

MGG-002

GEOMORPHOLOGY



Vol.

2

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GEOMORPHIC PROCESSES: STATIC AND DYNAMIC II

BLOCK 5

APPLIED GEOMORPHOLOGY

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COURSE INTRODUCTION: GEOMORPHOLOGY

Geomorphology is a field of geography that develops scientific explanations for the evolution of landforms. Geoscientists, especially geographers and geologists, have been studying geomorphology for centuries in order to better comprehend the Earth's surface. Geomorphology mainly is a part of physical geography which deals with the study of landforms, their characteristics and various processes, i.e., physical, chemical, biological and extra-terrestrial responsible for their formation and changes.

Traditional geomorphology analyses landform descriptions, whereas quantitative geomorphology, which is process-based, explains forces working on Earth's surface that create landforms and landform change. The change to a more quantitative approach was greatly influenced by the work of Horton, Strahler, and Leopold, who argued for a physically-based assessment of landforms in the mid-twentieth century. Novel techniques for comprehending the forms and processes were introduced. Geomorphology has various sub-disciplines, including tectonic, fluvial, aeolian, floodplain, glacial, climatic, coastal and many others. The study of geomorphology encompasses how various agents like water, ice, and wind shape the topography of the Earth's surface. Anthropogenic geomorphology investigates the effects of humans on landform alteration all over the world. As a result, it is impossible to envisage a place or condition that has not been influenced by geomorphic processes.

This course-MGG 002, consists of five blocks, is intended to introduce learners to the concepts, theories, geomorphic processes, and major landforms that exist under various structural and climatic conditions. Geomorphology applications in environmental management are also introduced.

Geomorphology-MGG 002 course is printed in two volumes. Volume-1 consists of first three blocks namely: Block 1: Fundamentals of Geomorphology, Block 2: Evolution of Landforms and Block 3: Geomorphic Processes: Static and Dynamic I; and the other two blocks namely-Block 4: Geomorphic Processes: Static and Dynamic II and Block 5: Applied Geomorphology are arranged in Volume-2.

Geomorphology encompasses a wide range of geographical dimensions, from micro-landforms to gigantic landforms. Geomorphology's history may be traced back to the ancient and classical periods of Greek and Roman scientists and thinkers.

From the classical perspective of cyclic development to systems approaches, the core notions of geomorphology, nature and scope, and the genesis of landforms are discussed. You will also learn about "form and process geomorphology," a novel way to studying landform evolution and change. You will get a better understanding of the fundamentals of geomorphology by studying the development of the discipline, basic postulates, geomorphic systems, and fundamental concepts in Block 1, which is divided into three units.

Block 2 describes the evolution of landforms. A landform is a natural or human-made feature on the Earth's surface. The study of landform evolution is essential to grasp the attributes of landforms, such as their shape, material composition, and spatial distribution throughout the Earth's surface. The theories of major landform formation by describing Earth's core structure, theories of isostasy, eustasy, continental drift, and plate tectonics are explained. You have been introduced to tectonic processes and landforms in this block 2. Further, geomorphic processes

both dynamic and static dealing with weathering, mass wasting, and fluvial processes and landforms are explained in three units. You will study in details about these processes and landforms in Block 3 of Volume I of this course on Geomorphology.

Volume II consists of Block 4 and Block 5. We have explained the geomorphic processes and landforms related to wind, underground, ice and waves in Block 4 under geomorphic processes static and dynamic. The applications of geomorphology including slope processes, geomorphic mapping and techniques, landforms and environment management are described in details in the last Block of this course.

We hope after studying this course, you will better understand the geomorphology with reference to fundamental concepts and theories, geomorphic processes and resultant landforms, techniques and applications landform analysis. Our best wishes are with you in this endeavour.

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MGG-002 GEOMORPHOLOGY

VOLUME- 1

BLOCK 1 FUNDAMENTALS OF GEOMORPHOLOGY

- Unit 1 Development of Geomorphology
 - Unit 2 Basic Postulates in Geomorphology
 - Unit 3 Geomorphic Systems and Concepts
-

BLOCK 2 EVOLUTION OF LANDFORMS

- Unit 4 Theories of Development of Major Landforms
 - Unit 5 Tectonic Processes and Landforms I
 - Unit 6 Tectonic Processes and Landforms II
-

BLOCK 3 GEOMORPHIC PROCESSES: STATIC AND DYNAMIC I

- Unit 7 Weathering
 - Unit 8 Mass Movement
 - Unit 9 Fluvial Processes and Landforms
-

VOLUME- 2

BLOCK 4 GEOMORPHIC PROCESSES: STATIC AND DYNAMIC II

- Unit 10 Aeolian Processes and Landforms
 - Unit 11 Karst Processes and Landforms
 - Unit 12 Glacial Processes and Landforms
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-

BLOCK 5 APPLIED GEOMORPHOLOGY

- Unit 14 Slope Processes
 - Unit 15 Geomorphic Mapping
 - Unit 16 Geomorphic Techniques
 - Unit 17 Landforms and Environment Management
-

BLOCK 4: GEOMORPHIC PROCESSES: STATIC AND DYNAMIC II

Geomorphological processes are the dynamic natural forces that shape and transform the Earth's surface over time. These processes, including weathering, erosion, deposition, fluvial and glacial activity, coastal dynamics, tectonic forces, and more, are fundamental in understanding the evolution of various landforms. Their relevance lies in unravelling the intricate history encoded within landscapes. For instance, the erosive power of water carving through rock layers reveals the story of river valleys and canyons. Glacial processes sculpt U-shaped valleys and moraines, serving as archives of past ice ages. Coastal processes shape coastlines, forming beaches and cliffs, while tectonic forces uplift mountains and create fault lines, offering insights into the Earth's dynamic geological history.

These geomorphic processes hold immense significance in both scientific and practical realms. Scientifically, they enable us to decipher the Earth's geological history and understand the interactions between natural elements. Practically, studying these processes helps manage environmental resources and mitigate natural hazards. By examining the patterns of erosion, experts can predict and manage soil loss and landslides. Coastal processes inform strategies to safeguard vulnerable coastal communities against erosion and sea-level rise. Moreover, these processes are vital for groundwater flow assessments and understanding the connectivity between surface and subsurface hydrology. Ultimately, comprehending geomorphic processes enriches our understanding of the Earth's past, present, and future, guiding land use, urban planning, and conservation efforts.

Several eminent personalities have left indelible marks on the study of geomorphic processes. William Morris Davis pioneered the concept of cycles of erosion, forming the basis for understanding landscape evolution. John Wesley Powell's exploration of the Grand Canyon elucidated the role of river erosion, emphasizing watershed importance. G.K. Gilbert's work on graded streams advanced river dynamics comprehension. Jean-Baptiste Lamarck recognized organisms' role in shaping landscapes. Waldo Tobler's "first law of geography" underlined spatial patterns in geomorphic interactions. Ian Burton integrated geomorphic processes into disaster risk analysis. Michael Church's contributions enhanced fluvial geomorphology knowledge, aiding river management. These luminaries collectively forged the path to unravelling Earth's surface evolution and informing land use practices.

This block introduces you to different geomorphic processes and associated landforms, like aeolian processes and landforms, karst processes and landforms, glacial processes and landforms, and coastal processes and landforms in detail in four units.

Unit 10: Aeolian Processes and Landforms

This unit explains the aeolian processes and associated landforms. Here you will study about the process of wind erosion, types of aeolian transport, types of wind deposition, aeolian landforms, and fluvial desert landforms.

Unit 11: Karst Processes and Landforms

This unit discusses the karst processes and associated landforms. Here you will also study about the global distribution of karst landforms. Different karst forms are also discussed here in detail with the karst cycle of erosion.

Unit 12: Glacial Processes and Landforms

This unit discusses the glacial processes and associated landforms. In this unit, you will study the geological past of glaciation, theories of glaciation, types of glaciers, glacier processes, glacial erosion, pathways, and deposition.

Unit 13: Coastal Processes and Landforms

This unit explains the coastal processes and associated landforms. Here you will study the profile of coastal zones, agents of coastal erosion, the mechanism of coastal erosion, erosional landforms, depositional landforms, and the Transportational work of sea waves.

We hope after studying this block, you will better understand the different geomorphic processes and how associated landforms are formed. Our best wishes are with you in this endeavour.

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UNIT 10

AEOLIAN PROCESSES AND LANDFORMS

Structure

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	Expected Learning Outcomes	10.5	Encroachment
10.2	Wind Erosion	10.6	Aeolian Landforms
	Deflation	10.7	Fluvial Desert Landforms
	Abrasion	10.8	Summary
	Saltation	10.9	Terminal Questions
10.3	Types of Aeolian Transport	10.10	Answers
10.4	Wind Deposition		References and Suggested
	Sedimentation		Further Reading
	Accretion		

10.1 INTRODUCTION

In the previous Unit 9, you studied about the fluvial processes and landforms. Now in this Unit 10, you will study the Aeolian processes and landforms in detail. The aeolian processes and landforms encompass a fascinating realm of geological and environmental phenomena shaped by the action of wind. Derived from the Greek word "Aeolus," the god of wind, aeolian processes refer to the transport, erosion, and deposition of sediment particles by wind. Over millions of years, the wind has played a crucial role in shaping Earth's surface, creating unique landforms, and leaving its mark on diverse landscapes around the world.

Aeolian processes are most prominent in arid and semi-arid regions, where sparse vegetation, limited precipitation, and loose, unconsolidated sediments provide optimal conditions for wind to exert its influence. However, wind-driven processes are not confined solely to deserts. They also occur in coastal areas and glaciated regions.

Aeolian landforms are diverse and remarkable, reflecting the complex interactions between wind, sediment, and topography. Some of the most iconic aeolian landforms include sand dunes, desert pavements, loess

deposits, and ventifacts. Sand dunes, in particular, come in different shapes and sizes, ranging from crescent-shaped barchan dunes to elongated transverse dunes and parabolic dunes with their U-shape. By delving into the dynamic world of aeolian processes, we gain a deeper appreciation for the profound influence of wind on Earth's ever-evolving surface and we will study this dynamic world of Aeolian processes in this unit.

In Section 10.2 of the unit, you will study the main processes of wind erosion. Here you will learn about the differential erosion of rocks by the wind. In Section 10.3, you will learn the different types of Aeolian transportation processes through which wind transports dust and sand. You will also learn the role of the size of particles in wind transportation. In Section 10.4, you will study the types and processes of wind deposition. In this section, you will also study the types, processes, and mechanisms of wind deposition. In Section 10.5, you will know about the erosional and depositional landforms developed by Aeolian processes, and in section 10.6, you will learn about the fluvial desert landforms.

Expected Learning Outcomes

After studying this unit, you will be able to:

- define and classify Aeolian processes;
- describe types of wind erosion;
- explain how wind deposition takes place; and
- describe the origin and evolution of Aeolian landforms.

10.2 WIND EROSION

The wind is an effective geomorphic agent. It erodes and can transport loose, unconsolidated fragments of sand and dust. Wind, like running water, transports, corrades, and deposits; but it is different from running water both in its mode of action and in its effects. It has not the power of a rapid river and cannot move such heavy fragments as a river often does. The strength of wind is independent of the slope over which it blows, and it can carry material both upwards and downwards. Here and there a turbulent stream may throw sand and mud upon its banks, above the general level of the water, but the upward movement is never more than a few feet. Wind on the other hand whirls the finer particles to great heights, and in desert regions, it often blows clouds of dust across a mountain range. It transports sand by saltation and surface creep. Dust is transported in suspension, and it can remain high in the atmosphere for long periods. The erosional work of wind is mainly completed in physical or mechanical form. Some of the important processes of wind erosion are mentioned below:

10.2.1 Deflation

Deflation is the process by which wind removes dry, loose sand, silt, and clay from the land surface, especially in arid and semi-arid regions. This is the progressive removal of fine material by the wind leaving pebble-strewn desert pavements or reg. Dry river courses, beaches, and areas of recently formed

glacial deposits are more susceptible to deflation. In dry climates, much of the ground surface is subject to deflation because the soil or rock is largely bare of vegetation.

The deflation action of the wind is selective. The finest particles, those of clay and silt sizes, are lifted and raised into air-sometimes to a height of a thousand meters or more. Sand grains are moved only when winds are at least moderately strong and usually travel within a meter or two (about 3 to 6ft) of the ground. Gravel fragments and rounded pebbles can be rolled or pushed over the flat ground by strong winds, but they do not travel far. They become easily lodged in hollows or between other large grains. Consequently, where a mixture of sizes of particles is present on the ground, the finer-sized particles are removed and the coarser particles remain behind. A saucer-shaped or trough-shaped landform produced by deflation is a shallow depression called a **blowout** (deflation hollows). The size of the depression may range from a few meters (10 to 20 ft) to a kilometer (0.6 mi) or more in diameter, although it is usually only a few meters deep. The groundwater table is the base level of wind erosion and limits the depth of deflation.

Desert is any area where the rate of evaporation is higher than the rate of precipitation.

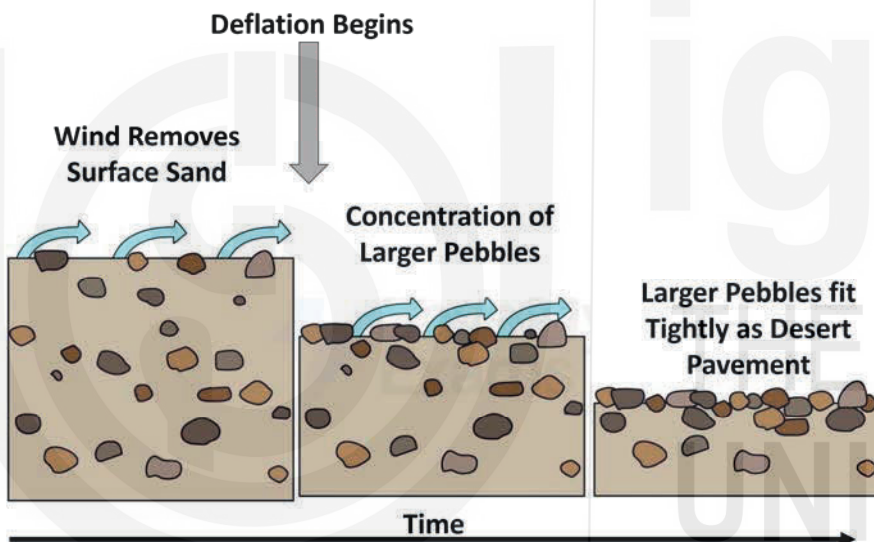


Fig. 10.1: Deflation.

The deflation process may be observed in all types of regions (Humid, semi-arid, and desert) but it is more significant in all arid regions. Deflation commonly occurs in semi-arid regions where the protective cover of grass and shrubs has been removed by the activity of humans and animals. It does not occur where there are thick covers of vegetation or layers of gravel. From a geomorphological point of view, deflation is more pronounced in the areas of sandstone. The process is thus limited to areas such as deserts, beaches, and barren fields. There are numerous blow-outs (deflation hollows) in the valley of the Nile. Of these, the most well-known is the Qattara depression in the western part of Egypt. The Qattara depression has been excavated to nearly 135 meters below sea level.

10.2.2 Abrasion

The mechanical wearing away of a rock by friction, rubbing, scraping, or grinding is known as abrasion. In the process of abrasion, the winds pick up

The rock pieces having three abraded facets are called dreikanter, while the boulders with two abraded facets are called zweikanter.

dust and sand and drive them with tremendous force against the rocks. In fact, in the desert and semi-desert areas winds carry with them enormous quantities of sand, dust, and small angular fragments which act as tools of erosion as they strike against the rock surfaces. Through this process, the less resistant rocks are etched and in time completely worn away, while the hard and very resistant rocks are polished and smoothed to a remarkable degree. Usually, the sandblast effect is greatest within 2 meters (about 6 feet). As the wind cannot lift sand more than a few meters, the effect of abrasion becomes insignificant after a few meters in height.

In areas where soft, poorly consolidated rock is exposed, wind erosion can be both spectacular and distinctive. Some pebbles, known as *ventifacts* (literally meaning 'wind-made', are shaped and polished by the wind. Such pebbles generally have two or more flat faces that meet at sharp ridges and are generally well-polished. Other ventifacts have a variety of shapes. A ventifact rock boulder/cobble may have as many as eight abraded facets.

Abrasion refers to the mechanical wearing down of Earth's surfaces by the grinding action of sediment particles transported by wind, water, or ice. It is a process that involves the physical impact and rubbing of sediment against rocks or other surfaces, resulting in the removal of material and the modification of landforms.

Abrasion occurs when sediment particles, such as sand, gravel, or rock fragments, are moved by erosional agents like wind, water, or glacial ice. As these particles are transported, they collide with and scrape against the underlying surfaces, wearing them down through repeated friction and impact. The degree of abrasion depends on factors such as the hardness and angularity of the particles, the velocity of the erosional agent, and the duration of the process.

We have different examples of abrasion which occurs in different geomorphic settings. Some of them are discussed below:

- **Coastal Abrasion:** Along coastlines, waves and tidal currents carry sediment, including sand and pebbles, and continuously impact the shoreline. The abrasive action of these sediments against coastal rocks leads to the formation of distinct landforms, such as sea cliffs, sea caves, and rocky platforms. Over time, the repeated collision and rubbing of the sediment against the coast can result in the smoothing, sculpting, and eventual erosion of the rock surfaces.
- **Glacial Abrasion:** During glaciation, large bodies of ice called glaciers move downhill, carrying a significant amount of debris, ranging from clay to boulders, within their icy mass. As the glacier slides over the land, the embedded sediment particles act as a grinding tool, abrading the underlying bedrock. This glacial abrasion leads to the formation of glacial polish, striations (parallel grooves), and roche moutonnée (smooth, elongated bedrock hills). These landforms bear the signature of the glacial erosion caused by the abrasive action of the transported sediment.
- **Riverine Abrasion:** In rivers, sediment particles transported by the flowing water collide with the riverbed and the banks. This abrasion

process can significantly affect the shape and size of river channels, leading to the formation of river cliffs, meanders, and potholes. Potholes, in particular, are cylindrical depressions carved into the bedrock by the swirling action of sediment particles in the river.

- **Wind Abrasion:** In arid and semi-arid regions, wind-blown sediments, such as sand, are carried by the wind and impact exposed surfaces. This process, known as wind abrasion or wind deflation, can result in the erosion of rocks and the sculpting of landforms like ventifacts. Ventifacts are rocks that have been shaped and polished by the abrasive action of wind-blown sediments over an extended period.

10.2.3 Saltation

Saltation refers to a specific process of sediment transport by wind or water, where particles are lifted and moved in a series of short hops or jumps. It occurs when the force of the wind or water flow is sufficient to lift and transport sediment particles, but not strong enough to keep them suspended continuously. Saltation plays a significant role in shaping landscapes and influencing the distribution of sediments in various environments, including deserts, rivers, and coastal areas.

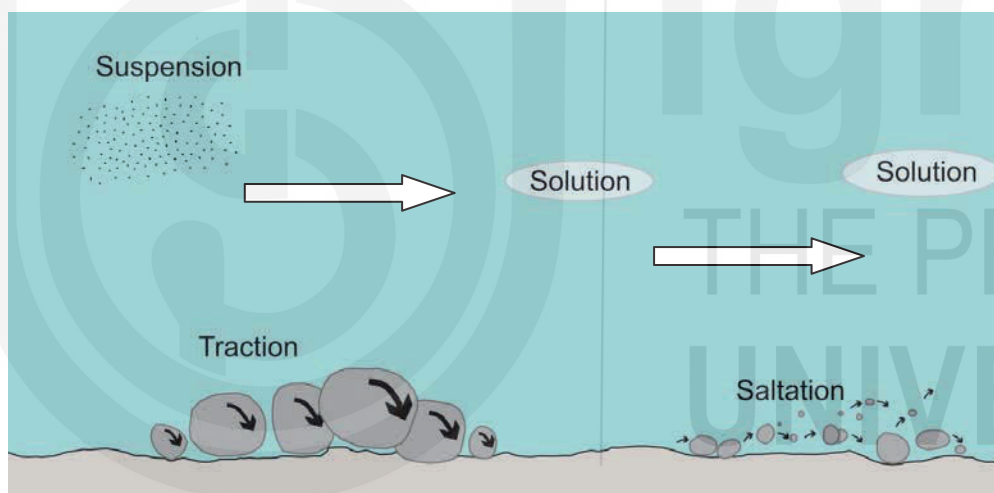


Fig. 10.2: Saltation.

In the context of wind erosion and deposition, saltation is a common mechanism for moving sand-sized particles across the Earth's surface. As the wind flows over loose sand or sediment, it imparts enough force to lift particles into the air. These particles are then carried for a short distance before gravity pulls them back to the ground. Upon impact, they dislodge and displace additional particles, creating a chain reaction of saltation. The repeated process of lifting, transporting, and impact leads to the movement of sediment in a leapfrogging motion. The movement of sand dunes in a desert environment is a classic example of saltation. As the wind blows across a desert landscape, it picks up sand grains through saltation. The particles are transported in a series of short jumps, with each grain briefly suspended in the air before falling back to the ground. Over time, this process causes the sand dunes to migrate or change shape, as the sand grains are continuously transported in a saltatory manner.

Through the process of abrasion, the most common landforms developed are mushroom-shaped blocks called *gara* in the sahara desert.

Similarly in rivers and streams, saltation can also occur as a mechanism for sediment transport. When the water flow becomes turbulent, it can entrain sediment particles and transport them in a bouncing or hopping motion along the streambed. This process is particularly significant during high-flow events when the velocity and turbulence of the water increase, allowing for the saltation of coarser sediments. For example, in a fast-flowing river, when the water velocity increases due to heavy rainfall or snowmelt, the sediment particles on the riverbed may be lifted and transported by saltation. Coarser particles, such as pebbles or small rocks, are particularly prone to saltation under high-flow conditions. The repeated lifting and dropping of these particles contribute to the erosion and deposition processes, shaping the riverbed and influencing the overall geomorphology of the stream.

SAQ I

Write three main processes of wind erosion.

10.3 TYPES OF AEOLIAN TRANSPORT

Aeolian transport refers to the process by which wind transports and moves sediment particles, such as sand, silt, and dust, across the Earth's surface. Wind transports dust and sand in several ways. The fine, light materials are picked up, suspended in the air, and carried away. Heavy or large sand grains are dragged along the surface of the ground. The wind carries the load generally in suspended condition, and some particles are dragged along the surface. The dust storms, carrying dust at long distances are known as Haboobs in Arabic language, especially in Sudan, Egypt, Saudi Arabia, and Yemen.

This type of transport is primarily driven by the force exerted by the wind on the loose particles, causing them to be lifted and transported. Aeolian transport plays a significant role in shaping landscapes, particularly in arid and coastal regions. There are three main types of aeolian transport: saltation, suspension, and Surface creep.

- i. **Suspension:** Suspension refers to the transport of very fine particles, such as dust or silt, in the air without direct contact with the ground. The process of suspension is observed where the material is very fine, i.e., less than 0.15 mm in diameter, it can be picked up by the wind, raised to considerable heights, and carried great distances. Such particles will remain in suspension as long as the strength of the upward currents of air exceeds the tendency of the particles to fall down to the surface under gravity pull. Suspension is prevalent in areas with loose and fine-grained sediments, such as dry riverbeds, arid regions, and areas affected by dust storms.

Example: Dust storms are an excellent example of suspension aeolian transport. During a dust storm, strong winds lift fine dust particles into the air, where they remain suspended and are carried over long distances. These particles can travel across continents and even reach remote areas far from their original source. Dust storms often occur in arid and semi-arid regions and can have significant impacts on air quality, visibility, and human health.

- ii. Saltation: Saltation is the most common form of aeolian transport, and it occurs when windblown particles are lifted and moved in a series of short bounces or hops. The particles are lifted from the surface and carried in the air for a short distance before gravity pulls them back to the ground. During the airborne phase, the particles collide with the surface, causing them to dislodge other particles that are then lifted in a similar manner. This continuous process results in the movement of sediment in a hopping or bouncing motion. Saltation is most effective for sand-sized particles (0.06-2.0 mm in diameter) and accounts for the majority of sediment transport in sandy deserts, riverbeds, and coastal areas. It occurs when wind speeds exceed the threshold velocity (the speed required to initiate grain movement), and fine and coarse-grained sand particles are lifted. They may rise almost vertically for several centimeters before returning to the ground in a relatively flat trajectory of less than 12 Degree.

Example: In a desert environment, such as the Sahara Desert, the wind can lift and transport sand particles through saltation. As the wind blows across the sandy surface, it lifts sand grains into the air, causing them to hop and bounce along the ground. This process can result in the formation of sand dunes and the gradual movement of sand across the desert landscape.

- iii. Surface Creep: Surface creep is the slowest form of aeolian transport, involving the movement of larger particles through a rolling or sliding motion along the surface. As the wind continues to blow, the sand particles bounce along, leap-frogging over one another. Every time a sand particle is transported by saltation, it may dislodge and push forward larger particles (more than 0.25mm diameter) that are too heavy to be uplifted and that causes surface creep. This constant bombardment gradually moves small stones and pebbles over the desert surface. Surface Creep is most effective for larger and heavier particles that cannot be easily lifted into saltation or suspension. It is commonly observed in regions with coarse or gravelly sediments, such as deserts with a mix of sand and pebbles.

Example: In gravelly deserts like the Mojave Desert in the United States, the wind can transport pebble-sized particles through creep. As the wind blows across the desert surface, it imparts a force on the larger particles, causing them to roll and slide along the ground. Over time, this process leads to the slow movement of gravelly sediments across the desert landscape.

Aeolian transport processes are interconnected, and in many cases, multiple types of transport occur simultaneously. The proportions of each type of transport depend on various factors, including wind speed, direction, sediment size and composition, surface roughness, and moisture content. These factors can significantly influence the extent and effectiveness of aeolian transport in a particular environment. Let's discuss these additional **factors of Aeolian transport processes** in more detail:

- Wind Speed: The velocity of the wind plays a crucial role in determining the type and intensity of aeolian transport. For saltation, there is a threshold wind speed, called the "critical shear velocity," which is required to initiate particle movement. Higher wind speeds can lift larger and

heavier particles, resulting in increased saltation and creep. Suspension, on the other hand, is more dependent on wind turbulence and can occur at lower wind speeds, especially for fine particles.

- **Wind Direction:** Wind direction influences the direction of sediment transport. It determines the predominant pathways and deposition areas. In areas with variable wind directions, sediments may be transported back and forth, resulting in complex patterns of deposition and erosion.
- **Sediment Characteristics:** The size, shape, and composition of sediment particles affect their susceptibility to aeolian transport. Smaller particles are more easily lifted and transported through saltation and suspension, while larger particles tend to move through creep. Angular and rough particles are less likely to be lifted than rounded and smooth particles. Additionally, cohesive and well-cemented sediments are less prone to aeolian transport compared to loose and unconsolidated sediments.
- **Surface Roughness:** The roughness of the surface over which the wind blows influences the intensity of aeolian transport. Rough surfaces, such as vegetation, dunes, or rocky terrain, can cause the wind to become turbulent, enhancing the lift and movement of sediments. Smooth surfaces, such as water bodies or compacted soils, reduce the effectiveness of aeolian transport.
- **Moisture Content:** Moisture affects the cohesion and stability of sediment particles. Dry and loose sediments are more easily entrained by the wind, facilitating saltation and suspension. However, the presence of moisture can increase the cohesive forces between particles, making them less prone to aeolian transport.

It is essential to consider these factors collectively to understand the dynamics of aeolian transport in a specific environment. The relative dominance of each type of transport and their interactions shapes the landforms and contribute to sediment redistribution, which has implications for ecosystem dynamics, land degradation, and geological processes.

SAQ 2

Mark the following statements as True or False:

- a) Dust-size particles are carried in suspension.
 - b) Suspension is the most common form of wind transport in arid regions.
 - c) The effectiveness of the transportation method is related to particle size.
 - d) Transportation of eroded material by wind is related to the slope of the land.
-

10.4 WIND DEPOSITION

Wind deposition, also known as aeolian deposition, refers to the process by which sediment particles carried by the wind are deposited and settle onto the Earth's surface. When wind loses its energy, it becomes incapable of transporting particles further, causing them to settle and accumulate in specific locations. Wind deposition plays a vital role in shaping various

landforms and landscapes, and it occurs in diverse environments, including deserts, coastal areas, and glaciated regions.

Sooner or later the material carried by the wind must be deposited. It may be dropped when the wind dies down, and fall either on the land or into the sea, or it may be drifted into a sheltered hollow or banked against an obstacle. The wind is a good sorting agent. So, in depositional landforms made by wind, good sorting of grains can be found. Since wind is there everywhere and wherever there is a good source of sand and with constant wind directions, depositional features in arid regions can develop anywhere.

Wind deposition may take place in three ways which are mentioned below and discussed in brief:

(1) sedimentation, (2) accretion, and (3) encroachment.

10.4.1 Sedimentation

Sedimentation refers to the process of sediment particles being deposited and settling onto the Earth's surface as a result of wind deposition. Sedimentation occurs when sediment grains fall out of the air or stop creeping forward. For sand grains, this happens if the air is moving with insufficient force to carry the grains forward by saltation or to move other grains by creep. For silt and clay, this happens if particles are brought to the ground by air currents or if the air is still enough for them to settle out (dry deposition), or if they are brought down by rain (wet deposition). Wet deposition appears to be significant where dust plumes pass over humid regions and out over the oceans. It is the main process of bringing down Saharan dust in the Mediterranean region. Wet deposition may give rise to blood rains and red rains.

Sedimentation plays a crucial role in shaping landforms and ecosystems. As sediments are deposited, they can form layers or beds, which over time can build up to create significant features. Sedimentation can occur through various modes of wind deposition, including saltation, suspension, and creep.

Examples: In desert environments, sedimentation through wind deposition can result in the formation of sand dunes. As wind transports sand particles, they eventually settle and accumulate, forming distinctive dune shapes and patterns. Similarly, fine dust particles carried by the wind can settle on vegetation, soil, or water bodies, leading to the deposition of dust layers.

10.4.2 Accretion

Accretion refers to the gradual growth or enlargement of landforms through the deposition of sediment over time. Accretion occurs when grains being moved by saltation hit the surface with such force that some grains carry on moving forward as surface creep, but the majority come to rest where they strike. Accretion deposits are thus moulded by the combined action of saltation and surface creep and accumulate, increasing the size and volume of existing features or creating new ones.

Accretion is particularly significant in coastal areas, where wind transports sediment from beaches or dune systems and deposits it offshore or along the shoreline. Over time, this accumulation of sediment contributes to the growth and expansion of land areas, forming coastal features such as barrier islands, spits, and sandbars.

Examples: Barrier islands are a prime example of accretion through wind deposition. As wind carries sand particles from the beach, they settle and accumulate offshore, gradually building up the landform. Over time, these deposits form long, narrow islands parallel to the coast, providing protection to the mainland from the ocean.

10.4.3 Encroachment

Encroachment takes place when deposition occurs on a rough surface. Under these conditions, grains moving as surface creep are held up, while saltating grains may move on. Deposition by encroachment occurs on the front of a dune when grains roll down the surface and come to rest. Coarse grains are often associated with erosional surfaces, as the fine grains are winnowed by the wind. Fine grains tend to occur on depositional surfaces. Coarse particles may also move to the ground surface from below.

The remarkably high rate of sand transport and the increase in development activities in the desert areas are responsible for the enhancement of the sand encroachment problems. Almost all installations, roads, and farms are significantly affected by the accumulation of considerable amounts of aeolian sand. These problems have pronounced adverse environmental and economic impacts.

Encroachment refers to the process of wind-driven deposition causing the expansion or advancement of sediment onto existing land areas. It occurs when wind-borne sediment accumulates and extends the boundaries of landforms or encroaches upon adjacent areas.

Encroachment is commonly observed in arid and semi-arid regions where wind erosion removes fine particles, leaving behind coarser sediments that are subsequently transported and deposited. The deposited sediments can encroach upon vegetation, infrastructure, or other landforms, altering the landscape and potentially causing changes in ecosystems.

Examples: In desert environments, wind-driven deposition can lead to encroachment of sand onto roads, agricultural fields, or human settlements. As wind transports and deposits sand particles, it can gradually cover and modify these areas, requiring mitigation measures to prevent further encroachment.

Overall, sedimentation, accretion, and encroachment are interconnected processes in wind deposition. They play significant roles in shaping landscapes, influencing ecosystems, and contributing to landform evolution over time. Understanding these concepts is crucial for studying the effects of wind transport and deposition on various environments.

SAQ 3

Write the factors of Aeolian transport processes.

10.5 AEOLIAN LANDFORMS

Aeolian landforms are landforms that are created or significantly influenced by the action of wind. They are formed through various processes such as erosion, transportation, and deposition of sediment by wind. Aeolian landforms can be found in arid, semi-arid, and coastal environments around the world. Landforms developed by Aeolian processes are classified into two broad categories, i.e., erosional landforms and depositional landforms.

A) Erosional Landforms

Some of the important erosional landforms of Aeolian processes are briefly described below:

(i) Yardangs

Yardangs are sharp-crested elongated ridges aligned in the direction of the prevailing winds in the deserts. The windward face of this feature is rounded, and the leeward extension appears like a long and sharply crested ridge (Fig. 10.3).

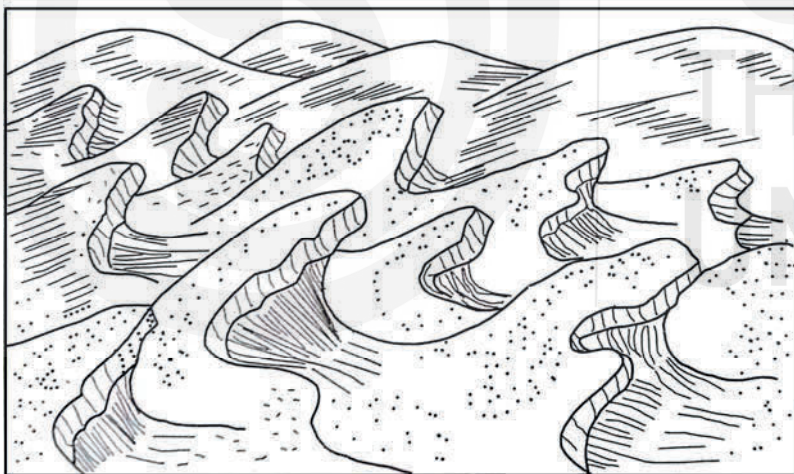


Fig. 10.3: Yardangs.

Yardangs can vary in size, ranging from a few meters to several kilometers in length, and are commonly found in arid and desert regions.

The formation of yardangs begins with the removal of loose surface material by wind erosion, primarily through the process of deflation. As the wind blows over the landscape, it carries small particles, such as sand and silt, which act as abrasives. These particles impact the surface, gradually wearing it down and sculpting the characteristic streamlined shape of yardangs.

The shape and orientation of yardangs are determined by the prevailing wind direction. The wind erodes the softer, less resistant materials, leaving behind the more resistant rock formations or consolidated sediments. Over time,

repeated erosion and selective removal of weaker materials result in the elongated ridges and valleys that define yardangs.

Yardangs often occur in clusters or fields, where they are aligned with the prevailing wind direction. They can form in various geological settings, including deserts, semi-arid regions, and glacial outwash plains. Yardangs are typically composed of sedimentary rocks, such as sandstone or siltstone, although they can also occur in areas with softer volcanic ash deposits.

Prominent examples of yardangs can be found in the Gobi Desert in Mongolia and China, the Badain Jaran Desert in China, the Chalbi Desert in Kenya, and the Mojave Desert in the United States. These landforms not only showcase the erosive power of wind but also provide unique and visually striking features in desert landscapes.

(ii) Zeugens or Rock Mushrooms

The tabular masses of more resistant rock resting on undercut pillars of softer material are known as zeugens or rock mushrooms (Fig. 10.4a & b).

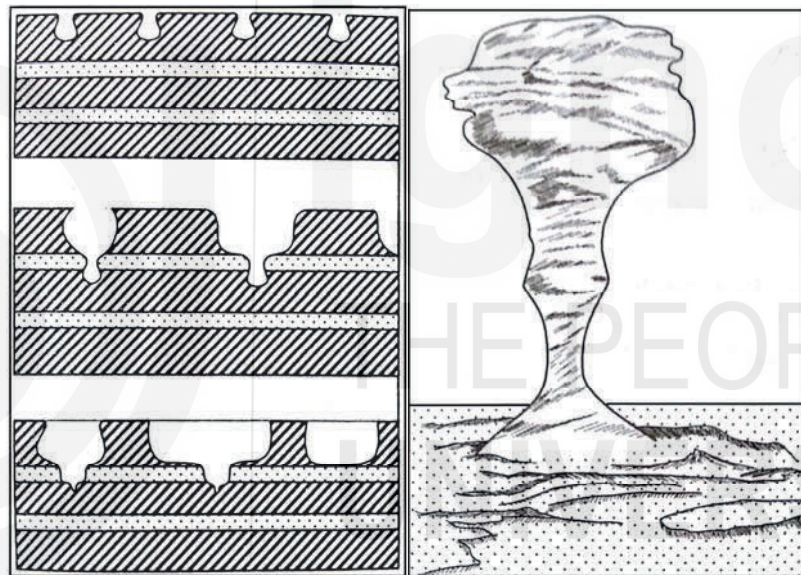


Fig.10.4: a) Formation of Zeugen in different stages; b) Rock Mushroom.

Zeugens are characterized by the presence of a resistant cap-rock, but some are elongated in the direction of the prevailing wind. These landforms are formed by the rocks of varying hardness which are characterized by horizontal strata. The more resistant cap rocks are attacked by frost action and probably by other agencies which results in the exposure of points of weakness in them. Zeugens are also called **pilzfelsen**. They are known as **garas** or **gours** in the Sahara Desert.

(iii) Wind Bridges

The continuous abrasion of a rock by powerful wind results in the formation of holes in the rocks which are gradually widened. Such holes are called as wind windows. The holes are further widened and enlarged through the process of abrasion and deflation in such a way that an arch-like feature, having an intact roof is formed. Such formations are called window bridges.

(iv) Inselbergs

Inselberg is a German word which means island mountain that has been widely adopted to describe a prominent steep-sided hill of solid rock, rising abruptly from a plain of low relief. It is a characteristic of tropical landscapes, particularly in the Savanna zone, and is generally composed of resistant rock, such as granite. According to W. M. Davis, the inselbergs are taken to be the end-product of the arid cycle of erosion (Fig. 10.5).

Inselbergs in arid regions are also called 'Bornhardts'.

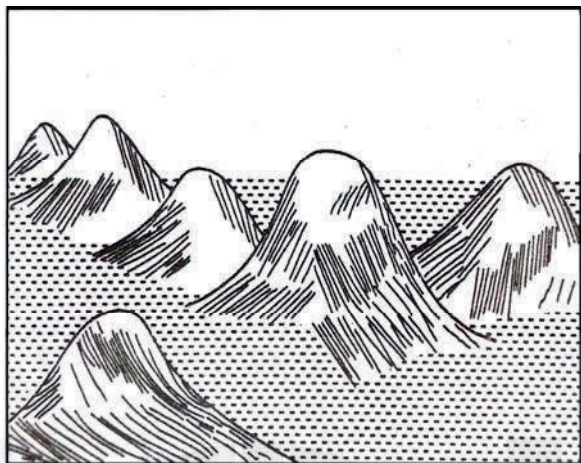


Fig. 10.5: Rock Inselberg.

Although inselbergs occur more frequently in the savanna regions, they are also found throughout the world and formed under different climatic conditions, from humid to semi-arid regions. In humid regions, they are exemplified by the sugar-loaf Mountains in Brazil. They are also found in southern Georgia in the USA. In semi-arid regions and arid regions, they are found throughout southern Africa, especially in Zimbabwe, South Africa, and Namibia as well as in Australia. Several theories on inselberg formation have been envisaged by several geomorphologists such as L.C. King, Twidale (1980), Peel (1960), Linton (1955), and many others.

King (1948) states that inselbergs are created when scarps retreat backward leaving a vast pediplain in the wake. Initially, for scarps to backward or retreat, interfluvies (the upland region separating adjacent valleys see diagram) or coastal cliffs must be present. Lateral erosion by rivers, sea waves, wind, or weathering acts along valley sides and or coastal scarps wearing them backward leaving a pediment behind which then coalesce with other pediments to form a pediplain. As time goes on, the interfluvie is reduced to an inselberg called a monadnock (Fig. 10.6).

Several monadnocks can be seen protruding in the plains of Africa including Tanzania, Zimbabwe, South Africa, New Hampshire, USA, and many others. In Zimbabwe, isolated hills can be seen in areas such as Banket.

King's theory practically doesn't apply to inselbergs such as Bornhardts or Tors rather, it applies to medium and large-scale hills. Other researchers suggest that bornhardts are formed as scarps retreat which is mostly argued with.

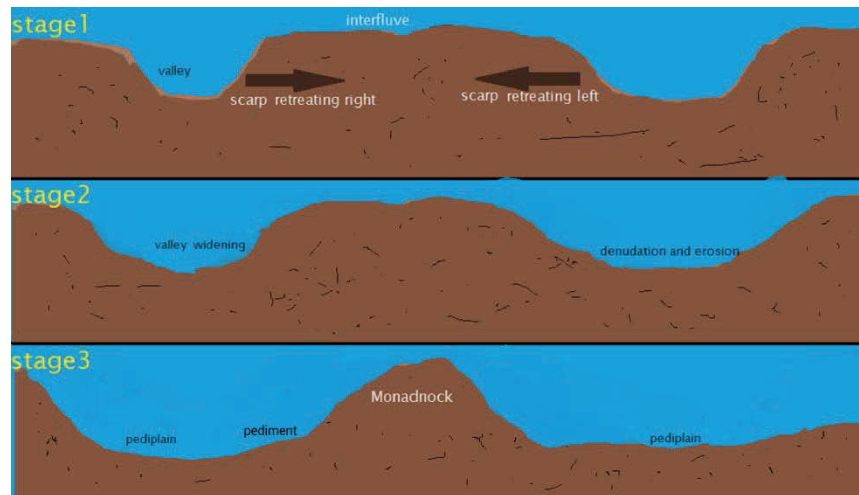


Fig.10.6: Formation of Inselberg (L. C. King).

Several geomorphologists envisaged the etchplanation theory including Twindale, Linton, and Ollier. This theory takes into account deep weathering which mostly occurs in sub-tropical climates where successive periods of wetness and dryness exist. During the rainy season, deep weathering is more pronounced which produces deep regolith. During dry periods erosion and denudation then strips away the regolith revealing seated basal surfaces or weathered boulders as tors. This theory implies that the rate of denudation and stripping must overtake that of deep weathering. If deep weathering is faster than the basal surface will not be exposed to the surface but rather keeps on lowering etchplanation makes more sense in explaining inselberg protrusions such as bornhardts, tors, or dawallas but not hilly inselbergs. However, some argue that deep weathering and stripping occur at the same rate a process called double planation.

R.F. Peel (1960, 1966) viewed the inselbergs in the Savanna landscapes as, in fact, the products of humid climatic conditions prevalent during the Quaternary period when rivers were common and lateral erosion was dominant.

(v) Demoiselles

Demoiselles is a term of French derivation used to describe an earth pillar (often till) in which a boulder has protected the underlying material from weathering and now survives as a cap-stone precariously perched on the pinnacle of the slender pillar. The demoiselles are maintained so long as the resistant cap rocks are seated at the top of the pillars. Once the cap-stone falls from the pinnacle, the pillar is soon destroyed.

B) Depositional landforms

The following are the main depositional landforms produced by the depositional action of wind in the arid regions:

(i) Ripple marks

Ripple marks are small-scale sedimentary structures formed on the surface of a sediment layer, such as sand or silt, as a result of the movement of fluids, such as wind or water. Ripple marks typically have a regular or irregular wavy

pattern and can be found in many environments, including rivers, beaches, deserts, and underwater.

There are two main types of ripple marks: symmetrical and asymmetrical. Symmetrical ripple marks have a crest and trough of equal size and shape, while asymmetrical ripple marks have a steeper, upstream-facing slope and a gentler, downstream-facing slope. The direction of the fluid flow that formed the ripple marks can be determined by examining the asymmetrical ripples.

Ripple marks can also vary in size, ranging from a few millimeters to several centimeters in height, depending on the size and velocity of the fluid that formed them. In some cases, ripple marks can form in a series of parallel ridges, known as dunes, which can be much larger in scale and can have significant impacts on the surrounding landscape.

(ii) Sand dunes

A mound or ridge of wind-blown sand with a crest or definite summit is known as a sand dune. Sand dunes are undoubtedly the most spectacular features of the sandy deserts. An ideal dune has a long windward slope rising to a crest and a much steeper leeward slope. The dunes are generally mobile. There is a wide range of variations in their shape, size, and structure. They also vary in height, length, and width. On an average, their height ranges between a few meters to 20 meters, but there are some sand dunes that are more than several hundred meters in height and 5 to 6 km in length. The windward slope of a sand dune is generally gentle (5° to 15°) while the leeward slope is always relatively steep (20° to 30°).

Sand dunes have been classified on the basis of morphology, structure, orientation, location, and ground pattern. Two basic types of dunes on the basis of forms are: Transverse or crescentic dunes (barchans or barchans), and (ii) longitudinal dunes (seifs). Some basic main types of sand dunes are the following:

Sand seas in the Sahara Desert are called 'ergs'.

(a) Barchans Dunes

Sand dunes of crescentic shape having two horns are called barchans. In fact, barchans are special types of transverse dunes. The windward side having a gentle slope is convex in plan while the leeward side is concave in plan with a steep slope (Fig. 10.7). The horns always project downwind.

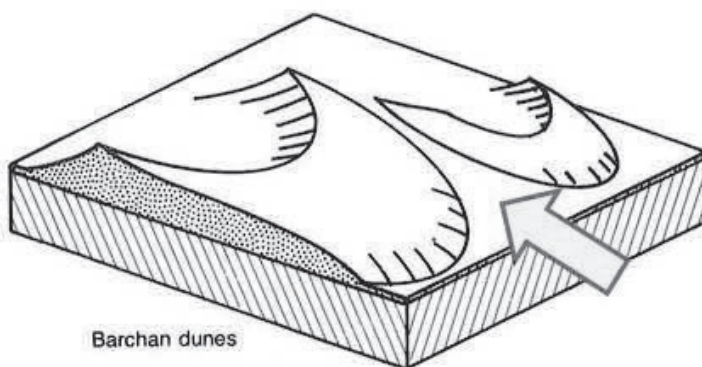


Fig.10.7: Barchan Dunes.

The Barchans are formed where the supply of sand is limited and winds of moderate velocity blow in a constant direction. Typically, they are small, isolated dunes from 1 to 50 m high. The tips (horn) of barchans point downwind, and sand grains. They can be scattered over a bare rock or desert pavement or commonly in dune fields. They are found in sandy deserts all over the world.

(b) Barchanoid Ridge Dunes

Asymmetrical wavy dune ridge consisting of parallel rows of coalesced barchans (connected crescents) in plain view (Fig. 10.8). It is oriented transverse to the predominant wind direction and migrates forward. It has gently dipping windward slopes and steeply dipping ($32-34^\circ$) leeward slopes. Barchanoid ridges are typically separated by open, inter-dune corridors. Inter-dune depressions between closely spaced barchanoid ridges are termed fulje (Glenn 1979).

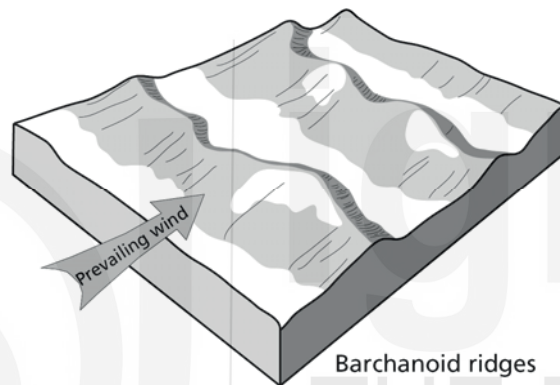


Fig.10.8: Barchanoid Dunes.

(c) Transverse Dunes

A large, strongly asymmetrical, elongated dune lying at right angles to the prevailing wind direction is known as a Transverse dune. These dunes have a gently sloping windward side and a steeply sloping leeward side (Fig. 10.9). They generally form in areas of sparse vegetation and abundant sand. Most beach dunes are transverse dunes. These dunes result from relatively ineffective wind and abundant sand supply (e.g., Rub-al-Khali).

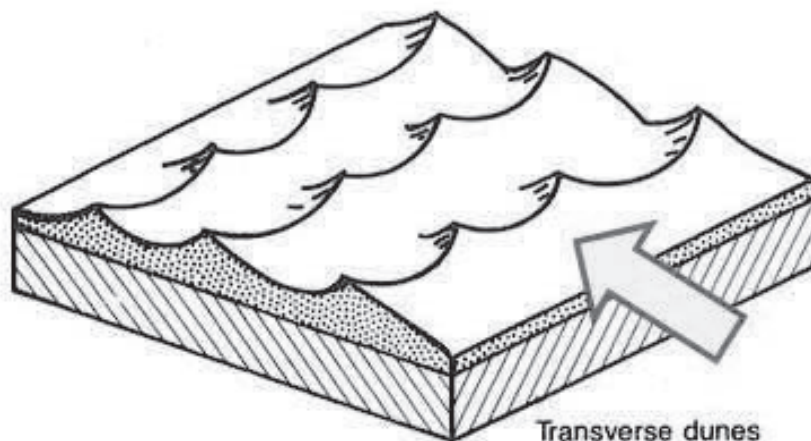


Fig.10.9: Transverse Dunes.

(d) Parabolic Dunes

Parabolic dunes also called U-shaped, blowout, or hairpin dunes tend to form where vegetation covers the sand. Winds may erode a section, pushing the sediment leeward (Fig. 10.10). The vegetation will hold back the arms of the dune so that the dune points in the leeward direction. They are most common in coastal deserts. Sometimes, parabolic dunes can come from transverse or barchan dunes, given that the dunes stay static enough for vegetation to grow on them. Role of anchoring vegetation is important in forming of these dunes.

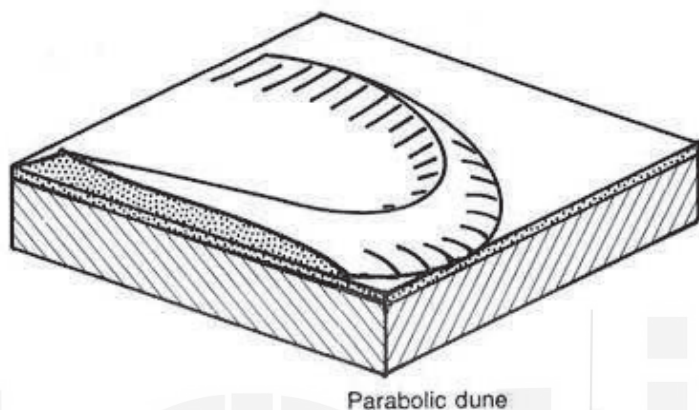


Fig.10.10: Parabolic Dunes.

(e) Longitudinal Dunes

They are also called linear dunes, longitudinal dunes look like large, parallel needle-esque features on the landscape. They are straight, and long, unlike the typical dune that people imagine (Fig. 10.11). This dune type forms when sand is not in excess, and when wind blows in one constant direction. Over an extended period of time, the dunes will migrate in the direction the wind is blowing.

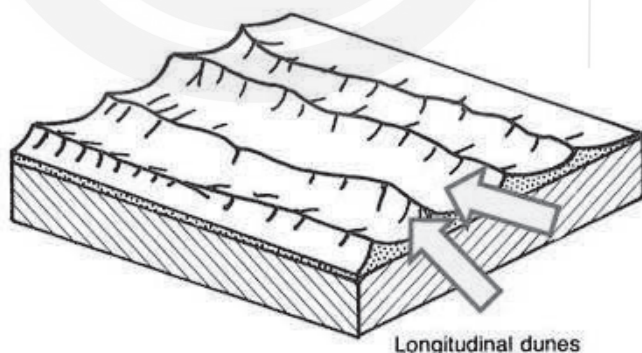


Fig.10.11: Longitudinal Dunes.

(f) Seif Dunes

A seif is a long, narrow sand dune or a chain of dunes that is generally directed parallel to the prevailing wind or in a direction formed by two or more winds blowing at sharp angles to one another. The dune crest is made up of a sequence of peaks and gaps, and the steep, or slip. The majority of seif dunes are found in the open desert, resting on a coarse sand sheet. They are very common in Libya and southern Iran.

(g) Star Dunes

Star dunes are rare, interesting dune structures, that pepper landscapes in sandy deserts. They form when alternating and multiple wind directions pile sand in a location, and form a peak, with many arms extending from the center. Star dunes make up 8.5 percent of all the dunes on the planet, and they often form in large groups in a dune field (Star Dunes). Many of these fascinating dunes can be seen in the Sahara Desert, especially in the Grand Erg Oriental, a “sand sea” of dunes. They are usually pyramidal or star-shaped with three or more sinuous radiating arms extending outward from a central peak. These dunes result from effective winds shifting in all directions. They tend to form isolated mounds in high effective winds and connected sinuous arms in low effective winds.

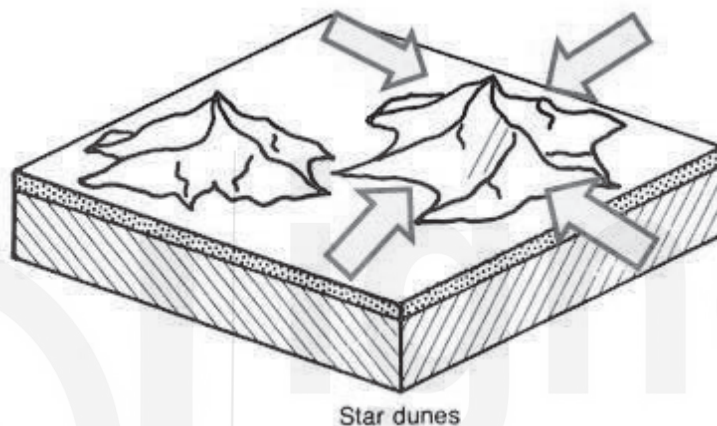


Fig.10.12: Star Dunes.

(h) Nebkha or Coppice Dunes

Nebkha dunes (also known as coppice dunes) are simple dunes that form around vegetation, primarily on the sand sheet. Nebkhas are a type of anchored dune that forms by sediment accumulation around grasses, shrubs, or trees.

The formation of dunes is a dynamic (constantly changing) process. There are different stages in the process that forms dunes – a quiet stage, an erosion stage, and an accretion stage. The process is sometimes called the cut and fills cycle.

Nearly all types of sand dunes are found in India. Large longitudinal sand dunes are found abundantly in the western part of the Great Indian Desert (Thar Desert). These sand dunes attain a height of about 30 metres or so. Coastal sand dunes are found along the Malabar coast, Odisha coast, Kutch coast, etc. where mainly longitudinal dunes have developed. Transverse dunes are found along the riverine banks of the Ganga, the Kosi, the Krishna, the Godavari rivers, etc.

(iii) Loess

Loess is a type of sedimentary deposit consisting of fine-grained, wind-blown silt and clay particles. It is typically yellowish-brown or buff in color and is

composed of loosely packed, unconsolidated material. Loess deposits are widespread and can be found in various regions around the world.

Loess forms through the accumulation of wind-blown dust and sediment, primarily during periods of glaciation or in areas with extensive arid or semi-arid climates. The source of loess particles is often glacial flour or fine-grained sediment derived from glaciers or deserts. As wind currents transport these particles over long distances, they settle and accumulate in sheltered areas, such as river valleys, floodplains, or the leeward sides of hills and dunes.

In the Midwest of the United States there are deposits of loess which are called adobe.

Loess deposits are characterized by their fine particle size, typically ranging from 0.002 to 0.06 mm in diameter. The particles are well-sorted and angular, reflecting the abrasive action of wind transport. Loess is highly porous and can retain significant amounts of water, making it suitable for agriculture in certain regions. It is also known for its ability to form vertical cliffs or steep slopes due to its cohesion and lack of internal structure.

Loess deposits have several important implications. Due to their high water-holding capacity, loess soils are fertile and can support agriculture. They are often associated with productive agricultural regions, such as the Loess Plateau in China and the Great Plains of North America. Loess also preserves a wealth of paleoclimatic and paleoenvironmental information. The fine layers of sediment can contain valuable records of past climatic conditions, vegetation changes, and human activities, providing insights into Earth's history.

Loess Plateau in China, where extensive loess accumulations cover vast areas, and the Loess Hills region in the United States, which stretches across parts of Iowa, Missouri, and Nebraska are some notable examples of loess deposits.

10.6 FLUVIAL DESERT LANDFORMS

Fluvial desert landforms are geological features that result from the interaction of rivers and water in arid or semi-arid desert environments. Despite the scarcity of water, rivers in these regions can have intermittent or ephemeral flows during periods of rainfall or flash floods. As the water flows across the arid landscape, it erodes the terrain, transports sediment, and deposits it in distinctive patterns. Fluvial desert landforms include wadis (dry riverbeds), alluvial fans, playa lakes, etc. In this section we will be studying some fluvial desert landforms like Badland, Pediments, and Bajadas in some detail.

(i) Badland Topography

Badland topography refers to a type of highly eroded, rugged, and barren landscape characterized by deep and narrow gullies, sharp ridges, and steep slopes which are extensively eroded by numerous rills and channels which are developed due to occasional rain storms (Fig. 10.13).

The linear fluvial erosion results in the formation of ravines and gullies which are divided by numerous undulating narrow ridges. Thus, the ground surface becomes so uneven and corrugated due to numerous gullies and ravines that it becomes entirely difficult to walk on it. Such a type of landscape is called

badland topography. It is typically found in arid or semi-arid regions where the combination of soft sedimentary rocks, sparse vegetation, and intense rainfall or runoff results in rapid erosion.



Fig. 10.13: Badland Topography.

Badland topography can be found in various regions worldwide, including parts of the United States (e.g., Badlands National Park in South Dakota), China (e.g., Zhangye Danxia Landform), Spain (e.g., Bardenas Reales), and Argentina (e.g., Ischigualasto Provincial Park).

(ii) Bolsons and Playas

Bolsons and playas are distinct landforms commonly found in arid and semi-arid regions. While they are related to each other in terms of their formation and association with arid environments, they have different characteristics and processes involved (Fig. 10.14).

Bolsons are large, enclosed basins or valleys typically surrounded by mountains or hills. They are characterized by their flat or gently sloping floors, which often lack a well-defined outlet for water drainage. Bolsons can vary in size, ranging from a few square kilometers to hundreds or thousands of square kilometers.

Bolsons are typically formed through tectonic processes, such as faulting or crustal deformation, which create a depression or basin in the landscape. They can also result from the erosional removal of underlying softer rocks, leaving behind a resistant layer that forms the basin floor. Bolsons are commonly found in regions with arid or semi-arid climates, where limited precipitation and drainage result in the accumulation of sediment and the formation of closed basins. Bolsons often have a flat or gently undulating floor, which can be covered by sedimentary deposits, such as sand, silt, clay, or evaporite minerals. They may also contain playa lakes, which are temporary or intermittent shallow water bodies that form during periods of high rainfall. Bolsons are typically devoid of permanent rivers or streams and have limited vegetation cover. The Bolson de Mapimí in Mexico and the San Luis Valley in Colorado, USA, are examples of bolson basins.

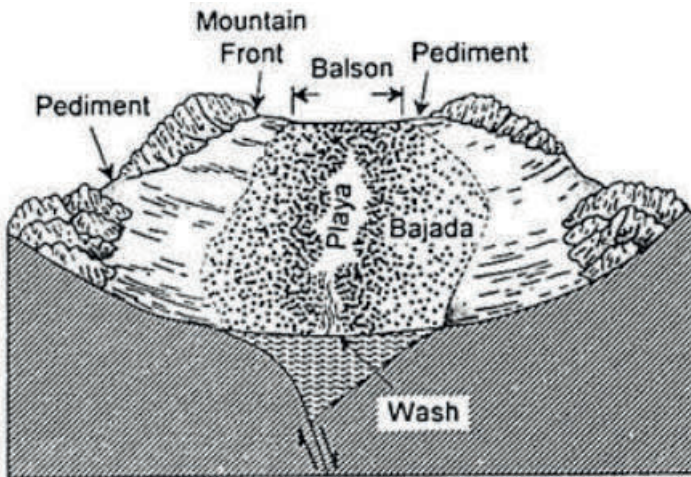


Fig. 10.14: Bolsons and Playas.

Whereas, Playas are flat, typically dry lake beds or basins that are characterized by a hard, flat surface consisting of clay, silt, or evaporite deposits. They can vary in size, ranging from small depressions to extensive areas spanning from a few square metres to tens of square kilometres. These are called 'khabari' and 'mamlaha' in Arabian deserts while they are known as 'shafts' in Sahara. Playa lakes may last for days, weeks, or even longer before they are completely dried up by evaporation. Evaporation of playa lake water results in the formation of encrustation of alkaline materials (sodium bicarbonate or sodium carbonate), salt deposits such as borax. Such salt-covered playa beds are called salinas.

(iii) Bajada

Bajada refers to a gently sloping, which ranges between 8 to 10 degrees in its upper part which becomes zero to 1 degree in its lowermost portion, broad alluvial fan or apron of sediment that forms at the base of a mountain range or hills. It is commonly found in arid and semi-arid regions where the lack of significant rainfall and intense erosion processes contribute to the accumulation of sediment (Fig. 10.14).

Bajadas are formed through the process of aggradation, which involves the deposition of sediment carried by water flow from the mountains or hillsides. The sediment is transported downhill by ephemeral streams or flash floods during periods of heavy rainfall. As the streams reach flatter terrain at the base of the mountains, the flow velocity decreases, resulting in the deposition of sediment. Over time, this sediment accumulates and spreads out, forming a gently sloping apron or fan-shaped landform.

Bajadas typically have a gentle gradient, ranging from a few degrees to several degrees, and can extend for several kilometers. They are composed of coarser materials near the mountain front, such as gravel, pebbles, and cobbles, which gradually transition to finer sediment, such as sand and silt, farther away from the source. The sediments are typically unconsolidated and porous, allowing for good water infiltration and storage.

Bajadas often support unique vegetation due to their favorable soil conditions. The sediments deposited on bajadas are relatively well-drained, have good water-holding capacity, and can provide nutrients, making them suitable for

plant growth. Bajadas may be covered with vegetation adapted to arid conditions, such as desert shrubs, grasses, and scattered trees.

Bajadas play important roles in the hydrology and ecology of arid and semi-arid environments. They serve as a crucial water storage and infiltration zone, allowing rainfall and runoff to percolate into the ground and replenish groundwater reserves. Bajadas also provide habitats for a variety of plants and animals adapted to the arid conditions, contributing to regional biodiversity.

Colorado Plateau in the southwestern United States, where extensive bajadas are present at the base of mountain ranges, such as the Grand Canyon region.

(iv) Pediments

Pediments situated between mountain front and bajada in the intermontane basin are broad, extensive, and gently sloping areas of rock-cut surfaces that spread as aprons around the bases of mountains (Fig. 10.14). The term (pediment) was first used by G.K. Gilbert (1882) for the surfaces of the alluvial fans that encircle mountains in deserts.

According to Kirk Bryan (1922), 'pediments are slopes of transportation cut on bedrock, usually covered with a veneer of alluvium in transit from high to lower levels. In form and function, a pediment is similar to an alluvial fan, the difference being that a pediment is an erosional landform and a fan is constructional' (A. Bloom).

It may be pointed out that pediments are now not considered to be confined only to the arid and semiarid regions rather they are found widely in tropical and temperate climates. A true pediment represents rock-cut surfaces of mountain side.

This feature is, in fact, a slope of derivation or transportation as a thin veneer of debris also moves through this surface down the slope. These bare rock surfaces extend for several kilometres in length. The general gradient ranges between 1 to 7 degrees.

Pediments are formed through a combination of erosion and sedimentation processes. They result from the gradual retreat of the mountain front due to erosion, as well as the deposition of eroded materials onto the lower-gradient slope at the base of the mountains. The retreat of the mountain front can occur through various erosion mechanisms, including water erosion, wind erosion, and mass wasting. As the sediment is transported downslope, it accumulates and spreads out, forming a gently sloping surface.

Pediments typically have a gentle gradient, often ranging from 1 to 5 degrees, although this can vary depending on local conditions. They are composed of a mixture of weathered rock debris, sediment, and alluvial deposits. The surface of a pediment is usually covered with a thin layer of soil and can exhibit various rock types and weathering patterns. Vegetation cover on pediments can range from sparse desert vegetation to more extensive grasses and shrubs, depending on the local climate and soil conditions.

Pediments are also of three types which are mentioned below:

- i. **Pediment Slope:** This is the gently sloping portion of the pediment that extends from the base of the mountain range. It represents the area of sediment accumulation and erosion retreat.
- ii. **Piedmont Pediment:** A piedmont pediment occurs when the slope of the pediment merges with a surrounding alluvial fan or bajada, forming a continuous landform.
- iii. **Inselberg Pediment:** In some cases, isolated hills or rocky outcrops, known as inselbergs, may be present on the pediment surface. These inselbergs are more resistant to erosion compared to the surrounding materials and can stand out as prominent features.

Examples of pediments can be found in various arid and semi-arid regions worldwide. One example is the Saharan Desert in Africa, where extensive pediment surfaces can be observed at the base of the Atlas Mountains. In India, the Aravalli Range in Rajasthan exhibits pediment features, particularly in areas such as the Mount Abu region.

Several theories have been postulated to account for the development of desert pediments.

The following points highlight the top four theories for the development of pediments. The theories are:

1. Lawson's Recession Theory
2. Sheet-Flood Theory of McGee
3. Lateral Erosion Theory
4. Composite Theory.

1. Lawson's Recession Theory

According to A.C. Lawson (1915), pediments are developed because of the gradual recession of the mountain front caused by weathering and erosion. Due to back wasting of the mountain front through mechanical disintegration of rocks and consequent aeolian and fluvial erosion mountain front is subjected to gradual recession. This process results in the formation of more and more smooth rock-cut plains.

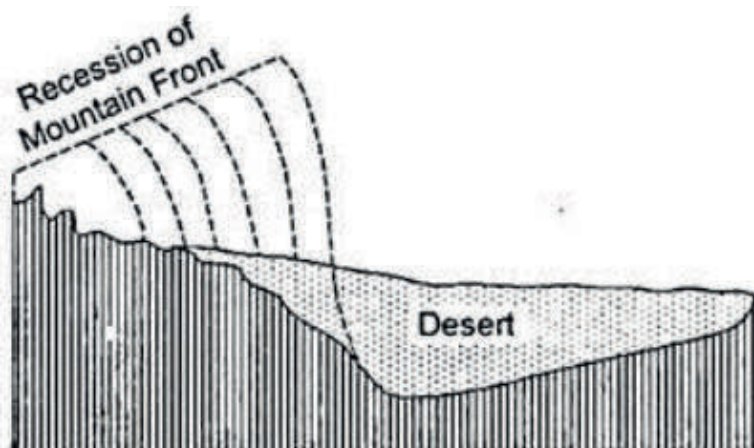


Fig. 10.15: Formation of Pediments due to Recession of Mountain Front.

As the mountain front recedes debris is deposited in the lower segment of the pediment and thus the alluvial deposits in the form of alluvial fans extend upslope on the pediments. Thus, the thickness of the veneer of deposits also increases. Pediments are exhumed due to the removal of deposits under the impact of diastrophic movements. The thin cover resting on the pediment may also be removed through climate changes or from long-continued aeolian deflation (Fig. 10.15).

2. Sheet-Flood Theory of McGee

According to W.J. McGee (1897) pediments are formed due to erosion of weathered bedrocks by sheet-floods originating from occasional torrential rainfall in deserts. The eroded materials are transported downslope and are deposited as bajadas. The advocates of this concept do not attach any importance to lateral erosion in the development of pediments because, according to them, concave surface of pediments cannot be formed by lateral erosion. The critics maintain that sheet-floods may have an ancillary influence on pediments once they are formed but they cannot initiate the formation of pediments.

3. Lateral Erosion Theory

G.K. Gilbert attributed the formation of pediments to lateral corrasion by streams. Later on, S. Paige (1912), Eliot Black-welder (1931), D.W. Johnson (1932), Berkey, Morris, etc. also advocated for lateral erosion by streams as a powerful mechanism of pediment formation.

According to D.W. Johnson, there are 3 zones along the mountains encircling an intermontane basin viz.:

- (i) Inner zone,
- (ii) Outer zone, and
- (iii) Intermediate zone (Fig. 10.16)

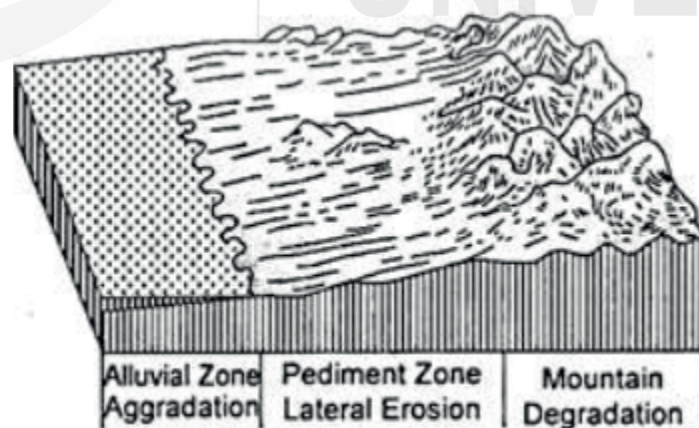


Fig. 10.16: Formation of Pediments according to D. W. Johnson.

Inner zone represents the mountain front where down-cutting (vertical erosion) by streams is most active. This zone is, thus, a zone of degradation. The outer zone represents the lower segment which extends upto the margin of the intermontane basin (playa). In fact, this zone is characterized by deposition to form bajada. This zone, thus, is the zone of aggradation.

The intermediate zone represents the zone between the degradational zone (inner zone) and the aggradational zone (outer zone) where lateral erosion is most active. This zone is also called a zone of pedimentation. The formation of the pediment is initiated by active down-cutting of the inner zone resulting in a rapid rate of erosion of the mountain front. The eroded materials are removed and deposited by ephemeral streams resulting from occasional strong rainstorms in the basins.

Thus, several alluvial fans are formed on the lower segments of hillslopes. These alluvial fans gradually coalesce to form bajadas. Gradually, the streams are graded and braided in the intermediate zone. Rock fans are formed in the intermediate zone due to lateral erosion by the streams. These rock fans gradually extend to become pediments.

4. Composite Theory

It may be mentioned that the above-mentioned theories of pediment formation are based on the mechanism of the mono-geomorphic process. On the other hand, some Geomorphologists have opined that pediments are formed by more than one geomorphic process. For example, Kirk Bryan, W.M. Davis, R.P. Sharp, James Giluly, J.L. Rich, W.H. Bradley, L.C. King, T.J.D. Fair etc., have pleaded for composite origin of pediments.

- (i) Kirk Bryan (1923) has postulated that pediments are developed in three ways viz.:
 - (a) due to lateral erosion by streams coming out from the mountain front,
 - (b) due to the erosion of foothill zones by rills, and
 - (c) due to the disintegration of mountain fronts under the impact of mechanical weathering.
- (ii) According to W.M. Davis (1938) first the mountain front is disintegrated due to mechanical weathering and then the weathered materials are transported downslope by sheet-floods. These twin processes cause gradual recession of the mountain front and consequent development of rock-cut pediment surface. It is evident that Davis' concept involves the views of A.C. Lawson (recession of mountain front) and McGee (sheet-flood erosion) for the development of pediments.
- (iii) According to R.P. Sharp (1940) lateral erosion, weathering, and rill wash play their relative roles in the development of pediments. According to him the pediments of Nevada (USA) owes their existence 40 percent to rain-wash.

SAQ 4

- (i) What is Badland Topography?
 - (ii) Make a list of Fluvial Desert Landforms.
-

10.7 SUMMARY

In this Unit, you have studied so far:

- Aeolian processes, involving erosion, transportation, and deposition of sediments by the wind. The wind is most effective in deserts, sandy coasts, and alluvial plains next to glaciers. Wind erodes by deflating sediments and sandblasting rocks.
- Deflation and Abrasion are two main processes of wind erosion. Wind transports eroded material in several ways. Wind can move material through three processes: suspension, saltation, and surface creep are the main processes through which wind transports the eroded particles.
- The fine, light materials are picked up, suspended in the air, and carried away. Heavy or large sand grains are dragged along the surface of the ground. In other words, wind transports sand and saltation surface creep. Silt and dust-size particles are carried in suspension. The materials carried by the wind are deposited. Wind deposition may take place in three ways (1) sedimentation, (2) accretion, and (3) encroachment.
- Aeolian processes develop different types of erosional and depositional landforms. Examples are Yardangs, Zeugen, Inselbergs, Demoiselles, Sand dunes and Loess. Badlands, pediments, bajadas, and playas are special types of landforms of arid and semi-arid regions caused by the mechanical disintegration of rocks and water action.
- The arid cycle of erosion passes through different stages, i.e., early, youth, mature, and old. Wind erosion can often be a self-inflicted hazard to humans, damaging agricultural and recreational land and harming human health.
- Fluvial desert landforms are geological features that result from the interaction of rivers and water in arid or semi-arid desert environments. Despite the scarcity of water, rivers in these regions can have intermittent or ephemeral flows during periods of rainfall or flash floods. As the water flows across the arid landscape, it erodes the terrain, transports sediment, and deposits it in distinctive patterns. Fluvial desert landforms include wadis (dry riverbeds), alluvial fans, playa lakes, etc.
- Several theories have been postulated to account for the development of desert pediments like 1. Lawson's Recession Theory; 2. Sheet-Flood Theory of McGee; 3. Lateral Erosion Theory; 4. Composite Theory.

10.8 TERMINAL QUESTIONS

1. What is wind erosion? Discuss the processes of wind deposition.
2. Discuss Sand Dunes with their types.
3. Explain the main type of Aeolian Transport.
4. What are the main theories for the development of Pediments? Discuss them in brief.

10.9 ANSWERS

Self-Assessment Questions (SAQ)

1. Deflation, Abrasion, and Saltaion.
2. a) True; b) False; c) True; d) False
3. Wind speed, wind direction, sediment characteristics, surface roughness and moisture content are the main factors of Aeolian transport processes.
4. i) Badland topography refers to a type of highly eroded, rugged, and barren landscape characterized by deep and narrow gullies, sharp ridges, and steep slopes which are extensively eroded by numerous rills and channels which are developed due to occasional rain storms.
ii) Badlands, pediments, bajadas, and playas are important fluvial desert landforms.

Terminal Questions

1. Wind erosion is a natural process in which the force of the wind lifts and transports loose particles, such as sand, silt, and dust, from the Earth's surface. It occurs in areas with limited vegetation cover, sparse rainfall, and strong winds. Wind erosion can have significant effects on the landscape, including the erosion of soil, the formation of distinctive landforms, and the redistribution of sediment. (You can refer to section 10.2 for detailed answers).
2. Sand dunes are fascinating landforms created by the accumulation of wind-blown sand. They are found in desert regions, coastal areas, and even some inland locations with sufficient sand supply and prevailing winds. Sand dunes come in various shapes and sizes, and their formation and characteristics are influenced by factors such as wind patterns, sand availability, and local topography. (You can refer to section 10.5 for detailed answers).
3. Aeolian transport, the process of wind carrying and moving sediment, occurs through various mechanisms. The main types of aeolian transport include saltation, suspension, and surface creep. Saltation is the most common form, where the wind lifts and transports sand-sized particles in short hops or bounces. Suspension involves the transport of fine-grained particles, such as dust and silt, which can remain suspended in the air and travel long distances. Surface creep refers to the slow rolling or sliding movement of larger particles along the ground surface. These types of aeolian transport work in tandem and are influenced by factors such as wind speed, direction, and the nature of the sediment. Understanding these mechanisms is crucial for comprehending the movement and deposition of sediment by wind, and their significance in shaping and transforming landscapes. (You can refer to section 10.3 for detailed answer)
4. The development of pediments, gently sloping surfaces found at the base of hills or mountains, has been a subject of interest for geologists, and

several theories have been proposed to explain their formation. One prominent theory is the weathering-limited theory, which suggests that pediments form through the gradual weathering and erosion of the underlying bedrock. Over time, weathering processes such as chemical decomposition and physical disintegration weaken the bedrock, allowing the overlying sediments to slowly erode and create a flat or gently sloping surface. Another theory is the stream-limited theory, which proposes that pediments form through the lateral migration and aggradation of alluvial fans. According to this theory, streams originating from mountainous areas transport sediment and deposit it at the base of the slope, gradually building up the pediment surface. The combination of weathering and fluvial processes is likely involved in the development of pediments, but the specific mechanisms can vary depending on factors such as climate, lithology, and tectonic activity. Further research is needed to gain a more comprehensive understanding of the formation and evolution of pediments. (You can refer to section 10.5 for a detailed answer)

10.10 REFERENCES AND SUGGESTED FURTHER READING

1. Dayal, P. (1996). *A Text Book of Geomorphology*. Shukla Book Depot, Patna.
2. Hussain, M. (2007). *Fundamentals of Physical Geography*. Rawat Publications, Jaipur.
3. Huggett, R.J. (2011). *Fundamentals of Geomorphology*. Routledge, New York.
4. Lal, D.S. (2009). *Physical Geography*. Sharda Pustak Bhawan, Allahabad.
5. Livingstone, I. and Warren, A. (1996). *Aeolian Geomorphology: An Introduction*. Longman, UK.
6. Singh, S. (2012). *Physical Geography*. Prayag Pustak Bhawan, Allahabad.
7. Strahler, A. N. and Strahler, A. M. (2010). *Physical Geography-Science and Systems of Human Environment*. Wiley India (P) Ltd., New Delhi.
8. Waugh, D. (2002). *Geography- An Integrated Approach*. Nelson Thornes UK.

KARST PROCESSES AND LANDFORMS

Structure

11.1	Introduction		Subterranean Forms
	Expected Learning Outcomes	11.5	Karst Cycle of Erosion
11.2	Karst and Its Global	11.6	Summary
	Distribution	11.7	Terminal Questions
11.3	Karst Processes	11.8	Answers
11.4	Karst Forms	11.9	References and Suggested
	Surface Forms		Further Reading

11.1 INTRODUCTION

In the previous Unit10 of this block, you have learned about the Aeolian processes and associated landforms. Similar to Aeolian processes, you will study karst processes which also erode, modify and develop landforms in this Unit. Karst processes are geological processes in regions characterised by soluble rocks such as limestone, dolomite, and gypsum. These processes are responsible for forming unique landforms and features, collectively known as karst landscapes. Karst landscapes are characterized by distinctive surface and subsurface features.

The study of karst processes is important for various reasons. Karst aquifers serve as important water resources, supplying fresh water to communities and ecosystems. Understanding karst hydrology is crucial for the sustainable management and protection of these valuable water resources. Karst landscapes also provide valuable records of past environmental conditions and are of great scientific interest.

In view of its importance, you will be studying the origin and meaning of the term Karst, the global distribution of karst regions, and the types of rocks favorable for the development of karst topography in section 11.2. In Section 11.3, you will learn the different types of karst processes which are responsible for the development of karst topography. You will also learn the role of temperature, pressure, and CO₂ in the development of karst landforms. In Section 11.4, you will study the type, origin, and development of surface and subterranean karst landforms. In this section, you will also study the

processes, mechanisms, and evolution of different karst landforms.

Expected Learning Outcomes

After studying this unit, you will be able to:

- define and classify Karst processes;
- describe the global distribution of karst topography; and
- describe the process and types of Karst landforms.

11.2 KARST AND ITS GLOBAL DISTRIBUTION

Water that occupies pores, cavities, cracks and other spaces in the crustal rocks is known as **Groundwater**, or **subsurface water**.

Karst is a term used to describe a distinct type of landscape characterized by the dissolution and erosion of soluble rocks. The term "karst" has its roots in the Indo-European word "kar," which means rock. The term has been adopted in various languages to describe landscapes characterized by soluble rock formations and distinct features. In German, "karst" is used, while in Italian, it is referred to as "carso," and in Slovenian, it is known as "kras." In Slovenia, "kras" or "krš" specifically refers to a rugged region in the western part of the country characterized by bare stony ground. This region showcases typical karst landforms such as sinkholes, caves, and limestone pavements. The name "karst" has become internationally recognized as a term to describe similar landscapes around the world that exhibit similar geological and geomorphological features.

The word "karst" originates from the Karst region in Slovenia, where this type of landscape was first extensively studied. The development of karst landscapes involves a combination of chemical weathering, erosion, and underground drainage processes. Karst landscapes are known for their unique landforms and features, both on the surface and in the subsurface. Some of the prominent features of karst landscapes include sinkholes, caves, underground rivers, disappearing streams, and karst springs. These features are a result of the dissolution of soluble rocks by water, which leads to the creation of voids and cavities that can develop into complex underground networks.

The term "karst" was first introduced by geologist Jovan Cvijić in the late 19th century. Cvijić extensively studied the Karst region of Slovenia and proposed a classification system for karst landscapes based on their characteristics and development stages. His work laid the foundation for the understanding of karst processes and landforms. The study of karst landscapes is interdisciplinary, involving various fields such as geology, hydrology, geomorphology, and environmental science. Geomorphologists use a range of techniques, including field surveys, geological mapping, and laboratory analysis, to investigate karst processes and landforms.

In terms of geomorphology, **karst** is a terrain in which soluble rocks are transformed above and below the surface by the dissolving action of water and that bears unique characteristics of relief and drainage. It generally denotes limestone terrain normally lacking surface drainage, possessing a patchy and thin soil cover, containing many enclosed depressions and

supporting a network of subterranean features. However, all rocks are soluble to some extent in water, and karst is not limited to the most soluble rock types. Karst may form in evaporites such as gypsum and halite, in silicates such as sandstone and quartzite, and in some basalts and granites under favorable conditions.

Topographical features formed by underground water can be seen particularly, in a highland composed of limestone on a large scale. This distinctive topography formed due to the action of underground water in the limestone region is known as Karst topography. The term 'Karst' comes from the narrow strip of limestone plateau in Croatia and Bosnia-Herzegovina (erstwhile Yugoslavia) and adjacent portions of Italy, bordering the Adriatic Sea. Landforms developed anywhere by solution in limestone are called karst landforms. A karst landscape is characterized by sinks, solutions, valleys, and other features produced by groundwater activity.

Global Distribution: Significant karst areas are found in different parts of the world. There are many areas where karst topography is found, even though these areas do not possess all of the possible karst forms. Such areas are New South Wales, Western Australia, Southeast Asia, Celebes, Causse region of Southern France, Spanish Andalusia, Northern Puerto Rico, Central New Guinea, Western Cuba, Tabasco in Mexico, Sri Lanka and Myanmar.

In addition to these countries, there are four areas in the United States which have major karst topography. These areas comprise the Great Valley region of Pennsylvania, Maryland, Virginia, and Tennessee; a belt extending from south-central Indiana into the Mammoth cave region of Kentucky; The Yutacama Peninsula; Central Florida; and the Salem-Springfield plateaus areas of Missouri. In regions such as southern China and west Malaysia, the karst landscape is dominated by steep-sided, conical limestone hills or towers. These towers are sometimes capped by beds of more resistant rock or by impure limestones that dissolve more slowly.

In India, the Rohtas Plateau (Western Jharkhand), Sahastradhara (Dehradun), Panchmarhi (Madhya Pradesh) and Bastar (Chhattisgarh), Vishakhapatnam (Andhra Pradesh) and Cherrapunji (Meghalaya) have limestone topography.

It may be pointed out that there are some other areas where karst features are found, but they are different from the ideal karst landscape present in the karst region of Yugoslavia. It may be stated that wherever soluble rocks such as limestone, dolomite, rock salt, or gypsum are found at or beneath the surface, some solution may be expected and there may be a few features of karst landscape, but they do not dominate the landscape.

SAQ I

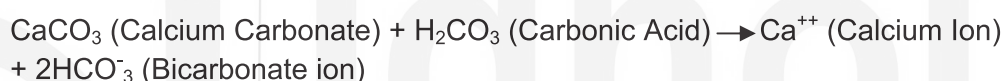
Define the term 'Karst topography'.

11.3 KARST PROCESSES

The chief geomorphic processes characteristic of karst landscapes are solution and precipitation, subsidence, and collapse. Fluvial processes may be significant in the formation of some surface and subterranean landforms. Hydrothermal processes are locally important in caves. The process of karstification is intense under tropical climates and produces landforms, which are not produced, at least not to the same degree, under temperate and cold climates.

Karst processes involve chemical reactions that contribute to the dissolution of soluble rocks and the formation of unique karst features. The primary chemical reaction involved is the dissolution of calcium carbonate, the main component of limestone, in the presence of carbonic acid. The chemical equation for this process is as follows:

Water being the universal solvent dissolves carbon dioxide absorbed from the air so that the rainwater contains carbonic acid (H_2CO_3).



Solubility of Bedrock, Temperature, Moisture, Structure of Limestone, Acidity (pH) of groundwater, and atmospheric CO_2 are the factors that affect **Karst Processes**.

Carbonic acid reacts with several minerals, particularly limestone, in a process known as carbonation. Carbonation means that carbon combines and alters minerals containing calcium, magnesium, potassium, and sodium into carbonates. When rainwater falls on the formations of limestone which is calcium carbonate, CaCO_3 , the ingredient minerals are dissolved and washed away with the rainwater. In this way, ordinary rainwater containing carbon dioxide can dissolve a considerable amount of carbonate of lime.

While passing through a bed of limestone, the percolating water takes away a small amount of material in solution, and the resultant effect, acting over a long period of time, is of great significance. Water follows the easiest paths and flows through cracks, which are progressively enlarged by the process of solution and become still easier channels than before. As time passes on, the water concentrates in these enlarged channels and in a limestone formation, the underground water often forms streams of significant size. These underground channels become wider and wider to such an extent that they form a series of caverns running for several kilometers into the ground. The carbonate of lime is dissolved and is carried away in solution. The impurities that are insoluble are left behind to evolve a covering for the rock.

Karst forms achieve their complete evolution in beds of fairly pure limestone, with more than 80 percent calcium carbonate, that are very thick, mechanically strong, and have massive joints. These settings are fulfilled in the typical karst area of countries bordering the eastern side of the Adriatic Sea. Chalk, although being a very pure limestone, is mechanically weak and does not promote the evolution of underground drainage, which is a prerequisite for the development of medium-scale and large-scale surface karst landforms. Few geomorphic processes are confined to karst landscapes, but in areas underlain by soluble rocks, some processes operate

in unique ways and produce characteristic features. The solution is often the dominant process in karst landscapes, but it may be subordinate to other geomorphic processes. In sections where the groundwater table has dropped; pressure release promotes the precipitation of minerals creating a variety of chemical precipitates.

SAQ 2

What is the primary chemical reaction in the process of Karst formation?

11.4 KARST FORMS

Karst forms refer to the distinctive landforms and features that are characteristic of karst landscapes. These forms are a result of the dissolution and erosion of soluble rocks, such as limestone, dolomite, and gypsum, by water. It will be interesting to know that, the topographical features or landscapes created by the work of underground water on limestone are of two types and are discussed below:

- (a) Topographical features formed on the surface, like sinkholes and swallow holes.
- (b) Topographical features formed underground like caverns, stalactites, and stalagmites.

11.4.1 Surface Karst Forms

Surface karst landforms are formed by the dissolution of soluble rocks, such as limestone, gypsum, or dolomite, at or near the Earth's surface. Slow-moving groundwater can dissolve huge quantities of soluble rocks and carry it away in solution. In some areas, it is the dominant agent of erosion and produces karst topography, which is characterized by sinkholes, solution valleys, and disappearing streams. Some of the unique surface karst landforms are discussed below:

Terra Rossa

Terra Rossa is a type of soil commonly found in Mediterranean regions, particularly in areas with limestone bedrock. The term "Terra Rossa" is Italian for "red earth," and it refers to the distinctive reddish-brown color of this soil.

Terra Rossa soils are formed through a combination of weathering processes, including the breakdown of limestone and the accumulation of clay minerals. The soil develops as rainwater percolates through the limestone bedrock, dissolving calcium carbonate and other minerals along the way. This dissolved material is then transported by water and deposited in the upper layers of the soil.

The key characteristic of Terra Rossa soils is their high content of fine-grained clay particles. These clay particles are rich in iron oxide, giving the soil its reddish color. The clay particles contribute to the soil's fertility and ability to retain moisture, making Terra Rossa soils well-suited for agricultural purposes. Terra Rossa soils are known for their excellent drainage

properties, which allow excess water to flow through the soil profile. This drainage capability is essential in Mediterranean climates, where rainfall can be relatively low and sporadic. The soil's ability to retain moisture helps sustain plant growth during dry periods.

Lapies

Lapies is a term used for highly corrugated and rough surface of limestone lithology, characterized by low ridges and pinnacles, narrow clefts, and numerous solution holes (Fig. 11.1). Lapies, also known as karren or limestone pavement, is a distinctive landform that occurs in karst regions where limestone or other soluble rocks are exposed at the surface. It is characterized by a series of interconnecting shallow channels, grooves, and ridges that are created through the dissolution and weathering processes associated with karst landscapes.

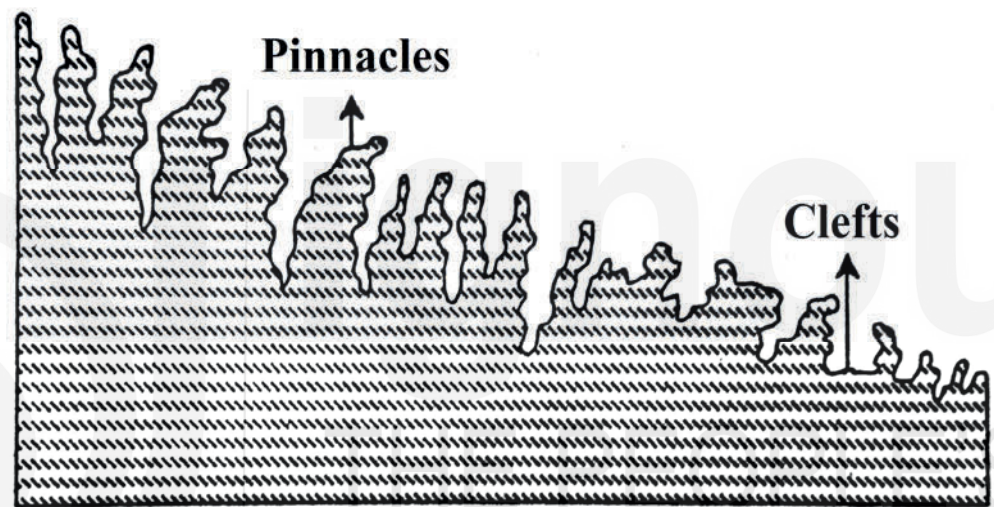


Fig. 11.1: Lapies.

The formation of lapies begins with the chemical weathering of limestone by acidic water. Over time, the water gradually dissolves the limestone, creating small channels and grooves. These channels and grooves may be further deepened and widened by physical weathering processes, such as the abrasion caused by rock fragments being moved by flowing water or by freeze-thaw cycles.

The resulting surface of a limestone pavement consists of irregular blocks or clints (upstanding rock) separated by deep, elongated grooves or grikes. The clints often have a smooth, polished appearance due to the water erosion, and they can vary in size from a few centimeters to several meters across. The grikes, on the other hand, are the depressions or fissures that separate the clints.

Lapies are commonly found in karst areas around the world, including regions such as the Dinaric Alps, the Burren in Ireland, and the Yorkshire Dales in England. They are particularly prominent in regions with abundant rainfall, as the water plays a significant role in the dissolution and weathering processes that shape the landscape.

Sinkholes

Sinkholes are the most common features formed by the work of rainwater on limestone. Sinkhole is a funnel-shaped or cylindrical-shaped hole, depression or sink in the ground surface of a limestone formation or chalk terrain (Fig. 11.2).

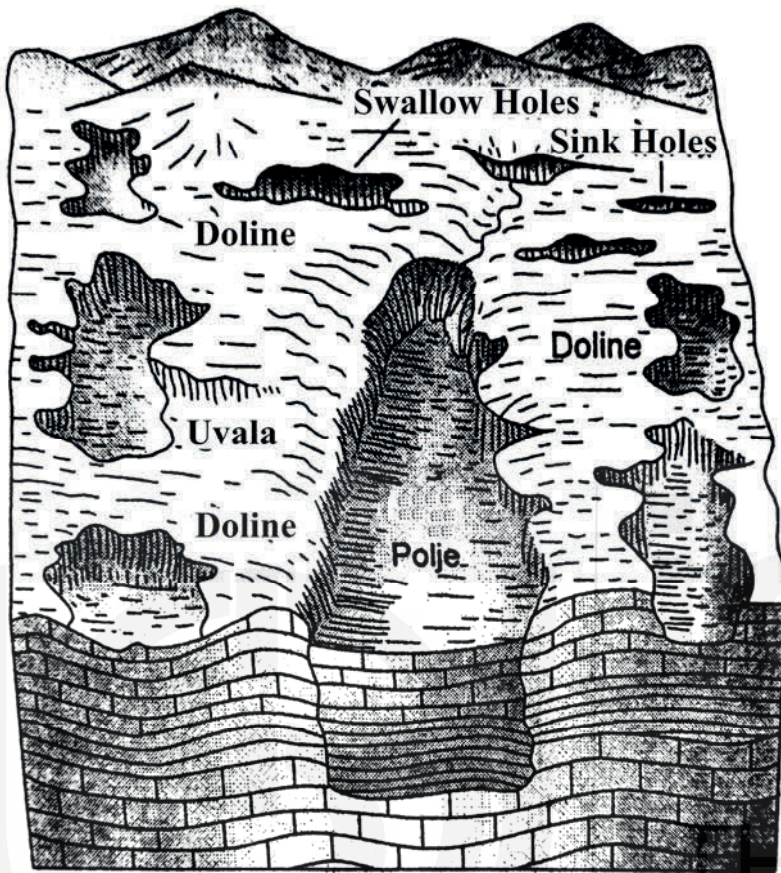


Fig. 11.2: Idealised Features of Karst Topography.

Sinkholes occur when the ground collapses or sinks, creating a depression or hole in the Earth's surface. They can vary in size, ranging from small pits to large craters. Sinkholes are commonly associated with karst landscapes, where the underlying bedrock is composed of soluble rock such as limestone, gypsum, or dolomite.

There are two main types of sinkholes: dissolution sinkholes and cover-collapse sinkholes.

- i. **Dissolution Sinkholes:** These sinkholes form gradually over time as groundwater containing dissolved minerals seeps into the soluble rock. The water dissolves and carries away the rock, creating voids or cavities underground. As the voids enlarge, the overlying surface layer may eventually collapse, resulting in a sinkhole. Dissolution sinkholes typically have a relatively gradual and slow formation process.
- ii. **Cover-Collapse Sinkholes:** These sinkholes can occur suddenly and are more dramatic in nature. They are typically associated with a covering layer of sediment or soil that rests on top of the soluble rock. Over time, the underground cavities form due to water erosion and the gradual dissolution of the underlying rock. However, the collapse of the surface layer is often triggered by a specific event, such as heavy rainfall or an

increase in groundwater levels. The sudden collapse can lead to a large, deep sinkhole.

Sinkholes can pose significant risks to both human structures and the environment. They can damage buildings, infrastructure, and roads, leading to safety hazards and costly repairs. In areas where sinkholes are common, precautions may be taken during construction to avoid vulnerable locations. Sinkholes can also disrupt natural drainage patterns and affect groundwater flow, leading to changes in the hydrological system.

Some well-known sinkhole-prone regions include the Yucatan Peninsula in Mexico, the karst areas of Florida in the United States, and various parts of China and Australia. Sinkholes are studied by geologists and engineers to better understand their formation processes and develop strategies for managing the associated risks.

Doline

The term doline is used for solution sinkhole. Solution of limestone along intersecting joints produces circular depressions. These depressions gradually develop and join so that the whole land is lowered giving rise to a landform called doline which comes from the Serbian terminology Dolinas. The shape of a doline is circular and its sides are steeper (Fig. 11.2).

Dolines are typically formed through a combination of chemical weathering and erosion processes. Rainwater, which is slightly acidic, seeps into the ground and interacts with the soluble rock. Over time, the water dissolves and removes the minerals, creating voids and cavities underground. As the voids enlarge, the overlying surface layer becomes unsupported and eventually collapses, forming a doline. The size and shape of dolines can vary widely. They can range from a few meters to hundreds of meters in diameter and can be relatively shallow or very deep, reaching depths of several hundred meters. Some dolines may have steep vertical walls, while others have gentler slopes.

Dolines often have distinctive features and characteristics. They can be surrounded by a ring of higher ground called a rim, which marks the edge of the collapsed area. The bottom of a doline is typically concave, and it may contain soil, vegetation, or water, depending on the local hydrological conditions. Dolines play an important role in the hydrological system of karst landscapes. They act as natural sink points for surface water, which drains into the underground cavities and contributes to the recharge of groundwater. Dolines can also serve as temporary or permanent water reservoirs, holding water during periods of heavy rainfall or forming lakes or ponds.

Dolines are found worldwide, particularly in regions with extensive karst landscapes, such as parts of the Balkans, China, Mexico, and Australia.

Swallow Holes Swallow holes represent the surface openings through which surface runoff enters into dolines (Fig. 11.2). This is the point at which a surface stream disappears underground in the karst region. It is called water sink in the U.S.A., embut in France, and ponor in Yugoslavia. Swallow holes form when water flows over soluble rock, such as limestone or dolomite, and

enters openings or fissures in the rock. These openings can be joints, fractures, or conduits that have been enlarged through chemical weathering and dissolution processes over time. As the water enters these underground passages, it disappears from the surface and continues its flow underground.

The size and shape of swallow holes can vary greatly. Some swallow holes may be small and inconspicuous, while others can be quite large and impressive. They can appear as circular depressions or openings in the ground, often surrounded by rocky or vegetated rims.

The water that enters swallow holes continues its journey underground through underground rivers or conduits, contributing to the development of extensive underground cave systems in karst regions. Swallow holes serve as important entry points for surface water into these underground networks, allowing for the recharge of groundwater and the continuation of hydrological processes.

In areas where swallow holes are common, they can pose challenges and risks for land use and infrastructure. Swallow holes can result in the diversion or loss of surface water, impacting water resources and affecting the stability of the surrounding land. They can also pose risks for construction and development, as the ground around swallow holes may be unstable.

Sinking Creek

Sinking Creek is a term used to describe a creek or stream that disappears underground in the karst region. The surface of the karst plain looks like a sieve because of numerous, closely spaced sinkholes. When surface water disappears through numerous sinkholes located in a lime, the resultant feature is called a sinking creek.

It is a common occurrence in karst regions where the underlying bedrock is composed of soluble rock, such as limestone or dolomite.

A sinking Creek occurs when the creek's water flows over the soluble rock and enters openings or fissures in the rock. These openings can be joints, fractures, or conduits that have been enlarged through chemical weathering and dissolution processes. As the water enters these underground passages, it disappears from the surface, and the creek appears to sink into the ground.

The disappearance of the creek into underground passages is an example of a swallow hole or ponor. The water that enters the underground system continues to flow through underground rivers or conduits, contributing to the development of extensive cave systems and groundwater networks in the karst landscape.

Sinking Creek systems often support unique ecological communities due to the presence of underground habitats and specialized species adapted to the fluctuating water conditions. Examples of notable Sinking Creeks include Sinking Creek in Tennessee, USA, which flows through parts of the Cumberland Plateau and disappears underground, as well as Sinking Creek in Missouri, USA, which flows through the Ozark Highlands and exhibits similar characteristics of disappearing into sinkholes.

Uvala

Uvala is a landform found in karst regions characterized by a large, elongated depression or valley. It is created through the combination of various karst processes, including dissolution, collapse, and erosion. Uvalas are typically wider and shallower compared to other karst landforms such as sinkholes and dolines.

Uvala is characterized by having an irregular floor which is the result of former elevations, and the character of the degraded slopes of the dolines (Fig. 11.2). It has an irregular floor which is not as smooth as that of polje. Uvalas often have flat or gently sloping floors and can vary in size from a few hundred meters to several kilometers in length. They are typically elongated in shape, with parallel or sub-parallel sides. Uvalas may also be interconnected, forming a network of depressions and valleys.

The hydrological characteristics of uvalas are important features of these landforms. They often have internal drainage systems, with streams and rivers flowing within the depressions. These watercourses can disappear underground into swallow holes or resurge at lower elevations, contributing to the complex underground hydrology of karst regions. Examples of uvalas can be found in various karst regions worldwide, including the Dinaric Alps in Europe, the Nullarbor Plain in Australia, and the Apennine Mountains in Italy.

Polje

The term Polje refers to an elongated depression in Karst terrain. The long axis is developed over a lengthy distance parallel to the structural grain (Fig. 11.2). This kind of depression is thought to have been produced by the merger of collapsed cave systems. The floor of Polje is invariably covered by alluvium. Poljes are characterized by their flat topography and often have a flat or gently sloping floor covered with fertile soil.

Poljes form through a combination of geological and hydrological processes. They typically result from the subsidence and collapse of underground caverns or chambers due to the dissolution of soluble rock, such as limestone or dolomite. As the caverns collapse, the overlying surface sinks, creating a large depression.

The hydrological characteristics of poljes are significant. They often serve as natural catchment areas for surface water, with streams and rivers draining into the polje. Poljes may also have a complex underground drainage system, with sinking streams and swallow holes that contribute to the recharge of groundwater. Some poljes have intermittent lakes or wetlands, especially during periods of high rainfall.

Poljes are important agricultural areas due to their fertile soils, which are often deposited by rivers and streams that drain into the polje. The flat topography and abundant water supply make poljes ideal for farming and cultivation. They are often utilized for growing crops, grazing livestock, and supporting local communities. Poljes can vary in size, ranging from a few square kilometers to several hundred square kilometers. Examples of well-known poljes include

the Imotski polje in Croatia, the Zeta Polje in Montenegro, and the Lasithi Plateau in Crete, Greece.

Karst Window

Karst window is formed due to collapse of upper surface of sinkholes or dolines. It is through these open parts that the subsurface features formed by the underground drainage are visible. So, these open parts are called karst windows. A karst window is formed when a portion of a river or stream disappears underground into a cave or underground passage, leaving a dry valley or depression behind.

The formation of a karst window starts with the dissolution of soluble rock, typically limestone or dolomite, by groundwater. Over time, the underground water erodes and enlarges fractures and conduits within the rock, creating underground passages. As the river or stream encounters one of these underground passages, it flows into it and disappears from the surface, leaving a dry or partially dry valley or depression behind.

Karst windows often have distinctive characteristics. They are typically elongated in shape and may have steep or vertical walls. The floor of a karst window may be covered with sediments, debris, or vegetation. In some cases, the river or stream may re-emerge further downstream as a resurgence, creating a separate drainage system. Examples of karst windows can be found in various karst regions around the world, including the Dinaric Alps in Europe and the Yucatan Peninsula in Mexico.

SAQ 3

- i. Define Lapiés.
 - ii. Define Uvala.
-

11.4.2 Subterranean Karst Forms

Subterranean karst forms refer to the various landforms and features that are found beneath the surface in karst landscapes. These forms are created through the processes of dissolution, erosion, and deposition that occur within the soluble rock, such as limestone or dolomite, in the subsurface. When water combined with CO_2 , it reacts along the fissures and joints of limestone terrain. Flowing through the karst surface, the water and its load abrade and corrode the rock, helping to produce subsurface landforms. These **subterranean landforms** contain a rich variety of erosional and depositional forms. Below some Subterranean karst landforms are given and discussed.

Cave or Cavern

Caves or underground caverns present the most important subterranean landforms produced by the solution of limestone.

Limestone caverns and caves are large sub-surface voids where the rocks have been dissolved by carbonation. One of the most important factors for cavern development is the joining of the limestone strata. Groundwater

Mammoth Cave in Kentucky and Carlsbad Caverns in New Mexico are two of the largest cave systems in North America.

solution works along jointing planes. Cave forms created by weathering and by water and wind erosion are called **speleogens**.

In India, such caves are found in the Meghalaya plateau near Cherrapunji, near Dehradun in Uttarakhand, in south western Bihar, and at Chitrakut in Madhya Pradesh.

The formation and development of limestone caverns is the most debatable of all the karstic landforms. Various contrasting theories have been put forward by different geomorphologists to account for the origin and development of limestone caves viz.:

- (1) Corrasion theory of Lapparent, Martonne, Martel, Weller, and C. A. Malott,
- (2) Two-cycle theory of W.M. Davis and supported by J.H. Bretz,
- (3) Water table theory of A.C. Swinnerton,
- (4) Static water zone theory of J.H. Gardner,
- (5) Invasion theory of C.A. Malott etc.

It may be pointed out that difference of opinions about the formation of caverns and galleries is related to solution process, water table of groundwater, and corrasion process.

According to 'Corrasion theory' caves are formed due to corrasion (abrasion) of limestones by groundwater in the vadose zone above the water table of groundwater. W.M. Davis contradicted the corrasion theory in 1930 and postulated his "Two-Cycle Theory" for the development of limestone caverns. According to him, caves are formed by phreatic water i.e., water under hydrostatic pressure below water table. In the first cycle or stage caves are formed due to solution of limestones in the phreatic zone below water table. In the second cycle or stage the area is uplifted and thus the cave comes under vadose zone because of lowering of water table and the cavern becomes dry resulting into the formation of depositional landforms (speleothems).

'Water Table Theory' of A.C. Swinnerton states that caves are not formed by phreatic water under hydrostatic pressure but are formed by lateral flow of water in the vadose zone or by freely moving water at the level of water table.

According to 'Static Water Zone Theory' of J.H. Gardner caves are formed due to solution of limestone above the water table. The 'invasion theory' of C.A. Malott states that most of the present caverns and galleries in limestone regions have been formed by the subterranean streams. According to Malott surface streams disappear at sink holes and take underground courses where they dissolve and abrade limestones to form their passages. These passages are gradually enlarged due to corrosion and abrasion of limestones and thus caverns and galleries are formed.

Depositional Features in Caves

In sections where the groundwater table has dropped; pressure release promotes the precipitation of minerals creating a variety of chemical precipitates known as **speleothems**.

Most speleothems are made of carbonate deposits, with calcite and aragonite accounting for about 95 percent of all cave minerals. The carbonates are deposited mainly by carbon dioxide loss (degassing), reduction in pressure, and by evaporation. Formations of carbonate may be arranged as Dripstone and flowstone, **Dripstone** is a deposit, usually composed of calcite, formed of drips from cave ceilings or walls. **Flowstone** is a deposit, again usually composed of calcite, formed from thin films or trickles of water over floors or walls. The forms fashioned by dripstone and flowstone are stalactites, stalagmites, and cave pillars.

Stalactites are icicle-like forms that hang from the roofs of caves. In other words, Stalactites are icicle-shaped mineral formations that hang from the ceilings of caves, typically made of calcium carbonate minerals such as calcite. They form through a process known as precipitation or dripstone deposition (Figure 11.3). When water containing dissolved minerals, often derived from the surrounding limestone or other soluble rocks, seeps into a cave, it carries the minerals with it. As the water drips from the ceiling, it leaves behind a small deposit of minerals. Over time, these mineral deposits accumulate and elongate, forming the characteristic stalactite shape.

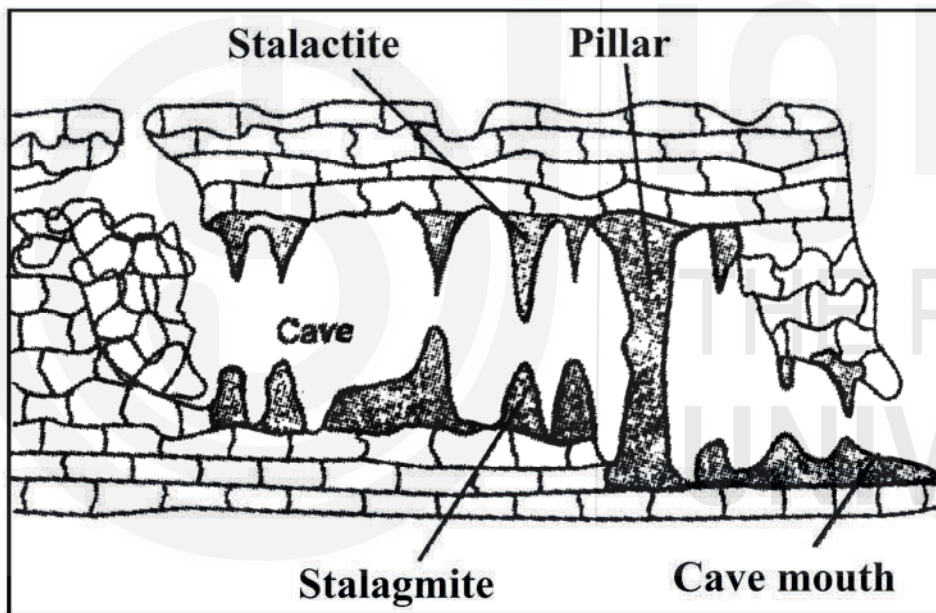


Fig. 11.3: Idealized diagram of cave deposits-Stalactites, Stalagmites, and Cave Pillars (Columns).

Stalactites grow very slowly, with growth rates typically measured in millimeters per year. The minerals in the water may give the stalactites various colors, ranging from white to brown to red, depending on the impurities present.

The shape and size of stalactites can vary, with some reaching several meters in length. They often appear in clusters or rows, creating beautiful and intricate formations within caves. Stalactites can take on various forms, including thin and delicate formations, thick and columnar structures, or even intertwined and branching shapes.

Natural tunnels represent an underground route or conduit through which the subterranean water flows.

Stalactites are one of the most recognizable features of caves and are a result of the ongoing geological processes within karst landscapes. They

provide valuable information about the hydrological and geological history of the cave system and contribute to the aesthetic appeal of cave environments. It is also important to note that stalactites are fragile formations and should be preserved and appreciated in their natural state. Visitors to caves are often advised not to touch or disturb stalactites to avoid damaging these delicate geological wonders.

Stalagmites are upward-growing mineral formations found on the floors of caves, typically made of calcium carbonate minerals such as calcite. They are formed through the same process as stalactites, known as precipitation or dripstone deposition. Stalagmites grow from the floor, and their exact form (columnar or conical) depends upon drip rates, water hardness, and the cave atmosphere (Fig. 11.3). A **column** forms where an upward-growing stalagmite joins a downward-growing stalactite. It is also known as a cave pillar (Fig. 11.3).

Stalagmites form when water containing dissolved minerals drips from the ceiling of a cave and falls onto the floor. As the water hits the ground, it leaves behind a small deposit of minerals. Over time, these mineral deposits accumulate and build upwards, forming the characteristic shape of stalagmites. Like stalactites, stalagmites grow very slowly, with growth rates typically measured in millimeters per year. The minerals in the water give the stalagmites various colors, often similar to those of stalactites.

Stalagmites can take on various shapes and sizes, ranging from small cones to tall columns. Some stalagmites may fuse with stalactites hanging from the ceiling, forming columns that connect the floor and ceiling of the cave. As with stalactites, it is important to preserve and respect stalagmites in their natural state. Touching or damaging these formations can disrupt their growth and degrade the cave environment. Responsible cave exploration and tourism practices involve minimizing human impact on stalagmites and other cave features.

Blind Valley

A blind valley, also known as an endorheic valley or a closed valley, is a type of valley that does not have an outlet for surface water to flow out. Instead, the water within the valley remains trapped and does not drain into a larger river or body of water. Blind valleys often occur in mountainous or hilly regions where the valley floor is lower than the surrounding terrain, creating a natural basin-like shape. The lack of an outlet means that any water entering the blind valley will remain there and accumulate, forming lakes, wetlands, or marshy areas.

The formation of a blind valley can have several causes. It may be the result of tectonic activity, where the valley floor subsides or drops, trapping the water within the valley. It can also occur in areas with impermeable or poorly drained soils, preventing the water from easily flowing out of the valley.

Examples of blind valleys include the Salar de Uyuni in Bolivia, the Qaidam Basin in China, and the Owens Valley in California, USA. These valleys are known for their vast salt flats or closed basins, where water accumulates and evaporates, leaving behind mineral deposits.

Karst Valley

A karst valley, also known as a polje or karst depression, is a distinctive landform that forms in karst landscapes. It is also known as Solution Valley sometimes. It is characterized by a large, elongated depression or basin with flat or gently sloping floors and steep-sided walls. Karst valleys are typically found in regions where soluble rocks such as limestone or dolomite are prevalent.

The formation of a karst valley begins with the dissolution of soluble rock by groundwater. As water infiltrates the ground, it chemically weathers and erodes the rock, creating underground channels and cavities. Over time, the roof of these underground passages may collapse, forming sinkholes or dolines. When multiple sinkholes coalesce or merge, they create a larger depression known as a karst valley.

Karst valleys can vary in size, ranging from a few hundred meters to several kilometers in length. They often have flat or gently undulating floors, which may be covered with soil, sediments, or vegetation. The walls of karst valleys are steep and can be several hundred meters high, creating a dramatic landscape. One notable feature of karst valleys is their hydrological behavior. Due to the permeability of the soluble rock, surface water often quickly drains into underground passages, resulting in the absence of permanent surface streams or rivers within the valley. Instead, intermittent streams or temporary lakes may appear during periods of high rainfall or when the underground drainage system becomes overwhelmed.

Logar Valley in Slovenia, the Tiankengs of China's Huanjiang Maonan Autonomous County, and the Great Karoo in South Africa, etc. are famous examples of karst valleys.

Natural Bridge

Natural bridge is an erosional feature in karst topography. They are formed either due to the collapse of the roofs of caves or due to the disappearance of surface streams as subterranean streams.

Natural bridges are erosional features that can form in karst topography. In karst landscapes, soluble rocks such as limestone are susceptible to dissolution by water, leading to the development of caves and underground passages. Natural bridges can be formed through two main processes. The first process involves the collapse of the roof of a cave or cavern due to the weakening of the underlying rock or the erosion of supporting materials. Over time, as the cave roof progressively weakens, it may eventually collapse, leaving behind a natural bridge.

The second process involves the diversion of surface streams into subterranean channels. As water flows over the surface, it may find openings or sinkholes in the karst terrain and enter underground systems. This creates a situation where the surface stream disappears from sight and continues to flow underground, eroding the rock and forming a natural bridge.

These natural bridges in karst landscapes can exhibit various sizes and shapes, depending on the specific geological conditions and erosional processes involved. They are often visually striking features and can become significant landmarks within a region.

Famous examples of natural bridges in karst areas include the Natural Bridge in Virginia, USA, as previously mentioned, and the Xkeken Cenote in Mexico's Yucatan Peninsula, which features a natural bridge formed by the collapse of a cave ceiling.

Aven (Ponors)

'Aven' is a French term that has been universally adopted to describe a deep shaft-like hole in limestone terrain, leading down into extensive cave systems (karst) (Fig. 11.4).

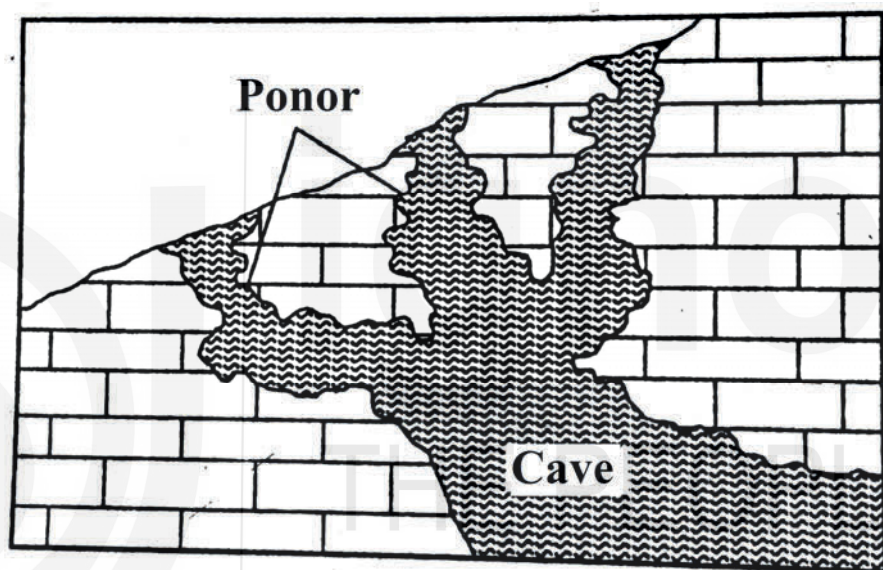


Fig.11.4: Aven or Ponor.

An aven, also known as a ponor, is a geological feature commonly found in karst landscapes. It is a vertical shaft or funnel-shaped opening that connects the surface of the land to an underground cave system or subterranean drainage network. Aven formation is closely associated with the processes of dissolution and erosion in karst regions.

Avens are typically formed by the downward erosion of water through soluble rock layers, such as limestone or gypsum. As water percolates through the ground, it dissolves the rock along vertical joints and fractures, gradually enlarging the openings and creating a vertical shaft. Over time, these shafts can develop into larger aven features. The size and shape of avens can vary, ranging from small openings to large vertical shafts extending several meters or even hundreds of meters deep. Some avens may have narrow entrances at the surface, widening into larger chambers or passages below.

The term "ponor" is often used interchangeably with aven, particularly in Central Europe, where it refers to a specific type of aven that acts as a swallow hole or sinkhole. Ponor features occur when surface water enters an aven and disappears underground, flowing through underground channels or

caverns. This process contributes to the complex network of underground watercourses in karst regions.

Aven formations can be found in various karst areas around the world, including the Dinaric Alps in Europe, the Nullarbor Plain in Australia, and the Guizhou Province in China.

11.5 KARST CYCLE OF EROSION

The concept of the cycle of erosion was also applied in limestone areas by J.W. Beede in 1911 and by Jovan Cvijic in 1918. W.M. Davis (1930) regarded the karst cycle of erosion as a special phase of the normal fluvial cycle of erosion characterized by the development of surface drainage, the disappearance of surface drainage underground, and the reappearance of subterranean drainage as surface drainage. The karst cycle of erosion is simpler than other geomorphic cycles because of the uniformity of structure (generally limestones) and dominance of mono-process (solution process). The difficulties are related to the nature of the movement of groundwater and the base level of erosion which are not precisely known.

Most geomorphologists believe that the water table of groundwater should be taken as the base level of erosion. According to some geomorphologists the rainwater infiltrates through the joints of the rocks in a vertical manner until it reaches the surface of the water table and thereafter it moves horizontally below the surface of the water table.

Two types of conditions have been recommended for the initiation of the karst cycle of erosion e.g. (1) Exposure of thick limestone cover at the ground surface and (2) Limestone cover overlain by non-soluble rocks (e.g., sandstones, shales, etc.). Karst cycle of erosion becomes more operative over two types of structures viz. (1) Folded limestones and (2) Faulted beds of limestones. It may be pointed out that the karst cycle of erosion becomes more effective where thick beds of limestones, whether folded or faulted, are exposed on the ground surface because rainwater immediately comes in contact with the rocks and starts dissociating them. Beede postulated a 3-stage karst cycle (e.g., youth, mature and old stages) whereas Cvijic presented a 4-stage karst cycle (e.g., youth, maturity, late maturity, and old stage). The characteristic features of different stages of the karst cycle of erosion are summarized below-

(1) Youth

The karst cycle starts with the initiation of surface drainage in the regions of thickly bedded limestones of folded or faulted structures or even of horizontal structures [Fig. 11.5 (1)]. The limestones are directly exposed to the ground surface. If the limestones are overlain by thin deposits of insoluble or non-calcareous formations, the surface runoff first removes these formations. The rainwater mixed with atmospheric carbon dioxide now reacts with limestones along the interfaces of their joints and thus forms 'sink holes' and 'swallow holes' through the mechanism of the solution process. These sinkholes gradually increase in number and are enlarged due to the continuous solution of limestones. The ground surface is characterized by rough terrain due to the

development of 'lapies' because of the dissolution of limestones along their joints. With the enlargement of sink holes and swallow holes into 'dolines' surface drainage starts disappearing under-ground through different 'sinks' or 'blind valleys'. The underground drainage initiates the formation of caves and caverns through underground solution and abrasion. The characteristic geomorphic features of this stage are sinkholes; swallow holes, dolines, lapies, blind valleys, sinking creeks, caves, and caverns of smaller dimensions. The termination of the youth stage is marked by the total disappearance of surface drainage.

(2) Maturity

The initiation of early maturity is heralded by total disappearance of surface drainage underground. Thus, the ground surface is characterized by dry water-less conditions. The surface drainage disappears under-ground through dolines and blind valleys. Thus, numerous sinking creeks are formed. The processes of underground solution and abrasion are augmented because of an increased volume of water due to the maximum development of subterranean drainage. Increased solution of carbonate rocks results in gradual enlargement of caves, galleries, and passages. The covering roofs of caves and caverns undergo the process of thinning because of all-round enlargement of caves. The thinning of cave roofs causes their collapse giving birth to 'uvalas', 'poljes', and 'karst windows' [Fig. 11.5(3)]. The residual uplands with highly pitted surfaces between uvalas become ridges. The late maturity is characterized by the destruction of most of the solutional landforms.

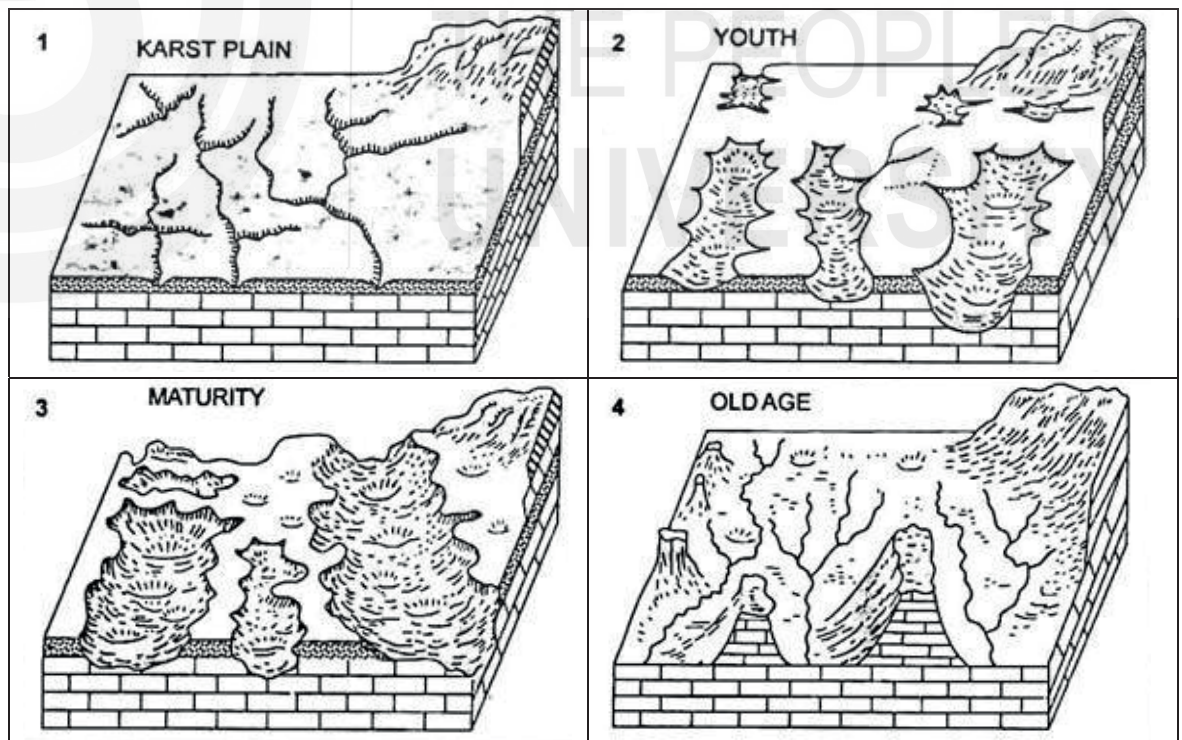


Fig. 11.5: Development of Karst Cycle of Erosion-1. Karst Plain, 2. Youth, 3. Maturity and 4. Old Stage, after A.K. Lobeck.

(3) Old Stage

The cave roofs are totally collapsed and ridges with the pitted surface between uvalas are considerably narrow down [Fig. 11.5(4)] and reduced in height. The residuals of carbonate rocks project slightly above the ground. These are called 'hums'. Most of the ground surface is levelled and thus resembles the 'peneplain' of the normal fluvial cycle of erosion (river cycle of erosion). The subterranean drainage again appears on the ground surface. Nearly all of the karst valleys, solution holes, and sinking creeks are eliminated. The second karst cycle of erosion may start with fresh upliftment of the karst plain.

SAQ 4

Mark the following statements as True or False:

- a) Swallow holes are formed due to deposition.
 - b) Dripstone is a deposit, usually composed of calcite, formed of drips from cave ceilings or walls.
 - c) Stalactites are erosional features.
 - d) The carbonates are deposited mainly by carbon dioxide loss.
-

11.6 SUMMARY

In this Unit, you have studied so far:

- Karst is terrain with scant surface drainage, thin and patchy soils, closed depressions, and caves. Its distinctive features develop on fairly pure limestones but also occur in evaporites and silicate rocks. It forms by the dissolution of limestone or other soluble rocks. Fluvial and hydrothermal processes may affect karst development.
- The chief geomorphic processes characteristic of karst landscapes are solution and precipitation, subsidence, and collapse. Groundwater solution works along jointing planes. While passing through a bed of limestone, the percolating water removes a small amount of material in the solution, and the resultant effect, acting over a long period of time, is of great significance. The solution is often the dominant process in karst landscapes, but it may be subordinate to other geomorphic processes.
- In sections where the groundwater table has dropped, pressure release promotes the precipitation of minerals creating a variety of chemical precipitates.
- Karst processes continuously develop landforms both on the surface and beneath the surface of limestone. Terra Rossa, Lapies, Sinkholes, Doline, Swallow holes, Uvala, and Polje are important surface landforms developed by the karst processes while Cave or Cavern, Stalactites, Stalagmites, Blind Valley, Natural Bridges, and Ponors are the main subterranean landforms.

- Subterranean karst forms refer to the various landforms and features that are found beneath the surface in karst landscapes. These forms are created through the processes of dissolution, erosion, and deposition that occur within the soluble rock, such as limestone or dolomite, in the subsurface. When water is combined with CO₂, it reacts along the fissures and joints of limestone terrain. Flowing through the karst surface, the water and its load abrade and corrode the rock, helping to produce subsurface landforms.
- Most speleothems are made of carbonate deposits, with calcite and aragonite accounting for about 95 percent of all cave minerals. The carbonates are deposited mainly by carbon dioxide loss (degassing), reduction in pressure, and by evaporation.
- Various contrasting theories have been put forward by different geomorphologists to account for the origin and development of limestone caves viz.: (1) Corrasion theory of Lapparent, Martonne, Martel, Weller, and C. A. Malott; (2) Two-cycle theory of W.M. Davis and supported by J.H. Bretz; (3) Water table theory of A.C. Swinnerton; (4) Static water zone theory of J.H. Gardner; (5) Invasion theory of C.A. Malott, etc.
- The concept of the cycle of erosion was also applied in limestone areas by J.W. Beede in 1911 and by Jovan Cvijic in 1918. W.M. Davis (1930) regarded the karst cycle of erosion as a special phase of the normal fluvial cycle of erosion characterized by the development of surface drainage, the disappearance of surface drainage underground, and the reappearance of subterranean drain-age as surface drainage.

11.7 TERMINAL QUESTIONS

1. Describe the global distribution of karst regions?
2. Discuss the theories associated with the origin and development of limestone caves.
3. What do you mean by Stalactites and Stalagmites?

11.8 ANSWERS

Self-Assessment Questions (SAQs)

1. Topographical features formed by underground water can be seen particularly, in a highland composed of limestone on a large scale. This distinctive topography formed due to the action of underground water in limestone regions is known as Karst topography.
2. CO_2 (Air) + H_2O (Water) $\longrightarrow$ H_2CO_3 (Carbonic Acid)
 CaCO_3 (Calcium Carbonate) + H_2CO_3 (Carbonic Acid) $\longrightarrow$ Ca^{++} (Calcium Ion) + 2HCO_3^- (Bicarbonate ion)

3. i. Lapiés is a term used for the highly corrugated and rough surface of limestone lithology, characterized by low ridges and pinnacles, narrow clefts, and numerous solution holes.

ii. Uvala is a landform found in karst regions characterized by a large, elongated depression or valley. It is created through the combination of various karst processes, including dissolution, collapse, and erosion.
4. a) False; b) True; c) False; d) True

Terminal Questions

1. Significant karst areas are found in different parts of the world. There are many areas where karst topography is found, even though these areas do not possess all of the possible karst forms. Such areas are: New South Wales, Western Australia, Southeast Asia, Celebes, Causse region of Southern France, Spanish Andalusia, Northern Puerto Rico, Central New Guinea, Western Cuba, Tabasco in Mexico, Sri Lanka, and Myanmar. (For a detailed answer, refer to section 11.2)
2. Various contrasting theories have been put forward by different geomorphologists to account for the origin and development of limestone caves viz.: (i) Corrasion theory of Lapparent, Martonne, Martel, Weller, and C. A. Malott, (ii) Two-cycle theory of W.M. Davis and supported by J.H. Bretz, (iii) Water table theory of A.C. Swinnerton, (iv) Static water zone theory of J.H. Gardner, (v) Invasion theory of C.A. Malott, etc. (For detail answer, refer to section 11.4.2).
3. Stalactites and stalagmites are both types of mineral formations that can be found in caves. They are formed through the deposition of minerals carried by dripping or flowing water. The main difference between stalactites and stalagmites lies in their position and growth direction within a cave. (For a detailed answer, refer to section 11.4.2).

11.9 REFERENCES AND SUGGESTED FURTHER READING

1. Dayal, P. (1996). *A Text Book of Geomorphology*. Shukla Book Depot, Patna.
2. Ford, D. and Williams, P. (2007). *Karst Hydrogeology and Geomorphology*. John Wiley & Sons Ltd, UK.
3. Huggett, R.J. (2011). *Fundamentals of Geomorphology*. Routledge, New York.
4. Hussain, M. (2007). *Fundamentals of Physical Geography*. Rawat Publications, Jaipur.
5. Lal, D.S. (2009). *Physical Geography*. Sharda Pustak Bhawan, Allahabad.
6. Livingstone, I. and Warren, A. (1996). *Aeolian Geomorphology: An Introduction*. Longman, UK.

7. Singh, S. (2012). *Physical Geography*. Prayag Pustak Bhawan, Allahabad.
8. Strahler, A. N. and Strahler, A. M. (2010). *Physical Geography-Science and Systems of Human Environment*. Wiley India (P) Ltd., New Delhi.
9. Waugh, D. (2002). *Geography- An Integrated Approach*. Nelson Thornes UK.



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UNIT 12

GLACIAL PROCESSES AND LANDFORMS

Structure

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12.1 INTRODUCTION

In Unit 11, you have studied karst processes and landforms created by karst processes in detail. Like karst processes glacial processes also is an important factor that creates different landforms. Glaciers are large masses of ice that form over long periods of time in areas where snowfall exceeds melting. As glaciers flow downhill under the force of gravity, they exert tremendous pressure on the landscape, resulting in various erosional and depositional features.

In this Unit, you will be studying glacial processes and the landforms associated with it. You will study Ice and glaciers in section 12.2. You will also study glaciation in the geological past and theories of glaciation in section 12.2. You will study types of glaciers in section 12.3, glacier processes in section 12.4, glacial erosion, pathways, and deposition in section 12.5, and glacial landforms in section 12.6.

Expected Learning Outcomes

After studying the unit, you should be able to:

- understand the dynamics of the frozen world of the earth;

- discuss the theories of glaciation and its evolution;
- define the types of glaciers and the processes of its formation;
- explain the glacier processes that occur within glaciers and ice sheets
- Identify and discuss the different glacial landforms.

12.2 ICE AND GLACIERS

Snowline is an altitude above which winter snow remains intact in summers also. However, below snowline the winter snow melts in summer season.

You may have observed the snowfall in winter at some higher mountain locations such as Shimla, Srinagar, Manali, etc. The tiny particles of snow are known as snowflakes and these snowflakes become compact and turned into ice when layer after layer of snow accumulated for many years thus forming the record-keeping pages of climatic history. This ice becomes a glacier as it moves down the slope. Therefore, Glaciers are defined as the natural mass of ice originating on land having distinctive movement downslope or outward under the impact of gravity and/or its partial pressure. In this way, the movement is an essential part of the glacier and the reason for all the glacial processes and resulting landforms.

The processes involved in evolving landforms and the process within itself the glacier, are termed *glacial*. The mechanism involved in the growth of these ice bodies is called glaciation. A glacier can grow where the mass balance (input-*accumulation*) is positive compared to loss (melting-*ablation*). Glaciers can only form at latitudes or elevations above the snowline, which is the latitude/elevation above which snow can stay throughout the year. The snowline, at present, lies at sea level in polar latitudes and rises to 6000 m in tropical areas. Glaciers grow in these areas if the snow becomes compacted, forcing out the air between the snowflakes. As compaction occurs, the weight of the overlying snow causes the snow to re-crystallize and increase its grain-size, until it increases its density and becomes a solid block of ice. Glaciers exhibit many variations in form, size, and origin. As a result, many different names have been applied to individual types.

The Antarctic ice sheet forms an almost continuous cover of ice above the Antarctic land mass. Only in a few places do mountain ranges and isolated peaks penetrate through the ice, and over most of the continent the ice sheets reach thicknesses in excess of 1000 m. The only other present-day ice sheet, in Greenland, is much smaller than its Antarctic counterpart. The formation and disintegration of these ice sheets is believed to have played an active part in causing the cycle of the Ice Ages. Ice reflects a much greater proportion of incoming solar radiation than other types of land surfaces. Consequently, the growth of an ice sheet decreases the energy budget of the Earth. In turn, the resultant lowering of surface temperatures may lead to increased snowfall and suppress snowmelt, thus contributing to the growth of the ice sheet. Conversely, the melting of an ice sheet allows more radiation to be absorbed and can thus lead to further temperature increases and accelerated melting, thus supporting a positive feedback mechanism.

Far from being static elements of the Earth's surface, glaciers are thus dynamic features with potentially significant climatic impact. The response of an ice sheet to changes in snowfall and melt patterns is mediated through the flow of ice from areas with higher snowfall or accumulation rates to areas where ice is lost from the ice sheet, which may either be regions of net melt or coastal

regions where icebergs can break away from the ice sheet. Such flow occurs essentially as a result of the ice sheet spreading under its own weight. At the center of the ice sheet, its surface elevation is greatest and decreases towards the margins. This causes a lateral pressure gradient which drives the flow.

Glaciers vary in their nature of nourishment, movement, and wastage. Changes in the regime of a glacier determine whether it is in a state of advance, recession, or stagnation. A glacier can change its size by accumulation, which occurs by the addition of snowfall, compaction and re-crystallization, and ablation, the loss of mass resulting from melting, usually at a lower altitude, where temperatures may rise above freezing point in summer. Thus, depending on the balance between accumulation and ablation during a full season, the glacier can grow or shrink. The line separating the zones of accumulation and ablation of a glacier is called the equilibrium line, and the altitude at which this line exists in a glacier is called the equilibrium line altitude (ELA).

Apart from the high latitude areas in both hemispheres, we have a large number of glaciers in the Himalayas also and the Himalayan Mountain chain has the largest concentration of glaciers outside the polar world. Glaciers in the Himalayas are broadly classified as belonging to the temperate category.

However, the ice, forming a glacier in the Himalayas, in its vertical profile, can exhibit the characteristics of a cold glacier at certain levels and that of a temperate glacier at other levels (Raina, V. K. and Srivastva 2008). The Temporary Technical Secretariat (TTS) for World Glacier Inventory (WGI) emphasized the need for the preparation of an inventory of glaciers. The Geological Survey of India (GSI) had prepared the glacier inventory of the Indian Himalayas which reveals that the Indian Himalayas encompasses two first-order basins, viz. Indus (5Q) and Ganga (5O). The number of basins and the basin-wise number of glaciers in the Indian Himalayas is given in Table 12.1.

Table 12.1: Distribution of Glaciers in Indus and Ganga Basin

Basin	No. of glaciers	Glacier-covered area (km ²)	Basin	No. of glaciers	Glacier-covered area (km ²)
Ravi	172	193	Yamuna	52	144
Chenab	1278	3059	Bhagirathi	238	755
Jhelum	133	94	Alaknanda	407	1229
Beas	277	579	Ghagra	271	729
Satluj	926	635	Tista	449	706
Upper Indus	1796	8370	Brahmaputra	161	223
Shyok	2454	10810	-	-	-
Nubra	204	4288	-	-	-
Gilgit	535	8240	-	-	-
Kishenganga	222	163	-	-	-
	7997	36431	-	1578	3787

Total number of glaciers in the Indian Himalaya: 9575.

Glacier-covered area in the Indian Himalaya: 40212 km².

(Source: Raina and Srivastva, 2008)

12.2.1 Glaciation in the Geological Past

Glaciation in the geological past refers to periods in Earth's history when extensive ice coverage occurred, leading to the formation of large ice sheets and glaciers. These glaciations had a profound impact on the planet's climate, landscapes, and ecosystems. Glaciation in the geological past occurred during specific time periods, known as glaciations or ice ages. The most well-known glaciation is the Pleistocene glaciation, which began around 2.6 million years ago and lasted until about 11,700 years ago.

However, glaciations have occurred throughout Earth's history, with major glaciations occurring during the Neoproterozoic Era (Snowball Earth events) and the Paleozoic Era (Carboniferous and Permian glaciations). The Neoproterozoic glaciations, often referred to as Snowball Earth events, occurred approximately 720-635 million years ago. During these periods, Earth experienced extreme global glaciation, with ice covering much of the planet's surface. The intense glaciations had a profound impact on the Earth's climate and led to significant changes in the composition of the atmosphere.

In the Paleozoic Era, two major glaciations are recognized: the Carboniferous glaciation (approximately 360-300 million years ago) and the Permian glaciation (approximately 300-250 million years ago). These glaciations occurred during times of lower global temperatures and resulted in the formation of extensive ice sheets and glaciers. The Carboniferous glaciation, in particular, played a crucial role in the formation of coal deposits due to the accumulation of plant remains in swamps and peat bogs during glacial retreats.

The timing and duration of glaciations in the geological past were influenced by various factors, including changes in Earth's orbit and tilt (Milankovitch cycles), the distribution of landmasses, and atmospheric composition. These glaciations had significant impacts on the Earth's surface, reshaping landscapes, carving out valleys and fjords, and depositing vast amounts of sediment.

Throughout the geological history of the Earth, long periods of warm climate were alternated with shorter phases of generally cold climate, during which, ice sheets and glaciers appeared (Embleton and King 1975). The periodicity of glacial phases has been roughly 250 million years. Evidence of earlier glaciations was obliterated by the great ice ages. The Quaternary is the most recent period in geological history and together with the Tertiary it forms the Cenozoic, the fourth of the great geological Eras.

The causes of the Quaternary climatic changes are very complex and poorly understood. Major factors are lithospheric plate motions, vertical tectonism, fluctuating atmospheric CO₂ content, and most important the Milankovitch Cycles. A recent theory propounded by Ehrlich (2007), establishes that there are magnetic instabilities in the core of the Sun, which cause fluctuations with periods of either 41,000 or 1,00,000 years. These could provide a better explanation for the Ice Ages than the Milankovitch cycles. Yet there is no consensus on the causes and initiation of these high-magnitude low-frequency events.

The geologic past has witnessed several distinct periods of glacial activity on various parts of the Earth's surface. The Precambrian glaciation is known to

be the most widespread phenomenon of global significance. Every continent, except Antarctica, was invaded by glaciers. North Africa, including the Sahara Desert, was invaded by Late Cambrian or Ordovician glaciation about 450 million years B.P. In the Permo-carboniferous, parts of all the continents positioned in the southern hemisphere, namely Africa, India, Australia, South America, and Antarctica were glaciated (Sharma, 2010).

The fact, however, is that the evidence of earlier glaciations was destroyed to great extent by successive glacial advances because the last was the largest. The Quaternary has been divided into glacial and interglacials, with further subdivision into stadial and interstadial episodes (Lowe and Walker 2014). Different number of total glacial episodes has been identified in different parts of the earth. Penck and Bruckner (1909) identified four glacial stages in the European Alps. Flint (1971) assigned corresponding four ice ages in Central North America. In Northern Europe, West (1977) identified seven glacial stages, in Britain however, eight glacial stages are identified by Mitchell et al. (1973) and West (1980). These glacial stages of different parts of the earth, separated by interglacial warm stages, are presented in Table 12.2.

Table 12.2: Glacials and Inter-glacials (*italics*) in different regions.

European Alps Penck & Bruckner (1909)	Central North America Flint (1971)	Northern Europe West (1977)	Britain Mitchell (1973) & West (1980)
<i>Postglacial</i>	<i>Holocene</i>	<i>Holocene</i>	<i>Flandrian</i>
<i>Wurm</i>	<i>Wisconsinan</i>	<i>Weichselian</i>	<i>Devensian</i>
<i>Riss-Wurm</i>	<i>Sangamon</i>	<i>Eemian</i>	<i>Ipswichian</i>
<i>Riss</i>	<i>Illinoian</i>	<i>Saalian</i>	<i>Wolstonian</i>
<i>Mindel-Riss</i>	<i>Yarmouthian</i>	<i>Holsteinian</i>	<i>Hoxnian</i>
<i>Mindel</i>	<i>Kansan</i>	<i>Elsterian</i>	<i>Anglian</i>
<i>Gunz-Mindel</i>	<i>Aftonian</i>	<i>Cromerian</i>	<i>Cromerian</i>
<i>Gunz</i>	<i>Nebraskan</i>	<i>Menapian</i>	<i>Beestonian</i>
		<i>Waalien</i>	<i>Pastonian</i>
		<i>Eburonian</i>	<i>Pre-Pastonian</i>
		<i>Tiglian</i>	<i>Bramertonian</i>
		<i>Pretiglian</i>	<i>Bavention</i>
		<i>Reuverian</i>	<i>Antian</i>
			<i>Thurnian</i>
			<i>Ludhamian</i>
			<i>Reuverian</i>

(Source: Lowe and Walker, 2014)

However, it now appears that there were at least twenty glacial/interglacial cycles within the Quaternary Period (Lowe and Walker 2014). Regarding the Quaternary glaciations in the Himalayas, De Terra and Paterson (1939), following the classic concept of four glacial periods in Europe and North America, had assigned four glacial ages to the Indian subcontinent. This view, however, is not fully established by recent researchers. Some excellent work on the Quaternary reconstruction of glacial stages in the Himalayas has been carried out in recent decades (Derbishire, E., Li, J., Perrott, F.A., Xu, S. and Waters 1984; Sharma and Owen 1996; Derbyshire and Owen 1997; Owen et al. 1997; Owen et al. 2001; Owen et al. 2002; Deswal et al. 2017).

These studies suggest that the Himalayan glaciation has been more complex than previously believed as the Himalayas receive moisture from two different sources i.e., Indian summer monsoon (ISM) and the western disturbances (WD). The western Himalayas is more dominated by the mid-latitude westerlies and therefore the glaciers in the western Himalayas are of winter accumulation type as opposed to the monsoon-dominated eastern Himalaya and the summer accumulation type glaciers. These two climatic drivers behaved differently in the geologic past making the Himalayan glaciers asynchronous to the glaciers in the higher latitudes.

12.2.2 Theories of Glaciation

There are several important theories that help explain glaciation and its mechanisms. These theories provide insights into the causes and processes of glacial formation and dynamics. Some of the key theories of glaciation are discussed below:

- i. **Milankovitch Cycles:** Milankovitch Cycles, named after the Serbian scientist Milutin Milankovitch, refer to the cyclical variations in Earth's orbital parameters that occur over long periods of time. These cycles include changes in eccentricity, axial tilt (obliquity), and precession. The interaction of these cycles with the Earth's climate system is believed to be a key factor in the onset and progression of glaciation.

The eccentricity cycle refers to changes in the shape of Earth's orbit around the Sun. It has a period of roughly 100,000 years and affects the amount of solar radiation reaching Earth. When eccentricity is at its maximum, the orbit becomes more elongated, causing variations in the distance between the Earth and the Sun. This can lead to differences in the amount of solar radiation received by different latitudes and seasons. Higher eccentricity can contribute to the development of glaciation by increasing the contrast between summer and winter temperatures, particularly at high latitudes.

However, Axial tilt, or obliquity, refers to the tilt of Earth's axis relative to its orbital plane. This tilt is responsible for the changing seasons. Axial tilt varies between approximately 22.1 and 24.5 degrees over a period of about 41,000 years. Higher axial tilt results in more pronounced differences between summer and winter temperatures. When axial tilt is higher, the summers can be warmer and the winters colder, providing favorable conditions for the growth and persistence of ice sheets.

Precession relates to the wobbling motion of Earth's axis as it spins, causing the orientation of the axis to change over time. This motion alters the timing of the seasons. Precession has a cycle of approximately 26,000 years. The changing orientation of the axis affects the timing of when Earth is closest to or farthest from the Sun during specific seasons. These changes can influence the amount and distribution of solar energy received by the Earth. Precession can impact the development and duration of glaciation by altering the timing of the seasons and the distribution of solar radiation.

The combined effects of these Milankovitch Cycles create a complex interplay of climate variations. When the cycles align in a way that increases the amount of solar radiation reaching higher latitudes during summer and

reduces it during winter, it can create conditions conducive to the growth of ice sheets. This alignment promotes positive feedback mechanisms, where increased ice cover reflects more sunlight back into space, further cooling the climate and promoting the expansion of ice sheets. Conversely, when the cycles are out of phase or minimize the differences in solar radiation, it can lead to periods of ice sheet retreat and warmer interglacial periods.

- **Ice-Albedo Feedback:** The concept of Ice-Albedo Feedback was proposed by the Swedish scientist Svante Arrhenius in the late 19th century. Arrhenius was a pioneer in the field of climate science and is well-known for his work on the greenhouse effect. He recognized that changes in the Earth's surface albedo, or reflectivity, due to the presence or absence of ice and snow can amplify or dampen the effects of climate change.

Arrhenius suggested that as the Earth's climate warms, the melting of ice and snow reduces the surface albedo, causing more solar radiation to be absorbed rather than reflected back into space. This leads to further warming and a positive feedback loop, where higher temperatures result in more ice melt, lower albedo, and even higher temperatures. Conversely, when the climate cools, an increase in ice and snow cover raises the surface albedo, reflecting more solar radiation back into space. This leads to cooling and a negative feedback loop, where lower temperatures promote ice and snow accumulation, higher albedo, and further cooling.

The Ice-Albedo Feedback is a crucial component of understanding climate dynamics, particularly in polar regions where ice and snow play a significant role. It helps explain the amplification of climate change effects and contributes to the understanding of past and future glaciation events.

- **Glacial-Interstadial Dynamics:** Glacial-interstadial dynamics play a crucial role in the occurrence and progression of glaciation. It suggests that during glacial periods, large ice sheets expand and cover significant portions of the Earth's surface, resulting in colder temperatures and lower sea levels. However, within these glacial periods, there are periodic shifts known as glacial-interstadial cycles, characterized by alternating phases of more extensive ice cover (glacial) and reduced ice cover (interstadial).

These glacial-interstadial cycles are driven by various factors, including changes in the Earth's orbit and axial tilt, which are collectively known as Milankovitch cycles. These orbital variations influence the amount and distribution of solar radiation received by the Earth, which in turn affects the climate.

In interstadial phases, temperatures tend to be relatively warmer, resulting in a reduction in ice cover and the retreat of glaciers. This can lead to the melting and calving of ice, causing sea levels to rise. In contrast, during glacial phases, colder temperatures prevail, causing ice sheets to expand and glaciers to advance.

The dynamics between glacial and interstadial phases are complex and influenced by multiple factors, including oceanic circulation patterns, atmospheric circulation, and feedback mechanisms. These dynamics have

significant implications for global climate patterns, sea levels, and the shaping of landscapes.

It is important to note that the timing, duration, and intensity of glacial-interstadial cycles can vary, and different regions of the Earth may experience these cycles differently. The study of glacial-interstadial dynamics provides valuable insights into past glaciations and helps scientists understand the processes and mechanisms that drive glaciation and its impacts on the Earth's climate system.

- **Heinrich Events:** Heinrich events are large-scale ice-rafting events characterized by the discharge of massive icebergs from ice sheets into the North Atlantic Ocean. These events are associated with periods of rapid climate cooling and are believed to have played a role in shaping glacial dynamics during the last glacial period.

The concept of Heinrich events was first proposed by marine geologist Hartmut Heinrich in the 1980s. Heinrich studied sediment cores from the North Atlantic and observed distinct layers of coarse sediment composed of rock fragments that were not locally derived. These sediment layers, known as Heinrich layers, were found to be deposited during Heinrich events.

Heinrich events are thought to have originated from the Laurentide Ice Sheet, which covered a large portion of North America during the last glacial period. The events occur when large parts of the ice sheet destabilize and discharge enormous numbers of icebergs into the North Atlantic Ocean. The released icebergs carry with them rock debris that was incorporated into the ice as it advanced over the landscape.

Heinrich events are believed to be triggered by internal ice sheet instabilities, possibly related to changes in the climate system or the dynamics of the ice sheet itself. The precise mechanisms leading to their initiation and termination are still debated among scientists. However, it is thought that factors such as increased meltwater input, changes in ocean circulation, or interactions between the ice sheet and the underlying bedrock may have played a role.

Heinrich events have had significant impacts on the climate and environment of the North Atlantic region. The discharge of icebergs into the ocean can cause abrupt cooling by introducing freshwater and disrupting oceanic circulation patterns. These events may also have influenced the variability of the Atlantic Meridional Overturning Circulation (AMOC), a crucial component of global ocean circulation.

- **Threshold Hypothesis:** The Threshold Hypothesis, also known as the Glacial-Interglacial Threshold Hypothesis, is a concept that proposes a threshold or tipping point for the initiation and termination of glaciation. It suggests that there are critical thresholds in climate conditions that need to be crossed in order to trigger the onset or retreat of ice ages.

According to the Threshold Hypothesis, certain climatic factors, such as the amount of solar radiation received during summer, play a crucial role in determining the presence or absence of glaciers. These factors are influenced by various orbital and atmospheric changes over long timescales.

During interglacial periods, when the climate is relatively warm, glaciers retreat and the Earth experiences a relatively stable climate. However, as the climate gradually cools, it reaches a critical threshold where the conditions become favorable for the growth and expansion of glaciers. Once this threshold is crossed, glaciers start to advance and the Earth enters a glacial period.

Likewise, the termination of a glacial period occurs when the climate reaches another critical threshold that triggers a warming trend. This warming leads to the retreat of glaciers and the transition to an interglacial period.

The Threshold Hypothesis suggests that small changes in climate conditions can have significant effects on the extent and duration of glaciations. It emphasizes the role of feedback mechanisms and nonlinear responses in climate systems, where relatively minor changes can lead to large-scale shifts in ice sheet dynamics and global climate patterns.

SAQ I

- i. What is glaciation?
 - ii. Carboniferous glaciation and Permian glaciation belong to which era?
 - iii. Which is the most recent period in geological history?
 - iv. Who gave the concept of Ice-Albedo Feedback?
-

12.3 TYPES OF GLACIERS

Glaciers are large bodies of ice that form over many years from compacted snow. They flow under their own weight and can shape the landscape through erosion and deposition. Glaciers exhibit wide variations in shape, size, and nourishment regimes, as a result, many different names are applied to individual types. There are cold glaciers that remain below freezing point throughout their vertical profile. Warm or temperate glaciers are those glaciers that are at pressure melting point at their base.

We can classify the glaciers in two broad categories viz. Continental glaciers or continuous ice sheets from which ice may move in all directions and the glaciers confined to more or less marked courses which direct their main movement. The glaciers of all mountainous regions of the world fall in this second category. There is also a third category which may be called a transitional type. Glacier ice which spreads in large or small sheets on plain areas at the foot of glaciated terrain is in this transitional category. There are however, many sub-types of glaciers and most of the glaciers are not independent but connected with some other type. You will study some important types of glaciers mentioned below:

i. Continental Glaciers

Continental glaciers, also known as ice sheets, are immense masses of ice that cover large portions of continents or subcontinents. They are not confined to mountain valleys but spread over extensive areas. Unlike valley glaciers, which flow through mountain valleys, continental glaciers flow outward from their center in all directions. Continental glaciers or ice sheets are assumed to

be larger than 50,000 km² in size (Benn and Evans 2014). The two primary examples of continental glaciers are:

- a. **Antarctic Ice Sheet:** The Antarctic Ice Sheet is the largest continental glacier on Earth. It covers the entire continent of Antarctica, with an area of approximately 14 million square kilometers. The ice sheet contains about 90% of the world's ice and has an average thickness of about 2,160 meters. It is composed of layers of snow and ice that have accumulated over millions of years. The Antarctic Ice Sheet is a vital component of the Earth's climate system and plays a significant role in regulating global climate and sea levels.
- b. **Greenland Ice Sheet:** The Greenland Ice Sheet is the second-largest continental glacier and covers most of the island of Greenland in the Arctic. It spans an area of approximately 1.7 million square kilometers. The ice sheet has an average thickness of about 1,500 meters and contains an estimated 2.8 million cubic kilometers of ice. The Greenland Ice Sheet is important for studying past climate conditions and understanding the impacts of climate change, particularly its contribution to rising sea levels.

ii. Cirque Glacier

A cirque glacier, also known as a corrie or a cirque, is a type of glacier that forms in a cirque, which is a bowl-shaped hollow found on the side of a mountain. Cirque glaciers are typically found in high-altitude and high-latitude regions where snow accumulation is greater than snowmelt.

Cirque glaciers have distinct features. They are characterized by a concave shape with steep walls on three sides, while the fourth side is open. The headwall, formed by the steep back wall of the cirque, often exhibits erosion features such as glacial polish and striations. The glacier fills the cirque and flows downhill, shaping the landscape through processes like erosion, abrasion, and plucking. As the ice melts and retreats, it can leave behind a tarn, which is a small mountain lake, in the cirque basin.

Famous examples of cirque glaciers include the Mer de Glace in the French Alps and the Lilliput Glacier in the Canadian Rockies. One notable example of a cirque glacier in India is the Gangotri Glacier, located in the state of Uttarakhand. It is one of the largest glaciers in the Himalayas and is a primary source of the Ganges River. The Gangotri Glacier is nestled within a cirque in the Garhwal Himalayas at an altitude of approximately 4,000 meters.

iii. Ice Cap

An ice cap glacier is a large mass of ice and snow that spreads outwards from a central point, covering the underlying terrain and forming a broad, rounded topography. Unlike continental glaciers, which can cover entire continents, ice caps are generally smaller in scale, typically ranging in size from a few hundred square kilometers to a few thousand square kilometers and is characterized by its dome-like shape and extensive coverage of land.

Ice caps are commonly found in polar and high-altitude regions, such as Greenland and the Arctic, as well as in some mountainous areas. They form through the accumulation of snowfall over many years, which gradually

compresses into ice under its own weight. The ice cap acts as a reservoir of frozen water, and its movement is relatively slow compared to other types of glaciers.

One well-known example of an ice cap is the Vatnajökull Ice Cap in Iceland, which is the largest ice cap in Europe, covering an area of approximately 8,100 square kilometers. Siachen Glacier, located in the eastern Karakoram Range in the Himalayas is another example of ice cap. The Siachen Glacier is the longest glacier in the Karakoram Range and the second longest non-polar glacier in the world. It is an expansive ice cap that covers an area of approximately 76 square kilometers.

iv. Valley Glacier

A valley glacier is a type of glacier that forms within a mountain valley or canyon. It is characterized by its long, narrow shape, with the ice flowing downhill along the valley floor. Valley glaciers are also known as alpine glaciers or mountain glaciers (Fig. 12.1). The valley glaciers flow down in a well-defined terrain confined between valley walls. At times, such glaciers are formed by the merging of many tributary glaciers along the length. These glaciers are also known as compound and simple basin types, depending on the number of tributary glaciers feeding into the main trunk glacier.



Fig. 12.1: The icewall of the terminus of Gangotri glacier in Garhwal Himalaya. See the people in the circle for an estimation of the scale.

Valley glaciers can have a significant impact on the surrounding landscape. As they flow, they erode the valley floor and walls through processes such as plucking and abrasion. This erosion creates characteristic features such as U-shaped valleys, cirques, and moraines. When valley glaciers reach lower elevations or warmer climates, they may melt, forming glacial lakes or feeding into rivers.

Examples of well-known valley glaciers include the Mer de Glace in the French Alps, the Columbia Glacier in Alaska, and the Franz Josef Glacier in

New Zealand. These glaciers have shaped the surrounding landscapes and are popular tourist destinations for their natural beauty and geological significance. Gangotri Glacier, India, is also an example of valley glacier which lies in the western Himalayas. It is one of the largest glaciers in the Himalayan region, stretching over a length of approximately 30 kilometers. The Gangotri Glacier is the source of the Ganges River, one of the holiest rivers in India.

v. Piedmont Glacier

A piedmont glacier is a type of glacier that forms when a valley glacier spills out onto a flatter plain or valley floor. It spreads out and expands horizontally, resembling a wide lobe or fan-shaped mass of ice. Piedmont glaciers typically occur at the base of steep mountain valleys or in areas where a valley glacier reaches a relatively flat area.

The formation of a piedmont glacier is influenced by the interaction between the flow of ice and the topography of the land. As the valley glacier reaches the lower, wider area, it slows down and spreads out due to reduced slope and confinement. This causes the ice to pile up and form a broad, lobate shape. The spread of the glacier is often aided by the deposition of glacial sediment and debris at the terminus.

One notable example of a piedmont glacier is the Malaspina Glacier in Alaska, USA. It is one of the largest piedmont glaciers in the world, covering an area of over 3,900 square kilometers. The Malaspina Glacier extends from the St. Elias Mountains to the Gulf of Alaska, spreading out in a vast expanse of ice over low-lying coastal plains. Other examples of piedmont glaciers can be found in regions such as the Antarctic Peninsula and the Patagonian Icefields in South America.

vi. Hanging Glaciers

Hanging glaciers are a type of glacier that are characterized by their position on steep slopes or cliffs. They are named "hanging" because they appear to be suspended or "hanging" above the surrounding terrain. Hanging glaciers typically form in cirques, which are bowl-shaped basins carved into mountainsides by glacial erosion. Hanging glaciers are formed when snow accumulates in a cirque and compacts into ice. As the glacier grows, it flows downslope under the force of gravity. However, due to the steep slope or cliff below the cirque, the glacier does not reach the valley floor. Instead, it ends abruptly, with its terminus hanging above the valley or dropping into the void below.

The ice of a hanging glacier can create impressive features such as icefalls, seracs, and crevasses. Icefalls are steep sections of ice that form when the glacier encounters a steep slope or cliff, causing the ice to fracture and cascade down in a series of ice cliffs. Seracs are large blocks or towers of ice that are often found at the base of icefalls. Crevasses are deep cracks that form in the surface of the glacier as it moves over uneven terrain.

Hanging glaciers are commonly found in mountainous regions with steep slopes, such as the Swiss Alps, the Canadian Rockies, and the Himalayas. They are important features of alpine landscapes and contribute to the overall dynamics of glacial systems.

SAQ 2

Write two primary examples of the continental glaciers?

12.4 GLACIER PROCESSES

Glacier processes are the dynamic actions and movements that take place within glaciers and ice sheets. These processes shape the land, erode the landscape, and transport and deposit sediments. Now you will study how glacier processes takes place. You know that, the flow of the glacier ice is different from that of rivers for the obvious reason that the ice is a solid state of water. Glaciers move down the slope by gliding under the impact of gravity as solid slabs of ice. At the same time, glacier ice has internal deformation due to its weight and due to its physical state as a plastic solid. While moving over the bedrock obstacles the flow can be compressive on stoss side and tensional or enhanced on the lee ward side of the obstacle. The enhanced flow creates transverse crevasses on the glacier surface while the compressive flow creates over-thrusting of ice (Figure 12.2).



Fig. 12.2: Google Earth 3D view of the upper portion of the 26 km long Miyar glacier in the Lahaul Himalaya with the longitudinal pattern of strips showing the debris transport and flow velocity variations across the glacier. Note the transverse crevasses in the tributary glacier indicating the enhanced plastic flow.

(Source: Google Earth)

Glaciers are very important gradational agent in cold climate regions of the earth's surface. The term gradation is applied to all processes which include degradation or denudation (erosion or veneering off the top layer), transportation of eroded material, and aggradation of transported material or debris. Glacier erosion is primarily a subglacial process and glaciers erode while sliding over their bed. Temperate or warm-based glaciers are controlled by underlying topography to a great extent and are at or near their pressure-melting point throughout the ice mass. This characteristic is the deciding factor of glacial geomorphology in mountain areas. Because of the pressure melting underneath the glaciers, there is a variety of subglacial processes.

Due to heavy sediment yield, such glaciers have a sheet of subglacial sediments which makes the sole of the glacier. Therefore, temperate glaciers have great abrasive power. Landsystems in glaciated valleys tend to have certain recurrent features as a result of two main factors (Benn et al. 2005). These are the strong influence of topography on glacier morphology, sediment transport paths, and depositional basins, and secondly, the importance of debris from supraglacial sources in the glacial sediment budget. A landsystem is an area with common terrain attributes, different from those of adjacent areas (Evans and Hiemstra 2005).

In the zone of accumulation, vectors of particle motion are downward into the ice mass as a new surface layer adds to the glacier every year. As a result of this, erosion at the glacier bed is intensified. Sediment load which is taken from valley sides, moves downward with the downward movement of glacier ice in the accumulation zone, leaving clean ice at the glacier surface. In the zone of ablation, vectors of particle motions point toward the ice surface, bringing the englacial debris to the glacier surface. Because of this, ablation zones of alpine glaciers are under huge supra-glacier debris cover. At the cross-section of the glacier where up-glacier net accumulation and down-glacier net ablation are in exact balance, internal flow vectors are parallel to the glacier surface (Bloom 1998). This equilibrium cross-section of a glacier is located beneath the equilibrium line, the down-glacier edge of net annual accumulation.

Glacier processes are complex and fascinating, involving a range of actions and movements that occur within glaciers and ice sheets. Important glacier processes are discussed below:

- **Accumulation:** Accumulation is the process by which snow and ice accumulate on the surface of a glacier. It occurs in regions where snowfall exceeds melting and evaporation. It begins with the falling of snowflakes onto a glacier or ice sheet, gradually building up layers of snow over time. The accumulated snow adds to the mass of the glacier and contributes to its growth. As new layers of snow accumulate, the weight of the overlying snow compresses the lower layers, resulting in compaction. This, combined with the metamorphism of snowflakes into ice crystals, transforms the compacted snow into firn, an intermediate stage between fresh snow and glacial ice. The uppermost layer of the glacier, called neve, is where fresh snow accumulates each year, and its high density sustains the glacier in the long term. The cumulative layers of snow and firn form a snowpack, which acts as an insulating layer protecting the underlying ice from melting during warmer periods.

The accumulation of snow is a crucial component of a glacier's mass balance, where positive mass balance leads to glacier growth and negative mass balance causes glacier retreat. Accumulation rates are influenced by climate factors, such as temperature, precipitation patterns, and wind, with regions experiencing high snowfall and low melting rates typically having higher accumulation rates.

- **Ablation:** Ablation refers to the loss of ice from a glacier. It includes processes such as melting, sublimation (ice turning directly into vapor),

calving (breaking off of icebergs from the glacier's front), and wind erosion.

Melting is the primary form of ablation, occurring when the temperature surpasses the ice's melting point. Factors like solar radiation, air temperature, and heat from the surroundings contribute to melting, causing meltwater to flow over the glacier's surface and form streams and rivers. Sublimation is another ablation process where ice transitions directly into water vapor without becoming liquid. It typically happens in dry and windy conditions. Evaporation occurs when liquid water on the glacier's surface turns into water vapor, driven by solar heat and surrounding air. Calving, on the other hand, is the process of ice chunks breaking off from the glacier's front, leading to the formation of icebergs in water bodies.

Ablation rates vary with seasons, being higher during warmer periods and lower during colder times. The balance between accumulation and ablation determines the overall health and size of a glacier. However, the impacts of climate change have greatly affected ablation processes, accelerating glacial retreat worldwide and contributing to rising sea levels. These changes in ablation highlight the vulnerability of glaciers to a warming climate and emphasize the importance of studying and understanding these processes for assessing future environmental changes.

- **Plastic Flow:** Plastic flow, also known as plastic deformation or creep, is a process that occurs within glaciers and ice sheets. It refers to the slow, continuous movement of ice in response to the force of gravity. Unlike brittle materials that fracture under stress, ice exhibits plastic behaviour due to its ability to deform and flow over time.

Plastic flow occurs within the deeper layers of the ice, where pressure and stress are high. Under these conditions, the ice crystals are subjected to shear stress, causing them to deform and reorient. The deformation occurs through a combination of mechanisms, including grain boundary sliding, dislocation movement, and recrystallization.

The process of plastic flow is influenced by several factors, including temperature, pressure, and the presence of impurities or water. Warmer temperatures enhance the mobility of ice molecules, facilitating greater plastic deformation. High pressure helps to compress the ice, making it more susceptible to flow. Impurities and water can act as lubricants, reducing the resistance to deformation.

Plastic flow is a critical mechanism by which glaciers and ice sheets respond to external forces, such as the gradient of the underlying terrain. It enables the ice to flow downhill and adjust to changes in the topography. The rate of plastic flow can vary depending on the specific conditions and characteristics of the ice mass.

- **Basal Slip:** Basal slip occurs when the glacier slides along its bed due to the presence of meltwater at the ice-bed interface. The water acts as a lubricant, reducing friction and allowing the glacier to slide more easily. Basal slip is responsible for the faster movement of glaciers.

Basal slip occurs when the pressure and weight of the overlying ice cause the ice at the base to melt slightly due to the pressure-induced decrease in melting point. This forms a thin layer of liquid water between the ice and the underlying surface, reducing friction and allowing the glacier to slide. The liquid water acts as a lubricant, facilitating the movement of the ice.

The rate of basal slip depends on several factors, including the slope of the underlying surface, the presence of water or sediments, and the pressure exerted by the ice mass. Steeper slopes and the presence of meltwater or sediments can enhance basal slip by reducing friction and increasing lubrication. Higher pressure from thicker ice masses can also contribute to more significant basal slip.

Basal slip is most pronounced in temperate glaciers, where the ice is near its melting point, and water is present at the base. In polar glaciers and ice sheets, basal sliding is generally less significant compared to other ice movement mechanisms, such as plastic flow.

Understanding basal slip is crucial for studying glacier dynamics and predicting their behaviour. Scientists use various methods, including field observations, ice core analysis, and remote sensing techniques, to measure and analyse basal slip in glaciers and ice sheets. This knowledge helps in modelling ice flow, estimating glacier velocities, and assessing the response of glaciers to environmental changes.

- **Internal Deformation:** Internal deformation, also known as plastic flow, is a fundamental process that drives the movement and deformation of glaciers and ice sheets. It occurs within the ice mass itself, as the individual ice crystals or grains undergo deformation under the pressure exerted by the overlying ice. This deformation results in the flow and reshaping of the ice, allowing glaciers to move and shape the landscape. Internal deformation is most prominent in the central and upper parts of glaciers, where the ice experiences the greatest pressure. Factors such as temperature, crystal size, and impurities influence the rate and pattern of deformation. Understanding internal deformation is crucial for comprehending glacier dynamics, predicting their behaviour, and assessing their contribution to sea-level rise.
- **Erosion:** Glaciers are powerful agents of erosion. As glaciers move, they can pluck and lift rocks from the underlying bedrock. This process, known as plucking, occurs when the ice freezes onto rocks and carries them along. The movement of the glacier also results in abrasion, where rocks and debris embedded in the ice scrape and grind against the underlying rocks, wearing them down.
- **Transportation:** Glaciers transport the debris they have eroded and entrained within the ice. This includes rocks, sediment, and other materials of various sizes. The transported material is carried within the glacier, either at the base as the glacier slides or within the body of the glacier. The debris is then transported downslope due to the movement of the glacier.
- **Deposition:** When a glacier melts or slows down, it deposits the sediment and debris it has been transporting. The deposition occurs as the glacier

retreats or at its terminus. The deposited material forms distinct landforms, such as moraines (ridges or piles of glacial debris), drumlins (elongated hills), eskers (long, winding ridges), and outwash plains (areas of sediment deposited by meltwater).

SAQ 3

What is Plastic Flow?

12.5 GLACIAL EROSION, PATHWAYS, AND DEPOSITION

Glacial erosion, pathways, and deposition are fundamental processes associated with the movement of glaciers and their interaction with the Earth's surface. Glacial erosion is facilitated by the presence of debris within the moving ice, which serves as tools for the erosion process. Two primary processes of glacial erosion are abrasion and plucking. Abrasion involves the grinding and wearing down of fine-grained material, while plucking refers to the failure and removal of larger blocks of rock. According to Benn and Evans (2014), these processes share common characteristics and can be described in three basic stages:

(i) Rock failure, in which fragments are loosened from the bed; (ii) Evacuation, in which fragments are removed from their original position; and (iii) transport, in which fragments are entrained by ice, water or in a subglacial deforming layer.

Now you will study glacial erosion in detail.

A. Glacial Erosion: Glacial erosion refers to the wearing down and shaping of the landscape by glaciers. As glaciers move, they exert tremendous pressure on the underlying bedrock, leading to the removal and transport of rock fragments and sediment. Glacial erosion occurs through two primary mechanisms: abrasion and plucking.

- **Abrasion:** Abrasion occurs when the embedded rock fragments within the glacier scrape and grind against the bedrock surface. This process smooths and polishes the bedrock, leaving behind striations (scratches on bedrock) and characteristic landforms.

Abrasion is a glacial process that involves the wearing down and smoothing of the Earth's surface by the movement of rocks and debris embedded within a glacier. As a glacier advances, it carries a significant amount of rock material, ranging from small particles to large boulders, along its path. These rocks act as tools that scrape and grind against the underlying bedrock, resulting in the process of abrasion.

During abrasion, the rocks embedded in the glacier's base or sides act like sandpaper, scraping and scouring the bedrock beneath them. The weight and pressure of the glacier, combined with the movement of the ice, enhance the erosive power of the rocks. This constant scraping and grinding action of the

rocks against the bedrock leads to the removal of loose material and the smoothing of irregularities on the surface.

The effects of abrasion can be seen in the distinctive features left behind by glaciers. For example, glacial valleys often have smooth, polished surfaces and characteristic U-shapes, resulting from the extensive abrasion of the surrounding rocks. The rocks themselves may exhibit striations, which are parallel grooves or scratches caused by the movement of the glacier.

Abrasion is most effective when the rocks are hard and resistant to erosion, as they have a greater ability to scrape and wear down the bedrock. Softer rocks and sediments are more likely to be worn away, leaving behind a smoother surface.

- **Plucking:** It is a process of glacial erosion that begins when water infiltrates into joints and fractures within the bedrock. This water can come from various sources such as meltwater, rainfall, or groundwater. As the infiltrated water freezes within the glacier, it expands and exerts pressure on the surrounding rock, causing it to fracture and detach from the bedrock surface. The subsequent thawing and refreezing of water widens the cracks and further weakens the rock. Once the rock is loosened, the flowing ice of the glacier engulfs and carries it through a process called entrainment.

The ice freezes onto the fractured surfaces of the rock, effectively lifting and entraining it. The strong adhesive properties of ice enable it to adhere to the rock surfaces. The entrained rocks become embedded within the glacier and are transported downslope as the glacier moves. Larger rocks may be carried at the base of the glacier, while smaller particles may be suspended within the ice matrix.

Plucking has significant effects on the landscape, including the creation of irregularities and depressions in the bedrock surface, such as basins or cirques. It also exposes fresh, unweathered bedrock surfaces and leaves behind angular rocks with striations or scratches from abrasion. Additionally, plucking plays a role in controlling the flow and dynamics of glaciers by altering the resistance to ice flow. This can result in uneven ice erosion and the formation of streamlined shapes as the glacier conforms to the topography of the bedrock.

B. Pathways: Pathways refer to the routes or channels through which glaciers move and transport material. Glaciers can follow pre-existing valleys, creating or modifying them as they advance. They can also create new pathways by overriding and eroding the underlying terrain. The pathways of glaciers are influenced by the topography of the landscape, the slope gradient, and the presence of obstacles or barriers. As glaciers move along their pathways, they interact with the surrounding environment and undergo various processes of erosion and deposition.

C. Deposition: Deposition on the other hand, refers to the laying down or accumulation of material by glaciers. As glaciers advance, they carry along a variety of sediments, including rocks, boulders, gravel, sand, and

finer particles. When the glacial ice melts or slows down, it deposits this sediment load in various forms and locations.

Glacial deposition occurs through different mechanisms. When a glacier melts, it can release its sediment load directly onto the ground surface, resulting in the formation of moraines. Moraines are accumulations of unsorted and unstratified material, ranging in size from large boulders to smaller particles. Terminal moraines are formed at the furthest point of glacier advance, while recessional moraines are created during periods of temporary glacier retreat.

Glacial deposition also occurs through meltwater processes. Meltwater from glaciers carries sediments and deposits them in the form of outwash plains, which are composed of sorted and stratified sediments. Braided streams, eskers (long, winding ridges of sediment), and kames (mounds of sediment) are other landforms associated with meltwater deposition. Glaciers can also deposit sediment in lakes or oceans when they terminate in water bodies. As the glacier melts, sediment-rich meltwater enters the water and settles, forming deltas or submarine fans.

SAQ 4

What is Plucking?

12.6 GLACIAL LANDFORMS

Glacial landforms are distinctive features that are created by the erosive and depositional processes of glaciers. These landforms can vary in size, shape, and composition depending on the characteristics of the glacier and the surrounding environment. Glacial landforms are present in the most scenic and mesmerizing places around the world. Let us now discuss the wide variety of landforms created by glacial processes. The criteria for identification of the landforms of glacial erosion and deposition have been listed in Table 12.2.

Table 12.2: Some glacial landforms and criteria for identification.

Landform	Identification Criteria	Boundary defined by	Significance
Ice-scoured bedrock	Widespread exposures of bare bedrock with smoothed, striated, or plucked upper surfaces	The outermost extent of bare bedrock	Evidence of glacier ice at its pressure-melting point
Drift limit	The edge of the cover of a glacial deposit that is not also marked by a moraine ridge. Drift limit may be identified by a change in vegetation type or by change in the density of glacially deposited boulders	Outermost extent of glacial deposit	The drift limit marks the extent of a glacier's advance

Trimlines are the lines of upper limit of glacial erosion on the valley sides of U-shaped valley. They indicate towards the thickness of former glaciers in deglaciated valleys.

Moraine ridge	A single ridge or collection of ridges composed of glacial material. Typically, 1-10m (but exceptionally 100m) in height. Sharp or rounded crests and either linear, curved, sinuous, or sawtooth in plan	Lower concave break of slope. The Crestline orientation can also be recorded if this is well defined	The moraine ridge marks the lateral or terminal extent of a glacier (except in the case of hummocky moraine)
Hummocky moraine	A seemingly chaotic assemblage of irregular hummocks and hollows. Hummocky moraine often shows order when viewed on an aerial photograph, or when mapped in detail in the field.	The outermost extent of the hummocky moraine. The Crestline orientations of individual hummocks can also be recorded if the scale of the map permits.	Formed by the slow melting of stagnant, debris-covered ice, by deposition of receding glacier margins, or the release of material from proglacial or englacial thrusts.
Drumlins	Smooth, streamlined, oval-shaped or elliptical hills with steep or blunt stoss faces. Composed of a variety of glacial sediments.	Upper convex and lower concave breaks of slope	Widespread subglacial modification of sediments. The steeper, blunt end usually indicates the up-ice face.
Meltwater channels	Channels cut in rock or sediment, often with abrupt inception and termination and lack of modern catchment. Subglacial meltwater channels may breach cols, displaying convex-up long profile	Thalweg of channels, location of channels inception and termination. An arrow to indicate the direction of former drainage can also be recorded if known	Evidence of former meltwater discharge routes
Trimline	The line separating areas of solifluction from extensive gulling or areas of mountain-top detritus/ weathered material from the upper limit of ice-scoured bedrock	The lower limit of solifluction or weathering and the upper limit of extensive gulling or ice-scoured bedrock	Former vertical dimensions of a glacier or englacial thermal boundary

(Source: Hubbard and Glasser, 2005)

12.6.1 Glaciated Valleys

In geomorphology, there is interest in distinguishing between valleys whose primary force of formation has been the motion of a glacier and those formed

by other processes such as rivers. Glaciated valleys tend to have a shape across the valley that is often described as U-shaped; whereas river-cut valleys tend to be V-shaped. As is obvious that glacier ice is a solid mass and the erosion mechanism is different from that of streams. Glaciated valleys are a product of the bulldozing effect of glaciers and the truncated spurs are the best example of such a mechanism. Whereas the streams are characterized by undercutting in their youth stage and due to entrenchment, valleys tend to be V-shaped in cross profile. Glacial troughs or U-shaped valleys are a characteristic feature of mountain glaciation (Figure 12.3). In cross-profile most glacial troughs are asymmetrical. Deep glaciated valleys at sea coasts of high latitudes partly submerged with seawater, are known as Fjords. They are usually straight, deep, and broad-based troughs confined between steep mountain walls. Vanderford and Skelton inlet fjords in Antarctica are 2287 and 1933 meters below sea level respectively.



Fig. 12.3: Broad and flat glacial trough (Miyar valley, Lahaul Himalaya) with clear evidence of truncated spurs on both sides.

12.6.2 Striations

Glacial striations are microrelief forms represented by parallel scratches on bedrock pavements. They are formed by the abrading fragments carried in the sole of glacier ice. In the areas of former glaciation, several sets of striae can be recognized. Micro striations are the imprints of former glacier movements on the micro-meter size particles which can be recognized only in the lab. Striations on the boulders which can be recognized by the human eye are known as macro striations. Interpretation of striations is very useful in the study of the flow direction of ice as well as in determining the thickness of ice on valley walls. Crossed striae on the bedrock represent shifts in ice motion during a phase of deglaciation, whereas crossed striae on boulders suggest the bouncing position of the boulder while on move (Figure 12.4).



Fig. 12.4: Evidence of macro striations on a boulder in the forefield of Menthosa glacier in Lahaul Himalaya at an altitude of 4400 m.s.l. The cross-striations suggest the changing position of the boulder underneath the glacier.

12.6.3 Polished Surfaces

Polished surfaces are smooth and shiny rock surfaces that result from the process of abrasion by glaciers. They are formed when glaciers move over bedrock, carrying and grinding fine-grained rock flour against the underlying surface. The constant friction and pressure exerted by the moving ice and the embedded particles cause the bedrock to become smooth and polished. Polished surfaces are typically found in areas that have experienced glaciation, such as regions with present or past ice sheets, alpine glaciers, or valley glaciers. These surfaces can be observed in various landforms, including valley floors, exposed bedrock outcrops, and glacially-polished rock walls.

12.6.4 Glacial Stairways

Glacial stairways are landforms characterized by alternating bands of exposed bedrock and debris-covered surfaces. They result from the differential erosion caused by glaciers and are formed through the process of plucking. Plucking involves the freezing and entrainment of rocks by the flowing ice of a glacier. The plucked debris acts as an abrasive, scraping and grinding against the bedrock surface. The areas covered by the debris experience less erosion compared to the exposed bedrock surfaces, leading to differential erosion. Over time, this differential erosion creates steps or terraces in the landscape, forming glacial stairways.

Glacial stairways are commonly found in glaciated valleys and provide evidence of past glaciation. They reflect the dynamic nature of glacial erosion and can be used to reconstruct the history of glacial advances and retreats. Glacial stairways highlight the erosive power of glaciers and the geological processes that shape the Earth's surface during glaciation.

12.6.5 Aretes and Horns

Aretes and horns are distinct glacial landforms that are formed through the erosive action of glaciers. An arete is a sharp, narrow ridge that is formed when two adjacent glaciers erode parallel U-shaped valleys on either side of the ridge. The erosive power of the glaciers carves away the rock on each side, leaving a steep, knife-like ridge in between. Aretes are typically steep and have jagged peaks, often resembling the edge of a saw blade. They are common in glaciated mountainous regions and are a result of the erosive forces of glaciers shaping the landscape.

Whereas, a horn, on the other hand, is a pointed mountain peak that is formed through the simultaneous erosion of multiple glaciers. When several glaciers erode a mountain from different sides, they create steep slopes that converge at the summit. The converging glaciers carve away the rock, gradually shaping the mountain into a distinctive pyramid-like peak. The best-known example of a horn is the Matterhorn in the Swiss Alps. Both aretes and horns are characteristic features of glaciated landscapes and provide evidence of past glacial activity. They showcase the power of glaciers in shaping the Earth's surface, and their presence is a testament to the dynamic processes that occur during glaciation (Figure 12.5).

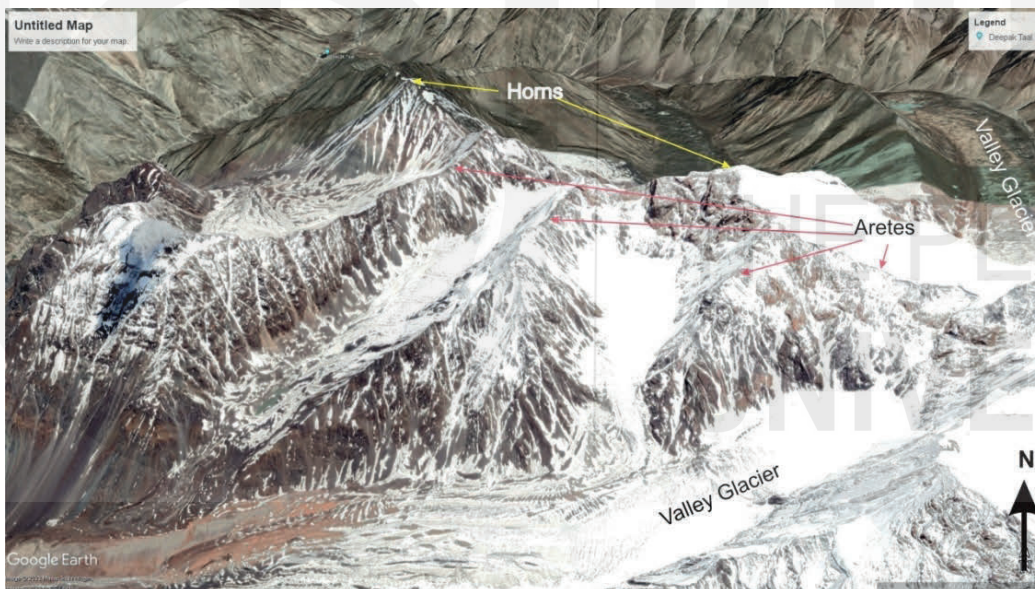


Fig. 12.5: Google Earth 3D view of the Central Lahaul showing the Aretes, Horns, and glaciers.

(Source: Google Earth)

12.6.6 Cirques

The cirques are universal in occurrence in glaciated mountain regions and the most recurrent worldwide feature in glaciated landscapes. These are confined to the areas of the present or former glaciations. The Palaeo-Cirque occurrence at different altitudes in mountain areas can be interpreted in terms of various cycles of glaciation of various degrees. Based on the cirque level, two to three Pleistocene advances of the Himalayan glaciers were proposed by Krenek (1945). Cirques that still have snow and ice filled have developed at different levels in different parts of the Himalayas based on regional ELA variations (Figure 12.6). The highest cirque level is recorded from Sikkim and

the lowest from the Kashmir valley. In morphology, cirques are amphitheatrical-shaped deep hollows on mountain slopes.



Fig. 12.6: A paleo Cirque with little snow/ice in its basin. It lies opposite Urgos village in Miyar basin (Base altitude is 4800 m). Cirques are excellent indicators of paleo climates.

There are four form elements of a cirque: a steep, nearly vertical shattered backwall; a rock basin, the floor of which is polished; a sharp break of slope at the foot of the backwall; and a convex, rounded lip at the entrance. Various hypotheses have been proposed to explain the cirque formation viz.

Bergschrund theory (Johnson, 1904), the meltwater theory (Lewis, 1938), and the rotational slip theory (McCall, 1960). But the evolution of cirques can be attributed to the simple fact of glacier mechanics that the vector velocity in a glacier above the equilibrium line is downward and below the equilibrium line the vector velocity is upward (Bloom 1998). This gives rise to cirque formation at considerable altitudes in glaciated mountains.

12.6.7 RochesMoutonnees

Roches Moutonnees are landforms of asymmetric prominences and small hills with gently abraded stoss slopes and a steeper and plucked lee slope. The feature resembles the back of sheep while looking from a distance. The orientation of the long axis of the feature happens to be roughly parallel to the ice motion. It is reasoned that differential erosion continuing for a long period would eventually result in an asymmetric form.

12.6.8 Drumlins

Drumlins are inverted spoon-shaped features of glacial deposition (Figure 12.7). Such landforms are widespread in occurrence in the areas of past and present continental glaciers. However, in Alpine valley glaciers these are less common. This is perhaps due to the mechanism of their evolution and space constraints. The Miyar basin and Chandra Tal area in Lahaul Himalaya

present a rare example of the occurrence of a vast drumlin field. A characteristic feature of drumlins is that they always occur in large numbers in an area, known as the drumlin field. Long-axis of drumlins preferred orientation paralleling the main direction of ice flow. The classical-shaped drumlin usually has a steeper stoss end and a tapered leeward side. Drumlins may vary from 5 to 200m in height, 10 to 100 m in width, and overall from 100 m to several kilometers in length (Goudie 2004).



Fig. 12.7: A typical inverted spoon-shaped drumlin at Thampatan plain, Miyar Valley.

12.6.9 Moraines

A moraine is a characteristic landform of glacial deposition or deformation of sediment by glacier ice. Many different types of moraine exist, reflecting many different processes by which glaciers deposit and deform sediment and the many locations and environments within the glacier system where deposition can occur. The material of which moraines are composed, which is generally referred to as till, is also highly variable, as its characteristics depend on the characteristics of the debris supplied by the glacier as well as on the processes and environment of glacial deposition. Moraines can be formed by dumping, sliding, pushing, ablation of glacier ice, and disintegration of glacier ice during the retreat. Moraines are landforms of immense geomorphic significance within glaciated landscapes, useful indicators of past glacial activity, and important components of the glacial sediment transfer system. There are various types of moraines reflecting the various phases of glaciation and the intensity of glacial processes. Some prominent types are described as under.

12.6.10 Ground Moraine

A ground moraine is a feature of basal till. Ground moraine develops flat to gently rolling terrain. The basal till of a glacier is left exposed by the receding terminus of the glacier, known as the ground moraine. In the Himalayas, almost every glacier which is receding has left an extensive blanket of the ground moraine. These normally get rapidly transformed by meltwater

subsequently. Goudie (2004) has stressed that the term ground moraine is falling into disuse and being replaced by non-topographic terms such as sub glacial till.

12.6.11 Lateral Moraine

Lateral moraines are the features of ice marginal deposition of heterogeneous sediments in the form of long ridges (Figure 12.8). This is a ubiquitous landform of Alpine valley glaciers, ablation zones of which are covered with a thick layer of sediments. The maximum elevation of the lateral moraines is useful to determine the ELA of the concerned glacier because they generally begin from the ELA downward to separate the accumulation zone from the ablation zone. Sliding of the supraglacial sediments on the lateral margins of the glacier is the major evolutionary process of the lateral moraines. In formerly glaciated valleys of the Himalayas, there exist lateral morainic ridges of several kilometers in length.



Fig. 12.8: Lateral Moraine Ridges (marked by dotted lines) of Sonapani glacier in Lahaul Himalaya descended up to main Chandra valley, showing the glacier expansion in the geological past.

12.6.12 Terminal Moraine

Moraines marking the maximum extent of a glacial advance are referred to as terminal moraines (Goudie 2004). Moraines deposited at successive frontal positions are destroyed and bulldozed to dump at the terminal position during periods of advance (Figure 12.9). Lateral and frontal moraines are ice-marginal moraines that occur around the edges of glaciers and are defined by their position. A terminal frontal moraine is defined as an end moraine. Benn and Evans (2014) have defined the terminal moraines as the outermost moraine ridge formed at the limit of a glacier advance. The geomorphic processes involved in the formation of ice-marginal moraines are the dumping of supraglacial, englacial, or basal debris transported through the glacier, and the pushing of sediments previously deposited in front of the glacier. Sometimes, these moraine types are not exclusively defined and as Benn and

Evans (1998) stressed, terminal moraines may be subdivided into frontal and lateral components, or described as latero-frontal moraines.



Fig.12.9: Terminal Moraine Dump of Neelkanth glacier, Lahaul Himalaya.

12.6.13 Recessional Moraine

Moraines deposited at successive positions of the margin during a period of progressive retreat are referred to as recessional moraines (Goudie, 2004). Recessional moraines are the younger moraines nested within a terminal moraine because they are formed during overall glacier recession even though they may have been deposited or pushed up during minor re-advances or standstills (Benn and Evans, 1998). The geomorphic significance of recessional moraines can easily be understood, as they are the best expression of the recessional history of the glacier.

12.6.14 Hummocky Moraine

Hummocky moraines are irregular mounds exhibiting a varying degree of order, ranging from entirely chaotic assemblages of mounds to suites of nested transverse ridges. Genetically hummocky moraines are the landforms of glacial sediment deposition in association with active and stagnant ice. Benn and Evans (1998) have used the term 'hummocky moraine' to refer to the moraines deposited during the melt out of debris-mantled glaciers. The genetic interpretation of various types of moraines is necessary to interpret their depositional environment and eventually the geomorphic history of the area. Hummocky moraines are a clear indication of the decayed glaciers. Decaying and retreating glaciers disintegrate into dead ice. Ice-cored mounds having Heavy supraglacial sediments turned into hummocky moraines after the melting of ice. According to Benn and Evans (1998), Hummocky moraines deposited from debris-mantled ice can appear chaotic or linear in pattern depending on the distribution of debris in the parent glacier and the pattern of debris redistribution and reworking during ice wastage.

12.6.15 Eskers

These are narrow irregular crested sinuous ridges or a series of ridges. They are composed of glacio-fluvial drift containing a wide range of particle sizes from sand to cobble. Large eskers may be tens of kilometers long, 400-700 m wide, and 40-50 m high. Eskers are deposited by meltwater streams in contact with the glacier ice. The deposits thus display a distinct fluvial environment which includes cross-stratification and irregularly bedded strata with abrupt grain-size variations in a vertical sequence.

12.6.16 Kames

Mound-like features formed in close association with stagnant glacier ice are known as kames. They may occur as isolated features or in groups. Kames are composed dominantly of stratified gravel and sand material. Most explanations trace the origin of kames to fluvio-glacial deposition in open ice crevasses of a stagnant ice body. In some situations, the material of kames accumulates in a lacustrine environment and forms a flat surface along the valley wall. Such flat surfaces are known as kame terraces.

12.6.17 Outwash Plain

Glacio-fluvial material transported beyond the margins of active glacier ice by meltwater streams is known as outwash. A sudden burst of ice-dammed lakes is the ideal condition for the rapid accumulation of outwash material. The outwash sediments are sorted and commonly stratified. Outwash plain is the major landform of outwash deposition. We can simply define an outwash plain as a single, low, fan-shaped surface, the apex of which is located where the meltwater stream emerges from a glacier. Such plains are more common in continental and piedmont glaciers.

12.6.18 Lacustrine Plain

Lacustrine plains are the result of the sedimentation of freshwater glacial lakes. Such lakes evolve as a result of the damming of meltwater streams by moraines and have the glacier melt as the only source of influx (Figure 12.10). Glacier melt varies with the seasons and so does the composition of the meltwater stream. In the summer season, due to increased meltwater flow, the stream carries a large volume of suspended load that settle at the base. Finer clay fractions stay in suspension and gradually settle down by the winter freezing of the lake. In the lacustrine environments, due to the annual sedimentation of coarser sediments followed by finer sediments, there evolve the annual layers of alternately coarser and finer sediments are known as the varve deposits. These are the annual rhythmites and the excellent timekeepers of the glacier fluctuations as Sharma (2010) has suggested.



Fig. 12.10: Gepang Gath glacier in the Lahaul Himalaya (India) calving into the pro-glacial lake.

SAQ 5

What are Moraines?

12.7 SUMMARY

In this Unit, you have studied so far:

- Glaciation is the process by which large areas of land become covered by glaciers, which are massive bodies of ice that move under their own weight. Glaciers form when snow accumulates over many years and transforms into ice. The movement of glaciers is a vital part of their existence and leads to various glacial processes and the formation of distinct landforms. Glaciers can only form in regions above the snowline, where snow remains throughout the year. The growth and shrinkage of glaciers depend on the balance between snow accumulation and ice loss through melting. Glaciers exhibit different forms, sizes, and origins, and they play a significant role in the Earth's energy budget and climate.
- Glaciation has occurred in various parts of the world throughout Earth's history, leaving behind impressive landforms and contributing to the Earth's climate system. Major glaciations, such as the Pleistocene glaciation, Neoproterozoic glaciations (Snowball Earth events), and Paleozoic glaciations (Carboniferous and Permian), occurred at different times in Earth's history. These glaciations were influenced by factors like changes in Earth's orbit, land distribution, and atmospheric composition. Glacial activity led to the formation of ice sheets, glaciers, and various landforms such as valleys and fjords. The causes and initiation of glacial periods are still the subject of ongoing research and debate among scientists.

- Glacial processes and mechanisms can be explained by several important theories. The Milankovitch Cycles describe variations in Earth's orbital parameters, such as eccentricity, axial tilt, and precession, which interact with the climate system to influence glaciation. The Ice-Albedo Feedback highlights how changes in surface albedo due to ice and snow can amplify or dampen climate change effects. Glacial-interstadial dynamics involve periodic shifts between extensive ice cover (glacial) and reduced ice cover (interstadial) driven by orbital variations. Heinrich events are large-scale ice-rafting events caused by ice sheet destabilization, triggering rapid cooling and influencing glacial dynamics in the North Atlantic. The Threshold Hypothesis proposes critical thresholds in climate conditions that initiate or terminate glaciation. These theories provide insights into the causes, processes, and impacts of glaciation, enhancing our understanding of past and future climate dynamics.
- Glaciers are large bodies of ice that form over time from compacted snow. They come in various types, including continental glaciers, cirque glaciers, ice caps, valley glaciers, piedmont glaciers, and hanging glaciers. Glaciers move due to gravity and pressure gradients, exhibiting unique flow mechanisms compared to rivers. They slide as solid slabs of ice due to gravity, while also experiencing internal deformation caused by their weight and plastic nature. This flow can be compressive or tensional, leading to the formation of crevasses and over-thrusting of ice. Glacier processes shape the land, erode the landscape, and transport and deposit sediments.
- Glacial erosion is the process of wearing down and shaping the landscape by glaciers through abrasion and plucking. Abrasion involves the scraping and grinding of bedrock by rock fragments embedded in the glacier, resulting in smoothed surfaces and striations. Plucking occurs when water infiltrates into bedrock fractures, freezes, and expands, causing the rock to detach and be carried by the flowing ice. Glacial pathways are the routes or channels through which glaciers move and transport material, influenced by topography and obstacles. Glacial deposition is the laying down of sediment by glaciers, forming various landforms such as moraines, outwash plains, braided streams, eskers, kames, and deltas.
- Glaciation in the geological past has had significant effects on the Earth's landscapes and ecosystems. It has shaped valleys, carved out deep fjords, and left behind U-shaped valleys and moraines. Glaciers have also played a role in shaping the distribution of freshwater resources, influencing the formation of lakes and rivers. Additionally, glacial activity has influenced the migration patterns of animals and the distribution of plant species.
- The study of glaciation and its processes is essential for understanding the Earth's climate system and its changes over time. By examining the history of glaciations, scientists can gain insights into the factors that drive climate variations and help refine climate models for future projections. Glaciation research also contributes to our understanding of the Earth's long-term climate cycles and the complex interactions between the atmosphere, oceans, and ice.

12.8 TERMINAL QUESTIONS

1. Discuss any two theories of Glaciation in detail.
2. Explain the types of glaciers in detail.
3. What do you mean by glacial processes? Discuss.
4. Define Abrasion and Plucking with example.
5. Explain any five glacial landforms.

12.9 ANSWERS

Self-Assessment Questions (SAQ)

1. (i) Glaciation refers to the process by which large areas of land become covered by glaciers, which are massive bodies of ice that move under their own weight.
(ii) Paleozoic Era.
(iii) Quaternary
(iv) Swedish scientist Svante Arrhenius
2. Antarctic Ice Sheet and Greenland Ice Sheet
3. Plastic flow, also known as plastic deformation or creep, is a process that occurs within glaciers and ice sheets. It refers to the slow, continuous movement of ice in response to the force of gravity. Unlike brittle materials that fracture under stress, ice exhibits plastic behaviour due to its ability to deform and flow over time.
4. Plucking is the process of glacial erosion that begins when water infiltrates into joints and fractures within the bedrock. As the infiltrated water freezes within the glacier, it expands and exerts pressure on the surrounding rock, causing it to fracture and detach from the bedrock surface. The subsequent thawing and refreezing of water widens the cracks and further weakens the rock. Once the rock is loosened, the flowing ice of the glacier engulfs and carries it through a process called entrainment.
5. Moraines are accumulations of unsorted and unstratified material, ranging in size from large boulders to smaller particles.

Terminal Questions

1. There are several important theories that help explain glaciation and its mechanisms. These theories provide insights into the causes and processes of glacial formation and dynamics. Milankovitch cycle and Ice-Albedo feedback can be discussed here (Refer to section 12.2).
2. We can classify the glaciers in two broad categories viz. Continental glaciers or continuous ice sheets from which ice may move in all directions and the glaciers confined to more or less marked courses which direct their main movement. The glaciers of all mountainous

regions of the world fall in this second category. There is also a third category which may be called a transitional type. Glacier ice which spreads in large or small sheets on plain areas at the foot of glaciated terrain is in this transitional category (Refer to section 12.3).

3. Glacier processes are the dynamic actions and movements that take place within glaciers and ice sheets. These processes shape the land, erode the landscape, and transport and deposit sediments (Refer to section 12.4).
4. Two primary processes of glacial erosion are abrasion and plucking. Abrasion involves the grinding and wearing down of fine-grained material, while plucking refers to the failure and removal of larger blocks of rock (Refer to section 12.5).
5. Glacial landforms are distinctive features that are created by the erosive and depositional processes of glaciers. These landforms can vary in size, shape, and composition depending on the characteristics of the glacier and the surrounding environment. Glacial landforms are present in the most scenic and mesmerizing places around the world (Refer to section 12.6).

12.10 REFERENCES AND SUGGESTED FURTHER READING

1. Benn D, Evans DJA. 2014. *Glaciers and glaciation*. [London and New York]: Routledge.
2. Benn DI, Owen LA, Osmaston HA, Seltzer GO, Porter SC, Mark B. 2005. Reconstruction of equilibrium-line altitudes for tropical and sub-tropical glaciers. *Quat Int* [Internet]. 138–139:8–21. <https://doi.org/10.1016/j.quaint.2005.02.003>
3. Bloom AL. 1998. *Geomorphology: a systematic analysis of late Cenozoic landforms*. [New Jersey]: Prentice Hall Upper Saddle River.
4. Bloom, A.L. 1998. *Geomorphology*. Pearson Education Inc.
5. Derbyshire, E., Li, J., Perrott, F.A., Xu, S. and Waters RS. 1984. Quaternary glacial history of the Hunza valley, Karakoram Mountains, Pakistan. In: Miller K, editor. *Int Karakoram Proj*. [Cambridge]: Cambridge University Press; p. 456–495.
6. Derbyshire E, Owen L a. 1997. Quaternary glacial history of the Karakoram Mountains and northwest Himalayas: A review. *Quat Int*. 38–39(96):85–102. [https://doi.org/10.1016/S1040-6182\(96\)00015-8](https://doi.org/10.1016/S1040-6182(96)00015-8)
7. Deswal S, Sharma M, Saini R, Chand P, Juyal N, Singh I, Srivastava P, Ajai, Bahuguna IM. 2017. Late Holocene Glacier Dynamics in the Miyar Basin, Lahaul Himalaya, India. *Geosciences* [Internet]. 7(3):64. <https://doi.org/10.3390/geosciences7030064>
8. Ehrlich R. 2007. Solar resonant diffusion waves as a driver of terrestrial climate change. *J Atmos solar-terrestrial Phys*. 69(7):759–766.
9. Embleton C, King CAM. 1975. *Glacial and periglacial geomorphology*.

10. Evans DJA, Hiemstra JF. 2005. Till deposition by glacier submarginal, incremental thickening. *Earth Surf Process Landforms*. 30(13):1633–1662.
11. Embleton, C. and King, C.A.M., 1975. *Glacial Geomorphology*. Edward Arnold Pub.
12. Flint, R.F., 1971. *Glacial and Quaternary Geology*. Wiley, New York, and London.
13. Goudie AG. 2004. *Encyclopaedia of geomorphology*. Routledge [London and New York].
14. Lowe JJ, Walker MJC. 2014. *Reconstructing quaternary environments*. [London and New York]: Routledge.
15. Owen LA, Bailey RM, Rhodes EJ, Holloway R. 1997. Style and timing of glaciation in the Lahul Himalaya, northern India: a framework for reconstructing late Quaternary palaeoclimatic change in the western Himalayas. *J Quat Sci*. 12(2):83–109.
16. Owen LA, Finkel RC, Caffee MW, Gualtieri L. 2002. Timing of multiple late Quaternary glaciations in the Hunza Valley, Karakoram Mountains, northern Pakistan: Defined by cosmogenic radionuclide dating of moraines. *Bull Geol Soc Am*. 114(5):593–604. [https://doi.org/10.1130/0016-7606\(2002\)114<0593:TOMLQG>2.0.CO;2](https://doi.org/10.1130/0016-7606(2002)114<0593:TOMLQG>2.0.CO;2)
17. Owen LA, Gualtieri LYN, Finkel RC, Caffee MW, Benn DI, Sharma MC. 2001. Cosmogenic radionuclide dating of glacial landforms in the Lahul Himalaya, northern India: defining the timing of Late Quaternary glaciation. *J Quat Sci*. 16(6):555–563. <https://doi.org/10.1002/jqs.621>
18. Raina, V. K. and Srivastva D. 2008. *Glacier Atlas of India*. Bangalore: Geological Society of India.
19. Ritter, D.F., Kochel, R.C. and Miller, J.R., 1995. *Process Geomorphology*. Wm. C. Brown Publishers.
20. Sharma M, Owen LA. 1996. Quaternary glacial history of NW Garhwal, Central Himalayas. *Quat Sci Rev*. 15(4):335–365. [https://doi.org/10.1016/0277-3791\(95\)00061-5](https://doi.org/10.1016/0277-3791(95)00061-5)
21. Sharma VK. 2010. *Introduction to process geomorphology*. [Boca Raton, London, New York]: CRC Press.



UNIT 13

COASTAL PROCESSES AND LANDFORMS

Structure

13.1	Introduction	13.5	Mechanism of Coastal Erosion
	Expected Learning Outcomes		Hydraulic Action
13.2	Coastal Processes		Corrosive Action or Abrasion
13.3	Profile of Coastal Zones		Attrition
	Shoreline		Corrosion
	Coastline (Coast)	13.6	Erosional Landforms
	Backshore	13.7	Transportational Work of Sea Waves
	Foreshore	13.8	Depositional Landforms
	Offshore	13.9	Summary
	Bays	13.10	Terminal Questions
	Estuary	13.11	Answers
13.4	Agents of Coastal Erosion	13.12	References and Suggested Further Reading
	Waves		
	Tides		
	Currents		
	Tsunamis		

13.1 INTRODUCTION

In the previous Unit 12, you studied the Glacial Processes and associated landforms. Like glacial processes, coastal processes are also making different landscapes with the processes of erosion, transportation, and deposition. Now in this Unit, you will study about the concept and mechanism of 'Coastal Processes' and how coastal processes make different landforms. In section 13.2 you will study the meaning and concept of coastal processes. In section 13.3, you will study the profile of Coastal zones which will include terms like Shoreline, Coastline, Backshore, Foreshore, Offshore, Bays, and Estuary. In section 13.4, you will study the agents of coastal erosion while in section 13.5. You will study the mechanism of coastal erosion. In section 13.6 you will study the erosional landforms and in section 13.7 you will study the Transportational

work of sea waves and in the last section 13.8, you will study the depositional landforms.

Expected Learning Outcomes

After studying this unit, you will be able to:

- define and classify Coastal processes;
- describe the types of marine erosion;
- explain how wave deposition takes place;
- understand the uniqueness of coastal landforms; and
- describe the origin and evolution of coastal landforms.

13.2 COASTAL PROCESSES

Coastal processes encompass the dynamic interactions between land and sea along coastlines, shaping the coastal environment over time.

Understanding these processes is crucial for studying coastal landforms and their management, as it provides a foundation for effective planning, conservation, and sustainable development of coastal areas.

Coastal processes are driven by a combination of natural forces, including waves, tides, currents, and sediment transport. Waves, generated by wind blowing across the ocean's surface, propagate towards the coastline. As waves approach shallow water, their height increases, and they eventually break, exerting erosive forces on the coast. This erosion occurs through hydraulic action, where the force of water against the coast erodes and undercuts the land, and abrasion, where sediment particles carried by waves wear down the coastline. Chemical processes, such as corrosion, also contribute to coastal erosion by breaking down rocks exposed to seawater.

Sediment transport is a significant aspect of coastal processes. Waves, tides, and currents play a role in the movement of sediment along the coast. Sediment is picked up by waves and transported along the shoreline in a zigzag pattern. Longshore currents, flowing parallel to the coastline, move sediment along the coast, leading to the formation of features like beaches, sandbars, spits, barrier islands, and coastal marshes. Tides, the periodic rise and fall of sea level, also influence sediment transport and coastal morphology.

Coastal processes are influenced by various factors, including coastal geology, sea-level changes, climate patterns, and human activities. Geological characteristics such as rock type and structure determine the resistance of the coast to erosion. Sea-level changes, both natural and anthropogenic, can modify coastal processes by altering the energy and reach of waves. Climate patterns, such as storm events and long-term climate change, can impact wave conditions and coastal erosion rates. Human activities, such as coastal development, construction of coastal structures, and alteration of sediment flows, can disrupt natural coastal processes and have both intended and unintended consequences on the coastal environment.

13.3 PROFILE OF COASTAL ZONES

Coasts are an interface between the lithosphere and hydrosphere. Coastal zones are very unique and typical land masses, bordered by seas and oceans. Coastal zones are not static but dynamic environments. They are affected by the action of waves and tides. All shorelines are subjected to both continental and oceanic processes. When we talk about the coastal zone, the first thing to know about is the coastline. A Coastline represents the boundary between the continental land masses and the oceanic water masses. A Coastal zone is the transition zone between the terrestrial habitat and the marine habitat. It is the interface between land and oceanic water. Coastal belts may be very wide or narrow. They also vary with reference to their slope, beach profile, rock types, climate, and vegetation. Generally, sea coast and sea shore are taken as synonymous but geomorphologically these two terms have quite different meanings important terms associated with the coastal landforms are discussed below:

13.3.1 Shoreline

If we look at the profile of a sea coast, we can see a shoreline belonging to the landward side. The width of this shore may vary from place to place. The sea shore represents the zone of land between high tide water and low tide water while the shoreline represents the actual landward limit of sea water at a given moment of time. The shoreline means the shifting line of contact between seawater and land. Shorelines are dynamic systems involving the energy of waves and currents. Wind-generated waves provide most of the energy for erosion, transportation, and deposition of sediments. Coastal belts are further divided into three divisions; Backshore region, Foreshore region, and Offshore region (Fig.13.1).

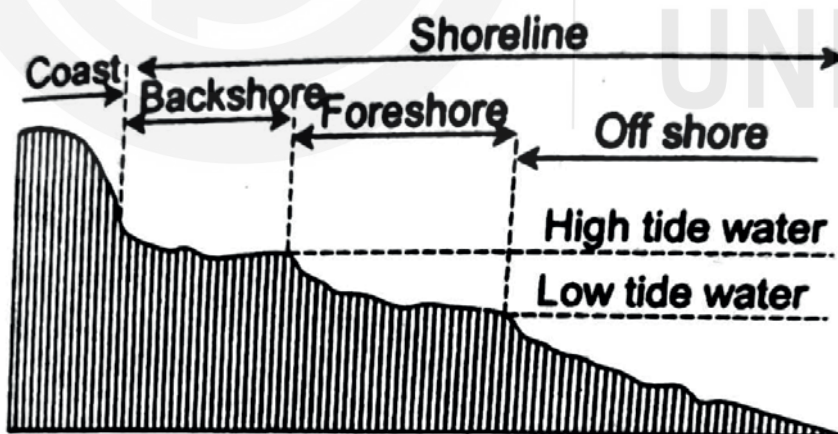


Fig. 13.1: Division of sea coast and seashore.

The shape and characteristics of the shoreline vary depending on several factors, including the geological features of the land, the energy of the waves, the tidal range, and the sediment supply. Shorelines can be classified into different types based on their morphology, such as sandy beaches, rocky cliffs, estuaries, deltas, and mangrove swamps.

The processes that shape the shoreline are a combination of erosion, transportation, and deposition of sediment. Waves, generated by wind or

other factors, play a key role in these processes. They erode the land by undercutting cliffs, wearing down rocks, and scouring sediment from the shoreline. The energy of the waves determines the intensity of erosion and the type of landforms that are created. For example, powerful waves may form sea cliffs, while gentle waves may result in sandy beaches.

13.3.2 Coastline

The coastline refers to the boundary between the land and the sea, encompassing the entire length of the land that is directly influenced by coastal processes, in general usage, the term refers to the line forming the boundary between the land and the water, more specifically, it is the highest limit reached by the swash of storm waves during high water (Spring tides).

The coastline can exhibit a variety of features and forms, ranging from sandy beaches to rugged cliffs, rocky shores, barrier islands, and estuaries. The specific characteristics of the coastline depend on factors such as the type of rocks or sediments present, the energy of waves and tides, the local topography, and the overall coastal geomorphology.

The width of the coastline can vary greatly. In some areas, it may be relatively narrow, with a steep slope leading directly into the sea. In other regions, it can extend over a considerable distance, encompassing a broader coastal plain or low-lying area. The width of the coastline is influenced by factors such as the rate of erosion, sediment supply, sea-level changes, and human interventions.

The composition of the coastline is determined by the geological materials found in the area. Sandy coastlines are composed of loose particles of sand, while rocky coastlines consist of solid rocks and boulders. Some coastlines may have a mixture of sediment types, including sand, gravel, and silt. The composition of the coastline influences its stability, erosion rates, and ecological characteristics.

13.3.3 Backshore

The backshore refers to the area on the beach located landward of the high-tide mark and extends inland until the limit of active beach processes. This zone experiences minimal wave action and is primarily influenced by terrestrial processes rather than marine forces.

The backshore is characterized by its relatively stable and dry nature compared to the foreshore and nearshore regions. It is typically above the reach of normal wave activity but can be occasionally impacted by storm surges, high tides, or extreme weather events. The width and characteristics of the backshore can vary depending on factors such as wave energy, sediment supply, coastal topography, and human interventions.

One of the key functions of the backshore is to act as a protective buffer against coastal hazards. During storms or high-energy wave events, the backshore absorbs the impact of waves, reducing their erosive power and safeguarding the landward areas from erosion and inundation. Its stability and natural resilience help protect coastal infrastructure and ecosystems. It

provides a habitat for specialized plant and animal species that are adapted to survive in this dynamic coastal environment. Dune systems, coastal grasslands, and shrub communities are often found on the backshore, playing a crucial role in stabilizing sediments, preventing erosion, and providing habitat for coastal flora and fauna.

13.3.4 Foreshore

The foreshore, also known as the intertidal zone, is the portion of the coastal environment that lies between the high-tide mark and the low-tide mark. It is a dynamic area that experiences the alternating effects of waves, tides, and currents. The width and characteristics of the foreshore vary depending on factors such as tidal range, wave energy, sediment type, and coastal morphology.

During high tide, the foreshore is submerged under water, while during low tide, it is exposed to the air. This constant immersion and exposure to the elements create unique ecological niches and adaptations for organisms that inhabit this zone. The foreshore is home to a diverse array of marine plants and animals that have adapted to survive the fluctuations in water availability, temperature, and salinity.

The composition of the foreshore is influenced by the types of sediments present, which can include sand, gravel, mud, or a mixture of these. The sediments may be loose and mobile, forming sandy beaches, or more cohesive and compact, forming rocky shores or tidal flats. The presence of vegetation, such as salt marshes or mangroves, can also play a role in shaping the foreshore environment.

13.3.5 Offshore

The offshore refers to the area of the ocean that extends beyond the nearshore and offshore zones of the coastline. It is the portion of the marine environment that lies beyond the breaking waves and extends seaward. The offshore zone is characterized by deeper water depths and is influenced by the interactions between the ocean, atmosphere, and seafloor.

In the offshore, the water depth gradually increases as one moves away from the coastline. This transition from the shallow nearshore to the deeper offshore is known as the continental shelf break. Beyond the continental shelf break, the seafloor slopes more steeply and leads to the continental slope and eventually the deep ocean basin. The offshore zone experiences different physical and biological processes compared to the nearshore and coastal areas. Oceanic currents, tides, and waves play a significant role in shaping the offshore environment. Strong currents, such as oceanic currents and upwelling zones, can occur in offshore, influencing the movement of water masses and the distribution of nutrients and organisms.

The offshore zone is of great importance for various human activities, such as commercial fishing, offshore energy production, and submarine cable installations. It is also an area of scientific interest for studying oceanography, marine geology, and marine biodiversity.

13.3.6 Bays

Bays are semi-enclosed coastal areas that are partially surrounded by land and open to the sea on one side. They are typically characterized by a curved or concave shape, with landforms, such as headlands and peninsulas, extending into the water and creating sheltered areas. Bays can vary in size and depth, ranging from small, intimate coves to large, expansive bodies of water.

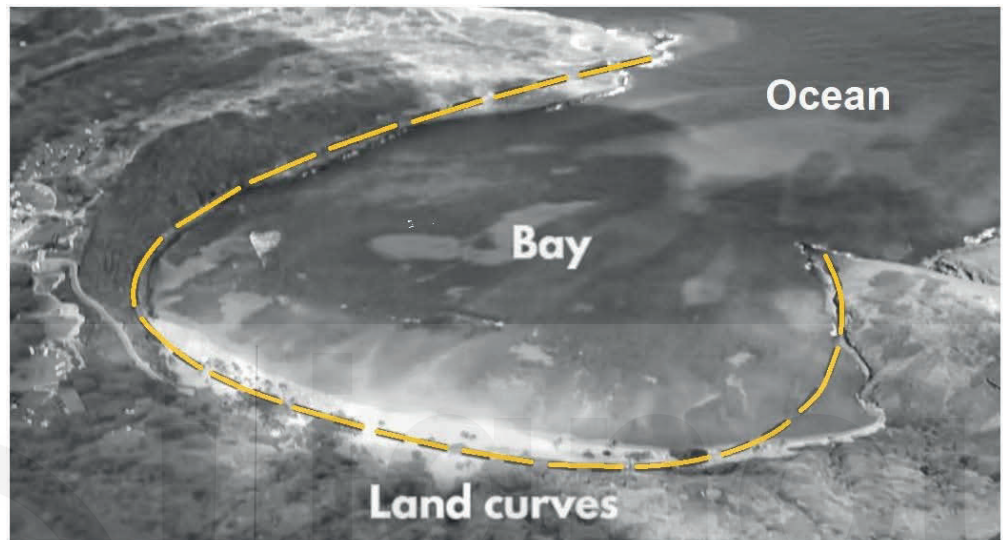


Fig. 13.2: Bays.

Bays exhibit unique characteristics that distinguish them from other coastal features. They often provide sheltered waters and reduced wave energy, making them suitable for harbors, ports, and marinas. The shape and size of bays can vary depending on local geological and geographical factors. Some bays have a narrow entrance, known as a bay mouth or bayhead, which can restrict water exchange with the open ocean. These narrow-mouthed bays, such as fjords and estuaries, often have distinct environmental conditions and support unique ecosystems. Other bays have broader entrances, allowing for more direct interaction with the open sea.

Bays are not only significant from an ecological and recreational standpoint but also have economic importance. They can support diverse marine ecosystems, including seagrass beds, salt marshes, and mangrove forests, which provide habitats for a wide range of marine species. Bays can also be important for commercial fishing, aquaculture, and tourism industries, contributing to local economies. However, bays are susceptible to various natural and human-induced impacts. Coastal erosion, sea-level rise, pollution, habitat degradation, and overfishing are some of the challenges that bays face.

13.3.7 Estuary

An estuary is a partially enclosed coastal body of water where freshwater from rivers and streams meets and mixes with saltwater from the ocean. It is a unique and dynamic ecosystem that forms at the transition zone between

land and sea. Estuaries are typically found in areas where river valleys meet the coast and are influenced by tidal fluctuations.

Estuaries exhibit distinct characteristics that make them ecologically rich and diverse. The mixing of freshwater and saltwater creates a gradient of salinity, which supports a wide range of plant and animal species adapted to these conditions. Estuaries are often characterized by marshes, mudflats, tidal flats, and mangrove forests, which provide important habitats for numerous species, including fish, shellfish, birds, and marine mammals. Estuaries serve several important ecological functions. They act as nurseries and feeding grounds for various aquatic species, supporting their reproductive cycles and providing abundant food sources. Estuaries also play a crucial role in nutrient cycling, as rivers bring nutrients from the land into the estuary, which are then utilized by organisms and transported to coastal areas. They serve as important migratory routes for fish and bird species, allowing them to travel between freshwater and marine environments.

Estuaries also have significant economic value. They support commercial and recreational fishing activities, providing a livelihood for coastal communities and contributing to regional economies. Estuaries are popular destinations for boating, kayaking, birdwatching, and other recreational activities, attracting tourists and generating revenue. However, estuaries face various threats and challenges. Human activities, such as coastal development, pollution from industries and agriculture, and overfishing, can degrade the water quality and disrupt the delicate balance of the estuarine ecosystem. Habitat loss, alteration of natural hydrology, and climate change impacts, including sea-level rise and changes in precipitation patterns, also pose significant risks to estuaries.

SAQ I

- a) What is shoreline?
 - b) Define Foreshore.
-

13.4 AGENTS OF COASTAL EROSION

The coastline, under the constant action of the waves, tides, and currents, is undergoing changes from day to day. Coastal landforms are produced by the joint action of oceanic waves, currents, and tides on the coastline along with the combination of processes, sediments, and the geology of the coast itself. Among all of these factors, waves are the most important of all in carving out coastal landforms. Now you will study the different agents of coastal erosion mentioned below:

13.4.1 Waves

Waves are one of the key driving forces that shape the coastal environment. They are generated by wind energy transferring momentum to the water's surface. As waves travel across the ocean, they carry this energy toward the coastline, where they interact with the seafloor and the coastline itself.

Waves are the powerful forces acting on the coastal zones. They are very dynamic systems with reference to space and time. Waves are capable of doing both constructive and destructive processes and for this reason, they are classified into two types known as constructive waves and destructive waves. Constructive waves have a long wavelength and low wave height. They tend to deposit sediments and build up beaches, contributing to the formation of landforms such as sandbars and barrier islands. Destructive waves, on the other hand, have a short wavelength and high wave height. They are more erosive and remove sediment from the coastline, leading to the formation of features such as sea cliffs and sea caves.

Sea waves are defined as undulations of seawater characterized by well-developed crests and troughs. The sea waves after being generated radiate outward from generating area of the sea. As the waves advance towards the coast the depth of water decreases, the wave height increases and the wave length decreases. As the waves move in shallow water, they lose energy because they suffer from friction and distortion caused by the bottom surface. The waves begin to touch the bottom when the depth of water becomes equivalent to about half of the wavelength. As the waves approach the shore the wavelength continues to decrease while the wave height increases. Finally, wave height reaches a point of instability, and the wave either collapses, producing surf, or topples forward, forming a curling breaker which then collapses.

The turbulent forward moving swash or breaker is also called surf.

The turbulent water, known as swash or uprush rushes shoreward with great velocity and force. The distance from the shore where the waves break is called the plunge line where the depth of seawater and the wave height are approximately equal. The breakers or swash or surfs after reaching the sloping beach return towards the sea as a backwash or undertow currents and rip currents. The process by which waves bend or change direction as they approach a shoreline owing to the shallowing of water is called wave refraction. Wave refraction results in the formation of littoral or longshore currents which move parallel to the sea coast.

There are three main factors that affect the strength of a wave:

1. The speed of the wind.
2. The duration of the wind - this is the length of time for which the wind has blown.
3. The fetch - this is the distance over which the wind has blown.

Sea waves are classified into two types on the basis of the depth of oceanic waters. They are:

- (a) **Oscillatory waves** (these are the waves in deep water) and
- (b) **Translatory waves** (these are the waves in shallow water).

Waves are one of the most significant forces in shaping the coastline.

Based on their actions, two main types of waves have been recognized. They are

(a) Constructive waves and**(b) Destructive waves.**

Constructive waves are low-energy waves that tend to arrive at the coast at a rate of fewer than 8 waves per minute. Constructive waves are small in height. They have a strong swash and a weak backwash. This means that constructive waves tend to deposit material and build up a beach.

Destructive waves have much higher energy and tend to arrive at the coast at a rate of more than 8 per minute. They are much larger in height than constructive waves, often having been caused by strong winds and a large fetch. Destructive waves have a weak swash but a strong backwash so they erode the beach by pulling sand and shingle down the beach as water returns to the sea. This means that less beach is left to absorb wave energy.

The west coast of our country is a high rocky retreating coast. Erosional forms dominate on the west coast. The east coast of India is a low sedimentary coast. Depositional forms dominate on the east coast.

Factors that affect the rate and magnitude of sea wave erosion are:

- i. The nature and hardness of rocks along the shore.
- ii. Structural features of the rock, like the degree of jointing and fracturing.
- iii. Tidal range.
- iv. Openness of shore to wave attack.
- v. Depth of water offshore.
- vi. Configuration of coastline.
- vii. Presence or absence of protective beach.
- viii. Abundance and size of abrasive tools.
- ix. Stability of sea level.

SAQ 2

What is the constructive wave?

13.4.2 Tides

Tides, which are the periodic rise and fall of the seawater produced by the differential attraction of the sun and the moon on the ocean. Tides occur in all bodies of water, but they are most noticeable in coastal areas where rising and falling water levels can have a significant impact on the shoreline and coastal processes. The gravitational force of the Moon attracts the water on Earth's surface, creating a bulge of water on the side of the Earth facing the Moon (the high tide). At the same time, there is a second bulge on the opposite side of the Earth (the high tide), caused by the centrifugal force resulting from the Earth and Moon's rotation around their common center of mass.

Tides go through a regular cycle known as the tidal cycle, which consists of two high tides and two low tides occurring approximately every 24 hours and 50 minutes. The time between successive high tides or low tides is about 12 hours and 25 minutes. This cycle is influenced by various factors, including the position of the Moon and Sun relative to the Earth and the geography of

the coastline. Tides have a significant impact on coastal processes and landforms. During high tides, the increased water level can lead to coastal flooding and erosion, particularly in low-lying areas and regions with steep coastlines. The regular rise and fall of tides also influence the movement of sediment along the coast, contributing to the formation of features such as sandbars, tidal flats, and estuaries.

Coastal ecosystems are highly influenced by tides. Intertidal zones, the areas between the high tide and low tide marks, experience regular exposure to both air and water, creating unique habitats for various species that have adapted to survive in this dynamic environment. Tidal currents also play a role in nutrient cycling and the distribution of food for marine organisms.

13.4.3 Currents

Currents are the horizontal movement of water in oceans, seas, and other large bodies of water. They are driven by various factors, including wind, tides, and differences in water density and temperature. Currents play a crucial role in shaping coastal processes and influencing the distribution of water, sediment, and nutrients along the coastline.

Wind-driven currents, also known as surface currents, are primarily influenced by the prevailing winds. The friction between the wind and the surface of the water causes the water to move in the same direction as the wind. These currents can be seen at the surface and are responsible for the drifting of floating objects and the transport of marine organisms and debris. Tidal currents are another type of current that is driven by the gravitational forces of the Moon and Sun. As tides rise and fall, water moves in and out of coastal areas, creating tidal currents. These currents can be particularly strong in narrow channels, estuaries, and areas with significant tidal range. Tidal currents can have a significant impact on coastal erosion, sediment transport, and the mixing of water masses.

In addition to wind and tides, density-driven currents, also known as thermohaline currents, are influenced by differences in water density caused by variations in temperature and salinity. These currents occur at deeper depths and are responsible for the vertical movement of water in the ocean. They play a vital role in global ocean circulation and the distribution of heat around the planet.

Coastal currents are influenced by the shape and geography of the coastline. Headlands, bays, and other coastal features can cause the deflection and concentration of currents, leading to the formation of eddies and the deposition or erosion of sediment along the coast.

Currents have significant implications for coastal processes and landforms. They can contribute to the erosion or deposition of sediment, resulting in the formation of beaches, spits, and sandbars. Strong currents can create rip currents, which are powerful narrow flows of water moving seaward from the shore. These rip currents pose a danger to swimmers and surfers, and it is important to be aware of their presence and how to respond if caught in one.

13.4.4 Tsunamis

Tsunami or seismic sea wave is a special type of wave that are primarily caused by large undersea earthquakes or volcanic eruptions and greatly affects distant coastlines. Tsunamis can travel across the ocean at high speeds, reaching coastal areas with devastating force. The speed at which tsunamis travel through deep ocean water is exceptionally fast compared to other types of waves. Their velocities commonly range between 600 to 800 kilometers per hour (373 to 497 miles per hour). These high speeds are attributed to the immense amount of energy and momentum they possess, generated by the undersea seismic activity that triggers their formation.

When an undersea earthquake occurs, it displaces a significant amount of water, creating a series of waves that radiate outward from the source. As these waves move through the deep ocean, they have a relatively small amplitude and are not easily noticeable. However, as they approach shallow water near the coast, the waves slow down, the water piles up, and the amplitude of the waves increases dramatically. This results in a tsunami, which can manifest as a fast-moving wall of water crashing onto the shoreline.

Tsunamis can cause widespread destruction and loss of life, as they carry enormous amounts of energy. The impact of a tsunami on coastal areas can be catastrophic, with the potential to submerge entire communities, erode coastlines, and devastate infrastructure. The force of the waves can also propel large debris and cause significant damage to buildings and structures.

Early detection and warning systems are crucial in mitigating the impact of tsunamis. Seismic monitoring stations are used to detect undersea earthquakes and assess the potential for generating a tsunami. When an earthquake is detected, warning systems can issue alerts to coastal communities, providing them with valuable time to evacuate to higher ground and seek safety.

13.5 MECHANISM OF COASTAL EROSION

Coastal erosion is the process by which the land along a coastline is worn away and gradually diminished due to the action of various natural forces like waves, currents, and tides. Now you will study the variety of gradational processes acting in the coastal zones which are mentioned below:

13.5.1 Hydraulic Action

Hydraulic action is a key mechanism of coastal erosion that occurs when the force of water against the coast dislodges and removes rock particles and sediment. It is primarily driven by the pressure and impact of waves crashing against the shoreline. During hydraulic action, waves approach the coast with significant energy. As the waves crash against cliffs, headlands, or other coastal features, the sheer force of the water can exploit weaknesses in the rock, such as cracks, joints, or faults. The water is forced into these openings, creating pressure and causing the rocks to break apart or be dislodged. The power of hydraulic action is amplified by the presence of air in cracks and crevices. As the waves crash, air trapped in these spaces is compressed,

leading to a sudden release of pressure. The rapid expansion of air further weakens the rock, contributing to its erosion.

The eroded rock fragments and sediment carried by hydraulic action are then transported along the coast by the waves, contributing to further erosion and sedimentation in different areas. Over time, hydraulic action can lead to the formation of sea caves, notches, or other coastal landforms as the relentless force of the waves shapes and reshapes the coastline.

Hydraulic action is particularly effective in areas with high-energy waves, steep cliffs, or vulnerable rocks that are prone to erosion. It is one of the primary processes responsible for the creation of coastal features such as sea cliffs, sea stacks, and wave-cut platforms. The waves are also capable of dislodging larger fragments of rocks weighing several tons in weight. This process of displacement of rock fragments is also called quarrying and plucking.

13.5.2 Corrosive Action or Abrasion

Corrosive action, also called abrasion, is another important mechanism of coastal erosion. It involves the wearing down of coastal rocks and landforms through the grinding and scraping action of sediment and rock particles carried by waves, tides, and currents.

Abrasion occurs when waves, loaded with sediment, crash against the coastline. The sediment acts as an abrasive agent, scouring and wearing away the rocks over time. The particles are often angular and vary in size, ranging from fine sand to larger pebbles or even boulders. As the waves continuously hurl these particles against the coast, they gradually erode and weaken the rock surface. The corrosive action of sand, gravel, and pebbles carried by waves against the shore is the most effective process in marine erosion. This process is also called 'artillery action' of tools moved against solid rock.

The effectiveness of abrasion in coastal erosion depends on several factors. First, the hardness and resistance of the rocks play a role in determining the rate of erosion. Softer rocks, such as sandstone or shale, are more susceptible to abrasion compared to harder rocks like granite or basalt. Additionally, the size and velocity of the sediment particles carried by the waves influence the degree of abrasion.

Coastal features that experience significant wave action, such as cliffs, headlands, or rocky shorelines, are particularly prone to abrasion. Over time, this process can lead to the formation of distinct landforms, including wave-cut platforms, sea arches, sea caves, and notches.

13.5.3 Attrition

Attrition refers to the process of wearing down and rounding of sediment particles as they collide with each other and with the coastal rocks and landforms. It occurs primarily in the surf zone where waves break and in areas where sediment is transported by currents. The process of attrition starts with the transport of sediment by waves or currents. As these particles

are carried along, they constantly collide with each other and with the underlying rock surfaces. These repeated impacts cause the particles to break apart and become smaller in size.

The effectiveness of attrition in coastal erosion depends on several factors. The composition and hardness of the sediment particles play a role, as softer materials are more easily broken down compared to harder ones. The energy of the waves or currents also influences the intensity of attrition, with higher-energy environments leading to more significant particle collisions.

The impacts of attrition are evident in the formation of sandy beaches, where larger sediment particles are gradually broken down into smaller grains of sand. It also contributes to the formation of sedimentary deposits such as sand dunes or offshore bars.

13.5.4 Corrosion

The sea wave operates as an agent of erosion in another way, i.e., by corrosion or the solvent and chemical action. It involves the gradual breakdown and dissolution of coastal rocks and landforms due to the action of corrosive agents, such as acids, salts, and moisture. This process is more effective on rocks with calcareous cement or on limestone. Otherwise, this process is of limited importance in the case of seawater.

Coastal corrosion primarily occurs in areas where the water contains high levels of dissolved salts, such as seawater. The presence of salts, particularly chloride ions, accelerates chemical reactions that lead to the deterioration of rocks and minerals. These reactions can include the dissolution of minerals, chemical weathering, and the formation of new compounds.

The corrosive action of seawater is influenced by factors such as the composition of the rocks, the duration of exposure to water, and the frequency of wetting and drying cycles. Rocks that contain minerals susceptible to corrosion, such as limestone or gypsum, are more vulnerable to this process.

In coastal areas, corrosion can manifest in various ways. It can result in the dissolution and weakening of rocks, leading to the formation of coastal cliffs or the collapse of rock formations. It can also cause the corrosion of metallic structures, such as piers, seawalls, or shipwrecks, which are exposed to the corrosive effects of seawater.

The impact of corrosion on coastal erosion can be significant over long periods of time. It can contribute to the gradual retreat of coastlines, the formation of coastal caves, and the creation of distinctive coastal landforms, such as sea arches or stacks.

13.6 EROSIONAL LANDFORMS

Significant coastal features formed due to marine erosion by sea waves and other currents and solutional processes include cliffs, coves, sea caves, stacks, blow-holes or ghoups, arch, inlets, notches, wave-cut platforms, etc., and are discussed below:

(i) Sea cliffs

Sea cliff is a very distinctive feature of marine erosion. It is a rocky coast rising almost vertically above seawater. It may or may not be precipitous, the slope angle being dependent partly on the jointing, bedding, and hardness of the rock and partly on the erosional processes at work (Fig. 13.3).

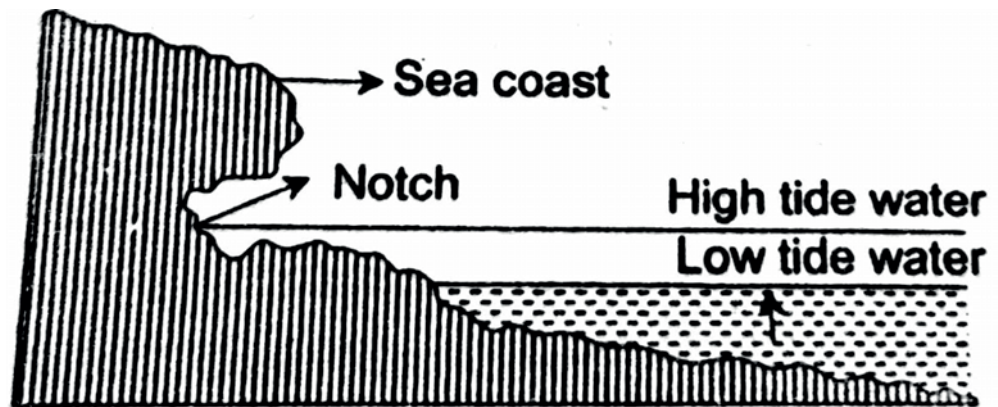


Fig. 13.3: Sea cliff and notch.

Sea cliffs are formed with the erosion of coastal rocks through the mechanism of hydraulic actions and abrasion by breaker waves (swash or surf currents). Because of the combined impact of waves and abrasion by eroding tools such as pebbles, a notch is formed at the cliff base below high tide level and the coast becomes vertical. There is a gradual extension of the notch landward due to continuous wave attack, with the result that the crest of the cliff overhangs the notch. If the notch at the base of the cliff is extended landward to such an extent that the support to the cliff crest is weakened, the overhanging head of the cliff breaks and falls down resulting in a gradual recession of the cliff landward. The rate of cliff recession varies both in space and time depending on the following conditions (a) rock lithology and structure, (b) susceptibility to chemical erosion, mass movement, and subaerial erosion, (c) cliff height, (d) orientation of the coast, (e) wave energy, (f) offshore topography, (g) rate of removal of debris from the cliff base by the backwash or the undertow currents, etc.

One example of a notable sea cliff is the Cliffs of Moher in Ireland, which is also a UNESCO Global Geopark and a designated Special Area of Conservation due to its stunning beauty and ecological significance.

(ii) Wave-cut Platform

Rock-cut flat surfaces in front of cliffs are called wave-cut platforms or abrasion platforms or beach platforms (Fig. 13.4). Wave-cut platform is a virtually smooth marine platform cut by ocean waves at a coastline. They are nearly horizontal surfaces formed at the base of a cliff. The wave-cut platform extends seaward from the base of the sea cliff and having a slope of less than 5 degrees, its width may extend several hundred meters. The platform is composed of bare rock or it may contain a temporary deposit of rock debris, pebbles, or sand. It is formed by wave erosion, and as the cliff recedes under the impact of marine erosion, so does the width of the wave-cut platform go on increasing. Thus, the platform gets extended towards the land by erosion of the coast. The debris derived from coastal erosion become smaller by

attrition and the undertow transports them towards the sea and deposits them after some distance. In areas of hard rocks, the surface of the wave-cut platform consists of bare rock and is relatively flat, but where there is a deposit of shingles, gravel, and sand, the slope is concave.

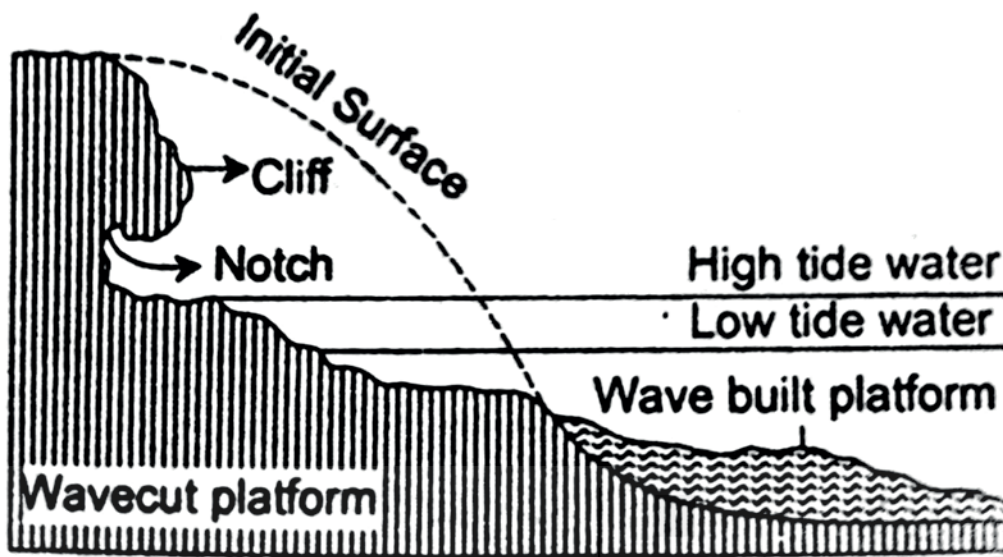


Fig. 13.4: Wave-cut and wave-built platform.

Jurassic Coast (England), Cape Bridgewater (Australia), Fundy National Park (Canada), Kaikoura Peninsula (New Zealand), etc. are some examples of Wave cut platforms.

(iii) Sea Cave

Sea cave is a natural cavity, chamber, or recess which develops along the coast due to the gradual erosion of weak and strongly jointed rocks by up rushing breaker waves (surf currents) (Fig.13.5).

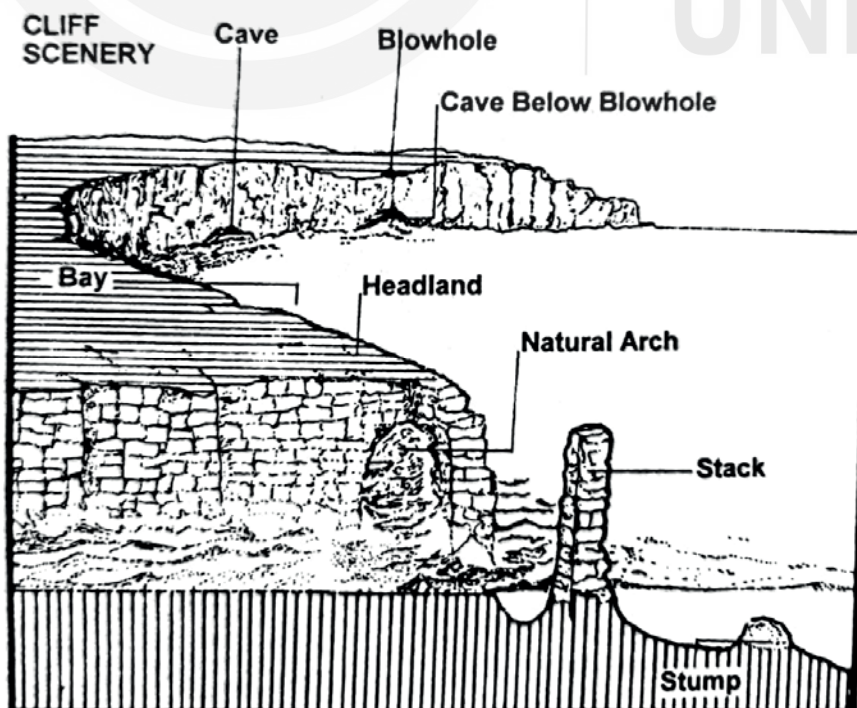


Fig. 13.5: Typical features along a wave-cut cliff.

The joints are widened into large cavities and hollows which are further enlarged due to gradual wave erosion into well-developed coastal caves. These caves are formed along the bases of cliffs by wave erosion, particularly when the lower portion of cliffs is composed of weak rocks with a lot of joints and fractures. A sea cave may resemble a passage or gallery in its shape which depends on the parts of the structure and joint pattern of the rock. The type of process involved in its excavation plays an important role in determining the shape of a sea cave. Sea caves are more frequently formed in carbonate rocks (limestone and chalks) because they are eroded more by solutional processes. Sea caves are, however not permanent as they are destroyed in due course of time. When the caves are enlarged to such an extent that their roofs become remarkably thin, they ultimately collapse and fall and the debris is removed by powerful backwash and thus long narrow inlets are called 'geo' in Scotland.

The elliptical hollows formed in the coastal area alternated by hard and weak rocks are called coves or mini-bays (Fig.13.6).

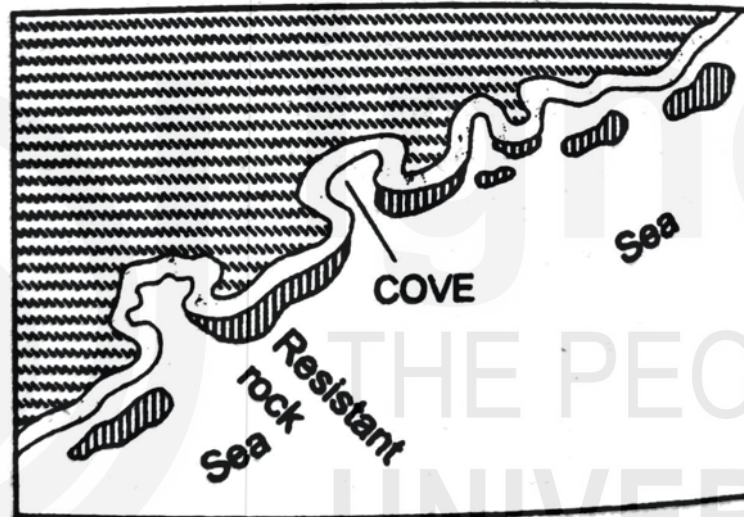


Fig. 13.6: Formation of coves and island.

Fingal's Cave in Scotland, Benagil Cave in Portugal, Cathedral Cove in New Zealand, Blue Grotto in Italy, Elephant Caves in India, and Phang Nga Bay in Thailand are some of the prominent examples of sea caves in the world.

(iv) Sea Arch

A sea arch is created by the erosive action of waves on rocky cliffs or headlands. It forms when waves gradually erode a section of a headland, wearing away the rock through processes like hydraulic action, abrasion, and attrition. As the erosion progresses, a small sea cave may be formed at the base of the headland. Over time, the back of the cave may be eroded further, creating a passage that extends through the headland. Eventually, the roof of the cave collapses due to erosion, leaving behind a bridge-like structure known as a sea arch (Fig. 13.7). The arch is usually formed from more resistant rock layers that are able to withstand the erosive forces of the waves. However, the continuous action of waves and weathering may eventually cause the sea arch to collapse, leaving behind a stack or isolated

pillar. Sea arches are prominent features along many coastlines around the world, and they provide fascinating geological formations and landscapes.

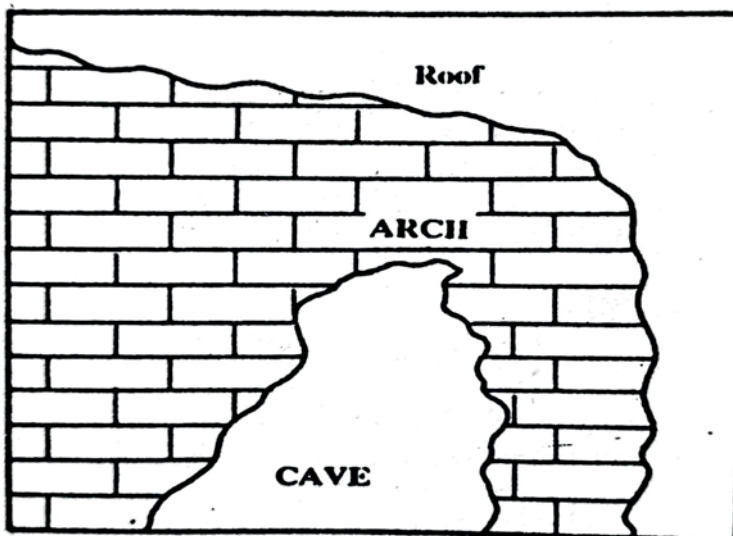


Fig. 13.7: Sea arch.

Examples of famous sea arches include the Azure Window in Malta, the Twelve Apostles in Australia, Durdle Door in England, Cabo da Roca in Portugal, and Baja California in Mexico.

v) Stacks

Sea arcs are not permanent coastal features because the roof, after becoming very thin, collapses and thus the seaward part of the arch stands detached from the coast. Such isolated remnant of headland projecting well above sea level is called 'stack' (Fig.13.8).

Stacks are also called needles, columns, pillars, skerries etc.

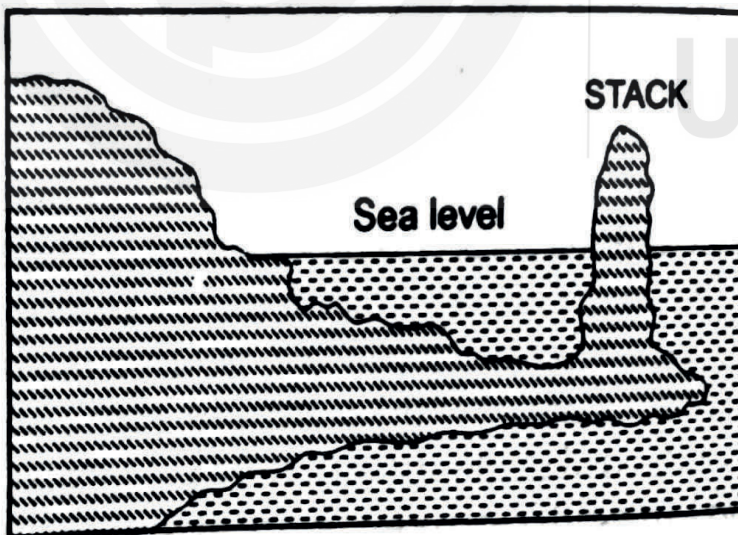


Fig. 13.8: Stack

This is also called as 'Chimney Rock'. The Old Man of Hoy (137 meters) in the Orkney Island of Scotland is a spectacular example of the stack. It is an isolated rock monolith or pillar rising steeply from the Sea. It was formerly part of the adjoining land but has become isolated from it by wave erosion, probably after having formed part of a marine arch (Fig.13.9). Stacks are one of the erosional forms that evolve along cliff-dominated coastlines.

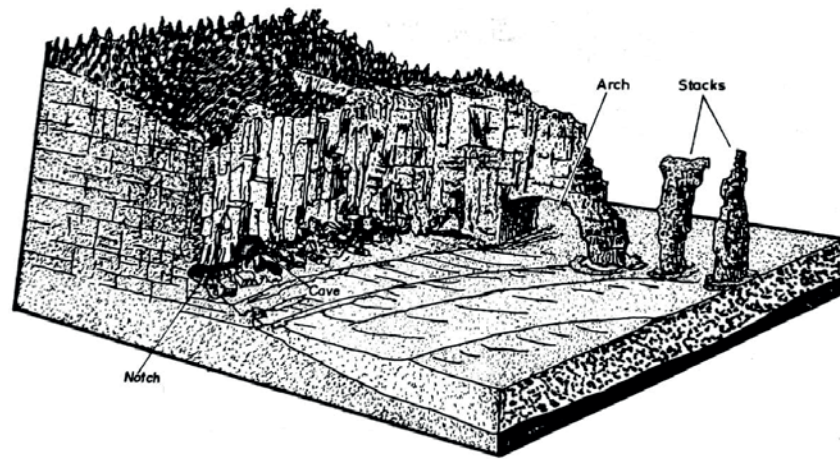


Fig. 13.9: Formation of Stack from sea arch

(v) Blow Holes or Gloops

The part of the cave-roof that persists after the formation of blow-holes is called 'the Devil's Bridge'.

Sometimes, the air in the cave is compressed by uprushing powerful storm waves, and finding no other route to escape, it breaks open the roof of the cave and appears with great force making unique whistling. Such holes are called 'natural chimneys' or 'blow-holes' or 'gloop'. A blow-hole forms when the roof of a sea cave at the landward end of a 'geo' may communicate with the surface by way of a vertical shaft at some distance from the edge of the Cliff. It is like a natural chimney. This opening is formed by wave erosion along a fault or a joint at the back of a sea cave. When a wave enters the cave the compressed air forces spray violently up the narrow opening. In Scotland, the term 'gloop' is used for blow-hole.

Bicheno Blowhole in Australia, Nakalele Blowhole in Hawaii, Moeraki Boulders Blowhole in New Zealand, Kiama Blowhole in Australia, and Whalers Bay Blowhole in the Falkland Islands are a few examples of sea caves.

SAQ 3

What is Attrition?

13.7 TRANSPORTATIONAL WORK OF SEA WAVES

The eroded materials are transported by sea waves. The backwash or undertow currents pick up the eroded materials and transport them seaward, but the operating breaker waves or surf currents pick up these materials and bring them again to the coast and beaches. Thus, the transportation of materials takes place from the coastland towards the sea and from the sea towards the coast. When oblique waves strike the coast, longshore currents are generated. These longshore currents transport the materials parallel to the shoreline. The materials transported by sea waves are silts, sand, gravels, pebbles, cobbles, and sometimes boulders. When there is equilibrium between incoming supplies of sediments by uprushing breaker waves and

removal of sediments by backwash or undertow currents on the wave-cut platforms, a profile of equilibrium is achieved.

If the wave-cut rock platform is characterized by a steep slope towards the oceanic slope, the destructive waves become very active, and thus resultant powerful backwash removes the materials from the landward side so that the slope of the platform is lessened. On the other hand, if the slope of the wave-cut platform is less steep, constructive waves become more effective as they favor sedimentation and beach deposition on the landward side so that the slope of the platform becomes steeper. The surface is therefore continually modified, and in such a way that at each point it tends to acquire just the right slope to ensure that incoming supplies of sediment can be carried away just as fast as they are received.

13.8 DEPOSITIONAL LANDFORMS

Sediment transported along the shore is deposited in areas of low wave energy and produces a variety of landforms, including sea beaches, bars, and barriers, offshore and longshore bars, spits, hooks, loops, connecting bars, looped bars, tombolo, barrier island, tidal inlets, winged headlands, progradation, the wave-built platform, etc., which you will study now.

(i) Beaches

Temporary or short-lived deposits of marine sediments consisting of sands, shingles, cobbles, etc. on the seashore are called beaches. A sea beach is a deposit of loose material within the reach of the waves along the shore. Beaches invariably lie between the lowest level of spring tides and the highest level reached by storm waves. A beach is composed of sand, gravel, or rounded pebbles. Beaches develop on gently sloping coastal plains. Where the wave-cut terraces are narrow, the undertow and littoral currents carry the debris from the land out into deep water to be deposited there.

The beaches are built slowly away from the coast line, thus extending the land seaward. Some beaches are broad sheets of sediments spread by waves and currents over the shore. On the contrary, there are sea beaches which resemble ridges with a crest and a steeper slope towards the land than the sea.

The major sources of the supply of beach materials are erosion of headlands and cliffs, sediments brought by the rivers at their mouths, mass wasting and mass movement of cliffs, scouring of the off-shore zone by storm waves, erosion of pre-existing beaches, etc. Beaches are infact wedge-shaped sediment deposits on the seashore. In width, beaches vary from a few meters to several kilometers. Beaches are generally formed when the sea is calm and winds are of low velocity.

The storm beach is a semi-permanent ridge which stands well above the level of the highest spring tide.

An ideal beach consists of two main elements e.g., upper beach and lower beach, and several minor elements e.g., storm beach, beach ridges or berms, beach cusps, small channels, ripples, ridges, and runnels, etc. (Fig.13.10).

The successive low ridges built by constructive waves parallel to the coastline and below the level of high spring tides are called beach ridge or berms.

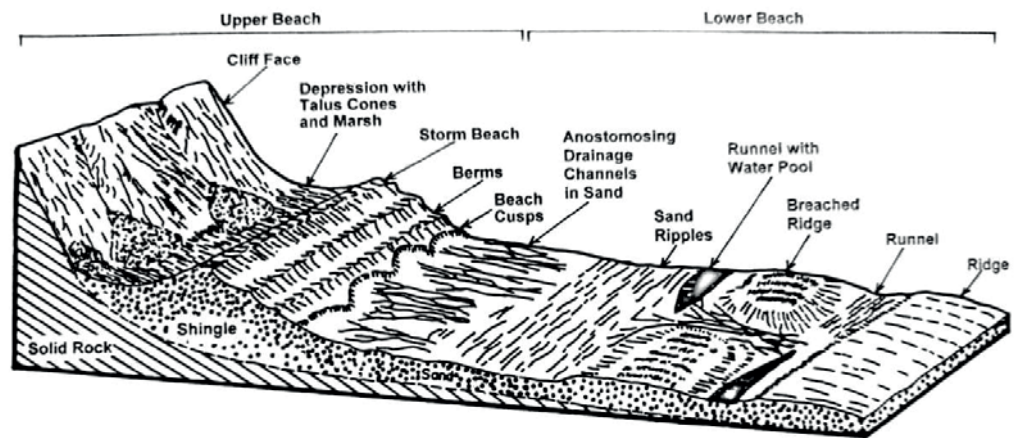


Fig. 13.10: Different elements of an ideal beach.

Beaches may be classified on the basis of deposited material on them into three types: (i) sand beaches, (ii) shingle beaches, and (iii) boulder beaches.

The names of famous beaches in India are: Juhu Beach (along Mumbai Coast), Kalangut Beach, Anjana, and Colba Beach (Goa) located along the west coast. Marina Beach on the Chennai coast, Puri Beach (Orissa), and Vishakhapatnam Beach are located on the east coast.

(ii) Beach Cusp

A beach cusp is a distinct coastal landform characterized by a series of regularly spaced, crescent-shaped embayment along the shoreline. It is formed through a combination of wave and sediment processes. Beach cusps typically have a rhythmic pattern, with alternating embayment (cusps) and protrusions (horns). The cusps are generally spaced evenly along the shoreline and can range in size from a few meters to tens of meters. The spacing and size of the cusps depend on factors such as wave energy, sediment characteristics, and beach slope.

The formation of beach cusps involves the interaction between waves and the movement of sediment along the beach. Waves approaching the shore at an oblique angle can generate longshore currents, which transport sediment along the beach in a zigzag pattern. This zigzag movement of sediment leads to the development of cusps.

The embayment (cusps) form due to the constructive interference of wave energy. As waves approach the shore, they refract and concentrate their energy on specific points along the beach. This localized concentration of wave energy results in erosion and the formation of embayment. The protrusions (horns) form in areas where wave energy is dispersed and sediment accumulates.

Beach cusps are dynamic features that can change over time due to variations in wave energy and sediment supply. They are commonly found on sandy beaches and can be observed in various locations around the world.

Alnmouth Beach in England, Crane Beach in Barbados, Ocean Beach in the United States, Manly Beach in Australia, and Durdle Door Beach in England, etc., are some of the beaches where Beach cusps are easily found.

Runnels are small, flat-floored channels carved by low-tide runoff.

The regular increase in the width of sea beaches towards the sea is called progradation.

As the sediment from the erosion of the Cliff is carried by littoral drift along the sides of the bay, converging on the head of the bay, a pocket-shaped beach is formed, known as pocket beach.

(iii) Bars and Barriers and Associated Features

A bar is an elongated deposit of sand shingle, or mud, occurring in the sea, more or less parallel to the shoreline and sometimes linked to it (Fig. 13.10). A bar that connects two coastal headlands is referred to as a bay bar. If a bar is periodically covered by tides, it is known as a 'tidal bar'. If a bar remains permanently submerged under seawater, then it is called a 'submerged bar'. Bars may be submerged or emergent embankments of sand and gravel built along the shore by waves and currents. The larger forms of bars are called 'barriers'. If the bars are formed in such a way that they are parallel to the coast but are not attached to the land, they are called 'offshore' or 'longshore' bars.

One of the most common types of bar is that which is known as spit. If the sand bars are formed in such a way that one end is attached to the land while the other end projects or opens out towards the sea, they are called 'spits' (Fig. 13.11).

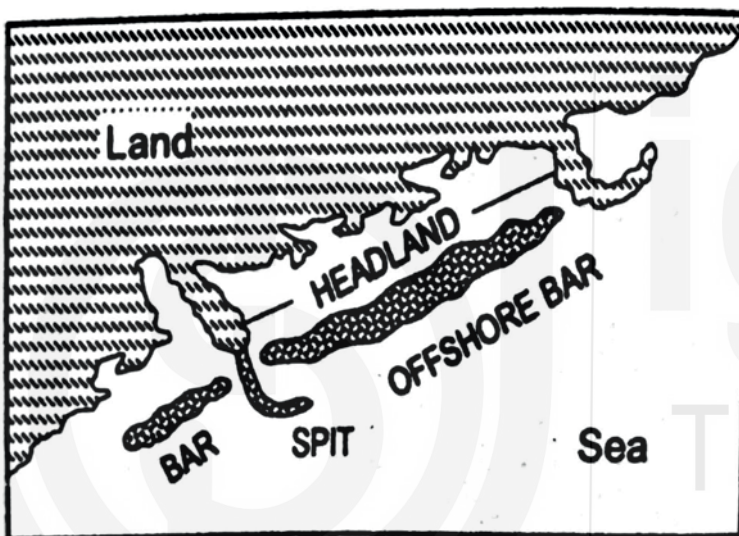


Fig. 13.11: Offshore bars and spits.

High-energy storm waves very often modify the shape of spits by bending them towards the coast. The curved spits assume the shape of hook and thus such spits are called 'hooked spits' or simply 'hooks' (Fig. 13.12).

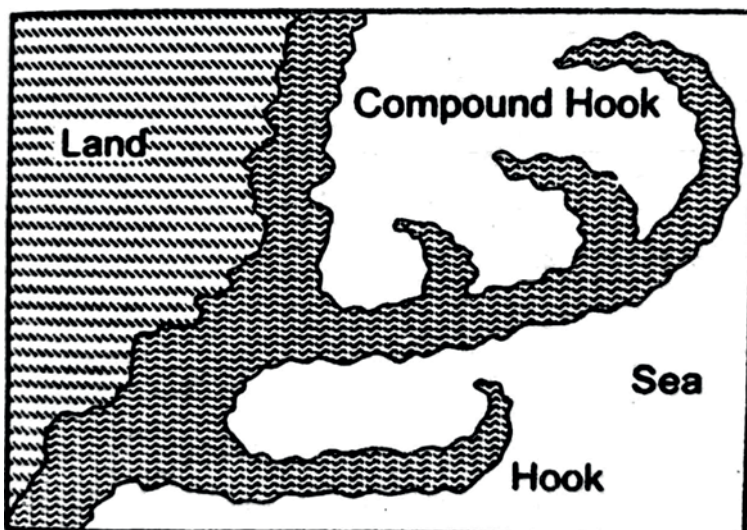


Fig. 13.12: Simple and compound hooks.

Under special conditions opposing currents may encounter littoral currents in such a way that it leads to the landward growth of hooks until they connect with the coastline forming 'loops' (Fig.13.13).

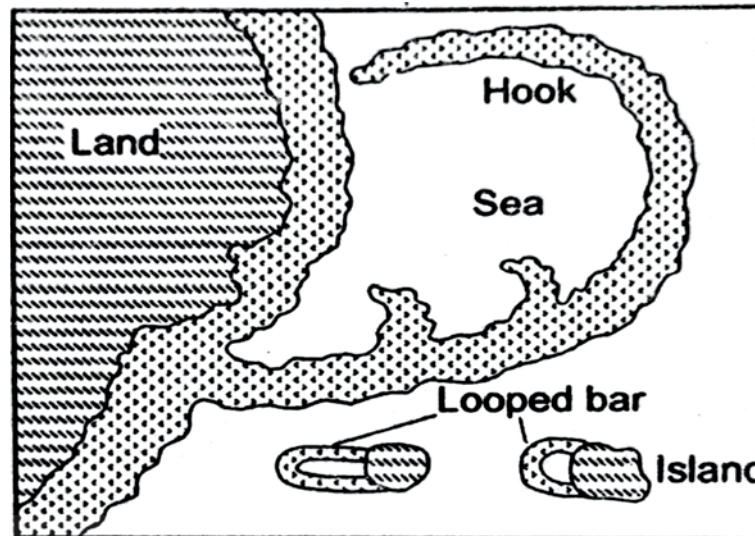


Fig. 13.13: Loop and looped bar.

When such a loop is formed around an island, it is called a 'looped bar'. Sometimes a spit is built across any stretch of water and joins islands, headlands, or islands and headlands. Such spit is called a 'connecting bar'. When a bar connects the mainland with an island or connects a headland with the island is known as Tombolo (Fig.13.14).

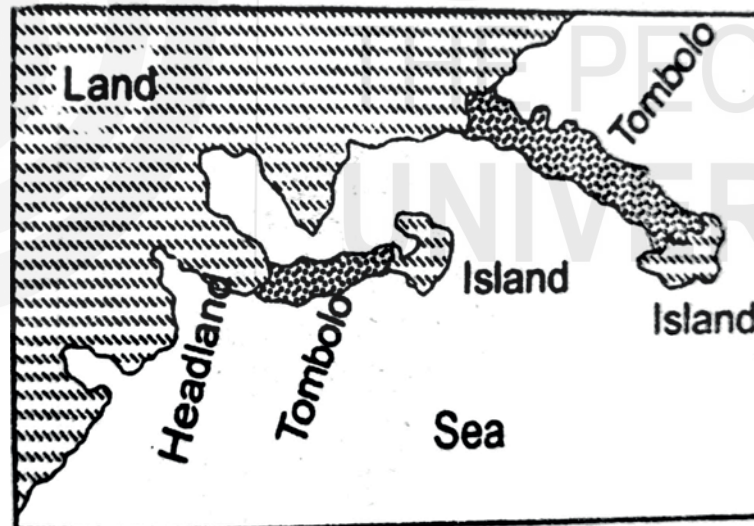


Fig. 13.14: Tombolo

When bars of pebbles and cobbles are formed on either side of a headland, such headland is called a winged headland. Flat and rolling marshy lands developed in the coastal areas of humid tropics are called 'coastal wetlands' which are generally formed behind spits or bars. There is an absence of reliefs and sea water remains stagnant in these wetlands. Sediments are fine and water is saline the floral environment is dominated by mangroves. Such wetlands are found extensively in the coastal zones of West Bengal where the mangroves of the wetlands are known as 'Sundarban'. Depositional coastal

areas having flat surfaces in the dry tropical zones are called 'Sabkhas' which are flat but barren coastal lands. Sabkhas are also called as 'saltflats'.

SAQ 4

What are Beach Cusps?

13.9 SUMMARY

In this Unit, you have studied so far:

- Coastal landforms are shaped by the relentless forces of waves, currents, and tides, with waves being the primary driver. Waves are generated by wind and can either deposit sediment (constructive waves) or remove sediments (destructive waves). Erosion along the coastline is caused by the impact and pressure of waves (hydraulic action) as well as the grinding action of sediments carried by waves (abrasion).
- The coastline marks the highest point reached by the sea on land, while the shoreline refers to the lowest point reached by the sea. Waves erode the coastline through hydraulic action and abrasion. Longshore drift, a significant process, occurs when waves approach the shore at an angle, causing water and sediment to move obliquely onto the beach face and return directly down the beach with backwash, resulting in net sediment transport parallel to the shoreline.
- Erosion along coastlines is primarily caused by the abrasive action of sand and gravel carried by water and currents. This process, along with the solution and hydraulic action, leads to the formation of sea cliffs as wave currents undercut the land. As sea cliffs retreat, wave-cut platforms are created. Other erosional landforms associated with sea cliffs include sea caves, sea arches, and sea stacks.
- The eroded materials are transported by waves. The backwash and undertow currents carry the eroded materials seaward, but breaker waves or surf currents bring them back to the coast and beaches. This results in a continuous cycle of material transportation between the coast and the sea. Accumulations of sediment between the coastline and shoreline form beaches.
- Various landforms are created by sea waves, such as sea beaches, bars, barriers, offshore and longshore bars, spits, hooks, loops, connecting bars, looped bars, tombolos, barrier islands, tidal inlets, winged headlands, progradation, and wave-built platforms.
- However, sudden coastal erosion events, such as tsunamis, can pose significant hazards to human life and infrastructure, causing damage to agricultural and recreational land. These events serve as a reminder of the dynamic and sometimes destructive nature of coastal processes.

13.10 TERMINAL QUESTIONS

1. Describe the profile zone of coastal zones in detail.
2. Discuss waves as an agent of Coastal Erosion.
3. Explain the mechanism of Coastal erosion.
4. Explain important Coastal Depositional landforms.

13.11 ANSWERS

Self-Assessment Questions (SAQ)

1. a) The shoreline means the shifting line of contact between seawater and land.
b) The foreshore, also known as the intertidal zone, is the portion of the coastal environment that lies between the high-tide mark and the low-tide mark. It is a dynamic area that experiences the alternating effects of waves, tides, and currents.
2. Constructive waves are low-energy waves that tend to arrive at the coast at a rate of fewer than 8 waves per minute. Constructive waves are small in height. They have a strong swash and a weak backwash. This means that constructive waves tend to deposit material and build up a beach.
3. Attrition refers to the process of wearing down and rounding of sediment particles as they collide with each other and with the coastal rocks and landforms.
4. A beach cusp is a distinct coastal landform characterized by a series of regularly spaced, crescent-shaped embayment along the shoreline. It is formed through a combination of wave and sediment processes. Beach cusps typically have a rhythmic pattern, with alternating embayment (cusps) and protrusions (horns).

Terminal Questions

1. A Coastline represents the boundary between the continental land masses and the oceanic water masses. A Coastal zone is the transition zone between the terrestrial habitat and the marine habitat. It is the interface between land and oceanic water. Coastal belts may be very wide or narrow. They also vary with reference to their slope, beach profile, rock types, climate, and vegetation. (Refer to section 13.3).
2. Waves are one of the key driving forces that shape the coastal environment. They are generated by wind energy transferring momentum to the water's surface. As waves travel across the ocean, they carry this energy toward the coastline, where they interact with the seafloor and the coastline itself. (Refer to subsection 13.4.1).
3. Coastal erosion is the process by which the land along a coastline is worn away and gradually diminished due to the action of various natural forces like waves, currents, and tides. (Refer to section 13.5).

4. Sediment transported along the shore is deposited in areas of low wave energy and produces a variety of landforms, including sea beaches, bars, and barriers, offshore and longshore bars, spits, hooks, loops, connecting bars, looped bars, tombolo, barrier island, tidal inlets, winged headlands, progradation, the wave-built platform, etc. (Refer to section 13.8).

13.12 REFERENCES AND SUGGESTED FURTHER READING

1. Davidson, A., R., Bauer, B. and Houser, C. (2019). *Introduction to Coastal Processes and Geomorphology*. Cambridge university press.
2. Dayal, P. (1996). *A Text Book of Geomorphology*. Shukla Book Depot, Patna.
3. Huggett, R.J. (2011). *Fundamentals of Geomorphology*. Routledge, New York.
4. Hussain, M. (2007). *Fundamentals of Physical Geography*. Rawat Publications, Jaipur.
5. Lal, D.S. (2009). *Physical Geography*. Sharda Pustak Bhawan, Allahabad.
6. Masselink, G., Hughes, M. and Knight, J. (2014). *Introduction to Coastal Processes and Geomorphology*. Routledge.
7. Singh, S. (2020). *Geomorphology*. Pravalika Publications, Allahabad.
8. Singh, S. (2012). *Physical Geography*. Prayag Pustak Bhawan, Allahabad.
9. Strahler, A. N. and Strahler, A. M. (2010). *Physical Geography-Science and Systems of Human Environment*. Wiley India (P) Ltd., New Delhi.
10. Waugh, D. (2002). *Geography- An Integrated Approach*. Nelson Thornes UK.



GLOSSARY

Ablation	: Ablation refers to the loss of ice from a glacier. It includes processes such as melting, sublimation (ice turning directly into vapor), calving (breaking off of icebergs from the glacier's front), and wind erosion.
Abrasion	: The mechanical wearing away of a rock by friction, rubbing, scraping, or grinding action of sediment particles transported by wind, water, or ice.
Attrition	: The process of wearing down and rounding of sediment particles when they collide with each other and with the coastal rocks and landforms.
Aven	: A vertical shaft or funnel-shaped opening in the karst landscapes connects the surface of the land to an underground cave system or subterranean drainage network.
Beach Cusp	: It is a distinct coastal landform characterized by a series of regularly spaced, crescent-shaped embayments along the shoreline.
Blowout	: A saucer-shaped or trough-shaped landform produced by deflation.
Bolsons	: Enclosed basins or valleys typically surrounded by mountains or hills, which are characterised by their flat or gently sloping floors, which often lack a well-defined outlet for water drainage.
Cirque Glacier	: A cirque glacier, also known as a corrie or a cirque, is a type of glacier that forms in a cirque, which is a bowl-shaped hollow found on the side of a mountain. Cirque glaciers are typically found in high-altitude and high-latitude regions where snow accumulation is greater than snowmelt.
Deflation	: A process by which wind removes dry, loose sand, silt, and clay from the land surface, especially in arid and semi-arid regions.
Estuary	: A partially enclosed coastal body of water where freshwater from rivers and streams meets and mixes with saltwater from the ocean.
Glacial Stairways	: Glacial stairways are landforms characterized by alternating bands of exposed bedrock and debris-covered surfaces. They result from the differential erosion caused by glaciers and are formed through the process of plucking.
Heinrich Events	: Heinrich events are large-scale ice-rafting events characterized by the discharge of massive icebergs from ice sheets into the North Atlantic Ocean. These events are associated with periods of rapid climate cooling and are believed to have played a role in shaping glacial dynamics

	during the last glacial period.
Kames	: It is a mound-like feature formed in close association with stagnant glacier ice, which may occur as isolated features or in groups. Kames are composed dominantly of stratified gravel and sand material.
Karst	: A distinct type of landscape characterised by the dissolution and erosion of soluble rocks,
Milankovitch Cycles	: Milankovitch Cycles, named after the Serbian scientist Milutin Milankovitch, refer to the cyclical variations in Earth's orbital parameters that occur over long periods of time. These cycles include changes in eccentricity, axial tilt (obliquity), and precession. The interaction of these cycles with the Earth's climate system is believed to be a key factor in the onset and progression of glaciation.
Moraine	: Moraine is a characteristic landform of glacial deposition or deformation of sediment by glacier ice.
Plastic flow	: Plastic flow, also known as plastic deformation or creep, is a process that occurs within glaciers and ice sheets. It refers to the slow, continuous movement of ice in response to the force of gravity.
Ripple marks	: These are small-scale sedimentary structures formed on the surface of a sediment layer, such as sand or silt, as a result of the movement of fluids, such as wind or water.
Saltation	: The process of sediment transport by wind or water, where particles are lifted and moved in a series of short hops or jumps. It occurs when the force of the wind or water flow is sufficient to lift and transport sediment particles, but not strong enough to keep them suspended continuously.
Sea arch	: A sea arch is created by the erosive action of waves on rocky cliffs or headlands.
Sinkholes	: Sinkhole is a funnel-shaped or cylindrical-shaped hole, depression or sink in the ground surface of a limestone which is formed by the work of rainwater on limestone.
Stalactites	: Icicle-shaped mineral formations that hang from the ceilings of caves are typically made of calcium carbonate minerals such as calcite. They form through a process known as precipitation or dripstone deposition.
Terra Rossa	: Soil type commonly found in Mediterranean regions, particularly in areas with limestone bedrock. The term "Terra Rossa" is Italian for "red earth," and it refers to the distinctive reddish-brown colour of this soil.