water.

Cold, salty water is much denser than warm and fresh water and will sink below the less dense layer. Depending on their densities, the water column of oceans is divisible into three zones. Less dense waters form a top layer called the **surface mixed zone.** The temperature and salinity of this layer can change frequently because it is in direct contact with the air. The second layer is the t**hermocline (pycnocline)**, or the **transition zone**. The density of sea water here does not change very much. This transition zone forms a barrier between the overlying surface zone and the bottom layer (**the deep zone)** and allowing little water movement between the two zones. When traced downwards the temperature of the ocean water shows a significant decrease in the thermocline and at its bottom the decrease reaches its maximum. Thereafter the temperature remains almost the same. The bottommost layer is the **deep zone**, where the water remains cold and dense.

Water is an excellent conductor of sound. This means that water does not significantly absorb sound, so it can travel for great distances before it dies out. The speed of sound in water is 1,448 to 1,570 metres per second. Dolphins and some whales use a process called echolocation in deeper, darker zones of the ocean by listening to echoes as the sounds bounce off objects, such as other fishes, boats, ocean floor or reefs, in their path. From the direction and strength of the echo, these animals can develop a mental image of their physical environment. They can sense the size and distance of objects in their path.

Check your progress

1. *Which is the largest ocean basin?*
2. *The average depth of ocean is ____________.*
3. *The average salinity of the sea water is ______________.*
4. *What are the factors that control the density of sea water?*

9.3. Movements of Ocean Water

Ocean water is constantly in motion. These movements are determined by many factors. The waters of oceans and seas are subjected to the action of wind, the attraction of the sun and the moon, and to changes of temperature, salinity, density etc. All these factors give rise to three main types of movement and they are (1) Waves, (2) Currents, and (3) Tides.

9.3.1. Waves

A wave can be considered as a rhythmic movement that carries and transfers energy through matter or empty space. Examples are sound waves, earthquake waves, electromagnetic waves (light waves, radio waves etc) and so on.

SIZE OF OCEAN WAVES

Ocean waves are mostly created by winds. There are three factors that determine the size of the ocean wave: 1) the speed of the wind, 2) the distance over which the wind has blown, and 3) the length of time that the wind has blown. Greater these factors, bigger the wave will be. Now analyze the given diagram (Fig. 9.1) and try to identify the parts of a wave.

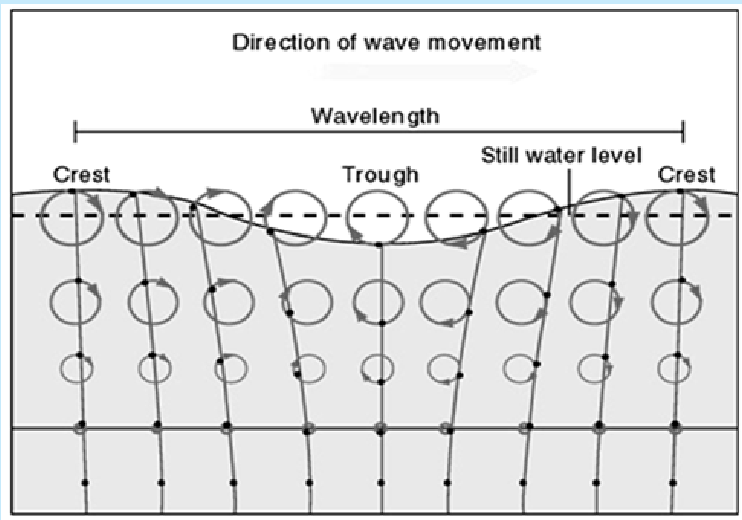


Fig. 9.1: Direction of movement of waves in oceans

Still-water line is the level of the ocean if it were flat without any waves. The **crest** is the highest part of the wave above the still-water line and the **trough** is the lowest part of the wave below the still-water line. The vertical distance between crest and trough is called the **wave height**. The distance between two waves is called the **wavelength** (L), and it is usually measured either from one crest to the next or from one trough to the next. The time it takes for waves to pass a reference point is called the **wave period**. During the movement of an ocean wave, particles in the ocean are not significantly moved by waves; these are only bobbled around by the waves, the particles tend to stay where they are. However, they perform circular motion. If you are standing on a pier and start a stopwatch as the crest of a wave passes and then stop the stopwatch as the crest of the next wave passes, you have measured the wave period. **Wave frequency** is the number of waves that pass a particular point in a given time period. **Fetch** is the distance the wind blows over open water. **Amplitude (wave height)** is the difference in height between the crest and the trough.

Not all waves coming into a coast are of the same size. Some are larger than average and others are smaller than average. About once in every hour, a wave which is double the size of the preceding ones arrives on the coasts.

Why is it important to make all these wave measurements? Sailors rely on reports of the size of waves for planning their voyages. Surfers rely on reports of the size of waves when searching for places to surf. Waves have an impact on currents at the coast and also on beach erosion.

Waves that travel very long distances – far from the winds that formed them – are called **swells**. Swells tend to be large waves with flatter crests and are very regular in shape and size. Apart from wind, ocean waves can also form when a rapid shift in ocean water is caused by submarine earthquakes, landslides, or meteors that hit the ocean. There are extremely large waves called **tsunamis**, which often travel alone and not in the direction of the other waves. These waves can travel at speeds of 800 kilometres per hour. It has such a long wavelength that it is not visible until it gets near shore. Tsunami warning systems are important for protecting coastal areas and low-lying countries.

An ocean wave is really a transfer of wind energy from one water molecule to the next. Waves propagate as wind transfers energy into the water. In open sea, ocean waves are nearly friction-free and capable of traveling great distances within the surface zone of the ocean. Friction between the wind and water transfers energy from the wind to the water. The energy in a wave moves forward, but the water particles do not! The water moves up and down in a circular pattern as they are temporarily displaced by the energy of the wave. As waves move into shallow water, they act differently (Fig. 9.2). The wave speed is slowed down by friction with the shallower ocean floor, which causes the wavelength to decrease, creating a much taller wave. When waves get closer to the shore their energy is typically released as they begin to "feel bottom", slow dramatically, and then break.

Waves break when they get close to the shore. That is due to the wave's interaction with the sea floor. When the wave hits the shore, the energy at the bottom of the wave is transferred to the ocean floor. The bottom of the

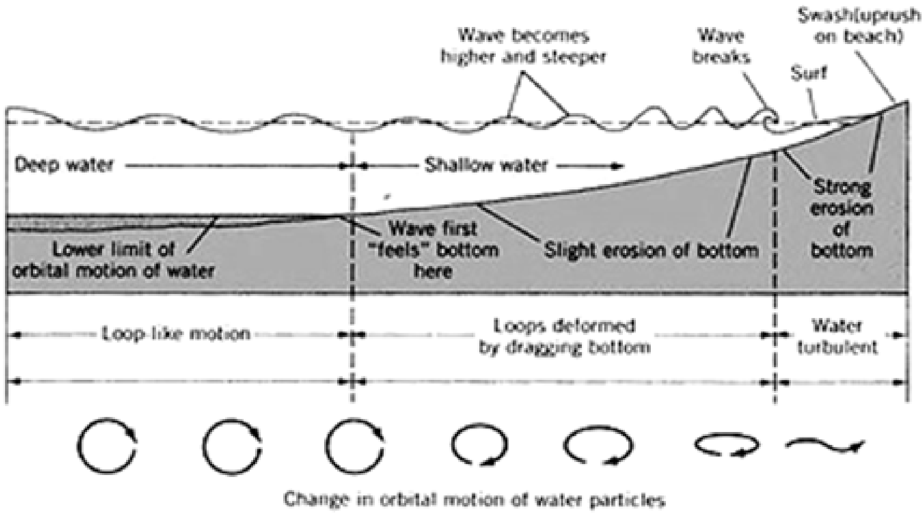


Fig. 9.2: Motion of water particles in ocean waves

wave is slowed down by friction with the ocean floor. The top of the wave travels faster than the bottom. Its momentum causes it to move past the bottom part of the wave. Since the top of this wave is going faster than the bottom, the crest falls over and crashes down. The wave topples over on itself, forming a **breaker**. In general, waves break when the depth of the water is a little more than the height of the wave. Generally, when the water depth is 1.3 times or less the wave height, then the wave breaks. A wave 30 cm high will break in 40 cm water.

The lower limit of wave action is called the **wave base**. Water deeper than half the wave length of a wave does not move. Thus, waves cannot erode the bottom or move sediment in water deeper than L/2, where L is the wave length.

9.3.2. Tides

Wind is the primary force that causes ocean surface waves, but it does not cause the tides. Each day the ocean surface rises and falls because of tides. The highest point of the rise is called **high tide**. The lowest point is called **low tide**. Most places of ocean experience two high tides and two low tides each day.

Tides form because of the gravitational pull of the Moon and Sun on ocean water. The Moon has a much greater impact on tides than the Sun because it is much closer. The Moon pulls water that is closest to it making a high tide on the side of the Earth closest to the Moon and there is a high tide on the opposite side of the Earth too. Low tides happen in places located between the high tides. Because Earth is rotating, the tides change over time.

Fig. 9.3 shows the effects of high tide and low tide in a coastal area.

Fig. 9.3: Effects of high tide and low tide in a coastal region

The difference between high tide and low tide is called the **tidal range**. The tidal range can be as little as a few centimetres to as much as several metres depending on the shape of the ocean floor, and geographic location.

TIDAL PATTERNS

Three main tidal patterns occur worldwide: 1) Diurnal tidal pattern, 2) Semi-diurnal tidal pattern and 3) Mixed tidal pattern. Duration of a **tidal day** is 24 hours and 50 minutes- not 24 hours. Diurnal tides are characterized by a single high tide and a single low tide each tidal day. Diurnal tides have a period of 24 hours 50 minutes. Semidiurnal tides occur twice each tidal day marked by two high tides of the same height and two low tides of the same depth. Semidiurnal tides occur every 12 hours and 25 minutes. The predominant type of tide throughout the world is semidiurnal. Mixed tidal pattern is similar to semidiurnal tidal patterns, and are characterized by large inequalities of high tide and low tide or both. These have 2 high tides and 2 low tides each day, but the heights of the 2 high tides and/or the 2 low tides are different.

In addition, there are also monthly cycles of tides. Two types of monthly tides - called **spring tides** and **neap tides**, can be observed. At times when the Sun, Earth, and Moon are in line with each other (during full and new moons), the tidal range is larger because in this case both the Sun's and Moon's gravitational pull create the tide. This is called a spring tide. Spring tides occur twice a month, around full moon day and new moon day. At this time, the sun and moon are aligned (come in a straight line) and their forces are added together and result is larger tidal bulges and larger tidal troughs. Neap tides have lowest tidal range and occur twice a month, about the time of the first and third quarters of the moon. During neap tides the gravitational forces of the moon and sun act on earth at right angles and thus the tidal range will be smaller. Each month, there are two spring tides and two neap tides, each about one week apart. Tides are gradually slowing the earth's rotation as a result of friction. High tides occur about twice a day, about every 12 hours and 24 minutes.

9.3.3. Ocean Currents

Sea water is in constant movement, in some places horizontally, in others, downward, and in still others, upward. A current is a continuous flow of water in a given direction, like a 'river' in the ocean. Ocean current is the mass of ocean water that flows from one place to another. The rate of movement varies from spot to spot. It has been estimated that there is a complete mixing of all the water of the oceans about once in every 1800 years. In currents, there is an actual movement of the water over great distances, which may be caused by various factors, such as the differences in temperature, salinity, action of steady and periodic winds etc. There are two types of ocean currents, viz., (a) surface currents and (b) deep sea currents.

(a) Surface currents

Wind-driven currents are called **surface currents**. These currents have primarily horizontal motion. Earth's major wind belts, called prevailing winds, influence the formation of ocean currents and the direction they move. Surface currents are movements of water that flow horizontally in the upper part of the ocean's surface. Surface currents are very important because they are a major factor in determining climate around the globe.

Surface ocean currents can be very large. The Gulf Stream, a surface current in the North Atlantic, carries 4500 times more water than the Mississippi River. Each second, ninety million cubic metres of water is carried past in the Gulf Stream. Some currents are deep and narrow. Other currents are shallow and wide. Some move quickly while others move slowly. A current can also change somewhat in depth and speed over time.

FACTORS CONTROLLING OCEAN CURRENTS

Currents on the surface are determined by three major factors: the overall global wind patterns, the rotation of the Earth, and the shape of ocean basins.

The difference in temperature between the equatorial region and the Polar Regions causes circulation of fluids of the atmosphere and ocean. Because the Earth's equator is warmed by the most direct rays of the Sun, air along the equatorial region is hotter than air further north or south. This hotter air rises up at the equator and as colder air moves in to take its place, winds begin to blow and push the ocean into waves and currents. Winds are able to move the top portion of the ocean creating surface ocean currents. Surface currents develop from friction between the ocean and the wind that blows across its surface. Surface currents extend to about 400 m below the surface, and they move as fast as 100 km/day.

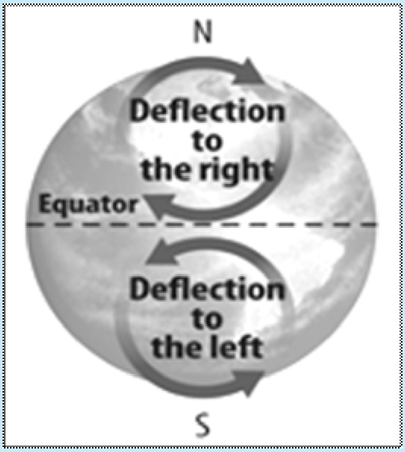


Fig. 9.4: Coriolis Effect

The 'Coriolis Effect' describes how Earth's rotation deflects winds and surface currents away from their original course (Fig. 9.4). The Earth is a sphere that spins on its axis in a counterclockwise direction when seen from the North Pole. While wind or an ocean current moves, the Earth is spinning underneath it. As a result, an object moving north or south along the Earth will appear to move in a curve, instead of in a straight line. Objects are deflected in a curved path. The Coriolis Effect bends the direction of surface currents. The direction that they deflect depends on the hemisphere that they are in.

If you throw a football towards north or south, its path curves slightly only due to the Coriolis Effect - far too small for you to ever notice. such an effect is what causes clouds in a hurricane to swirl. This is also why winds and currents move in circular paths.

The third major factor that determines the direction of surface currents is the shape of ocean basins. When a surface current collides with land, it changes to direction. Imagine pushing the water in a bathtub towards the end of the tub. When the water reaches the edge, it has to change direction.

Surface ocean currents are important for sailors for planning their voyage routes through the ocean. Currents are also important for marine life because they transport creatures around the world and affect the water temperature in marine ecosystems.

Ocean Gyres

Surface ocean currents form large (global scale) circular patterns called gyres. Ocean gyres are large swirling bodies of water that are often on the scale of a whole ocean basin or hundreds to thousands of kilometres across. Ocean gyres dominate the open ocean and represent the long-term average pattern of ocean surface currents. Gyres flow clockwise in Northern Hemisphere oceans and counterclockwise in Southern Hemisphere oceans because of the Coriolis Effect. Near the Earth's poles, gyres tend to flow in the opposite direction. Boundary currents, on the edges of the gyres, carry warm tropical water to the higher latitudes and cold polar water to the lower latitudes.

The major gyres of the ocean include: North Atlantic, South Atlantic, North Pacific, South Pacific and Indian Ocean gyres. A simplistic drawing of those can be seen in figure 9.5. Prominent Ocean gyres include, Subtropical gyres, centered about 30° N or S, Equatorial current, Western Boundary currents and Northern or Southern Boundary currents and Eastern Boundary currents. Other prominent surface currents are Equatorial countercurrents and Sub polar gyres.

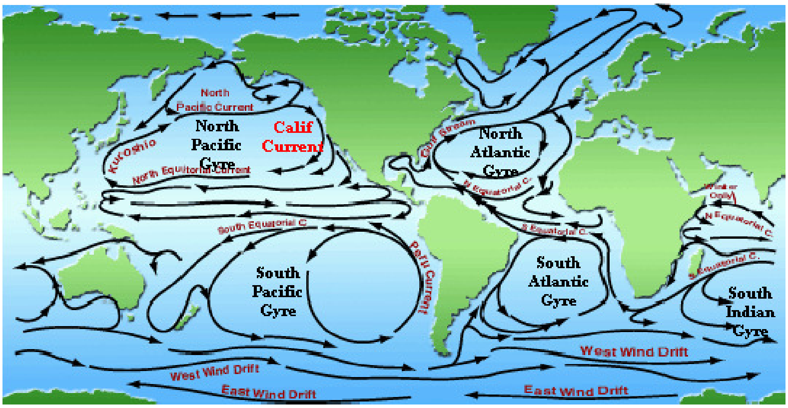


Fig. 9.5: Five main gyres of the world ocean
(South Indian Gyre cut in half by the ends of the diagram)

One of the largest ocean gyres, the North Pacific gyre, is home to an area called the Great Pacific Garbage Patch. This area contains approximately 3 million tons of plastic garbage, though much of this plastic is broken up into pieces too small to see with the naked eye.

(b) Deep Sea Currents

Surface currents occur close to the surface of the ocean and mostly affect the upper zone. Deep within the ocean, equally important currents exist and are called deep sea currents. These currents are not created by wind, but result from the differences in density of masses of water. In other words, these ocean currents are driven by differences in density caused by regional differences in temperature and salinity of ocean water. Deep currents have both vertical and horizontal motions. Deep sea currents are ocean currents that are driven by differences in density. **Density currents** are a variety of deep sea vertical currents that result from density differences among water masses. An increase in sea water density can be caused by a decrease in temperature or an increase in salinity. Deep-ocean currents begin their journeys in high latitudes. Density currents can also result from increase in salinity of ocean water due to excessive evaporation.

The denser water masses will sink towards the ocean floor. Just like convection currents in air, when denser water sinks, its space is filled by less dense water moving in. This creates convection currents that move enormous amounts of water in the depths of the ocean. Water cools as it moves from the equator to the poles via surface currents. Cooler water is denser and hence would start sink and move downwards. As a result, the surface currents and the deep currents are linked. Wind causes surface currents to transport water around the oceans, while density differences cause deep currents to return that water back around the globe.

In a simplified model, ocean circulation is similar to a conveyor belt that travels from the Atlantic Ocean, through the Indian and Pacific Oceans, and back again (Fig. 9.6). Scientists estimate that the Great Ocean Conveyor Belt model takes about 1,000 years to complete one cycle.

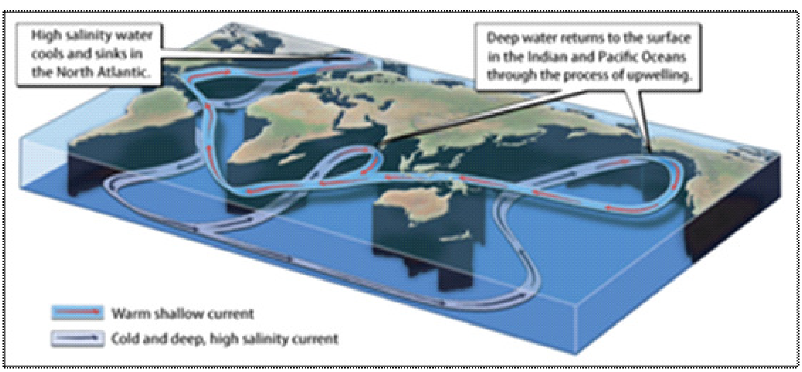


Fig. 9.6: Ocean circulation similar to a conveyor belt

Upwelling

You have already seen that water with higher density sinks to the bottom. However, in the right circumstances this process can be reversed. Denser water from the deep ocean can come up to the surface in an upwelling. Upwelling is the rise of cold water from deeper layers to replace warmer surface water. This process brings greater concentrations of dissolved nutrients, such as nitrates and phosphates, to the ocean surface.

Generally, an upwelling occurs along the coast when strong winds blow water away from the shore. As the surface water is blown away from the shore, colder water from below comes up to take its place. This is an important process in places like California, South America, South Africa, and the Arabian Sea because the nutrients brought up from the deep ocean water support the growth of plankton which, in turn, supports other members in the ecosystem. Upwelling also takes place along the equator between the North and South Equatorial Currents.

Surface ocean currents, ocean gyres, deep ocean circulation and the atmosphere are all parts of the Earth system. Understanding ocean-atmosphere interactions is a key for understanding global climate change as well as the mechanism of movement, distribution and trapping of water, energy, nutrients or pollutants through different parts of the Earth system.

Check your progress

1. *Why do waves break when it approaches a sea shore?*
2. *How do you differentiate surface currents from deep sea currents?*
3. *The gravitational pull of the __________ is important in creating tides.*
4. *What is the difference between neap tide and spring tide?*

9.4. Topography of the ocean floor

As one sails over the ocean or flies above the broad oceanic expanses, he/she receives only few hints of the complex sea floor topography lies hidden beneath. Yet the oceanic topography is just as varied, irregular and fascinating as the familiar land topography we see all around us. Earth's highest peaks, deepest valleys and flattest vast plains are all in the ocean. Present on the sea floor are long mountain chains, valleys and canyons, featureless plains, great escarpments and steep sided volcanic cones. In fact submarine terrain can be just as rugged as that on land with prominent relief features.

The Pacific Ocean is the biggest and deepest body of water and it occupies almost half of the earth's surface. It has an average depth of 4200 metres. The greatest depths so far recorded is the **Challenger Deep** (so named after the British exploration vessel HMS Challenger II)**,** of the **Mariana Trench** (a deep-sea trench in the floor of the western North Pacific Ocean). According to US National Oceanic and Atmospheric Administration, the depth of the Challenger Deep is 11,030 metres below sea level. This depth is far greater than the height of Mount Everest. The average depth of the oceans is about 3, 800 metres while the average land elevation is about 840 m.

Traditionally, the ocean floor is divided into three well defined regions. These are (a) Continental shelf, (b) Continental slope and (c) Abyssal Plains (generally smooth, flat regions that make up 40% of the ocean floor).

(a) Continental shelf

The best known and perhaps the most easily studied region of the ocean floor is the continental shelf. The broad and relatively shallow, gently inclined, submarine terrace of *continental crust*, forming the edge of continental landmasses are termed **continental shelves**. The continental shelf is generally considered as the zone adjacent to a continent or around an island that is between the shoreline and a noticeable break in slope, the **shelf break**, to the steeper continental slope or, where there is no break in slope, to a depth of about 200 m. In the profile of a continental margin, the greatest change in slope occurs at an average depth of around 132 metres. This sudden or abrupt break in slope forms the outer margin of the continental shelf. However for convenience, the outer margin of the continental shelf is taken at depths between 100 - 200 metres.

Continental shelves have an average slope of about 0.1°. The continental shelves are comparatively smooth. The width is variable but the average width of continental shelves is about 65 km. Exceptionally broad shelves occur off northern Australia and Argentina (South America). The world's largest continental shelf extends 1,500 km from the coast of Siberia into the Arctic Ocean. The width of the continental shelf of the Pacific coast of South America is almost insignificant.

As noted earlier, almost everywhere the shelves represent a continuation of the continental landmass beneath the ocean margins. Continental shelves make up about 8 percent of the entire area covered by oceans. These areas have an increased economic and political significance since they have been found to be sites of important mineral deposits, including large reservoirs of petroleum and natural gas, as well as huge sand and gravel deposits. The shelves are regions of abundant biological activity as there are substantial supplies of nutrients from both upwelling and upland runoff and there generally is good light penetration. The waters of the continental shelf contain many important fishing grounds that are significant sources of food. The portion of the sea or the ocean *situated above the continental shelf* is sometimes termed as **epi-continental sea**. Fig. 9.7 depicts the continental shelf of India.

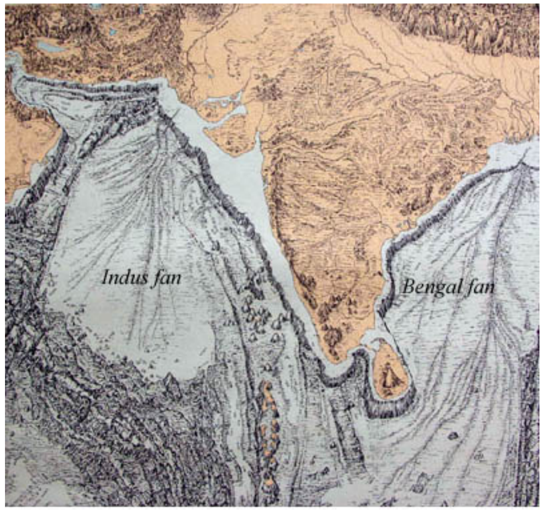


Fig. 9.7: Continental shelf of India

(b) Continental slope

Continental shelves end at their seaward edge with an abrupt drop in slope, known as the *shelf break*. Beyond the shelf break is the **continental slope**, leading down to deep water. The continental slope has a total length of approximately 300,000 km. This portion of the ocean floor descends at an average angle in excess of 4^{o} from the shelf break (at the edge of the continental shelf) to the beginning of the deep ocean basins – the abyssal plains.

The gradient (slope) of the continental slope is lowest off stable coasts without major rivers and highest off coasts with young mountain ranges and narrow continental shelves. Continental slopes of most parts of the Pacific Ocean are relatively steeper than those of the Atlantic Ocean.

The border between the continental slope and the abyssal plain usually has a more gradual descent, and is called the **continental rise**, which is caused by sediment cascading down the continental slope. Due to steeper gradient the sediments deposited on the slope tend to be unstable and move downward into deeper parts of the ocean floor.

About one-half of all continental slopes descend into **deep-sea trenches** (described further below) or shallower depressions, and most of the remainder terminates in fans of marine sediment or in **continental rises**.

The term **continental rise** is applied to a major depositional feature in ocean floor made up of thick sequences of continental material that accumulate between the continental slope and the abyssal plain. The typical continental rise is a wedge-shaped layer of sediments derived from the shelf areas and accumulated next to the base of the slope and these are also known under the name **continental aprons**. Continental rises form as a result of sedimentary processes such as submarine mass wasting, the deposition from currents, and the vertical settling of sedimentary and biogenic particles, and high-velocity sediment-laden density flows known as *turbidity currents*. In tectonically active areas, earthquakes are important triggering mechanisms for such currents.

About 8.5 percent of the ocean floor is covered by the *continental slope-rise system*. The transition from continental crust to oceanic crust usually occurs within the outer part of the continental margin i.e., continental rise. (The edges of all the continents are presently partially covered with water added to the oceans as the great continental glaciers have melted and retreated. These flooded continental edges are not part of the ocean to a geologist, but rather part of the continent). It is estimated that nearly 20 percent of the continental crust occur below the ocean waters. Beyond the shelf-slope break, the continental crust thins quickly, and the rise lies partly on the continental crust and partly on the oceanic crust of the deep sea. Unlike the continental crust which is dominantly of felsic (or granitic) composition, the oceanic crust has a mafic (or basaltic) composition, and it is very thin. Continental slopes are indented by numerous submarine canyons and mounds. **Submarine canyons** may be visualized as similar to gullies cut by erosion along hill slopes, but on an enormous scale.

The term **continental margin** is used for the *collective area that encompasses the continental shelf, continental slope, and continental rise*. Continental margins constitute about 28% of the oceanic area. The nature of the continental margins are influenced by factors such as crustal deformation, sea level changes, the proximity to major rivers, volume of sediment supply, the energy conditions (strength of the ocean waves and currents), etc.

Viewed from a background of Plate Tectonics, the continental margins may be any one of the two types (1) **Passive margins** – those not coinciding with a tectonic plate boundary and (2) **Active margins** – those coinciding a tectonic plate margin.

(c) Abyssal plain

Oceanwards beyond the edge of the continental rise lies the abyssal plain. Abyssal plains begin at the edge of the continental margin and continue into the ocean depths (Fig. 9.8). An abyssal plain is a submarine plain on the deep ocean floor, usually found at depths between 3000 and 6000 m. The surface slopes of abyssal plains are often less than 1 in 1000. These plains, which are extremely level, are the flattest places on earth and cover approximately one-half of the deep-ocean floors. In the North Atlantic, the Sohm Plain alone has an area of approximately 900,000 square km. abyssal plains are largest and most common in the Atlantic Ocean, less common in the Indian Ocean, and even rarer in the Pacific, where they occur mainly as the small, flat floors of marginal seas or as the narrow, elongate bottoms of trenches.

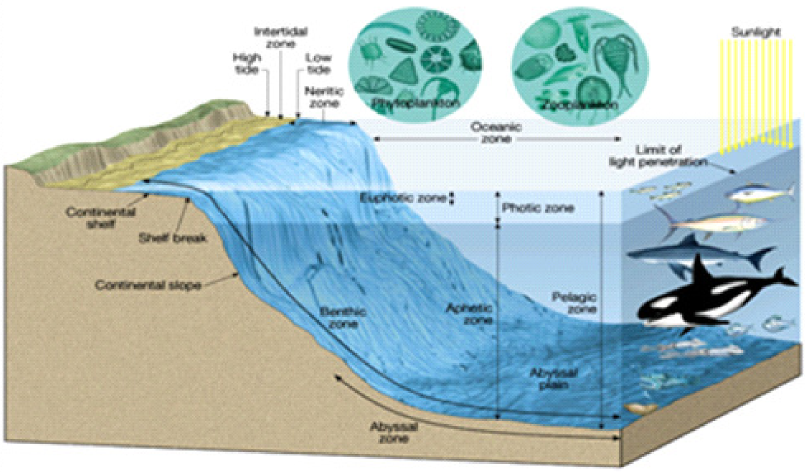


Fig. 9.8: Abyssal zone and abyssal plain

The abyssal plains are thought to be blanketed by land-derived sediments that accumulate in abyssal depressions, thus smoothing out a preexisting hilly or otherwise irregular topography. The flatness of these plains is the result of the accumulation of a blanket of sediments, up to 5 kilometres thick, which overlies the basaltic rocks of the oceanic crust. Incomplete burial of preexisting relief may result in the presence of isolated volcanic hills or hill groups that rise abruptly out of some abyssal plains. Sediment from the continental margins accretes at steep continental slopes, and occasional submarine slumping of this coarse material creates dense, sediment-laden slurries, called **turbidity currents**, that flow down the slopes in obedience to gravity. Part of the turbidity-current sediment settles out at the bases of the continental slopes, creating continental rises of lesser gradient, but some of the coarse sediment reaches the abyssal depressions. Horizontal silty, sandy, and even gravelly beds that are fractions of a centimetre to several metres thick comprise 2 to 90 percent of abyssal-plain sediment. Fig. 9.9 depicts the relation of abyssal plain with other topographic features of ocean floor basin.

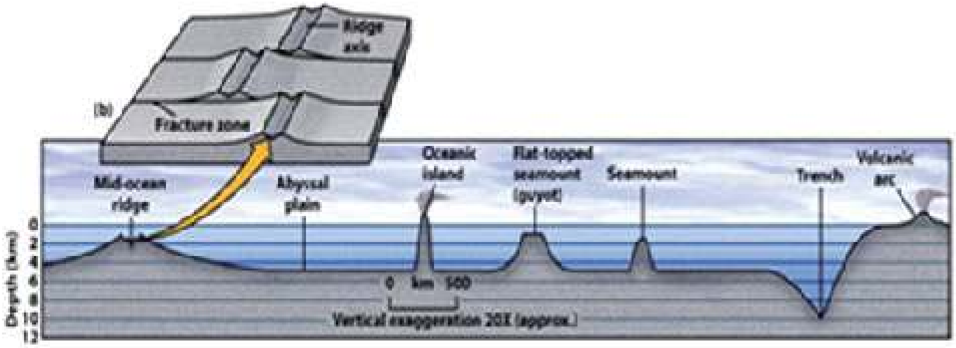


Fig. 9.9: Abyssal plain in relation to other topographic features of ocean floor

9.4.1. Features of Deep Ocean Floor

Oceanic ridge system is the most prominent submarine feature of the abyssal plains. Abyssal hills, guyots, sea scarps and others punctuate the relatively featureless abyssal plains. These occur where the sediments are not thick enough to cover the underlying rock completely.

(a) Oceanic Ridge System

The oceanic ridge (generally known as **mid-oceanic ridge**), as its name implies, is a mountain that runs through the middle of most of the oceans, between the continents. Oceanic ridge system is a continuous submarine mountain chain that extends approximately 80,000 km through all the world's oceans. This mountain chain lies almost entirely hidden under the waters of the oceans. Individually, ocean ridges are the *largest physiographic features of the ocean basins*.

Oceanic ridges are found in every ocean basin and appear to girdle the Earth. You should note the fact that apart from the *continents* and the *ocean basins* the entire *oceanic ridge system* (Fig. 9.10) constitutes the third most prominent major landform feature on Earth's surface. The ocean ridge is formed where tectonic plates are moving apart from each other, allowing magma to seep out in the space where the plates are pulled apart. Typically a rift runs along the axial zone of this ridge system. There are oceanic trenches and deep valleys, created by the mantle circulation movement from the mid-ocean mountain ridge to the oceanic trench, along some plate margins.

In earlier days, the oceanic ridges were known under the name **mid-ocean ridges**, but many of the largest oceanic ridges, such as the East Pacific Rise are not located along the middle part of the oceans and therefore they are simply called **oceanic ridges**.

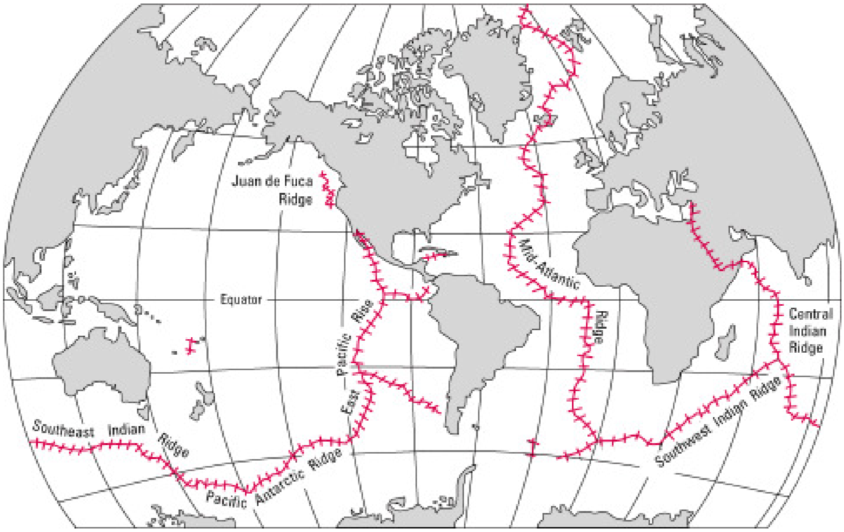


Fig. 9.10: Oceanic Ridge System

The Mid-Atlantic Ridge is a submarine ridge lying along the north-south axis of the Atlantic Ocean. It is a long mountain chain that extends for about 16,000 km in a curving path from the Arctic Ocean to near the southern tip of Africa (Fig.9.10). The ridge is equidistant between the continents on either side of it as it bisects the Atlantic Ocean basin. The mountains forming the ridge reach a width of 1,600 kms. Summits of these mountains sometimes reach above sea level, thus forming the islands or island groups such as the Azores, Ascension, St. Helena, St. Paul's Rocks, and Tristan da Cunha. The submarine ridge of the Indian Ocean known as the **Mid-Indian Ridge** is a direct continuation of the Mid-Atlantic Ridge, and both are segments of the worldwide Oceanic Ridge System.

The ridges rise from ocean floors at depths near 5 km from the abyssal plains and some portions attain widths that measure thousands of kilometres. In general, the summits of the ridges rise to an essentially uniform depth of about 2.6 km. (However, they are even found rising above the ocean waters as already noted). The cross section of ridges is roughly symmetrical. In places, the crests of the ridges are offset across by structures known as **transform faults** indicating lateral displacement. The ridge flanks are marked by sets of mountains and hills that are elongate and parallel to the ridge trend.

New oceanic crust or lithosphere (part of the Earth's upper mantle, together with the crust, makes up the lithosphere) is formed at seafloor spreading centres at the crests of the oceanic ridges. Fresh basaltic lavas are periodically injected along the axial zones of oceanic ridge. These lavas progressively move away from the axis of the ridge, cool and are gradually lowered and buried by sediments as the seafloor spreads away from the site.

(b) Deep Sea Trenches or Oceanic Trenches

These are important topographic features associated with deep ocean basin. The greatest ocean depths occur in great arcuate trenches on the sea floor, bordering some of the continents. Several of these trenches extend to more than 10,000 m below the ocean surface, and they may reach 200 km in breadth and 2400 or more kms in length. Puerto Rico trench of the North Atlantic Ocean is an example. Most trenches are found along the borders of the Pacific Ocean. The Mariana Trench, deepest of all recorded a depth of 11,030 m. (see page 188).

(c) Island Arcs

Subduction of the lithospheric plates occurs at the deep sea trenches and at great depths melting of the plates occurs. The magma rises slowly to the surface forming a curved line of volcanoes which form a string of volcanic islands (parallel to the oceanic trench) known as island arcs. Between the island arc and the adjacent continent there will be a marginal ocean basin, e.g., the Japanese islands.

(d) Abyssal Hills

Small hills having a height of few tens of metres to few hundred metres above the ocean basin floor are called as **abyssal hills**. Abyssal hills may often be found running parallel to mid-ocean ridges and may occur alone or in groups.

(e) Oceanic Rise

Oceanic rises are elevated regions within the ocean floor which do not form a part of a well defined oceanic ridge. These landforms rise several hundred metres above the surrounding abyssal plains and have widths of hundreds of kilometres. The Bermudas Rise, with submarine hills of 40 m to 100 m height and 3 m to 16 km width, is an example.

(f) Sea Mounts

Sea mounts are large, submarine, volcanic mountains that rise at least 1,000 m above the surrounding deep-sea floor (abyssal plain). Seamounts are exceedingly abundant and occur in all major ocean basins. Large numbers of sea mounts are present in the Pacific Ocean. By the late 1970s more than 10,000 seamounts had been reported from the Pacific Ocean basin alone. It is estimated that approximately 20,000 sea mounts exist in the oceans of the world.

Sea mounts that reach the ocean surface become volcanic islands, such as the Hawaiian Islands. Smaller submarine volcanoes are called **sea knolls**, and flat-topped seamounts occurring below ocean surface are called **guyots**. Great Meteor Table mount in the northeast Atlantic, standing more than 4,000 m. above the surrounding terrain, with a basal diameter of up to 110 km, illustrates the size that such features can attain.

(g) Guyots (Table Mounts)

Guyot, (also called table mount), is an isolated submarine volcanic mountain with a flat summit and occurring more than 200 metres below sea level whose top is cut off by the action of surface waves. Such flat tops may have diameters greater than 10 km. (The term 'guyot' is given for these volcanic mountains in honour of the Swiss American geologist, Arnold Henry Guyot.) Guyots occur in large numbers in Pacific Ocean, where most of their summits lie 1,000 to 2,000 metres below sea level.

Guyots originate as volcanic islands at the shallow crests of mid-oceanic ridges and rises. During and immediately after their formation, the islands are truncated by wave erosion and due to seafloor spreading moves laterally to deeper water zones.

(h) Submarine Canyons

These are narrow 'V' shaped submarine valleys with high steep walls and an irregular floor that cuts into the continental slope and deep ocean floor. The origin of the deep, submarine canyons is still in dispute. Submarine valleys (canyons), physically linked to fluvial systems are one of the main routes for sediments to move from coastal zones to the deep oceanic basins. One of the best known submarine canyons is the submerged extension of the Judson Valley of the eastern coast of the United States. Some of the valleys lie 4000m or more below the surface of the ocean. Canyons of this sort are known in both the Atlantic, and also around India and the Pacific Oceans.

(i) Aseismic Ridges

Long, linear and mountainous structures, forming submarine ridges, are known to cut across abyssal plains of some oceans. Earthquakes do not occur within these ridges (that is they are aseismic). Absence of seismicity or earthquake distinguishes these ridges from oceanic ridges.

The best known aseismic ridge is the Hawaiian-Emperor chain of the Pacific Ocean. The Hawaiian-Emperor chain stretches from the Big Island to the intersection of the Kuril (Kurile) and Aleutian trenches in the northwest Pacific. There are roughly 18 volcanoes or seamounts per 1,000 kilometres along the Hawaiian segment and 13 per 1,000 kilometres on the Emperor portion. The Hawaiian Islands are a part of the chain - the youngest part - that rises above sea level. Other prominent aseismic ridges include the Ninety East Ridge and the Chagos-Lakshadweep Plateau in the Indian Ocean and the Walvis Ridge and Rio Grande Rise in the South Atlantic.

Check your progress

1. *Where does the change from continental crust to oceanic crust occur?*
2. *What are the three seaward components of a typical continental margin?*
3. __________ *are the flattest places on Earth.*
4. __________ *is an example of a prominent oceanic ridge in the Atlantic Ocean.*

Let us do

Using a detailed atlas prepare a list of the summits of the Mid-Atlantic Ridge forming islands or island groups and arrange them from north to south.

Prepare a three dimensional model showing the topographical features of the ocean flow.

OCEANIC ENVIRONMENTAL ZONES

The ocean environment is divided into two broad categories, known as realms: (1) the benthic realm (consisting of the seafloor) and, (2) the pelagic realm (consisting of the ocean waters). These two realms are then subdivided into separate zones according to the depth of the water.

Ocean zones are layers within the oceans that contain distinctive plant and animal life. These layers, or "zones", extend from the surface to the most extreme depths, where light can no longer penetrate. They are sometimes referred to as *ocean layers* or *environmental zones*. The physical conditions and type of marine life varies notably in these marine zones. Scientists generally subdivide the ocean into five main layers (Fig. 9.11). The following are the zones in order of depth.

(a) Epipelagic Zone: This is the topmost zone and extends from the ocean surface to 200 metres depth. This surface layer of the ocean receives most of the visible sunlight and therefore it is called the *photic zone*. Light penetration causes heating and therefore a wide range of temperatures occur in this zone. About 90% of all marine life occurs in the photic zone.

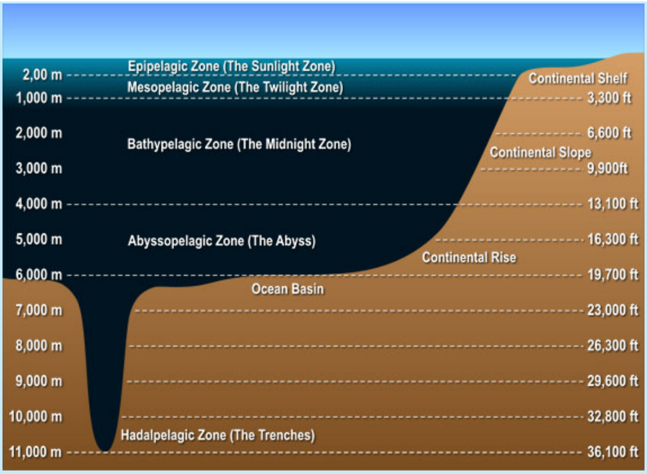


Fig. 9.11: Five main zones of ocean depth

(b) Mesopelagic Zone: Below the epipelagic zone is the mesopelagic zone, extending from 200 metres to 1000 metres. The mesopelagic zone is sometimes referred to as the *twilight zone* or the *mid-water zone*. The light that penetrates to this depth is extremely faint. It is in this zone that we begin to see the twinkling lights of bioluminescent creatures. A great diversity of strange and bizarre fishes can be found in this zone.

(c) Bathypelagic Zone: The third major layer is called the bathy-pelagic zone. It is sometimes referred to as the *midnight zone* or the *dark zone*. This zone extends from 1000 metres down to 4000 metres. Here the only visible light is that produced by the creatures themselves. The water-pressure at this depth is immense. In spite of the extreme pressure, a surprisingly large number of creatures are found here. Sperm whales can dive down to this level in search of food. Most of the animals that live at these depths are black or red in color due to the lack of sunlight.

(d) Abyssopelagic Zone: The next layer is called the abyssopelagic zone, also known as the *abyssal zone*. It extends from 4000 metres to 6000 metres. The water temperature is near freezing point, and there is no light at all in this zone. Very few creatures are found at these depths. Most of these are invertebrates such as basket stars and tiny squids. The deepest fish ever discovered was found in the Puerto Rico Trench at a depth of 8,372 metres.

(e) Hadalpelagic Zone: It is the zone of oceanic environment associated with deepest trenches in the ocean. This zone is found to extend from a depth of around 6,000 metres to the deeper portions of the ocean. The temperature of the water is just above freezing, and the pressure is incredible. In spite of the high pressure and very low temperature, life can still be found here. Invertebrates such as starfish and tube worms can thrive at these depths of the oceans.

9.5. Sediments of the Ocean Floor

Except the crestal zones of the spreading centres where new ocean floor has not existed long enough to allow accumulation of a sediment cover, the ocean basin floor is everywhere covered by sediments of different types and origins. The thickness of sediment on the oceanic crust increases with the age of the crust. Sediment thickness in the oceans averages about 450 metres. The thickness of sediment cover in the Pacific basin ranges from 300 to 600 metres, and that in the Atlantic is about 1,000 metres. Oceanic crust adjacent to the continents can be deeply buried by several kilometres of sediments.

The marine sediments forming today are generally classified according to their location and their source. On the basis of their *location on the seabed*, these are grouped under three categories:

a) **Littoral Deposits:** these are marine sediments formed between the extreme limits of low tide and that of high tide. E.g., beach deposits.

b) **Shallow Water Deposits:** The marine sediments that are deposited on the continental shelves and at similar depths around islands. These are also called **neritic deposits**.

c) **Deep Sea Sediments:** those marine sediments formed beyond the edge of the continental shelves and similar depths around of islands.

Based on the *source of sediments*, marine sediments fall under two broad categories:

(a) **Terrigenous Sediments:** Terrigenous sediments are sediments transported to the oceans by rivers and wind from land sources. Marine sediments deposited near continents cover approximately 25 percent of the seafloor, but they probably account for roughly 90 percent by volume of all marine sediment deposits. These are found forming huge thickness in areas bordering the lands, especially off the mouths of large rivers. These may be swept gently over to the deeper water environments, across the edge of continental shelves. Terrigenous sediments that reach the continental shelf are often temporarily stored in submarine canyons on the continental slope and turbidity currents (density currents) carry these sediments further down into the deeper portions of the oceans and build alluvial fan like **deep-sea submarine fans** in front of the mouths of submarine canyons, along the base of the continental slope. Such deep sea marine sedimentary deposits formed from the action of turbidity currents are called **turbidites**.

(b) Pelagic Sediments: Marine sediments that directly form from the ocean water are called pelagic sediments. These are deposited very slowly in the *open ocean* either by settling through the volume of oceanic water or by precipitation. The sinking rates of pelagic sediment grains are extremely slow because they ordinarily are not larger than several micrometres. Roughly 75 percent of the deep seafloor is covered by pelagic sediments.

Some of the constituents of pelagic sediments of the ocean floor appear to have crystallized directly from the sea water. These are called **authigenic minerals.** The most spectacular authigenic deposits are **manganese nodules**. These have average diameter of 25 cm, and when cut, in addition to oxides of manganese and iron, many oxides of rare elements are also found. In the Pacific floor alone these nodules are estimated to cover 20% of the deep sea floor. These nodules are a potential commercial source of not only of manganese, but also of such rarer elements such as titanium, chromium and so on.

The abyssal plains are also covered with extremely fine grained sedimentary deposits, known as **red clays** or **brown clays**. These clays are not pelagic in origin but are the transported terrigenous sediments, derived from shallow water environments.

Biogenic sediments: These sediments consist largely of the skeletal debris of microorganisms. Most of the pelagic sediments are composed of '**oozes**' – the marine sediments of which at least 30 % is made up of hard parts of very small, often microscopic, organisms. These organisms construct their hard parts using mineral matter extracted from sea water. With the death of the organisms, their hard parts slowly sink to the sea floor. In composition, oozes are of two types: (a) **Calcareous ooze** (consisting of calcium carbonate - $CaCO_3$) and (b) **Siliceous ooze** (consisting of silica or SiO_2). The organic sediments forming in the littoral and shallow water zones are mostly the hard parts of sea weeds, corals, sea urchins etc. Shell deposits accumulate in favourable sites and generally occur as dispersed accumulations in the terrigenous sediments of the littoral and shallow water zones. These later form fossiliferous marine limestone rocks. Limestone ridges of spectacular sizes, formed by the growth of corals, in shallow water zones of the oceans are noteworthy organic deposits.

9.6. Coral Reefs

Huge limestone structures built by certain marine organism called coral polyps are known as coral reefs. These structures are formed by the calcareous skeletons that house the corals (a type of soft-bodied, radially symmetrical, marine invertebrate). Millions of coral skeletons cemented together over a period ranging from a few thousand to millions of years give rise to coral reefs. Reefs can vary enormously in structure and complexity.

Coral reefs are found in the Atlantic, Pacific and the Indian Oceans in tropical zone. However, coral reefs are not randomly scattered throughout each of these great ocean basins. Majority of coral reefs are concentrated in shallow submarine platforms within tropical seas. This is not a coincidence, for the broad-scale distribution of coral reefs is largely determined by the restrictive ecological requirements of reef-building corals. Each species of hard coral differs somewhat in their ability to tolerate variations in these environmental factors, but each does best only within an even more narrowly defined set of "optimal" conditions - and shallow tropical seas are those parts of the oceans where "optimal conditions" for coral growth are most frequently found.

First, the corals that build tropical reefs require sunlight and therefore are found in clear, shallow ocean waters. These needs are tied to the coral animals' dependence upon the algal partners (zooxanthellae) dwelling within the coral tissues. Even in the clearest of tropical seas, most photosynthesis only occurs in the relatively thin uppermost 30 m - 60 m of the water column. Reef-building corals also require warm water. Although many species may survive brief exposures to more extreme temperatures, the limits tolerated for long periods are from about 17^o-34^o C annual temperature regimes.

Types of coral reefs

Three types of coral reefs are recognized viz., (1) Fringing Reefs, (2) Barrier Reefs and (3) Atolls (Fig. 9.12).

(a) **Fringing Reefs**: reefs that grow close to the shore and extend out into the sea like a submerged platform.

(b) **Barrier Reefs**: reefs that are separated from the land by wide expanses of water and follow the coastline.

(c) **Atolls**: a roughly circular ring of reefs encircling a lagoon, a low lying island. They are common in the Indian Ocean and South Pacific Ocean.

Fig. 9.12: Types of coral reefs

Coral Reefs of India

India with its coastline extending over 7,500 kilometers and subtropical climatic conditions has very few coral reef areas. The absence of reef in the Bay of Bengal is attributed to the immense quantity of freshwater and silt brought by the rivers and the heavy monsoonal rains and the high human presence on the coastline.

The mainland coast of India has two widely separated areas having reefs: the Gulf of Kutch in the north-west, which has some of the most northerly reefs in the world and Palk Bay and the Gulf of Mannar (with numerous fringing reefs occurring around small islands) in the south-east.

Important off-shore island groups of India with extensive reef growth include the Andaman and Nicobar Islands in the Bay of Bengal and the Lakshadweep group of islands in the Arabian Sea. The Andaman and Nicobar islands have fringing reefs and a 320 km long barrier reef on the west coast. The Lakshadweep Islands are mostly made up of atolls.

Check your progress

1. *What are the two types of pelagic sediments?*
2. *Sediments formed by settling out of ocean water far from land are called _____.*
3. *What are barrier reefs?*

Let us do

Collect pictures of various types of coral reefs that occur in the neighbourhood of Indian subcontinent.

9.7. Geological Processes of Coastal Zone

Coastal processes are among the most dynamic geologic processes; change in the morphology of many coasts can be observed on annual (or shorter) time scales. The ever-pounding waves generated by winds at sea release tremendous quantities of energy along margins of the continents that constantly modifies the form of its coasts.

9.7.1. Erosional processes of the coastal zone

Erosion, the wearing away of rock, soil and other biotic and abiotic earth materials, occurs in coastal areas as wind, waves, and currents in rivers and the ocean move sediments. Tectonic activity, sea level changes, and force of waves influence the physical structure and nature of coastal landforms. The shoreline is affected by waves and tides. Wave erosion and associated transport of sediments are carried out by the hydraulic action (force of waves pluck rock blocks from headlands), abrasion or corrasion (erosion as clasts cast against headlands) and by attrition (reduction of particle size as clasts bounce in the surf zone).

(a) Longshore current and longshore drift

As a wave crashes on the shore, the water pushes sediment up the beach and then pulls it back down the beach as the water slides back down. Waves generally never approach shoreline parallel to shore. When waves approach the beach at an angle, the part of the wave that reaches shallow water slows down, allowing the part of the wave that is farther offshore to catch up. In this way the wave is refracted (bent) so that it crashes on the shore more nearly parallel to the shore. Due to the wave refraction, wave energy is more concentrated towards headlands (Fig. 9.13), and become diffused in bays. Relatively large waves are found around headlands. Bays have quiet water (good for ship moorings) and are sites of deposition (nice sandy beaches).

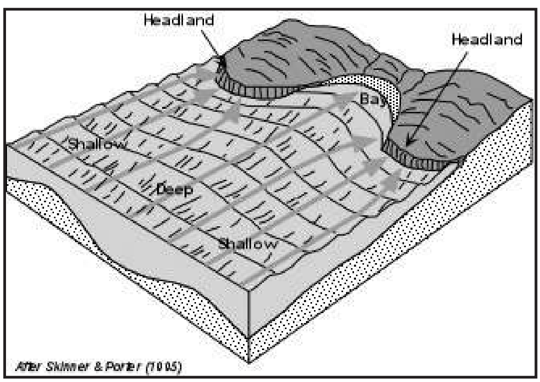


Fig. 9.13: Sea wave refraction in headlands

Longshore current is generated when waves hit the coastline at an angle. Most waves arrive at the shoreline at an angle, even after refraction (Fig.

9.14). Such waves have a velocity oriented in the direction perpendicular to the wave crests, but this velocity can be resolved into a component perpendicular to the shore (V*p*) and a component parallel to the shore (V*l*). The component parallel to the shore can move sediments and this component is called the **longshore current**. **Longshore drift** is the movement of nearshore *sediments* parallel to the shore.

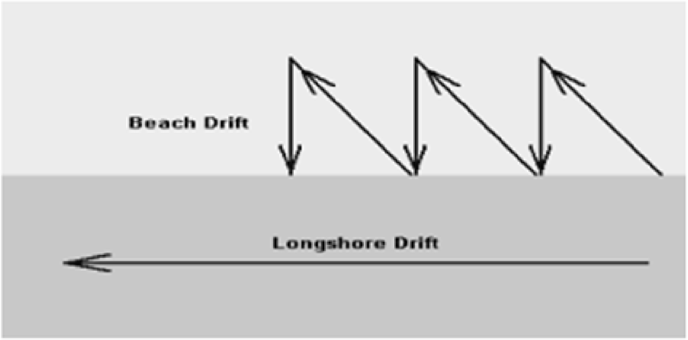


Fig. 9.14: Longshore drift of ocean current

(b) Rip Currents

A rip current (often wrongly called Rip tide) is a strong channel of water flowing seaward from near the shore, typically through the surf line (Fig. 9.15). When waves break directly on a straight coast, there is no place for water to return to sea. The water tends to return in *narrow* straight lines perpendicular to the coast. Such seaward returning currents carry swimmers rapidly to the deeper waters. To escape from such dangerous currents, one should swim parallel to the coast, then use the waves to help return to shore.

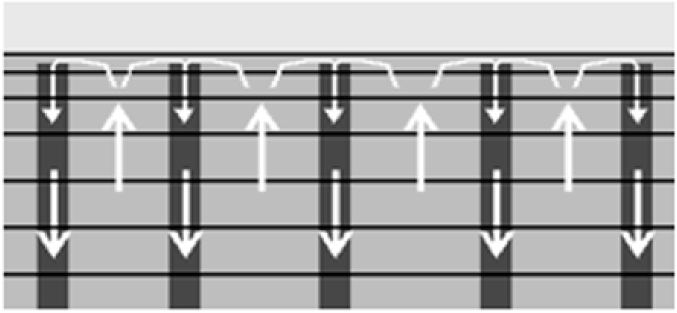


Fig. 9.15: Formation of rip currents

(c) Beach drift

Waves that approach at angles to beach retreat perpendicular to the shore line. This results in the *swash* of the incoming wave, moving the sand *up* the beach in a direction perpendicular to the incoming wave crests and the *backwash* moving the sand *down* the beach perpendicular to the shoreline. Thus, with successive waves, the sand will move along a zigzag path along the beach (Fig. 9.14).

9.7.2. Erosional Landforms of the Coasts

The major erosional landforms found in the coastal zones are described below.

(a) Coastal Cliffs

A cliff is a significant vertical, or near vertical, rock exposure. These landforms result from weathering and erosion. These are the most important features on coasts facing the full force of major storm waves (Fig. 9.16). Here the waves can break directly on the shoreline, and the greatest part of their energy is eroding the land.

(b) Shore Platform or Wave Cut Bench

A wave-cut bench (wave-cut platform, coastal benches, abrasion platform or shore platform) is the narrow, flat area, often found at the base of a sea cliff or along the shoreline that was created by the erosion of waves (Fig. 9.16). The remnant of erosion of headlands occurs at and above the water level. These gentle rock slopes extend from high tide to low tide and become most visible as extensive areas of flat rock at low tides. The landward side of the wave-cut benches is usually found covered by sand, forming a beach.

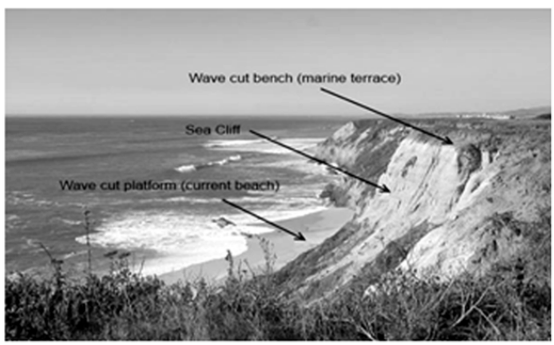


Fig. 9.16: Sea cliffs and wave cut benches

(c) Sea Stacks and Arches

Differential rates of erosion along a coast, with alternate bands of hard and soft rocks results in an irregular coastline with headlands and small bays.

A **stack** is an erosional geological landform consisting of a steep and often vertical column or columns of rock in the sea near a coast (Fig. 9.17). Headlands and cliffs with weaker rocks are more prone to *slump* and erode too fast to form stacks. Harder rocks such as granite would erode without any particular manner and do not form stacks. With wave refraction, headlands are eroded on three sides, causing sections of headland to be isolated as sea stacks.

In areas where differential erosion takes place, the undercutting may initially produces sea caves. Continuous erosion causes these back-to-back caves to extend backward till the sea caves meet and a natural tunnel is produced. The erosion of a cave(s) in a sea stack creates a **sea arch** (Fig. 9.17). The top portion of the sea caves becomes an arch, linking the tip of the headland with the mainland.

Fig. 9.17: Sea stack and sea arch

9.7.3. Depositional Landforms of the Coastal Zone

(a) Beach

A beach is defined as the gently sloping area of land between the high and low water marks. Beaches are formed by a combination of longshore current, which transports sediment parallel to shore within the surf zone, and wave action which bulldozes the sediment shoreward. Although most beaches are composed of quartz sand, the fragments may be pebbles, cobbles, or as large as boulders or composed of some other material such as carbonate skeletal or shell fragments. Higher gradient gravel, boulder or shingle beaches occur at the base of headlands and behind sandy beaches, that is, where there is higher wave energy capable of removing sand.

Beaches could be patchy or could extend for miles along the coastline. It is important to note that the most of the rock fragments on beach comes from land carried by various streams. Landslide, erosion and weathering of the sea cliff also contribute to beach fragments. Sand is carried onshore in the swash; the backwash seeps into the beach and flows seaward which has sufficient energy to suspend and remove only the finer sediments (silt and clay). Thus beaches are a lag deposit of sand drifting along the shore, as the swash commonly is oblique to the shoreline whereas the backwash is always directly seaward (down the beach).

(b) Spit

A spit is an elongate buildup of sediment that develops as a strong longshore current carries sand and silt out across a harbor or bay entrance,

BEACH PROFILE

A beach is comprised of two major parts: the foreshore and the backshore (Fig. 9.18). The foreshore, also called the beach face, is the intertidal seaward portion. The backshore, or berm, is above the high tide line and is covered by water only during storms or unusually high spring tides. The foreshore's slope is steeper, whereas the backshore is nearly flat.

Berm or backshore is simply a terrace formed by wave action along a beach. Berms commonly occur on beaches that have fairly coarse sand. Berms have a marked change of slope at their seaward edge and a flat or reverse-sloped platform that lies slightly higher than the mean high-water level. On broad beaches there may be three or more subparallel berms, each formed under different wave conditions. On some beaches a berm several metres wide may be laid down each summer and destroyed.

There are several zones on the seaward of the foreshore. Farthest out is the breaker zone, where waves coming in from the ocean become steeper and higher and begin to break. Nearer to shore is the surf zone, where waves actually break, and longshore transport occurs.

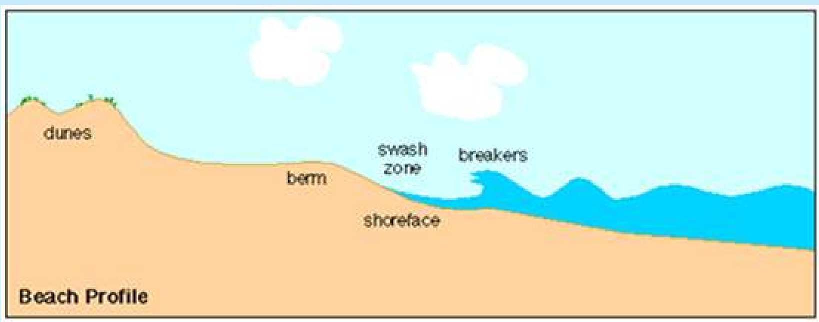


Fig. 9.18: Beach Profile

or from a point of land. Spit is a type of sediment ridge, where one end of the embankment is attached to the land while the other end is terminating in the ocean (Fig. 9.19). The open end of the spit may point landward if strong tides exist, resulting in a hook or recurved spit known as a **hook.**

(c) Baymouth Bar

Spits merge to create bars that extend across the mouths of bays to form baymouth bars (Fig. 9.19). Longshore current is responsible for the shore drift that produces spits and bars along the coast. Wave energy is dissipated on the bar and the bay becomes a lagoon. Lagoons fill with sediment, supporting salt marshes thereby, sediment progrades towards retreating headlands and coastlines become less irregular.

(d) Tombolo

Tombolo is a landform where an *island* is attached to the *mainland* by a narrow piece of land such as spit or bar (Fig. 9.19). A tombolo is formed when a spit continues to grow until it reaches an island, forming a link with the mainland. When both ends of a spit are attached to the headland, it is called **winged headland**.

(e) Barrier Island

A **barrier** is the long term accumulation of marine and aeolian (wind-blown) sediments at and behind the beach. **Barrier islands** are low-lying, elongated sandy islands separating the open ocean from a shallow lagoon and mainland (Fig. 9.19). Bars are usually slightly submerged features while barrier islands don't submerge even during the high tide. Barrier island coasts develop where there is a gentle offshore gradient, slight tidal range, and a low-lying landscape bordering the coast.

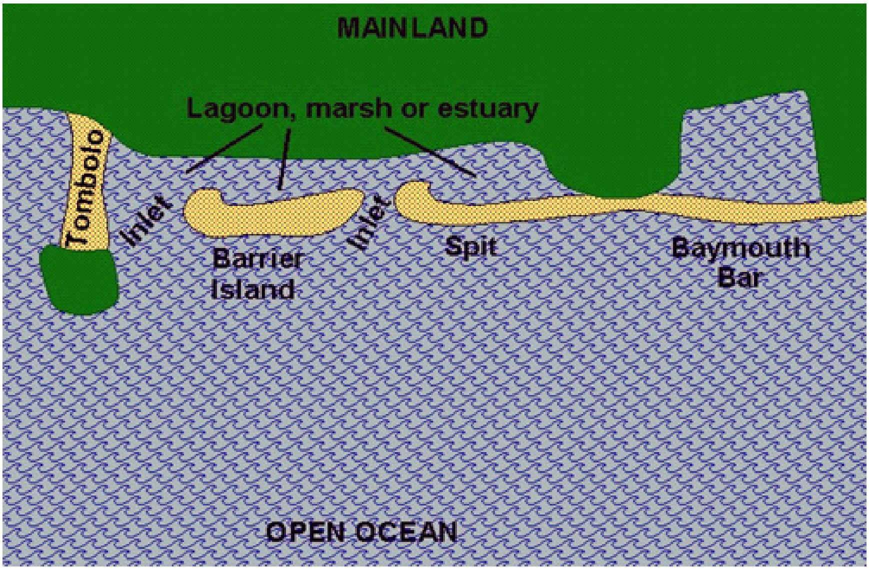


Fig. 9.19: Diagrammatic representation of spit, baymouth bar, tombolo and barrier island

9.8. Sea Level Changes

Sea level is the average height of the ocean relative to the land, taking into account the differences caused by tides. Sea level changes as plate tectonics cause the volume of ocean basins and the height of the land to change. It changes as ice caps on land melt or grow. It also changes as sea water expands and contracts when ocean water warms and cools. Sea level changes over time have expanded and contracted continental shelves, created and destroyed inland seas, and shaped the surface of land.

Reasons for sea level changes include (1) Change in geometry of continents and ocean basins, (2) Change in volume of water in ocean basins, (3) Melting of ice from the cryosphere to oceans, and (4) Change in temperature of water in ocean (1 degree C would increase sea level by ~20 cm). Since industrial revolution, concentration of greenhouse gases have increased in atmosphere and this is believed to increase temperature of atmosphere and oceans. Global average air temperature appears to be increasing. Predicted changes in air temperature for 21st century are of the order of ~3^{o} C.

Local changes in sea level are caused by factors such as (1) subsidence, from groundwater pumping, (2) earth movements (deformation of the crust and big changes during earthquakes) and (3) isostatic rebound from glacial loading (Earth's surface flexes slowly to heavy loads like ice sheets or deposition of sediments in deltas).

Check your progress

1. *Ridge of sand across a bay mouth is called a __________. Similar ridge of sand built up offshore that have a lagoon between it and the mainland is a __________.*
2. *Arrange the following sequences in the correct order of development of these features on a headland.*
   (Sea stack, sea arch, sea cave)

Let us do

Prepare a seminar paper on causes and effects of sea level changes.

9.9. Coast of Kerala

Kerala coast is a mixed coast. Lateritic cliffs, rocky promontories, offshore stacks, long beaches, estuaries, lagoons, spits and bars are characteristics of Kerala coast. The sand ridges, extensive lagoons and barrier islands are indicative of a dynamic coast with transgression and regression in the recent geological past. The central Kerala coast around Kochi is of recent origin. There are about 700 land-locked islands (including barrier islands) in Kerala. A number of barrier islands are present in central Kerala among which the about 25 km long Vypin Island is the major one.

A number of parallel beach ridges alternating with swales are observed in the field. The beach ridge and swale complex is seen especially at southern part of Vypin Island. The width of ridges varies from 50 to 150 m and the height is about 1 m. The width of the swales varies from 50 m to 200 m. These beach ridges represent successive still-stand positions of sea of an advancing shoreline. A new coastal land and well-developed curved spit of 2 km length and 200-400 m wide is observed in the southern part of Vypin Island.

Vembanad lagoon is a major lagoon of Kerala. It extends from Munambam in the north and Alappuzha in the south. The length of the Vembanad lagoon is about 80 km and the width varies from a few hundred metres to 14.5 km. The depth varies from <1m to 14m.

The **mudbanks or *chakaras*** of Kerala are unique transient nearshore features appearing during monsoon season. Though there are 41 rivers bringing enormous quantity of sediments, deltas are not formed due to the high energy condition of the coast. Cochin-Vembanad is one of the largest estuarine systems in the country. Ashtamudi is another major estuary in Kerala. It is estimated that 30 kms of the coast is undergoing high erosion and 21 kms is accreting. Though the Kerala coast is described as a mangrove forest in the resource history, it is left with just 16 sq. kms of mangroves restricted mainly at Valapattanam and Puthuvaipu (Kochi).

Let us sum up

Oceans and seas cover ¾ of the total surface area of the earth. Major oceans are Pacific Ocean, Atlantic Ocean and Indian Ocean. Continental shelf, continental slope, continental rise and abyssal plain are the major zones recognized in the ocean floor. Mid oceanic ridges, Deep sea trenches, Guyots, Submarine Canyons and Island arcs are the major topographic features present on the ocean floor.

Wind blowing over the surface of the ocean forms waves which transfer some of the wind's energy to the coastline. Tides result from the gravitational attraction of the sun and the moon on the oceans.

The most common coastal landscapes are cliffed coastlines of headlands and bays and barrier island coasts. Over time, coastlines of headlands and bays are straightened by erosion of headlands and deposition in the bays. Wave refraction concentrates wave energy on the headlands and disperses it in bays. As waves erode the softer rock in cliffs, they form caves and arches. Stacks form when arches collapse. As the cliffs erode backward, they leave a wave-cut abrasion platform at the base. In deeper water, a wave-built depositional terrace forms.

Waves that approach the coast at an angle cause beach drifting and longshore currents in the surf zone, which create a variety of depositional features such as spits, baymouth bars, and beaches.

Ocean floor contains several sedimentary deposits such as manganese nodules. Coral reefs develop from calcareous organisms growing in warm, clear water in tropical areas. Coral may take the form of fringing reefs, barrier reefs, or atolls.

Significant Learning Outcomes

The learner can:

- identify that ocean forms the major part of the globe.
- explain the composition and properties of the ocean water.
- differentiate the topographic features present on the ocean floor.
- explain the types of sediments found in the ocean.

- recognize the various geological processes and landforms of the coastal zone.
- identify the characteristics of the Kerala coast.

Let us assess

I. Fill in the blanks

(a) __________ is the mound of sand that links a small offshore island to the mainland.

(b) Erosion along a shoreline can form a flat platform of rock that gets exposed at low tide and is called a __________.

(c) Flat-topped and extremely steep-sided isolated volcanic mountains present in oceans are known as __________.

2. Name any two features that result from longshore drift.
3. What are the factors that would lead to sea level rise?
4. What are the three types of erosive processes along shore lines?
5. Why do the waters in estuaries have a higher salinity than normal sea water?
6. How are coral reefs formed?
7. Say whether the following statements are true or false.

   a) Longshore currents are caused when waves strike the beach at an angle.

   b) Tides occur at the same time each day.

10

MOUNTAINS

10.1. Introduction

The earth's relief features of first magnitude are the continents and ocean basins. The principal relief features of the continents are the mountains, the plateaus and plains which are known as second-order features. Internal earth processes such as diastrophism, magmatism and external earth processes such as weathering and erosion result in the formation of land forms with towering heights that stretch above the surrounding land. Mountains constitute the most conspicuous relief features of the earth.

10.2. Mountains and related terms

In physiography, any structure of rock mass raised to a conspicuous elevation relative to its surrounding area is termed a hill or mountain. The difference between a hill and a mountain is again relative. Hills of exceptionally high elevation may be termed as mountains. Structures raised up to a relative height of 300 m may be termed as hills and structures with greater relief as mountains e.g., The Himalayas, The Alps, etc.

In topography, a **summit** is a point on a surface that is higher in elevation than all points immediately adjacent to it. The topographic terms "acme", "apex", "peak" and "zenith" are synonyms. The term "summit" is generally used only for a mountain peak with some significant amount of topographic prominence. A **mountain peak** is a more or less cone-shaped mountain mass, i.e., it is a tall mountain with a pointed or narrow top. A mountain ridge is a relatively elongated, narrow mountain mass. It is also known as **mountain range**. When a number of mountain ranges and ridges continue for extensive distances for thousands of kilometers maintaining their characteristic features throughout, the resulting complex structure is called a **Mountain Belt** or **Mountain Chain**. A **mountain system** consists of two or more mountain ranges, of the same (or nearly the same) period of origin, belonging to a common region of elevation and generally either partial or in consecutive lines. **Cordillera** is a general combination of chains, systems and ranges in one general portion of a continent. A cordillera is made of several inter-related mountain chains.

10.3. Classification of Mountains

Mountains are broadly classified into two on the basis of their mode of origin. They are (a) Tectonic Mountains and (b) Relict Mountains. The process of mountain building is known as Orogeny.

a) Tectonic mountains

These mountains are formed due to the severe internal earth forces. This group includes: (i) Volcanic mountains, (ii) Fold Mountains, (iii) Fault Mountains (Block Mountains) and (iv) Dome Mountains.

i) Volcanic Mountains

The mountains that have been built up by the accumulations of igneous materials around the vents of volcanoes are called volcanic mountains (Fig. 10.1). In many cases, the volcanic mountains are made up of alternate layers of lava and fragmental materials. Volcanic mountains are symmetrical with respect to a central peak. Many volcanic mountains are found in Japan, USA and Philippines. Mount Vesuvius, Mount Etna and Mount Fuji are a few examples. The Hawaiian Islands represent the highest parts of a great, largely submarine volcanic mountain range hundreds of kilometres long.

Fig. 10.1: View of a volcanic mountain

ii) Fold Mountains

Most of the great mountain ranges of the Earth belong to the category of fold mountains. These are also called complex mountains. Folding of strata, accompanied by general uplift and consequent erosion are the important stages in the formation of fold mountains (Fig. 10.2).

Materials present in the fold mountains consist mainly of stratified rocks, i.e., sandstone, shale, conglomerate and limestone. These sediments were deposited in very large depressions known as **geosynclines** with a thickness of strata being more than thousands of feet. The deposition must have continued for millions of years. These sediments were deposited mainly under sea water. Therefore folded mountains contain several marine fossils. The sediments deposited in the Tethys Sea were uplifted during the formation of the Himalayas. During and after their formation, these mountains have been repeatedly bent, warped and faulted leading to the present day most complicated structures exhibited by folded mountains.

Fig. 10.2: Fold Mountains

The Himalayas, the Alps in Europe, the Rocky Mountain in North America, the Andes in South America, the Appalachian mountain and the Urals in Russia are all examples of folded mountains.

iii) Fault Mountains (Block Mountains)

Many mountain ranges are caused either partly or wholly by faulting, whereby great earth blocks are made to stand out in relief. Such blocks are often tilted, and they are called Fault Mountains or Block Mountains. These are a result of tensional forces of considerable magnitude. Faulting always results in relative displacement of blocks of the crust of the earth along a plane of rupture. Sometimes this displacement is lateral and at other times it is vertical or oblique. In some cases, a central rectangular or wedge shaped block stands elevated after faulting. The upthrown blocks are called Horsts which form Block Mountains and the downthrown blocks are called Graben, which form Rift Valleys (Fig. 10.3).

Horst and grabens are often complimentary structures. These types of mountains are typical in occurrence in the Basin and Range province of

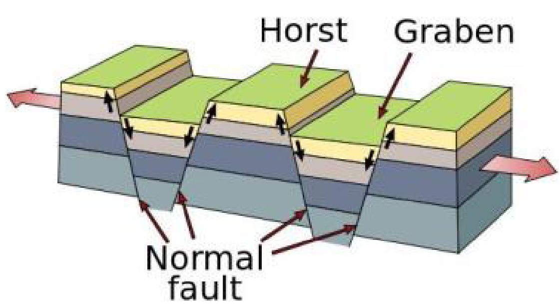


Fig. 10.3: Horst and graben structure

USA. Fault-block mountains often result from rifting which is an indicator of tensional tectonic forces (Fig. 10.4). These can be small or form extensive rift valley systems. A great example of Fault or Block Mountains is the Sierra Nevada Mountains that are located in California. The mountains of Salt Lake City of Utah in North America are also Fault/Block Mountains (Fig. 10.5).


Fig. 10.4: Fault Block Mountains


Fig. 10.5: Fault Block Mountains of Salt Lake City, Utah

iv) Dome Mountains

Dome mountains are also called upwarped mountains. These mountains are formed when large amounts of molten rock or magma push the earth's crust from underneath. The magma in this case never reaches the top surface of the earth. The Black hills of South Dakota in the USA and the Adirondack mountains in New York are example of dome mountains.

b) Relict mountains

In the extensive plateaus or highlands, the different geological agents cause large scale erosion. The highlands made up of softer rocks are worn out, whereas those made up of harder rocks are preserved. In this way the hard rocks form elevated landmasses, called **erosional mountains**. These are also known as **relict mountains** or **residual mountains** e.g., the Eastern Ghats, the Western Ghats (Fig.10.6) and the Vindhyan mountains.


Fig. 10.6: Relict Mountains (Western Ghats)

Let us do

Make a list of different types of mountains found on the earth's surface.

Let us sum up

Any structure of rock mass raised to a conspicuous elevation relative to its surrounding area is termed a hill or mountain. On the basis of origin of mountains, there are two types, viz., Tectonic Mountains and Relict Mountains. Tectonic mountains are formed due to severe internal forces. Three types of tectonic mountains are recognized: Volcanic Mountains, Fault Mountains and Fold Mountains. Volcanic mountains are formed due to the accumulations of volcanic materials. Fault Mountains are formed due to the process of faulting whereas Fold Mountains are very complex mountains formed due to folding of strata, their uplift and erosion, e.g., the Himalayas, the Alps. Relict mountains are formed due to large scale erosion. The remains of harder rocks are preserved as Relict Mountains, e.g., the Eastern and Western Ghats.

Significant Learning Outcomes

The learner can:

- identifiy different types of mountains and its types.
- explain the formation of different types of mountains.

Let us assess

1. Match the three columns given below.

A	B	C
Mountains of Accumulation	Tectonic movements	Western Ghats
Relict Mountains	Volcanoes	Compression
Orogeny	Large scale erosion	Pyroclastic mountains

2. The Himalayas is an example for __________ Mountains.
3. The Western Ghats is an example for __________ Mountains.
4. Differentiate between Horst and Graben.
5. Distinguish between volcanic mountains and relict mountains with examples.

11 THE DYNAMIC EARTH

11.1. Introduction

As a result of expeditions and explorations to unknown parts of the Earth, the first world maps were created over 350 years ago. Explorers and scientists who read these maps noticed something odd. They noticed that the edges of some continents and landmasses seem as though they could 'fit' together. A careful observation of a globe often reveals the fact that most of the continents seem to fit together like pieces of a jig-saw puzzle. The western coastline of Africa seems to fit perfectly into the eastern coast of South America. The fit is even more striking when the submerged continental shelves of the respective continents are compared rather than the coastlines.

11.2. Continental Drift Hypothesis

The theory of continental drift, postulated that there were large-scale, slow horizontal movements of continents during the geologic past, changing their positions relative to one another, and to the poles of the earth.

Everyone in the past believed that the landmasses (continents) were stationary, and also that there are no evidences to show any kind of lateral movements of continents. When a mapping of the Atlantic Ocean, showing the margins of neighbouring continents was almost completed, it was noticed that its opposite coasts had similar shapes. The bulge of eastern South America fitted nicely into the bight of Africa (Fig. 11.1). As you can see in the figure, the coastlines of South America and Africa nicely match as if they are pieces of a jigsaw puzzle.

Fig. 11.1: Coast lines of South America and Africa fitting with each other similar to a jigsaw puzzle

When accurate maps of the Atlantic Ocean floor were prepared during the middle of the 19th century, it became clearer that the opposite sides of the ocean (South America and Africa) could be fitted together quite closely, if the shallow underwater continental shelf which extends around their coastlines, is also taken into consideration.

Scientists started giving answers to the questions: Is this just a coincidence or were the continents really once joined? Why did they separate? And what is the mechanism that pushed them apart to their current positions? Convincing answers to these questions were only given within the last fifty years and revolutionized our understanding of the planet. The first truly detailed and comprehensive theory of continental drift was proposed in 1912 by Alfred Wegener (1880-1930), a German meteorologist (Fig. 11.2).

Fig. 11.2: Alfred Wegener

Studying global maps, Wegener noticed (like several others before him) that the continents of Africa and South America look like pieces of a jigsaw puzzle. Of course, his idea was not really a new one. The widespread distribution of certain rock formations and fossils in different continents further convinced him that all the continents had once been joined together into a single proto-continent which he called Pangaea (meaning "all lands") Pangaea was surrounded by an ancestral ocean - Panthalassa and also that over time they have drifted apart into their current positions. He believed that Pangaea was intact until the Jurassic period - some 200 million years ago, when it began to break up and the resulted fragments drifted apart.

Wegener offered several convincing lines of evidences in support of his proposal. Perhaps Alfred Wegener's greatest contribution to the scientific world was his ability to weave seemingly dissimilar and unrelated facts into a theory, which was remarkably visionary for his time. Wegener was one of the first to realize that an understanding of how the Earth works required input and knowledge from all branches of the Earth Sciences.

11.2.1. Evidences for Continental Drift

The following are a list of the evidences supporting continental drift.

(a) Fit of continental margins

(b) Similarity of rock sequences and structural features

(c) Palaeoclimatic evidences

(d) Fossil Evidences

Let us briefly discuss each one, in the following paragraphs.

(a) Fit of continental margins

Wegener's theory was based in part on what appeared to him to be the remarkable fit of the South American and African continents, first noted by Abraham Ortelius three centuries earlier. As mentioned earlier, the continental slopes of South America and Africa at 2,000 meters depth neatly match in shape like pieces of a jigsaw puzzle (Fig. 11.3).

Fig. 11.3: The fit of neighbouring continents across the Atlantic Ocean

(b) Similarity of rock sequences and structural features

Some mountain chains that end abruptly at the edge of a continent can be traced to continue on another continent located on the other side of an ocean. Similarly, the rock types, structural features (fold, fault, etc) as well as the ages of rock units of one continent can be correlated across the intervening oceans with those of the adjoining continents. An example of termination of mountain belts is shown in Fig. 11.4. The Appalachian Mountain Range of North America stretches northward from the eastern United States up into the Atlantic provinces of eastern Canada. There, it seems to suddenly stop at the island of Newfoundland. Very similar mountain ranges of the same age and rock-type also appear in eastern Greenland, Ireland, Great Britain, and Norway. When these landmasses are placed together, the mountains form a single, long range.

Fig. 11.4: Termination of mountain belts (shaded dark)

(c) Palaeoclimatic evidence

Rock deposits whose formation is restricted exclusively to certain climates (such as glacial till, coal deposits, and evaporites) have been found in areas having very different climates today. Glacial deposits of Palaeozoic age covered portions of South America, Africa, India, Antarctica, and Australia. Other rock deposits (for e.g., coal deposits indicative of luxuriant vegetation and evaporites indicating arid climate) show matches across the continents of Northern Hemisphere indicating a tropical climate (location near equator) when these were formed.

Some of the most telling climatological evidences for continental drift come from the continents of South America, Africa, India, and Australia. All of these continents show evidence of past glaciations (ice age). An observation favouring continental drift was the evidence for a continental glaciation during the Carboniferous period. Glacial striations are formed, (as you have already learnt in unit 8), when large boulders are dragged along beneath moving glaciers. As continental glaciers move, they drag the rock fragments along and scratch the underlying surface creating grooves parallel to the direction of movement of the glacier. Glacial striations left by Carboniferous glaciers over the land surface are known to occur in South Africa, South America, Peninsular India and the island continent of Australia. Wegener showed that, although glacial striations do indeed indicate that all these landmasses experienced continental glaciations at about the same time (during the Permo-Carboniferous times), in their current positions the directions shown by the striations point to continental glaciers that existed in different geographic locations (note the directions of the arrows in Fig. 11.5).

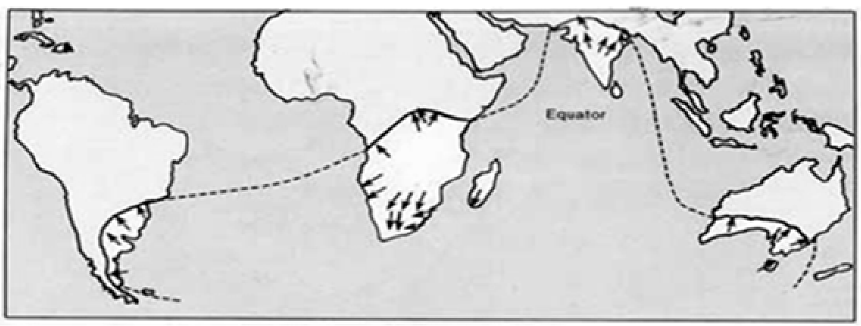


Fig. 11.5: Directions of glacial striations of Permo-Carboniferous time in southern continents

However, when the continents were reassembled and aligned to their former positions to their pre-drift condition (of Permo-Carboniferous time) the striations point to a single geographic location, indicating the centre of continental glaciation (Fig. 11.6).

Fig. 11.6: Reassembly of southern continents during Permo-Carboniferous times

Other palaeoclimatic evidences include geographic distribution pattern of deposits of coal, desert sandstone, deposits of rock salt, wind-blown sand, gypsum, and glacial deposits.

(d) Fossil Evidences

A fossil is any evidence of ancient life. Identical fossilized plant and animal species have been found in many different places, on different continents. Wegener came across a scientific paper suggesting that a land bridge had once connected Africa with Brazil. This proposed land bridge was an attempt to explain the well known palaeontological observation that the same fossilized plants and animals belonging to same portion of the earth's history were found in South America and Africa. The same was true for fossils found in Europe and North America, and Madagascar and India. It seems hard to believe that similar organisms would exist so far away from each other, or that they could have swam from one continent to another. Many of these organisms could not have traveled across the vast oceans that currently exist. Wegener's drift theory seemed more plausible than land bridges connecting all of the continents. When the continents are put together, the areas where some fossil organisms are found match across the line of joining indicating that these life forms once lived all together on a single continent, as shown in the following figure 11.7.

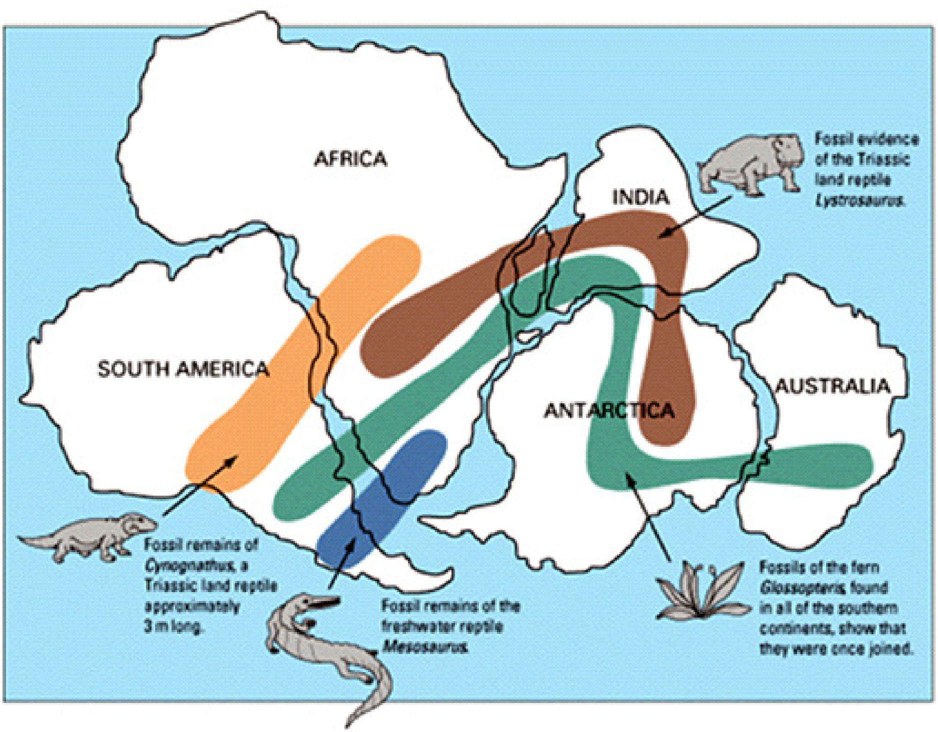


Fig. 11.7: Geographic distribution pattern of fossils in southern continents

Distribution of fossils provides the most compelling evidence for continental drift. Almost identical assemblage of plant fossils (known as Glossopteris flora) have been found in sedimentary rock formations of equivalent ages of the present day southern continents only. Its extensive pattern of dispersion in regions which are now widely separated by oceans seemed impossible to explain. Although some thought the wind might have carried the seeds a long way, the seeds of the plants of extinct Glossopteris flora were too large to have been carried by wind across oceans.

Geographic distribution patterns of vertebrate fossils such as mesosaurus (an extinct freshwater reptile) and those of other land-dwelling reptiles, also point to former linkages of South America, Africa and Antarctica. Moreover, the discovery of fossils of tropical plants (in the form of coal deposits) in Antarctica led to the conclusion that this frozen land previously must have been situated closer to the equator, in a more temperate climate where lush, swampy vegetation could grow. Other mismatches of geology and climate included distinctive fossil ferns (a variety of plants). Wegener was aware of reports that fossils of plants that once grew in humid, hot climates were being discovered in polar areas and that fossils from colder climates had been found in hot, equatorial climates. Wegener knew that scientists studying the fossil record of certain plants and animals were finding distribution of fossils in narrow geographic zone that stretched across several continents. The rocks of same age in South America and Africa when juxtaposed across ocean basins show a characteristic distribution pattern.

11.2.2. Evaluation of the Continental Drift Hypothesis

If the continents were pushed together, the geological, fossil, and other lines of evidence would join together accurately in the way that lines of print on a torn newspaper would join when the paper was reassembled. Bringing together a large mass of geologic and palaeontological data, Wegener postulated that throughout most of geologic time there was only one ancestral super continent, (which he called Pangaea) and also supposed that the ancestral continent began to break apart or fragment about 200 million years ago in the Earth's history and the parts began to move away from one another. Westward drift of the Americas opened the Atlantic Ocean, and the Indian peninsula drifted north and merged with the Eurasian continent resulting in the formation of the Himalayas. The figure 11.8 depicts the drifting of continents with time.

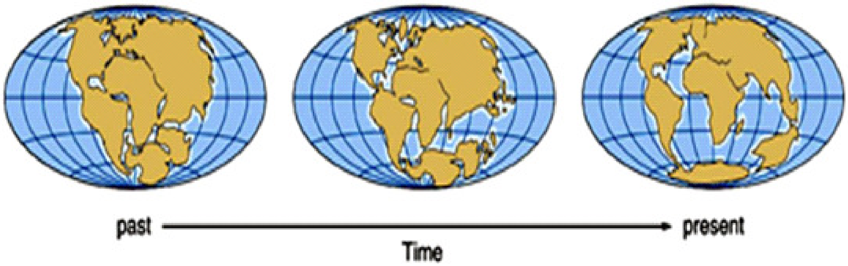


Fig. 11.8: Drifting of continents with time

The continental drift hypothesis also provided an alternate explanation for the formation of mountains (orogenesis). The theory being discussed during his time was the "Contraction theory" which suggested that the Earth was once a molten ball and in the process of cooling the surface cracked and folded up on itself. The big problem with this idea was that all mountain ranges should be approximately the same age, and this was known not to be true. Wegener's explanation was that as the continents moved, the leading edge of the continent would encounter resistance and thus compress and fold upwards forming mountains near the leading edges of the drifting continents. Wegener also suggested that Peninsular India drifted northward into the Asian continent thus forming the Himalayas.

Wegener also proposed a mechanism for continental drift as a centrifugal force towards the equator. He believed that Pangaea originated near the South Pole and that the centrifugal force of the planet resulting from the rotation of the earth caused the break up and the resultant drifting of continental blocks towards the equator. He called this the *Polflucht* or "pole-fleeing force". This idea was quickly rejected by the scientific community primarily because the actual forces generated by the rotation of the earth were calculated to be insufficient to move continents.

The concept of continental drift led to heated controversy during 1920's and 1930's. At the time Wegener introduced his theory, the scientific community firmly believed the continents and oceans to be permanent features on the Earth's surface. Wegener's hypothesis could not provide an explanation for a geological mechanism causing the movement of continents across the earth's surface. The weakness of Wegner's theory, and the reason it was not readily accepted by geologists was that he proposed that the continents slide over ocean floor. Not surprisingly, his proposal was not well received, even though it seemed to agree with the scientific information available at the time. A fatal weakness in Wegener's theory was that it could not satisfactorily answer the most fundamental question raised by his critics: What kind of forces could be strong enough to move such large masses of solid rock, such as a whole continent over great distances? Wegener suggested that the continents simply plowed through the ocean floor, but Harold Jeffreys, a noted English geophysicist, argued correctly that it was physically impossible for a large mass of solid rock to plow through the ocean floor without breaking up.

However, some geologists supported and accepted the idea of continental drift and they kept the subject alive although, most geologists and geophysicists either ignored or condemned it. Opponents regarded the idea of continents moving about through solid rock as so unbelievable and absurd. Wegener's theory was largely dismissed as being eccentric, preposterous, and improbable. Major evidence of continental drift was in the Southern Hemisphere and most geologists lived in the Northern Hemisphere. They also ignored all his other arguments, many of which, it is now clear, were essentially correct.

Check your progress

1. *What are the evidences that Wegener collected to substantiate the drifting of continents?*
2. *What was the driving force according to Wegener that caused the continental drift?*

Revival of the Continental Drift Hypothesis

Review of continental drift hypothesis was conducted in an international symposium (a meeting of experts) held by the American Association of Petroleum Geologists in 1928. Although the main organizers of the meeting were in favor of the continental drift idea, there were a lot of heated arguments about the existing data and what it meant. (That happens sometimes when you get a lot of scientists together!). Idea of continental drift was largely abandoned by 1929 because of the lack of a reasonable driving mechanism for continental motion (Wegener believed that continents plowed their way through oceanic crust under tidal energy). Undaunted by rejection, Wegener devoted the rest of his life to steadfastly pursuing additional evidence to defend his theory. Wegener died in 1930, (on a meteorological expedition to Greenland to establish a winter weather station to study the jet stream in the upper atmosphere), but the controversy he ignited raged on.

Among those who supported Wegener, was the South African geologist Alex L. Du Toit. The Wegener's hypothesis was refined by Du Toit (1937) who proposed that there had been two ancient supercontinents: **Gondwanaland** in the Southern Hemisphere (comprising the Indian peninsula, Australia, Antarctica, Africa, the island of Madagascar and South America) and **Laurasia** (comprising North America, Greenland, Europe, and most of Asia) in the Northern Hemisphere. (This concept was based on similar ages for glacial deposits on Gondwana landmasses and coal deposits on Laurasia landmasses).

In 1928, Arthur Holmes, a Scottish geologist and Professor at the University of Edinburgh, elaborated the concept of continental drift by introducing the idea thermal convection within the mantle. (Convection, along with conduction and radiation, is one of the three methods of heat transfer. Convection takes place through the actual movement of matter. This means that convection can only take place in fluids and not in solid matter). This idea is based on the fact that as a liquid is heated from below its density decreases with the temperature increases upward until a critical temperature gradient is formed. When the temperature is increased even further, thermal circulation currents form and rise to the base of the continent and cooled and sinks again. He suggested that convection currents associated with a number of convection cells formed in the mantle could provide the mechanism and enough energy to power continental drift. A convection cell is a system in which a fluid is warmed, loses density and is forced into a region of greater density in which upward motion of

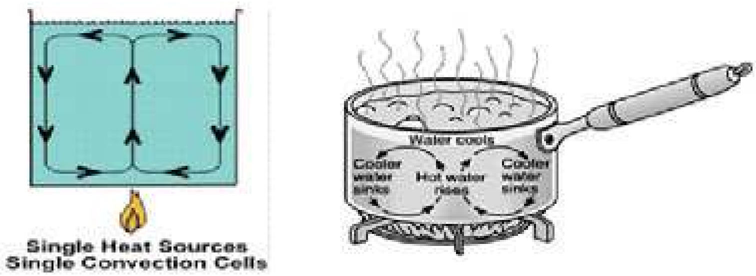


Fig. 11.9: Idea of thermal convection currents

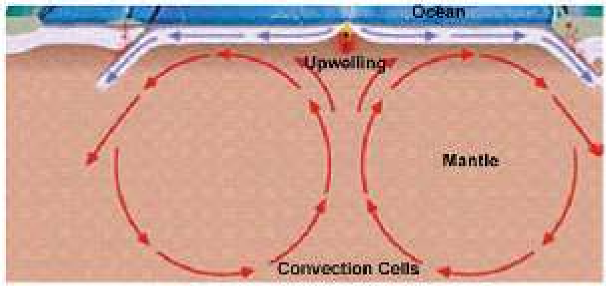


Fig. 11.10: Earth's thermal convection currents

warmer fluid in the centre is balanced by downward motion of cooler fluid at the periphery. Figure 11.9 gives you an idea of how the thermal convection currents work. Arthur Holmes suggested that this thermal convection was like a conveyor belt and that the upwelling pressure could break apart a continent and then forces the broken continent in opposite directions and to be carried by the convection of the upper segments of currents. This idea also received very little attention at the time. The diagrammatic representation of working of Earth's thermal convection current is shown in Figure 11.10.

Let us do

1. *Try to assemble the present day continents and reconstruct the hypothetical super continent, Gondwanaland and Laurasia by bringing a world map.*
2. *Collect relevant points in favour and against the continent drift hypothesis so as to conduct a debate on the topic.*

11.2.3. Subsequent Developments

Detailed mapping of the ocean floors began in the 1950s using echo-sounding techniques. This allowed topography of the ocean floor to be determined in more detail. Discoveries of features like mid-oceanic ridges, geomagnetic anomalies parallel to the mid-oceanic ridges, and the association of island arcs and oceanic trenches occurring together and near the continental margins, provided greater understanding of the ocean floor. During 1960's Arthur Holmes' idea of thermal convection received renewed attention as subsequent discoveries indicated that mantle convection might indeed be a possible mechanism. Harry Hess (1962) and R. Deitz (1961) published revised hypotheses on mantle convection currents, now known as "sea floor spreading". This idea was basically the same as that proposed by Holmes over 30 years earlier, but now there was much more evidence to further develop and support the idea. These can be summarized as follows:

(a) Extension of Mid-Atlantic Ridge

At first, only the portion (now known as the Mid-Atlantic Ridge) of the mid ocean ridge was inferred in 1850 followed by its discovery in 1872 during the expedition of HMS Challenger and further confirmation in 1925 by sonar. Initially it was thought to be a submarine feature specific to the Atlantic Ocean. However, by 1950s, when the mapping of the Earth's ocean floors was completed, it was found to be only a part of the longest and world encircling submarine mountain range traceable on the floors of all the oceans with a total length of 80,000 km.

(b) Seafloor spreading and relatively youthful nature of the ocean floor and recycling of oceanic crust

In the Deep-Sea Drilling Project (which began in 1968) many sediment and rock cores from the ocean floor have been obtained. The studies of the sediments and rock samples led to the following discoveries:

(1) The age of the ocean floor (located below the sediments) varies with location and is consistently younger at the oceanic ridges and older along the ocean margins (i.e., the ocean crust gets progressively older when traced away from the mid ocean ridges and the age increases symmetrically with distance from the ridge system).

(2) Analysis of rock samples from the ocean floor reveals that the oceanic crust is relatively young in comparison to the continents. The oldest oceanic rocks are less than 200 M yrs (million years) old. In contrast the maximum age of the continental crust has been established as four billion years (4,000 million). Oceanic rocks along the North American and African coastlines are approximately 180 M yrs old whereas rocks adjacent to the ridge may be less than one million years old.

(3) Ocean sediments are absent at the axial portion of the oceanic ridge.

(4) These oceanic sediments get progressively thicker away from the ridge.

(5) The absence of rocks older than 200 M yrs was interpreted to suggest that all of the older oceanic crust has been destroyed. This suggests that Earth has a crustal recycling system that constantly creates young crust at oceanic ridges and destroys old oceanic crust elsewhere.

(6) The presence of the older oceanic floor along the trenches was used to infer that the oceanic lithosphere was being consumed at the trenches. Scientists had long recognized that volcanoes and earthquakes were present in greatest concentrations around the rim of the Pacific Ocean (Ring of Fire). Seismologists Kiyoo Wadati and Hugo Benioff noted that the focal depths of earthquakes became progressively deeper underlying ocean trenches (Fig. 11.11).

1. Aleutian
2. Kurile-Japan
3. Mariana
4. Philippine
5. Bougainville
6. Tonga-Kermadec
7. Central America
8. Peru-Chile
9. PuertoRico
10. South Sandwich
11. Java

Fig. 11.11: Distribution of ocean ridges (white) and trenches (red)

The downward movement of the oceanic crust caused earthquakes down to depths of 700 to 800 km, explaining the presence of the deepest earthquakes adjacent to oceanic trenches. The term subduction zone was coined to refer to locations marked by Wadati-Benioff zones where the oceanic lithosphere is consumed adjacent to a trench. These discoveries eventually led to the Theory of Sea Floor Spreading.

11.3. Sea Floor Spreading

During the 1950s, subsequent development of geological studies caused a resurgence of interest in continental drift. The main reasons for this were due to the emergence of the theory of seafloor-spreading and associated recycling of oceanic crust; and the precise documentation that the world's earthquake and volcanic activity is concentrated along oceanic trenches and submarine mountain ranges. The theory of plate tectonics grew out of earlier hypotheses and observations collected during exploration of the rocks of the ocean floor.

The Theory of Sea Floor Spreading postulates that the ocean floors are spreading and moving away from the oceanic ridges (propelled by thermal convection cells in the mantle) and that ocean crust is continuously created along the axial portion of the oceanic ridges and destroyed at deep sea trenches (Fig. 11.12).

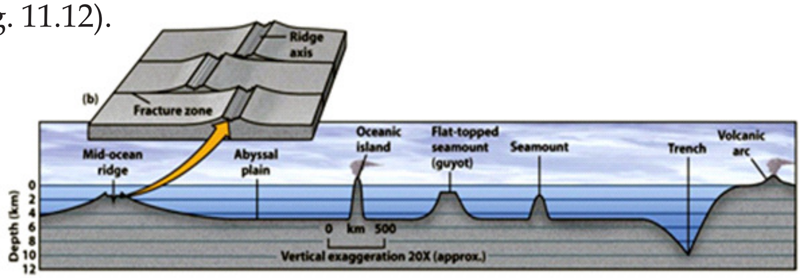


Fig. 11.12: Topography of ocean floor showing oceanic ridges (where oceanic crust is continuously created) and trenches (where oceanic crust is destroyed)

The mechanism was first described in 1960 by Princeton Professor Harry H. Hess. He developed the theory (supported or explained by palaeomagnetism, discussed further below), to explain the topographic features of the ocean floor and (the pattern of alternating stripes of normal and reversed polarity rocks on either side of the oceanic ridges) and increasing age of the oceanic crust with increasing distance from the ridge. Rates of sea-floor spreading vary from almost 2 cm/yr in the North Atlantic to more than 18 cm/yr in some sections of the Pacific oceanic ridge. Sea floor spreading provides a driving force for continental movement (Fig. 11.13), (continents ride on plates which are driven by the Earth's internal energy, as passive passengers).

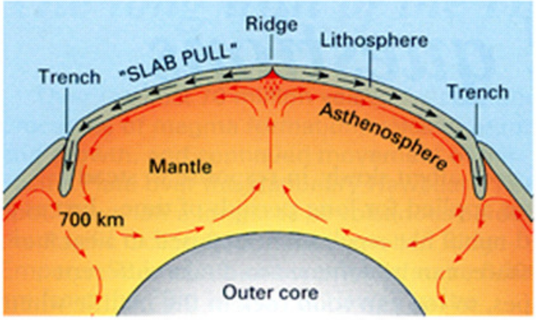


Fig. 11.13: Driving force behind sea floor

If ocean floor is being created at ocean ridges, surely somewhere it must get destroyed in order to keep the area of the Earth constant. (Otherwise, the Earth will gradually expand in volume day by day!).

The destruction happens at deep sea trenches which forms the so called "subduction" zones (Fig. 11.14). Here, oceanic crust turns down and slides back and is destroyed at depth and forms a part of the mantle layer which lies under the overlaying plate. The presence of guyots (submerged, flat-topped volcanoes) in the neighbourhood of deep sea trenches showing inclination towards the trench (like the Leaning tower of Pisa) affords another evidence of subduction of sea floor. The process of sea floor spreading points out to the fact that the oceanic crust undergoes continuous recycling.

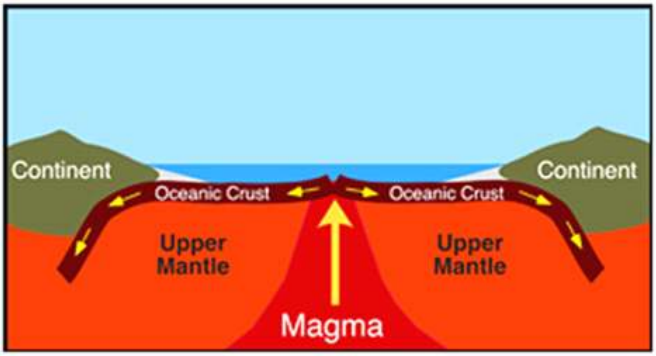


Fig. 11.14: Seafloor spreading and subduction

11.4. Palaeomagnetism

Palaeomagnetism is the record of Earth's magnetic field preserved in rocks. The science of palaeomagnetism or natural remnant magnetism is the branch of geology dealing with the study of magnetism of ancient rocks. This branch developed since the early 1950's.

Iron-bearing rocks contain ferromagnetic minerals like magnetite which act as fossil compasses. These acquire a permanent magnetization when they crystallize as constituents of igneous rocks. The Earth's magnetic field orientation is "frozen in" these iron-bearing minerals when igneous rocks are cooled below a temperature called Curie point (about 580° C for magnetite). Domains within the magnetic mineral take on an orientation parallel to any external magnetic field present at the time they cooled below this temperature. In other words, the direction of their magnetization will be the same as the direction of Earth's magnetic field at the time and place of crystallization and thus, be able to determine the position of the magnetic pole at that time (Fig. 11.15).

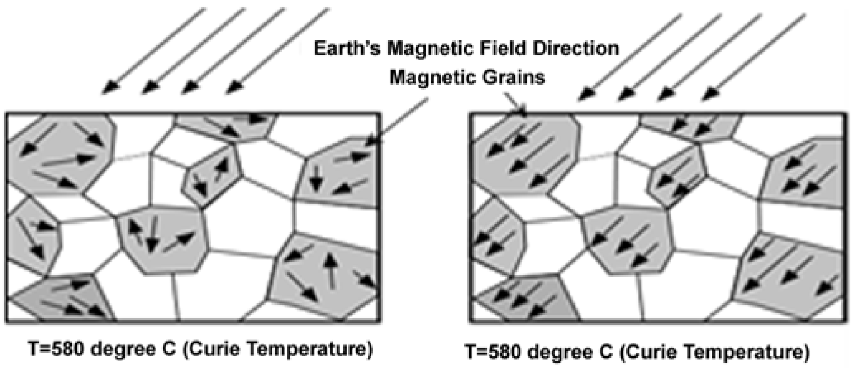


Fig. 11.15: Direction of Earth's Magnetic field in relation to magnetic grains

Any subsequent movement of the rock containing these minerals can be determined by the orientation of the current magnetic field compared to the rock's palaeomagnetism. The declination (angle away from true north) of the palaeomagnetism gives the longitude that the rock formed at, and the inclination (tilt from horizontal) gives the latitude.

Repeated reversals of the Earth's magnetic field in the geologic past

Magnetic mapping of the ocean floors began in the early 1960s and for most part of the ocean floor it is almost complete. The mapping led to an important discovery - of the presence of alternating, parallel and symmetric stripes of normal and reversed polarity rocks, on either side of the oceanic ridges (Fig. 11.16). Studies made on magnetism of rocks all

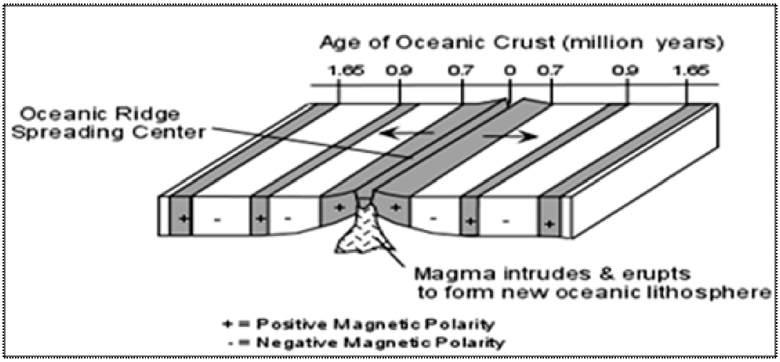


Fig. 11.16: Parallel and symmetric stripes of normal and reversed polarity rocks, on either side of the oceanic ridges

over the world indicate that reversals of the Earth's magnetic field (N becomes S and vice versa) have occurred, every few hundred thousand years, many times in the geologic past. By dating the rocks using radiometric dating techniques and correlating the reversals throughout the world they were able to establish the magnetic time scale. Ocean floor magnetic surveys also revealed the fact that (1) the youngest part of the oceanic crust of any ocean basin is located adjacent to the axis of spreading ridges and also that (2) the age of the crust increases with distance away from the ridge. The portions of ridge represent places where molten material from the mantle comes and solidifies. As the molten rock comes to the surface of the ocean floor, the material heaps up to form the ridge, and later it moves laterally with sea floor spreading.

The oceanic crust on both sides of the ridge moves away from each other like a pair of giant conveyor belts. At the ridge, the crustal rock being formed from mantle material is magnetized in the direction of the magnetic field of the time of eruption, and as it moves away from the ridge it carries with it a record of the magnetic direction corresponding to the time of their solidification. When the magnetic polarity reverses, the new rock being formed at the ridge is magnetized in the opposite direction, and as it moves away it too carries a record of the direction, opposite to the direction of the previously formed strip of oceanic crust. Therefore, one would expect to find alternating regions of normal and reversed magnetic directions symmetrically disposed on both sides of the ridge. Such a pattern has been discovered everywhere in the rocks associated with the oceanic ridges. It provides strong evidence for the main mechanism of continental drift - that is, spreading of the sea floor as new material wells up from the mantle.

Particles of magnetized minerals released from their parent igneous rocks by weathering may later realign themselves with the existing magnetic field at the time these particles are incorporated into sedimentary deposits. Studies made on the remnant magnetism in suitable rocks of different ages from Europe produced a "polar wandering curve" indicating that the magnetic poles were in different places at different times. The study showed that any one of the following should be inferred from the resulting data: (1) there was a migration of the magnetic pole itself during the Earth's past (i.e., polar wandering), (2) There was a displacement of the continent (Europe) relative to a fixed pole (i.e., continental drift) or (3) both continents and magnetic poles have changed their location with time. However, further studies showed that the polar wandering curves are different for the various continents. The possibility that they might reflect true wander of the poles was discarded, because it implies the Earth has had more than one magnetic pole over the same period in the past (not likely). However, these different paths are reconciled by joining the continents in the manner proposed by Wegener. The only way to reconcile the apparent palaeomagnetic inconsistency and obtain only one N and S pole (rather than different poles for each continent) is the second possibility noted above. When the continents are fitted together, the

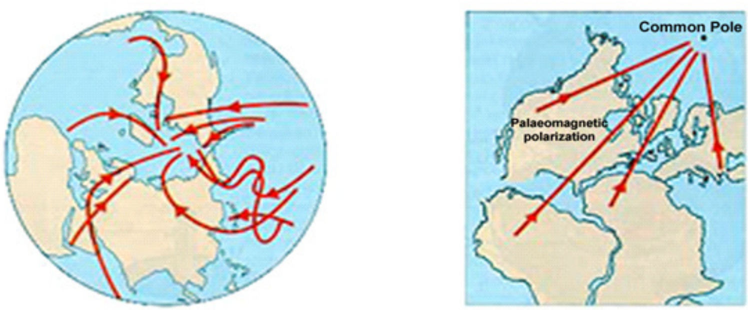


Fig. 11.17: Palaeomagnetic poles (a). Present direction (b) pre-drift pole direction

palaeomagnetic data points to one magnetic pole each in the Northern and Southern Hemispheres (Fig. 11.17).

The study of earthquakes has shown the fact that earthquakes do not occur randomly - but in patterns. As far back as 1954, the French seismologist J.P. Rothé published one of the earliest maps showing the concentration of earthquakes in linear zones. Precise documentation of the world's earthquake as well as volcanic activity during the latter decades of the

Check your progress

1. *What is meant by magnetic reversals?*
2. *Why do palaeomagnetic stripes on the ocean floor show symmetrical patterns on either flank of the oceanic ridges?*
3. *How can you explain the relative younger age of oceanic crust when compared to the continental crust?*

20th century confirmed the fact that these are concentrated along oceanic trenches and submarine mountain ranges.

11.5. Plate Tectonics

The branch of Geology known as Tectonics is concerned with the study of deformation in the earth and the forces which produce deformation. By the late 1960s, several American investigators combined the concepts of continental drift and sea-floor spreading together into a unified theory of the Earth's dynamics and formulated the basis of **Plate Tectonic theory**. It has revolutionized the way geologists think about the Earth as it explains many apparently unrelated geologic events and features.

According to the theory, the surface of the Earth is broken into large plates. Since the Earth is roughly spherical these plates are fractured into curved sections which are in constant motion relative to each other and meet in various ways along their edges - these are the 'plate boundaries'. Plate boundaries are sites of intense geologic activity, such as earthquakes, volcanoes, and mountain building. The mechanism by which plates move is still a highly controversial subject amongst Earth scientists.

Plates are on average 125 km thick, reaching maximum thickness below mountain ranges. Oceanic plates (50-100 km) are thinner than the continental plates (up to 200 km) and even thinner at the ocean ridges.

Lithospheric plates

When we use the term 'plate' in Plate Tectonics, there is more than a simple image of a 'cracked egg-shell'. Earth's 'tectonic plates' are more than just 'crust'. Another name used by earth scientists for 'tectonic plate', is 'lithospheric plate'. The chemistry (and therefore, the mineral composition) of rocks changes with depth. Along with this change mechanical properties of the rocks also change with depth, according to pressure and temperature. Both factors (i.e., pressure and temperature) affect rock's mechanical strength, whatever its chemical composition. As temperatures rise with depth, rocks reach temperatures that would cause them to melt if they were at the surface. The rocks remain solid at depth despite their temperature because of the extreme pressures acting upon them. However, they do become plastic. When subjected to immense forces, and with vast amounts of time, such rocks will exhibit a tendency to flow.

Some substances display this property of solid creep even at the surface. For example a piece of chocolate in a warm room may flow and deform without melting. (Many substances also flow under gravity, especially when warm. Pitch, used for roads, can be brittle when struck with a hammer, but still flow very slowly, just as ice does when a glacier moves downhill). Because of the temperature gradient of the Earth, at a certain depth in the upper mantle, peridotite rock will behave like this too. This occurs when peridotite reaches 1300°C and gives rise to a layer called the asthenosphere, where the rock is weaker than both overlying and underlying mantle. The scientists who study earthquakes call this layer as low-velocity zone or as LVZ.

The rocks above the asthenosphere, being the uppermost mantle plus the overlying crust (either continental or oceanic) behave mechanically as a single rigid (brittle) unit, and comprise what geologists call the 'lithosphere' (Fig. 11.18). According to the Plate Tectonic theory, the lithosphere which is partly made of crust and partly upper mantle, mechanically behaves as a single unit (Go back to unit 2 and once again read the section - Internal structure of the Earth). The important point you should note is that the term plates are not just pieces of continental

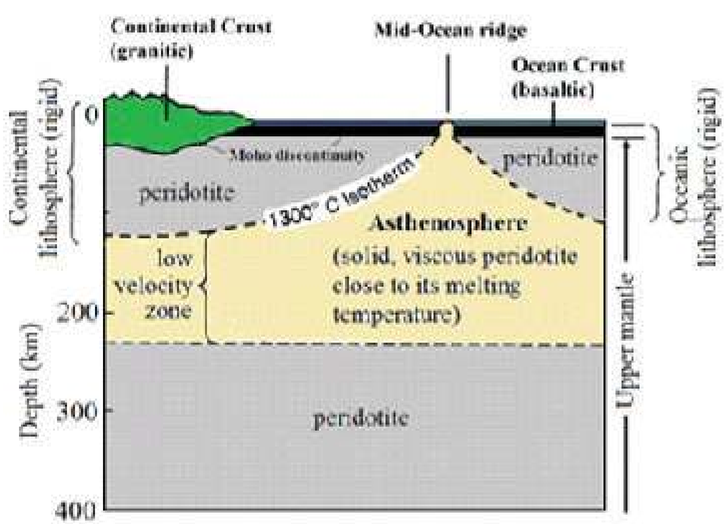


Fig. 11.18: Lithospheric plates (continental and oceanic) above the asthenosphere

or oceanic crust, but along with the crustal rock, they include a considerable thickness of the upper part of the mantle.

According to the Plate Tectonics, the outer rigid layer of the earth (the lithosphere) is divided into about a dozen "plates" that move across the earth's surface relative to each other. The lithosphere has a total thickness of approximately 100-125 km.

Carefully study the world map of tectonic (lithospheric) plates given below (Fig. 11.19). You can see that boundaries of most of the plates run across the oceans as well as across continents. For example, the boundary of the Indian Plate runs across the Indian Ocean (Arabian Sea, Lakshadweep Sea and Bay of Bengal) and also through the Mountain belt of Himalayas. You can also learn from the map that some plates, such as the Pacific Plate are almost entirely oceanic (i.e., consists of only oceanic crust and underlying asthenosphere -portion of the upper mantle) while majority of plate consists of both the oceanic and continental crust and underlying asthenosphere.

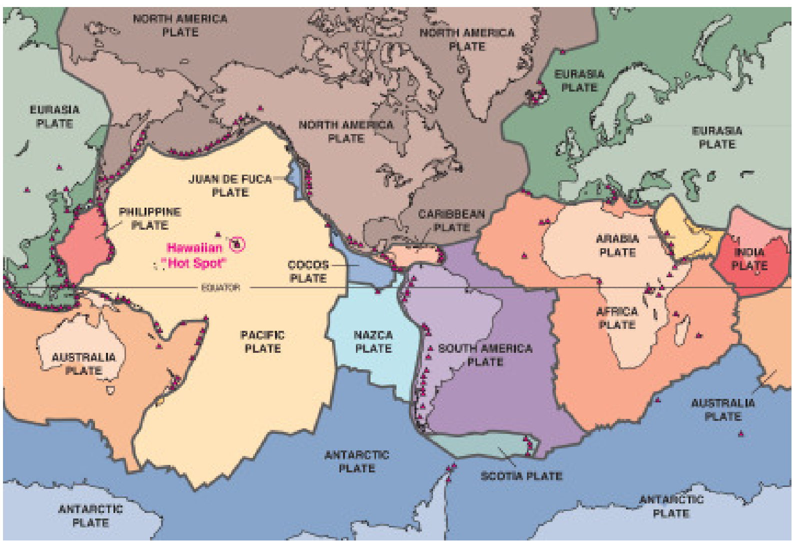


Fig. 11.19: World map of tectonic (lithospheric) plates

The rigid plates that make up the earth's lithosphere are constantly in motion over the asthenosphere - which is, as already noted a zone with relative lack of strength and lack of rigidity, facilitating the sliding of the overlying lithospheric plates. The rate of plate motion is a few centimetres per year, or approximately 0.1 mm per day (about as fast as your fingernails grow!).

The places where three tectonic plates meet are called **triple junctions**. Most of the triple junctions are in the oceans.

Let us do

1. *Find out the major and minor lithospheric plates shown in the world map of tectonic plates (fig 11.19). Also identify the triple junctions exposed in continental regions from the map of the tectonic plates.*

11.5.1. Plate Motion

The mechanism by which tectonic plates move is still a subject of much debate among Earth scientists. The Earth is dynamic because of its internal heat, which comes from deep within the mantle from the breakdown of radioactive isotopes. This causes convection in the mantle - hot rocks rise and cold rocks descend. This very slow motion in the solid state transfers stresses to the lithosphere (just as convection in a boiling pan of thick soup will cause the skin to buckle where the convection cells meet).

As the theory of plate tectonics developed, mantle convection was long thought to be responsible for the movement of tectonic plates across the Earth's surface. This theory is now largely out of favour, as modern research has been unable to identify convection cells in the mantle sufficiently large to drive plate movement.

Geologically, the most important things happen at plate boundaries, including most of the earthquakes, volcanoes, igneous rocks, major metamorphism, and mountain building processes. Interplate regions are generally aseismic (free from earthquakes), volcanic activity and any significant crustal deformation.

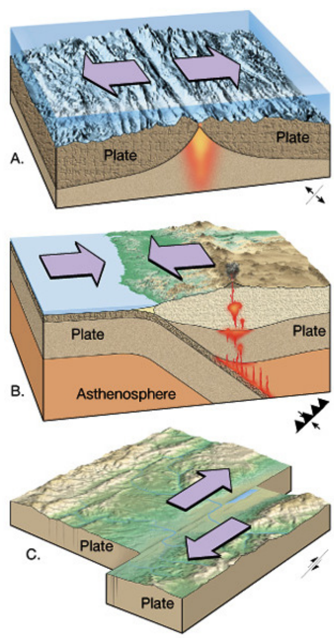


Fig. 11.20: Types of plate boundaries: (a) Divergent, (b) convergent and (c) transform

11.5.2. Plate Boundaries

There are three general types of plate boundaries: (1) divergent, (2) convergent, and (3) shear or transform (Fig. 11.20). Each general type has multiple subtypes.

(1) Divergent boundaries

Divergent boundaries are where plates separate from each other. In such plate margins, plates move apart and new lithosphere is created. In oceans, these coincide with the mid oceanic ridge system (which is a global range of underwater mountains that you have learnt in unit 9). The North American and Eurasian Plates are moving away from each other along the line of the Mid Atlantic Ridge. This ridge rises to heights ranging between 2 and 3 km above the ocean floor and has a rift valley at its crest marking the location at which the two plates are moving apart. The Mid Atlantic Ridge, like other ocean ridge systems, has developed as a consequence of the divergent motion between the Eurasian and North American, and African and South American Plates. As the mantle rises towards the surface below the ridge the pressure is lowered (decompression) and the hot rock starts to partially melt (Fig. 11.21). This produces basaltic volcanoes when an eruption occurs above the continental surface and characteristic basalt "pillow lava" in submarine eruptions. In this way, as the plates move further apart new ocean lithosphere is formed at the ridge and the ocean basin gets wider. This process is known as "sea floor spreading" and results in a symmetrical alignment of the rocks of the ocean floor which get older with distance from the ridge crest (as you have learnt in section - Continental Drift).

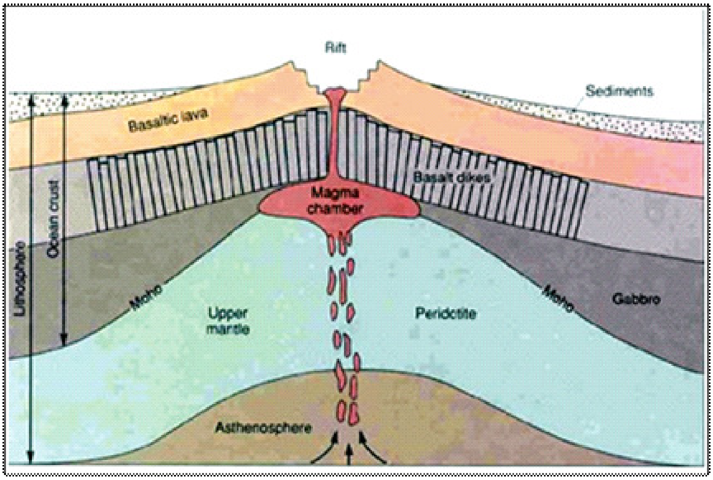


Fig. 11.21: Axial Rift of Mid Ocean Ridges

In continents, divergent plate boundaries coincide with rift valleys such as the Red Sea and East African Rifts; and the lesser known West Antarctic Rift. The Afar region in Northern Ethiopia is the centre of a "Y" shaped rift system, where the continental lithosphere is being stretched and is splitting. The point in the Afar region where the boundaries of all three plates meet is called a Triple Junction (Fig. 11.22). Here, the Arabian Plate is rifting away from the African plate along an active divergent ridge system, to form the Red Sea and Gulf of Aden. The rifting then extends southwards where the African Plate is itself becoming stretched along the line of the East African Rift Valley and is splitting to form two new plates; the Nubian and Somalian Plates. In time, as Nubian and Somalian plates move further away from each other, the area between them will grow thinner and drop below sea level. New ocean lithosphere may form along the centre of the rift, producing a new narrow ocean basin with its own mid ocean ridge.

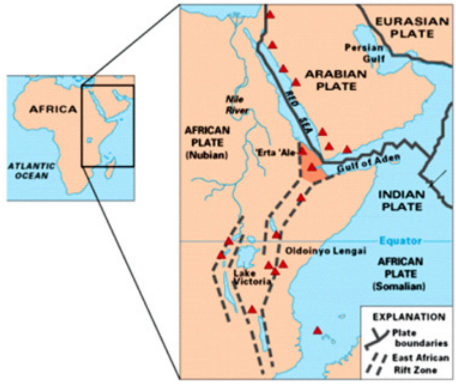


Fig. 11.22: Afar region triple junction (Afar: darker shading, Volcanoes: red triangles)

Spreading starts within a continental area with up-warping or doming, fracturing in a radial pattern - with three arms, and formation of a rift valley (such as the Rift Valley in eastern Africa) in one of the arms (Fig. 11.23). It is suggested that this type of valley eventually develops into a linear sea (such as the present day Red Sea), and finally into an ocean (such as the Atlantic Ocean).

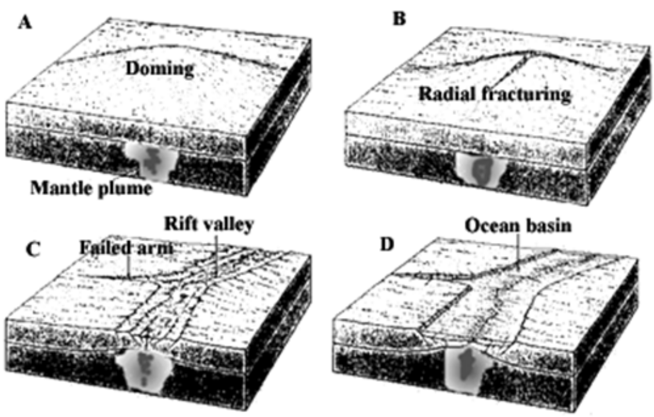


Fig. 11.23: Processes of spreading resulting in ocean basin

A major continental rift is assumed to be initiated by a series of hot spots. Each hot spot has an associated three-arm rift, but in most cases only two of these arms will continue to separate - the third one being termed a "failed arm". Some of these failed arms become major river channels. Rifting along a series of hot spots will then lead to continental rifting. It is thought that some 20 hot spots were responsible for the initiation of spreading along the mid-Atlantic ridge (Fig. 11.24).

(2) Convergent boundaries

Convergent plate margins are those margins where two plates moving towards one another or these are where plates come together face to face each other. Here plate destruction occurs and convergent margin is a zone of plate destruction, these are also known as destructive margins. Large Mountain chains and explosive volcanoes are characteristic of convergent margins.

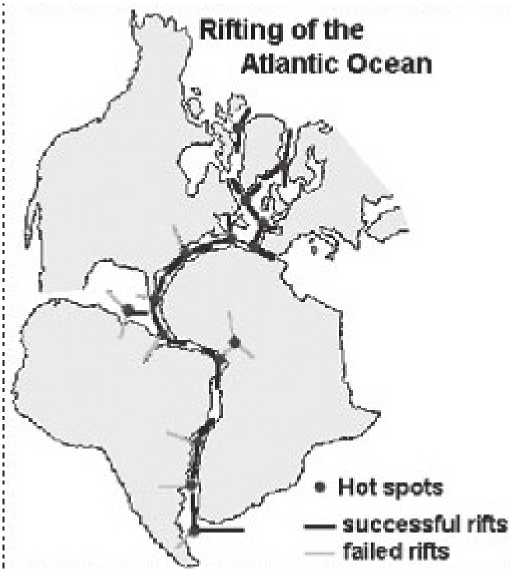


Fig. 11.24: Rifting of the Atlantic Ocean

Depending on the nature of adjacent plates, three types are convergent boundaries are possible: (1) Those where oceanic part of two plates meet, (2) those where an oceanic margin of a plate and continental margin of another plate meet, and (3) those where continental blocks of two plates meet. Convergent margins behave differently depending on the nature of convergent boundaries (1) to (3) noted above.

As lithospheric plates moves away from the divergent margin (as a result of sea floor spreading), it cools and becomes denser, and the further away from the plate boundary it moves, the thicker it becomes. At a convergent plate boundary the oceanic lithosphere sinks beneath the adjacent plate in a process known as 'subduction'.

Case 1: Oceanic-Oceanic Convergence

When two oceanic plates converge, one subduct beneath the other and in the process a deep sea trench is formed. Inboard of the overlying plate a volcanic arc forms. This is because water being released from the subducting slab facilitates melting of the overlying mantle. The melt rises to form volcanoes (e.g., the Aleutian Islands).

The South American Plate is moving westwards due to sea floor spreading at the Mid Atlantic Ridge. Where it meets the Caribbean Plate, it descends (subducts) beneath it. This is because the oceanic lithosphere of the South American Plate is cooler and denser than that of the Caribbean Plate. The subduction causes low density ocean floor sediment to be scraped off the surface of the South American Plate and thrust onto the Caribbean Islands as accretionary wedges, in a process called obduction. The line of subduction is marked by the deep sea Puerto Rico Trench. The Caribbean volcanic islands form a curved linear chain or 'volcanic island arc' parallel and to the west of the Puerto Rico Trench.

Case 2: Oceanic-Continental Convergence

You may like to find more about other examples - for instance the collision between the Australian Plate and the Pacific Plate (resulting in the Southern Alps of New Zealand); or the formation of the Aleutian Islands at the margin of the Pacific Plate and North American Plate.

The Nazca Plate is moving eastwards, towards the South American Plate, at about 79 mm per year. Where the two plates meet, the denser oceanic lithosphere of the Nazca Plate is forced down and under the more buoyant continental lithosphere of the South American Plate, descending at an angle into the mantle (subduction). This is marked on the ocean surface by the presence of the Peru-Chile (or Atacama) Trench. The friction between the plates prevents the subducting oceanic plate from sliding smoothly. As it descends, it drags against the overlying plate, causing both to fracture and deform. This results in frequent shallow focus earthquakes that get deeper as the ocean plate descends further, defining a zone of earthquake foci known as a Benioff zone (Fig. 11.25).

As subduction of the Nazca Plate continues, some of the sediments that accumulated on the ocean floor (together with some of the ocean crust) are scraped off and forced (accreted) onto the South American Plate in a process called "obduction". This forms an accretionary wedge (or 'prism'), where layers of the deformed and metamorphosed sediments and ocean

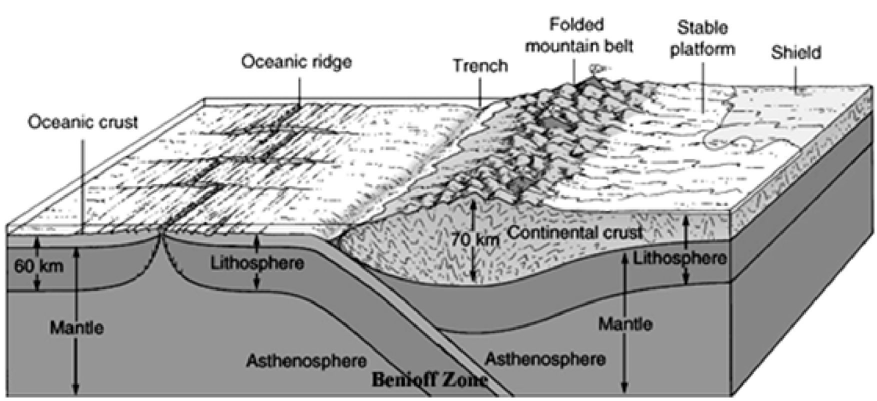


Fig. 11.25: Formation of Benioff zone due to subduction of plates

crust are thrust onto the South American Plate along faults - or thrust planes - adding to the size of the continent.

Continued subduction of the Nazca Plate brings sea water, locked in the ocean crust, deep into the mantle. As the plate heats up the water is liberated, lowering the melting point of the mantle and causing partial melting. This produces magma, which rises and may be erupted explosively as andesite at the surface.

Andesitic magma is less dense than the surrounding material, and can have a temperature of 1000°C. It is viscous, trapping gases as it rises. The water and gases in andesitic magma account for the explosive activity of andesitic volcanoes, which typically lie dormant for many hundreds or thousands of years. These volcanoes typically produce ash and pyroclastic flows, as well as small amounts of andesitic lava.

Andean volcanoes such as the stratovolcano Láscar, in northern Chile, are good examples of this type of activity. Láscar erupted ash and pyroclastic flows in 1993 and was still active in 2012.

Case 3: Continent-Continent Convergence

Where two continents meet head-on, in plate interaction neither is subducted, because the continental rocks are relatively light and resist downward motion. Instead, the crust of the zone of convergence tends to buckle and be pushed upward or sideways (Example: The Himalayan mountain range dramatically demonstrates one of the most visible and spectacular consequences of plate tectonics).

The Himalayan mountain range and Tibetan plateau have formed as a result of the collision between the Indian Plate and Eurasian Plate which began 50 million years ago and continues today. 225 million years ago India was a large island situated off the Australian coast and separated from Asia by the Tethys Ocean. The supercontinent Pangaea began to break up 200 million years ago and India started a northward drift towards Asia. 80 Ma India was 6,400 km south of the Asian continent but moving towards it at a rate of between 9 and 16 cm per year. At this time Tethys Ocean floor would have been subducting northwards beneath Asia and the plate margin would have been a convergent oceanic-continental one just like the Andes today. Between 40 and 20 Ma the rate of northward drift slowed as the two continental plates collided and the former Tethys Ocean closed (Fig. 11.26). Neither continental plate could be subducted due to their low density/buoyancy. This caused the continental crust to thicken due to folding and faulting by compressional forces. The continental crust here is twice the average thickness at around 75 km. The thickening of the continental crust marked the end of volcanic activity in the region as any magma moving upwards would solidify before it could reach the surface. The Himalayas are still rising by more than 1 cm per year as India continues to move northwards into Asia, which explains the occurrence of shallow focus earthquakes in the region today. However the forces of weathering and erosion are lowering the Himalayas at about the same rate. The Himalayas and Tibetan plateau trend east-west and extend for 2,900 km, reaching the maximum elevation of 8,848 metres (Mount Everest).

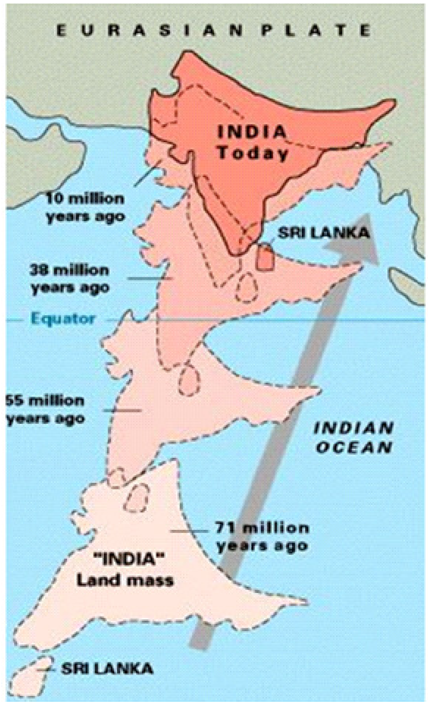


Fig. 11.26: Northward migration of India

In regions where an oceanic plate converges on a continental plate and the denser crust of the oceanic plate sinks beneath the more-buoyant continental plate. In this type of convergence, trenches, strong, destructive earthquakes and the rapid uplift of mountain ranges are common. Water released from subducting slab facilitates melting. Rising melt builds volcanic arc (Examples: Juan de Fuca plate subducting beneath the North American plate off shore in the Pacific Northwest. Off the coast of South America along the Peru-Chile trench, the oceanic Nazca Plate is being subducted beneath the South American Plate. In turn, the overriding South American Plate is being lifted up, creating the towering Andes Mountains).

(3) Shear boundaries (Transform boundaries)

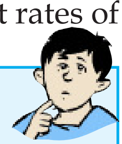
These are zones where plates slide past each other, ideally with little or no vertical movement and without production or destruction of crustal material. Therefore these are also known as conservative margins. Shear margins are where plates slide past each other, so that the relative movement is horizontal. These are also known as transforming faults. Transform faults are mainly found on the ocean floor, where they offset mid ocean ridges and enable the ocean to spread at different rates. It was through the work of John Tuzo Wilson that these faults were recognized as the connection between the ocean ridges (divergent margins) and ocean trenches (convergent margins). Because in shear margins lithosphere is neither created nor subducted these are also known as conservative margins. Shear margins are the sites of extensive shallow focus earthquakes, occasionally of considerable magnitude.

The San Andreas Fault marks the junction between the North American and Pacific Plates. The fault is 1300 km long, extends to at least 25 km in depth, and has a north west-south east trend. It is classified as a right lateral (dextral) strike-slip fault.

Although both plates are moving in a north westerly direction, the Pacific Plate is moving faster than the North American Plate, so the relative movement of the North American Plate is to the south east. The Pacific Plate is being moved north west due to sea floor spreading from the East Pacific Rise (divergent margin) in the Gulf of California. The North American Plate is being pushed west and north-west due to sea floor spreading from the Mid Atlantic Ridge (divergent margin).

Movement along the fault is not smooth and continual, but sporadic and jerky. Frictional forces lock the blocks of lithosphere together for years at a time. When the frictional forces are overcome, the plates slip suddenly and shallow focus earthquakes are generated. Landscape and manmade features (e.g., rivers, fences and roads) are displaced across the fault as movement occurs. San Francisco has historically suffered significant earthquakes, notably in 1906 and 1989.

The average rate of movement along the San Andreas Fault is between 30 mm and 50 mm per year over the last 10 million years. If current rates of



Check your progress

1. *What is a plate and how fast does it move?*
2. *At which boundary of plate movement is new oceanic crust being formed?*

movement are maintained Los Angeles will be adjacent to San Francisco in approximately 20 million years.

11.6. Continental Drift vs Plate Tectonics

Although Wegener and Du Toit proposed that the primitive continents began to break up about 200 million years ago, there is much evidence that drift began long before then, and that continental blocks have slowly been moving about the earth's surface throughout much of geological

TECTONIC ACTIVITY WITHIN THE PLATES (INTRAPLATE TECTONISM)

Although most of the tectonic activity of the Earth is concentrated along plate margins, plate interiors are not completely free from it. In some regions earthquakes and volcanoes do occur far from the margins of lithospheric plates. The causes of intraplate earthquakes are not fully understood. Some are associated with pre-existing weaknesses in plates which can become reactivated. The series of earthquakes which took place in New Madrid, Missouri, in 1811-12 and the 2001 Gujarat, NW India earthquake are examples of intraplate earthquakes which caused significant destruction. Intraplate volcanoes are thought to be associated with 'hot spots' in the mantle, which remain stationary as plates move over them. The mechanism by which such hot spots produce volcanic activity is a subject of much debate amongst Earth scientists. Some have suggested they are caused by mantle plumes - cylindrical bodies of material hotter than the surrounding mantle. The plumes are thought to originate at the outer core/lower mantle boundary, rising upwards to the base of the lithosphere over many millions of years.

The Hawaiian Islands are formed by volcanic activity, despite the nearest plate margin being 3,200 km away. Some geologists have suggested that a 'hot spot' in the mantle, which remains stationary as the Pacific Plate moves over it, explains the existence of the island chain. The hot spot may represent the top of a mantle plume which originated deep down at the outer core - lower mantle boundary. The plate moves in a north westerly direction due to sea floor spreading along the East Pacific Rise. As oceanic lithosphere moves away from the hot spot, volcanic activity ceases and it cools, becomes denser, and slowly subsides. As new oceanic lithosphere is positioned over the hot spot, a new island will begin to form above. The islands extend for around 2,400 km, forming a chain that is progressively older from the south east end to the north-west end. The volcanoes are often very wide, with gently sloping sides comprising many thin (1 to 5 metres thick) basaltic lava flows. These are referred to as 'shield volcanoes'. Kilauea and Mauna Loa on Big Island are currently active examples. The next island to appear in the Hawaiian chain has already been identified, and named as Lo'ihi. It is currently 975 metres below sea level, and is estimated to emerge above sea level in the next 10,000 to 100,000 years.

time. It seems that before the continents drifted apart and opened up the Atlantic, they had drifted together and closed up an earlier ocean. Another place where continents seem to have bumped into each other and piled up mountains between them is the Himalayas, which may have been produced when the Indian Peninsula detached itself from Gondwanaland and gradually drifted into Asia.

Today, on the basis of the plate tectonics, geologists are able to reconstruct what the Earth appeared in certain period of the geological time. Because of the plate tectonics behaviour, the distribution of continents and ocean basins on Earth definitely looked very different. The Americas, Africa, Antarctica, India and Australia were all joined together in a single super-continent called Pangaea, as originally conceived by Alfred Wegener and over millions of years they separated and moved their separate ways across the globe.

A major departure of the plate tectonic theory from the continental drift hypothesis is that large plates contain both continental and ocean crust and the entire plate moves. By contrast, in continental drift, Wegener proposed that the stronger continents "drifted" by breaking through the oceanic crust, much like ice breakers cut through ice.

The theory of plate tectonics is supported by (1) palaeomagnetism, the direction and intensity of Earth's magnetism in the geologic past; (2) the global distribution of earthquakes and their close association with plate boundaries; (3) the ages of sediments from the floors of the deep-ocean basins; and (4) the existence of island groups that formed over hot spots

Let us sum up

The theory of continental drift, postulated that there were large-scale slow horizontal movements of continents during the geologic past, changing their positions relative to one another, and to the poles of the earth. According to the theory of continental drift, the world was made up of a single continent through most of geologic time. That continent eventually separated and drifted apart; forming into the seven continents that we have today.

According to the generally accepted plate-tectonics theory, scientists believe that Earth's surface is broken into a number of segments called plates, which average about 125 km in thickness. These plates move relative to one another above a hotter, deeper, more mobile zone at average rates as great as a few inches per year. Most of Earth's seismic activity, volcanism, and mountain building occur along the dynamic margins of these plates.

Three types of plate boundaries are recognized, viz., Divergent, Convergent and Transform plate boundaries. Divergent plate boundaries occur where plates move apart, resulting in upwelling of material from the mantle to create new seafloor. Most divergent boundaries occur along the axis of the oceanic ridge system and are associated with seafloor spreading. Convergent plate boundaries occur where plates move together, resulting in the subduction of oceanic lithosphere into the mantle along a deep oceanic trench. Convergence between an oceanic and continental block results in subduction of the oceanic slab and the formation of a continental volcanic arc. Oceanic-oceanic convergence results in an arc-shaped chain of volcanic islands called a volcanic island arc. When two plates carrying continental crust converge, both plates are too buoyant to be subducted. The result is a "collision" resulting in the formation of a mountain belt such as the Himalayas. Transform fault boundaries occur where plates grind past each other without the production or destruction of lithosphere. Most transform faults join two segments of an oceanic ridge whereas others connect spreading centres to subduction zones and still others, like the San Andreas Fault, cut through continental crust.

Significant Learning Outcomes

The learner can:

- evaluate the theory of continental drift and the plate tectonic hypothesis.
- give the reasons for the formation of volcanoes, mountains and earthquakes in the world.
- explain the northward shift of the Indian plate and its present position.

Let us assess

(1) List out the evidences that Wegener and his supporters gathered to substantiate the drifting of continents.

(2) What is sea floor spreading and where does active spreading of sea floor occur today?

(3) What is a subduction zone? With what type of plate boundary is it associated?

(4) Briefly describe the significance of the hypothesis of plate tectonics.

(5) What is the average thickness of the lithospheiric plates?

(6) Give an example of a shear boundary.

(7) The process in which an oceanic plate slides beneath a continental plate or another oceanic plate is known as

a) exfoliation b) degradation
c) tectonism d) subduction

(8) Divergent boundaries are

a) constructive b) destructive
c) conservative d) submissive

12

MINERALS

12.1. Introduction

In nature, more than 4000 minerals are known to occur. But only about 20 are more common. Many of these have great importance in our daily life. Nearly all manufactured products we use are obtained from minerals.

Why are minerals important?... You can't live without them.

The branch of science which deals with the study of minerals is known as 'mineralogy'. Mineralogy deals with various aspects related to minerals, such as their chemical composition, physical properties, mode of formation, occurrence and their use.

12.2. Minerals

Mineralogists define the term 'mineral' as a naturally occurring inorganic substance that is solid and stable at room temperature, characterized by a definite chemical composition and with an internal ordered atomic structure.

It has been stated earlier that the solid crust of the earth is made up of rocks. Minerals constitute the components of all rocks that form the crust of the earth. A mineral is different from a rock, the latter can be an aggregate of one or more minerals, and therefore do not possess a definite chemical composition. The exact definition of a mineral is still under debate, especially with respect to the requirement that it is abiogenic, and to a lesser extent with regards to it having an ordered atomic structure.

Let us discuss the salient points of the definition of minerals given earlier. You should note that a substance must fulfill the following conditions for considering it as a mineral.

1. It must occur naturally.
2. It must be an inorganic substance.
3. It must have a fixed chemical composition that can be represented by a definite chemical formula.

AVERAGE COMPOSITION OF THE CRUST

There are 90 naturally occurring elements. Among these eight elements account for 98.7% of the earth's 'average' crust. Others occur in 'trace' (i.e., very low) concentrations (Table 12.1).

Table 12.1 Elemental Composition of the Earth's Crust

Element	Continental crust	Oceanic crust
Oxygen (O)	46.6 %	44.9 %
Silicon (Si)	27.7 %	24.1 %
Aluminum (Al)	8.1 %	7.7 %
Iron (Fe)	5.1 %	8.2 %
Calcium (Ca)	3.6 %	7.8 %
Sodium (Na)	2.8 %	1.6 %
Potassium (K)	2.6 %	0.5 %
Magnesium (Mg)	2.1 %	4.0 %
All Others	1.3 %	1.2 %

Note: all percentages are given in a weight per weight basis

4. It must have an orderly internal atomic structure.
5. Its physical properties must be fixed and controlled by composition and internal structure.
6. It should be stable at room temperature (i.e., minerals must be solids).
7. It should be in solid state of matter.

Minerals are natural materials, formed by any inorganic process. Only those materials which have been formed by natural processes alone are considered as minerals. Therefore, synthetically created materials (such as synthetic gems) and other materials, formed as by-products of industrial processes, resembling mostly naturally occurring minerals, are generally excluded from the definition. Likewise, naturally occurring substances having an organic origin (pearl, coal etc) are not included among mineral kingdom. Generally, liquids and gases are not considered as minerals. Solid substances alone are included among minerals. Naturally occurring mercury is considered as a member of the mineral kingdom by tradition. It is the only mineral in liquid state.

Let us answer the following questions:

- Is a cube of ice from a refrigerator a mineral?
- Is the snow on the windshield of a car a mineral?

- Although water is not considered as a mineral, glacial ice is considered as a mineral. Can you give the explanation for this?
- Why are granite, basalt, limestone etc. considered as rocks?

Minerals possess a definite chemical composition and often with a regular geometric shape which is an outward expression of its internal ordered atomic structure. A mineral must be homogeneous- down to the molecular and atomic scale. In the case of some minerals, chemical composition is variable, but this variation occurs within certain *definite* limits. Some minerals like native gold, native silver, native sulphur etc are made of only one element while others, like quartz and calcite, are combinations of two or more elements. Quartz is silicon dioxide (SiO_2) and calcite is calcium carbonate ($CaCO_3$). This means that the composition of minerals can be expressed by a specific chemical formula.

A mineral has a diagnostic atomic structure which is expressed externally as crystalline form and definite physical properties. Under suitable conditions, where the mineral *growth is unhindered*, because of the internal ordered atomic structure, minerals acquire their characteristic external crystalline form. In most cases, the natural conditions attending mineral growth results in the development of mineral grains without their characteristic crystal forms.

The formal definition of the term 'mineral' approved by the International Mineralogical Association (IMA) in 1995 is:

"A mineral is an element or chemical compound that is normally crystalline and that has been formed as a result of geological processes".

Classical examples of exceptions to the rules, as noted earlier, include native mercury, which crystallizes at 39°C, and ice, which is solid only below 0°C; as these two minerals were described prior to 1959, they were also approved as members of the mineral kingdom by the International Mineralogical Association (IMA).

Biogenic substances which are chemical compounds produced entirely by biological processes *without* a geological component (e.g., urinary calculi, oxalate crystals in plant tissues, shells of marine mollusks, etc.) are not regarded as minerals. However, if any geological process was involved in the genesis of a natural compound, then it can be accepted as a mineral. Coal and some varieties of graphite, derived from biogenic sources, are therefore considered as minerals as geological processes are involved in their further transformation.

Several naturally occurring substances very much resemble minerals but lack an orderly internal structure (crystalline nature). Mineralogists group such materials under the category of mineraloids. Examples are amber (fossil resin derived from resins of coniferous trees preserved in some sedimentary rocks), limonite (a natural mixture of iron oxides), opal (amorphous, hydrated silica), obsidian (rapidly cooled lava) etc.

12.3. Classification of minerals

Minerals can be classified on the basis of different criteria. They can be broadly classified into two groups.

1. **Rock forming minerals** – These are the minerals which form the major constituents of rocks. Quartz, feldspars, micas, pyroxenes, olivine etc. are the examples.
2. **Ore forming minerals** – These have economic value and are the minerals from which useful metals are extracted. Galena, sphalerite, magnetite, hematite, chromite, chalcopyrite, pyrolusite, rutile, monazite etc. are the examples.

In a similar manner minerals can be classified as

1. **Primary minerals** – formed as the product of consolidation of magma and
2. **Secondary minerals** – formed due to operation of secondary processes on surface, subsequent to the consolidation of magma.

Thus the mineral olivine is of primary origin while malachite is secondary.

A more scientific classification of minerals is on the basis of their chemical composition. In this classification, minerals are divided into groups depending on the dominant anion, or anionic group of their composition. The broadest divisions of minerals are as follows:

1. Native elements (all naturally occurring elements are included in this group: native gold and native copper are examples of metallic elements while diamond, sulphur, graphite are examples of non-metallic elements.)
2. Sulphides (pyrite, galena, sphalerite)
3. Oxides (quartz, magnetite)
4. Halides (halite, fluorite)
5. Carbonates (calcite, dolomite)
6. Sulphates (barite, gypsum)

7. Phosphates (apatite, monazite)
8. Silicates (garnet, mica, quartz, feldspar)

The silicate minerals compose over 90% of the earth's crust. The diversity and abundance of mineral species is an expression of the overall chemical composition of the crust (see table 12.1). Silicon and oxygen constitute approximately 75% of the earth's crust, and this is the reason for the predominance of silicate minerals in earth's crust.

Check your progress

1. *What types of materials are considered as minerals?*
2. *Which is the only mineral in liquid state?*
3. *What is the reason for the dominance of silicate minerals on the earth's crust?*

12.4. Properties of minerals and their identifications

More than four thousand minerals are known to occur in the crust of the earth. All these minerals have been studied and given specific names. This has been possible because each mineral has specific and determinable properties that reflect the unique proportion and arrangement of their atoms. Although each mineral has many properties, a mineral is *identified* (if previously unknown) or *recognized* (if previously known) on the basis of a combination of properties. By testing a mineral for such properties, therefore, we can easily identify them. The various properties of minerals, the study of which may help in their preliminary identification, can be grouped into three categories viz., (1) Physical properties, (2) Chemical properties and (3) Optical properties.

Of these three sets of properties, the more easily determined in the field or in the laboratory, are the physical properties. Physical properties are those properties which depend upon the degree of aggregation, degree of cohesion, sense, light, magnetism, heat etc. These physical properties are however, further supplemented by chemical and optical and a few other properties, so as to get a full confirmation about the identity of an unknown mineral.

A second group of properties, involving chemical analysis of the minerals to determine their constituents, qualitatively and quantitatively, fall under the category of chemical properties.

Thirdly, for the study of optical properties of minerals, extremely thin, glass mounted sections of minerals (thickness of 0.03 mm) through which light can pass, are required. For such studies use of special microscopes (polarizing microscopes) are employed.

12.4.1. Physical properties

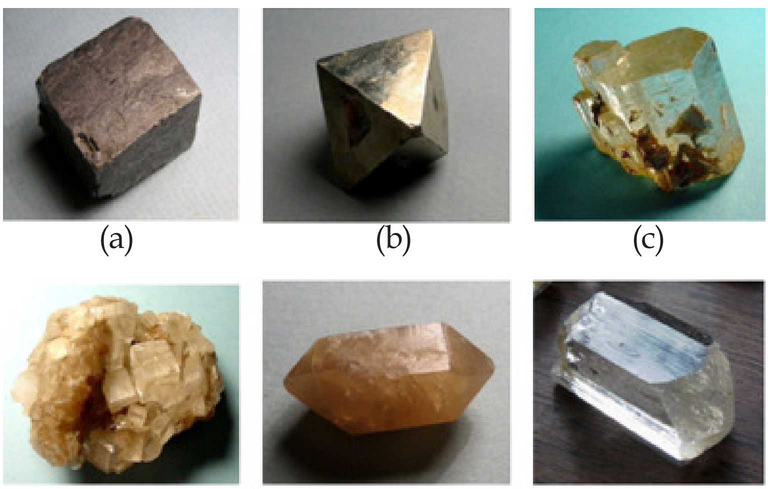
The important physical properties of minerals are:

1.	Form and habit	6.	Fracture
2.	Colour	7.	Hardness
3.	Streak	8.	Specific gravity
4.	Lustre	9.	Transparency (Diaphaneity)
5.	Cleavage	10.	Magnetism

(1) Form and Habit

Minerals often occur in characteristic crystal forms. Form defines the external morphology attained by a crystal or mineral. This is the geometric pattern that a lone crystal of the mineral will acquire, if it is allowed to grow without any external interference. Some of the characteristic crystal forms of a few common minerals are shown below (Fig. 12.1).

Shape of a crystal can reflect the orderly internal arrangement of atoms. Minerals crystallize from solutions, melts and vapour. They may precipitate from evaporating sea water, or crystallize from magmas and lava when they cool. During their unhindered growth, minerals may develop distinct crystal forms, generally with smooth, flat surfaces called *crystal faces*. These



(a) (b) (c)

(d) (e) (f)

Fig. 12.1: Some characteristic crystal forms of minerals - [a] Galena (PbS): Cubic crystal, [b] Pyrite (FeS): Octahedron, [c] Beryl ($Be_3Al_2Si_6O_{18}$): Hexagonal prism, [d] Calcite ($CaCO_3$): Rhombohedron, [e] Quartz (SiO_2): Hexagonal, [f] Topaz $Al_2SiO_4(F,OH)_2$: Orthorhombic

faces exhibit various types of symmetrical arrangements. The geometry and symmetry of crystal faces reflect the internal atomic arrangement. This is one of the most important features of minerals.

Various terms are applied for different crystal forms. The following are some of the terms: (1) Cube (2) Octahedron, (3) Dodecahedron, (4) Tetrahedron, (5) Rhombohedron, (6) Hexagonal prism, etc. (Fig. 12.2).

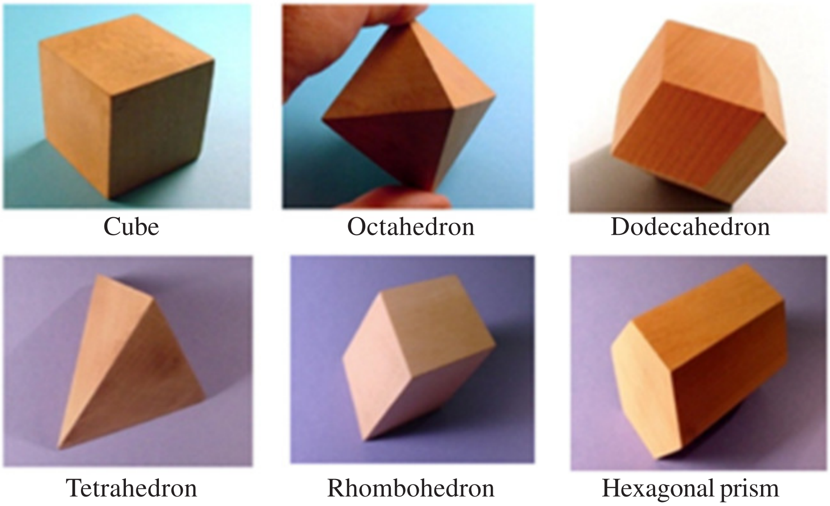


Fig. 12.2: Some characteristic crystal forms

The physical characteristic or make up of a mineral specimen is sometimes expressed by the term **habit**. It has been stated that most of the minerals are crystalline while a few are amorphous as well. When it is crystalline, it may occur either in the form of well developed crystals or, alternatively, it may be massive without the development of recognizable crystal forms.

Following are a few common habits observable in minerals.

- **Tabular:** Some minerals occur in the form of a flattened, square to rectangular shapes. Example, calcite, feldspar and barite.
- **Bladed:** the mineral appears as if composed of thin flat, blade like overlapping of juxtaposed parts. Kyanite generally occurs in bladed form.
- **Foliated:** When a mineral is made up of a thin paper like sheets that can be easily separated its habit is designated as foliated. Minerals of the mica family occur in foliated forms.
- **Fibrous:** When the mineral is composed of fibres, generally separable either easily (e.g., asbestos) or with some difficulty (e.g., gypsum).

Some characteristic crystal habits are shown below (Fig. 12.3).


Tabular


Fibrous


Foliated


Bladed

Fig. 12.3: Characteristic habits of minerals

(2) Colour

Colour is one of the most obvious physical properties of any mineral specimen. For some mineral species, such as pyrite or galena, it provides a useful clue for identification. Unfortunately the colour of most minerals is highly variable. Although colour should always be considered in the course of mineral description, it should never be used as a principal identifying characteristic. The colour is not a very reliable source for identifying a mineral, as it can be affected by impurities present in the mineral sample.

While colour seems to be a very simple property, it is not a reliable property for mineral identification. Impurities can greatly change the colour of a mineral. Dirt or other substances on the surface can also give a false reading. Colour is most reliable for the identification of metallic minerals. Gold and pyrite often appear golden yellow in colour. The similarity of colour and lustre of pyrite to gold is the reason for giving the name “fool’s gold” to pyrite. Colour is not a diagnostic property of transparent minerals.

(3) Streak

The streak of a mineral is the colour of its fine powder. Generally, the streak is sometimes different from the color observed in hand sample, and it can be much more diagnostic for identification purposes than colour of the mineral sample. The streak of a mineral can be readily observed by scratching or rubbing a corner of the specimen against a rough unglazed porcelain plate, called streak plate (a piece of white, unglazed porcelain tablet). The important minerals offering characteristic colour-streak combinations are given in the table 12.2 shown below.

Table 12.2: Characteristic colour-streak combinations of some minerals.

Mineral	**Characteristic colour combinations**	
	Colour	Streak
Hematite	Black	Cherry-red
Chromite	Greenish Black	Greenish brown
Pyrite	Golden yellow	Black

Almost every mineral has an inherent streak, no matter what colour the actual mineral is. For example, calcite occurs in many different colours, shapes, and varieties. But all of them have white streak. Streak is very useful in distinguishing two minerals with the same colour but different streaks. Some specimens of native gold, pyrite and chalcopyrite possess the same body colour (golden yellow). But they possess different streaks – streak of gold is yellow whereas streak of the other two minerals is black.

Unfortunately, because many light-coloured minerals have white streaks, a streak test is not particularly useful in identifying nonmetallic minerals. Moreover, minerals which are harder than a streak plate will not be powdered during a streak test.

(4) Lustre

The quality of light that is reflected off a mineral is called lustre. Technically speaking, it is the intensity and nature of reflection of light from the mineral surface. Lustre of a mineral depends on the refractive index of the mineral, absorption (of light) capacity of the mineral and the nature of reflecting surface. Any dirt present on the surface of the sample or an uneven surface will give an incorrect result.

Lustre may be classified into metallic and non metallic types. Metallic lustre is characteristic of high density, high refractive index and opaque minerals like galena, pyrite and chalcopyrite. Non-metallic lustre includes different types such as vitreous lustre, pearly lustre, silky lustre, resinous lustre, adamantine lustre and greasy lustre. Of these the adamantine lustre is exhibited by high density, high refractive minerals like diamond, zircon, corundum, etc. Minerals with a vitreous lustre have reflective properties similar to a glass. Of all the members of the mineral kingdom, 70 percent minerals possess vitreous lustre. A silky lustre is the result of a mineral having a fine fibrous structure. Dull lustre defines minerals with poor reflective qualities. The different types of lustre and their examples are given in the table 12.3 below.

Table 12.3: Different types of lustre, their characteristics and examples of minerals

No.	Type of Lustre	Represented by	Mineral
1	Metallic lustre	A mineral with a metallic shine	magnetite
2	Non-metallic lustre		
i.	Vitreous lustre	A mineral having a glassy shine	quartz and calcite
ii.	Pearly lustre	A mineral having pearly shine	muscovite
iii.	Silky lustre	A mineral with a silky shine	asbestos
iv.	Resinous lustre	A mineral with a greasy shine like that of a resin	talc
v.	Adamantine lustre	A mineral having a diamond like shine (brilliant, like a polished jewel)	diamond, zircon
vi.	Greasy lustre	A mineral that appears as if it were coated with grease	sulphur

(5) Hardness

Hardness is another property of minerals that is often used in identification as it is a fairly constant and diagnostic characteristic of minerals. Hardness may be defined as the resistance which the mineral offers to scratching or abrasion. This property is generally determined by scratching the given mineral with a mineral of known hardness. Thus, for example, if a given mineral gets scratched by a mineral or another substance of hardness say 6, but does not get scratched by that having a hardness of 5, then we can infer that the hardness of the given mineral is between 5 and 6. Moreover, the depth of scratch produced, will also help us to judge whether the hardness determined is nearer to 5 or 6.

The hardness of minerals is generally expressed on ***Mohs' Scale of Hardness***, which incorporates ten minerals, assigned each with a standard hardness, as shown in the table 12.4. The principle behind the scale is that any mineral that is higher in sequence is able to scratch another mineral occurring a lower position in the sequence.

Table 12.4: Mohs' scale of hardness

Mineral	**Hardness**
Talc	1
Gypsum	2
Calcite	3
Fluorite	4
Apatite	5
Orthoclase	6
Quartz	7
Topaz	8
Corundum	9
Diamond	10

Geologists also have a standard, empirical scale of hardness, on which steel or glass is 5.5, feldspar is 6, and quartz is 7. A finger nail has a hardness of about 2.5 and a copper coin 3. Some varieties of mica can be scratched with a finger nail. An iron nail or needle will scratch the mineral hornblende, but not feldspar or quartz. If, during a scratch test, a mark left after the scratching can be rubbed off, and no mark is visible on the mineral specimen tested, then we can conclude that the latter is having a higher hardness. Table 12.5 shows the typical hardness values of some common materials.

Table 12.5: Typical hardness of some common materials

Substance	**Hardness**
Finger nail	2.5
Brass or copper penny	3
Glass plate	5.5
Knife	6.5
Streak plate (Floor tile)	6.5

(6) Cleavage

Cleavage is a special type of fracture surface that develops in certain minerals. The property of cleavage is defined as *the tendency of a mineral to break along certain definite directions yielding more or less smooth, planar surfaces* (Fig. 12.4). Cleavage planes are generally the planes of easiest fracture, and are essentially indicative of directions of least cohesion in the atomic structure of the mineral. A good example of a mineral that shows an excellent property of cleavage is mica, which very easily cleaves giving very thin sheets.

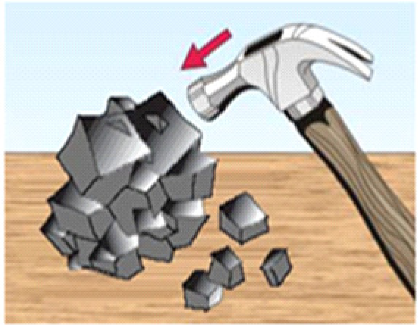


Fig. 12.4: Tendency of a mineral to break along certain definite directions yielding more or less smooth, planar surfaces defines its cleavage

Crystalline substances alone possess the property of cleavage and amorphous substances totally lack this property. In crystalline minerals, however, there exists no rule governing the presence or absence regarding the nature of cleavage. Thus the mineral quartz has no cleavage, while galena, calcite etc have well developed cleavages. The phenomenon of development of cleavage in crystalline mineral is ascribed to their particular internal atomic structures. In fact, cleavages form along the directions of weak bonding as shown in the figure 12.5.

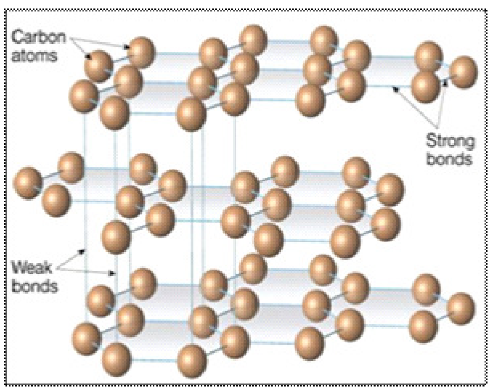


Fig. 12.5: Directions of weak bonding along which cleavages form

The number of cleavage directions in a mineral also varies. If a crystal cleaves along only one direction, it is said to have one set of cleavage: if two, two sets of cleavage and so on. Cleavage planes are parallel to either a particular crystal face or to set of faces. For example; in micas, there is only one direction of cleavage, viz., parallel; in hornblende, there are two sets of cleavages, intersecting at 120^o and 60^o and in galena there are three directions of cleavages, intersecting at 90^o, each one being parallel to the face of a cube.

On the basis of the ease with which a mineral cleaves, and on the degree of perfection of cleavage planes, cleavage is described as 'eminent', 'perfect', 'good', 'distinct' and 'poor' or 'indistinct'. In eminent cleavage, the mineral can be split very easily yielding extremely smooth surface: e.g., in mica. Perfect cleavage is seen in orthoclase and calcite.

(7) Fracture

The nature of the surfaces that form when a mineral breaks in a direction other than that of cleavage is generally expressed by the term *fracture*. Quartz, (a mineral lacking the property of cleavage) which develops curved surfaces when broken, is described to possess a *conchoidal fracture*. In some cases fracture becomes a characteristic property of a mineral. Common types of fractures are described in the following table 12.6.

Table 12.6: Different types of fractures developed in minerals

Sl. No.	Type of fracture	Description	Example
1	Even fracture	Surface of fracture being smooth and flat	Garnet, agate
2	Uneven fracture	Broken surface is rough or with random irregularities.	Pyrite and magnetite
3	Conchoidal fracture	Mineral breaks along curved, concentric surfaces	Quartz

(8) Specific gravity

The density of substances is a fundamental property of great significance and it is defined as the mass per unit volume of the substance. For minerals, it is expressed in g/cc. In mineralogy, the term specific gravity is used more frequently for the density and signifies the ratio between the density of a mineral and that of water at 4^{O} C. Water has a specific gravity of 1. If a mineral has a specific gravity of 2.7, it means that it is 2.7 times heavier than water.

In fact, the specific gravity of a mineral depends upon the weight and spacing of atoms composing the mineral. A mineral, possessing relatively heavier and more closely spaced atoms, will naturally have higher specific gravity than one possessing lighter and more widely spaced atoms. Specific gravity values of minerals vary between 1 and 20. Majority of them have specific gravities varying between 2 and 7. Minerals with a specific gravity below 2 are considered *light*, those between 2 and 4.5 as *average*, and greater than 4.5 as *heavy*.

An idea of the specific gravity of mineral can be obtained by simply weighing it or lifting it in hand. Its actual value can however, be determined by using different types of instruments such as Jolly's balance, Walker's steel yard balance, beam balance etc.

(9) Transparency

The amount of light able to be passed through a mineral specimen determines its transparency. Depending upon the extent to which light can pass through a mineral, they may be classified as transparent, translucent and opaque. When a mineral is found to allow light to fully pass through it, it is described as transparent. Colorless varieties of quartz and calcite are the best examples of transparent minerals. Translucent minerals partially let light pass through (examples are milky quartz, milky calcite), and opaque minerals do not let any light to pass through them. Minerals showing metallic lustre, such as pyrite, chromite, magnetite, etc. are opaque.

(10) Magnetism

Several minerals react when placed within a magnetic field. Some minerals are strongly attracted to the magnet (**Ferromagnetism),** others are weakly attracted (**Paramagnetism**), and a few are repelled (**Diamagnetism**). Magnetite and pyrrhotite are examples for the first type while hematite and franklinite are examples of the second type. Bismuth is an example of diamagnetic mineral.

Check your progress

1. *What are the important physical properties of minerals?*
2. *Which is the hardest mineral known?*
3. *Name any three minerals possessing the property of cleavage.*

Besides properties noted above, certain other physical properties such as taste, feel and odour are sometimes useful in mineral identification. Taste can be very useful in identifying halite, although one can get very sick of licking every transparent mineral in their collection hoping to find it. Reaction to dilute hydrochloric acid is another useful property, though not physical, in the identification of carbonate minerals, such as calcite.

FEW OTHER PROPERTIES OF MINERALS

Tenacity : The term 'tenacity' refers to the property of a substance to resist separation during crushing, bending or tearing. The different forms of tenacity displayed by minerals are described using following terms:

- Brittle - If a mineral is hammered and the result is a powder or small crumbs, it is considered brittle. Brittle minerals leave a fine powder if scratched, which is the way to test a mineral to see if it is brittle. The majority of all minerals are brittle. An example is Quartz.
- Sectile - When thin shavings can be separated with a knife or cut into thin slices (much like wax) it is said to be sectile. An example is Gypsum.
- Malleable - When a mineral can be flattened by pounding with a hammer, it is said to be malleable. All true native metals are malleable.
- Ductile - When a mineral can be stretched into a wire, it is said to be ductile. All native metals are ductile. An example is Gold.
- Flexible - When a mineral specimen is capable of bending on applying slight force, and remains in the new position after it is bent, it is described as flexible. Example: Native copper.
- Elastic - When flexible minerals are bent, if they spring back to their original position when the force of bending is removed, they are described as elastic. Example: All fibrous minerals, such as asbestos.

Radioactivity : Radioactivity is an attribute of minerals that contain radioactive elements. Radioactive elements are elements that contain disintegrating nuclei, emitting alpha, beta, and gamma rays. Uranium and thorium are the best known radioactive elements. Minerals that contain these elements in their structure are known as "radioactive minerals".

Fluorescence : This property is a phenomenon or property due to which a mineral starts to "glow" in the visible spectrum when exposed to ultraviolet light. Obviously, the reaction will only be visible in a dark area, where the presence of white light is weak. An example of such a mineral is fluorspar.

Phosphorescence : It is a phenomenon exhibited by some fluorescent minerals where the mineral continues to glow even after the source of input of radiation has been removed. The glow slowly fades, and after several seconds (or minutes in a few cases) is no longer visible to the naked eye. Some minerals phosphors when subjected to heating or rubbing. For example, diamond, when exposed to x-rays, quartz when rubbed together, and fluorite when heated emit visible radiations of low intensity.

Let us do

Identify the specified physical properties of the mineral specimens listed in the table below:

Specimen	*Property*	*Your Identification*
Quartz	*Lustre*	
Biotite	*Colour*	
Talc	*Hardness*	
Gypsum	*Streak*	

12.5. Minerals in daily life

Minerals are basic and essential raw materials in our daily lives, and are vital for economic, social and technological development. Every segment of society uses minerals as well as metals extracted from minerals. The examples below illustrate their extensive uses in everyday life.

Agriculture

Phosphate minerals (apatite), potash (sylvite, KCl) and limestone (calcite) are used in agriculture as fertilizers and other mineral products such as dolomite, vermiculite are used to improve soil.

Food

Salt (NaCl) is added to food. Sand is used to filter water. Diatomite and bentonite clay are both used to clarify drinks, such as beer, fruit juices and wine.

Packaging

Food and drinks may be packaged in cans made from aluminium or steel, or in glass made from silica sand. Plastic packaging is made from chemicals obtained from oil, natural gas or coal.

Utensils

Your plates may be ceramic and made from clay; glasses are made from silica sand, and cutlery from metals – usually aluminum or steel. Your cooker is partly made from metals and cooking pans are generally made from aluminum, steel or copper.

Construction

Buildings use a wide range of rocks, minerals and metals such as: iron (as steel) in the framework of large building; clay in bricks and roofing tiles; slate for roofing tiles; limestone, clay, shale and gypsum in cement and plaster; silica sand in window glass; sand and gravel and crushed rock as aggregates for fill and in concrete; copper for plumbing and wiring; clays for bathroom fixtures and fittings and tiles; paint may include pigments.

Energy

Energy is used at home and by all industries, services and transport, including hospitals, schools and workplaces. Energy resources – coal, oil, gas, uranium – are used to give you heat, hot water and electricity. Cars, buses and trains all use fuel which mainly comes from oil.

Transport

Every journey you make depends on minerals, whether by car, train, plane, boat or foot. Cars, trains, planes, boats and bicycles are all made using metals such as iron and aluminium. Aircraft engines depend on mixtures of metals called alloys which are made from metals including nickel, cobalt, chromium, aluminium and titanium.

Technology and communications

Information technology is part of our daily lives. Many of us have access to a computer and mobile phone, and many services depend on computers and other forms of telecommunication. These technologies require a wide range of metals, including copper, gold, platinum, tin, zinc and nickel.

Other areas

Graphite is used to make pencils. Slate is used to make blackboards. Limestone is used to make chalk. We use graphite and slate to make fireplaces. Cobalt is used for making super alloys for jet engines, chemicals, and much more. Fluorite is used in toothpaste as is limestone and calcium carbonate. Gold is used in dentistry, medicine, jewellery, and art. Pyrite is used in the manufacture of sulfur, sulfuric acid, and sulfur dioxide. Zinc is used in making nails and roofing. Silica sand is used in glass industry. Talc, feldspar and clay minerals are used in ceramic industry.

Minerals are used in medicine too. Bismuth is used in medicines for the treatment of stomach ulcers, soothing creams, and cosmetics. Magnetite, sulphur, boron etc., are used in making drugs. Silver is used in making dental and medical equipments.

12.6. Gemstones

Nature has given us stones with several strange properties. Of all the properties, colour and brilliance are the most attractive to our eyes. Majority of minerals found in nature are opaque, lack lustre, and are unattractive but sometimes minerals occur in attractive colours with high degree of transparency and capable of producing unusual optical properties when properly cut and faceted. When cut and polished some mineral specimens become valuable as pieces of jewellery and are considered as precious stones or as gemstones. Most of these are members of the mineral kingdom and some are of biogenic origin such as pearls and some others are artificial and synthetic.

Gemstones occur rarely in nature. To be regarded as a gemstone, a mineral must be a rare variety and possess colour and brilliance (which together make the mineral beautiful), and durable (meaning hard and tough). The study of gemstones is known as '***Gemology***'.

Gemstones are the enchanting gifts of nature. Sparkling diamonds, dazzling blood red ruby and lovely green emerald are all nature's gift to mankind. Gemstones have fascinated mankind for thousands of years throughout the entire history of mankind. Who will not be enchanted by the blood-red colour of ruby, the rich royal-blue colour of sapphire, the captivating velvety-green colour of emerald and the elegant sky-blue colour of turquoise? Similarly the bright reflection of light from the cut and polished surfaces of gemstones bewitches the eyes. Deep colour or delicate colour, gemstones are alluring. There are colourless stones also which have their own beauty. For example colourless stones described as white stones such as 'white diamond' or white sapphire' are beauties of their kind.

Diamond is found rarely in some rocks called kimberlites in some parts of the world, for example in South Africa. Even when it occurs, majority of them are tiny, lack clarity, only some of them are transparent, flawless and devoid of impurities. Cutting and polishing of these raw diamonds results in the magnificent diamond that we know in the jewellery world. You must have heard about the Koh-i-noor diamond and its fame in this world.

Gemstones are known by a variety of names as shown in Table 12.7 given below.

Table 12.7: Popular gemstones and their Indian names

Gemstones	Indian Name
Ruby	*Manikya (Manek), Padmaraga*
Blue sapphire	*Indra Neela (Mahanila)*
Yellow sapphire	*Pushyaraga (Pucraj)*
Diamond	*Vajra / Hiraka (Heera)*
Emerald	*Marataka (Panna)*
Orange zircon	*Gomedhaka (Gomedh)*
Chrysoberyl	*Vaidurya (Lahsuniya)*

Let us do

Some common household items are given in the table below. Discuss in groups and try to understand the various minerals and metals contained in each item.

Household Items	*Minerals and metals*
Paint	
Glass	
Ceramic tiles	
Stainless steel	
Table salt	
Toothpaste	
Cosmetics	
Knife	
Cement	
Utensils	

The following table (Table 12.8) gives a summary of some common rock forming minerals.

Table 12.8: Salient properties of some common rock forming minerals

Minerals / Properties	Quartz	Feldspars	Micas	Pyroxenes	Amphiboles
Chemical Composition	SiO_2	KAl Si_3O_8 –NaAl Si_3O_8 –$CaAl_2Si_2O_8$	Hydrous potassium aluminium silicate	Silicates of Ca,Na,Mg,Fe,Ni,Li,Cr,Al and Ti	Meta silicates with a Si:O ratio of 4:11, the metallic ions are Ca, Mg, Fe, Al and sometimes Mn, Na, K and H. Presence of (OH) ion which may be replaced by F and Cl. General chemical formula is : [Si4O11]2(OH)2
Colour	Colourless or white when pure but some varieties may be coloured	Variable, usually white or light coloured, but also pink, red, grey, green and colourless	Colourless, white or pale yellow, black, brown or red	Generally dark in colour, but also colourless, green, black, grey, yellow, green-brown, purple, brownish-black, etc	Generally dark in colour, but also brown, grayish brown, grey, black, greenich-black, blue, bluish-black, bluish-gray, yellowish or brownish red, green
Lustre	Vitreous	Vitreous, semi-vitreous to pearly	Pearly, splendent	Vitreous to pearly	Vitreous
Streak	White in coloured varieties	White	Colourless	White, light green or light brown, grey	White with greenish tint, grayish-green or grayish-brown
Diaphaneity	Transparent when clear, to translucent when white	Subtransparent to translucent to opaque	Transparent to translucent	Translucent to subtransparent, Subtranslucent to opaque	Transparent to subtranslucent, translucent to opaque
Hardness	7	6.0 – 6.5	2.5 – 3.0	5.0 – 6.5	5.0 – 6.0
Tenacity	Brittle	Brittle	Flexible and elastic	Brittle	Brittle
Specific Gravity	2.65	2.55 – 2.76	2.77 – 2.88	3.1 – 3.6	2.8 – 3.6
Cleavage	Absent	Two directional	One perfect basal	Two good prismatic meeting at about 90O	Perfect, prismatic
Fracture	Conchoidal	Conchoidal to uneven and splintery	Doesn't fracture	Uneven to brittle	Uneven to brittle
Form/Habit	Crystals occur as hexagonal prisms , also as massive, granular	Usually prismatic, also tabular	Six sided hexagonal plates, or massive	Prismatic crystals, even granular or massive	Elongated, slender, acicular, columnar, fibrous, prismatic

Minerals / Properties	Calcite	Talc	Fluorite	Corundum	Olivine	Garnet
Chemical Composition	$CaCO_3$	$Mg_6[Si_8O_{20}](OH)_4$	CaF_2	Al_2O_3	$(Mg, Fe)_2SiO_4$	$X_3Y_2Si_3O_{12}$ where X = Ca, Mg, Fe2+, Mn, etc. and Y = Al, Fe3+, Cr and Ti
Colour	Colourless or white, milky-white, sometimes with grey, yellow, blue, red, brown or black tints	White, silvery white, apple green, greenish grey, dark green	Variable, Colorless, white, purple, blue, green, yellow, orange, red, pink, brown, blue, bluish black	Commonly grey, greenish ore reddish but occasionally colourless. Colorless, gray, brown; pink to pigeon-blood-red, orange, yellow, green, blue, violet	Shades of green, yellow to yellow-green, pale green, olive green, brown, white, brown or even black	Virtually all colors, pale olive green, greenish white, yellow or pink, deep crimson, deep red, brownish red, dark brown, emerald green, white
Lustre	Vitreous to dull or earthy	Pearly	Vitreous	Vitreous to dull, adamantine	Vitreous	Vitreous
Streak	White	White to pearl green	White	White	Colourless/None, white	White
Diaphaneity	Transparent to opaque	Translucent	Transparent to translucent	Transparent, translucent to opaque	Transparent to translucent	Transparent to translucent to opaque
Hardness	3.0	1.0	4.0	9.0	6.0 – 7.0	7.0 – 7.5
Tenacity	Brittle	Sectile	Brittle	Brittle	Brittle	Brittle
Specific Gravity	2.71	2.58 – 2.83	3.0 – 3.25	3.98 – 4.02	3.22 – 4.39	3.5 – 4.3
Cleavage	Perfect rhombohedral	Perfect basal	Octahedral perfect	Absent	Poor	Absent
Fracture	Conchoidal	Flat surfaces uneven fracture	Conchoidal to uneven	Conchoidal to uneven	Conchoidal, brittle	Imperfect conchoidal to uneven
Form/Habit	Well formed crystals, combinations of scalenohedron, rhombohedron and prism, also fibrous, lamellar, massive and stalactitic or stalagmitic	Foliated to fibrous masses, rare as platy to pyramidal crystals, tabular	Cubes very common, also as well-formed coarse sized crystals also nodular, botryoidal, rarely columnar or fibrous; granular, massive	Barrel-shaped or pyramidal crystals, also as massive and granular forms	Stubby prismatic crystals, also as massive and compact grains, granular	Well-formed, distinct, dodecahedral and trapezohedral crystals, also as grains, massive or rounded crystals

Minerals / Properties	Dolomite	Apatite
Chemical Composition	$CaMg(CO_3)_2$	$Ca5(PO_4)_3(F,Cl,OH)$
Colour	White when pure, also shades of brown, red, grey, green and black	Pale sea green, bluish green, yellowish green and greenish yellow, also shades of blue, grey, red, violet, pink and brown
Lustre	Vitreous to pearly of crystals, dull of massive varieties	Subresinous to vitreous
Streak	White	White
Diaphaneity	Translucent to opaque	Transparent, translucent to opaque
Hardness	3.5 – 4.0	5.0
Tenacity	Brittle	Brittle
Specific Gravity	2.84 – 2.86	2.9 – 3.5
Cleavage	Perfect rhombohedral	Indistinct or poor
Fracture	Conchoidal or uneven	Conchoidal to uneven
Form/Habit	Rhombohedra common, usually with curved faces, Tabular crystals, often with curved faces, also columnar, stalactitic, granular, massive	Tabular, prismatic crystals, massive, compact or granular, fibrous to columnar, globular or botryoidal

Let us sum up

Minerals are naturally occurring inorganic substances characterized by definite chemical composition and internal atomic structure with or without external form. Study of minerals is referred to as mineralogy. Minerals are classified on different criteria into rock forming minerals, ore forming minerals, primary minerals, secondary minerals etc. Most scientific classifications are those based on chemical composition.

Minerals possess certain physical properties which help us to identify them in the lab or field. Crystal form, colour, streak, lustre, cleavage, hardness, specific gravity etc., are some of the physical properties of minerals. Colour is referred to the body colour whereas streak to colour of the powder. Lustre indicates the nature of reflection of light at the surface. Hardness means the resistance that a mineral offers to abrasion. Cleavage is the tendency of a mineral to break along certain particular direction. Specific gravity depends on the weight and spacing of atoms in the mineral.

More than 4000 minerals are known to occur in nature. Minerals are of great importance in our daily life. Every segment of society uses minerals. Nearly all manufactured products we use are obtained from minerals. Gemstones are valuable minerals used generally for adornment. Rarity, beauty and durability make a mineral precious. Diamond, ruby, emerald etc., are some example of gemstones.

Significant Learning Outcomes

The learner can:

- explain the concept and characteristics of minerals.
- identify some physical properties of minerals.
- explain the basics of gemstones.
- assess the importance of minerals in everyday life.
- identify some common minerals.

Let us assess

1. What is the basic difference between cleavage and fracture?
2. How do you assess the hardness of a given mineral?
3. Give suitable mineral examples for the following:
   a) A mineral possessing magnetic property.
   b) A mineral possessing property of fluorescence.
   c) A mineral, some specimens of which resemble colourless glass.
4. What quality of diamond enables it to be used as an abrasive in drilling rocks?
5. Give four examples of gemstones and their diagnostic gem qualities.
6. Identify the uses of the following minerals in everyday life.
   a) Talc b) bauxite c) graphite d) mica
7. Differentiate between colour and streak of minerals with examples.
8. Give a brief description on the crystal habit of minerals as a physical property.

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