Engineering Geology

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Preface

Objective

Because of structural failures in the past few decades, the importance of engineering geology has increased manifold for civil engineers. Considering the rate at which infrastructure development is taking place, site selection, planning and safe and sound construction of civil engineering projects, therefore, needs an in-depth knowledge of engineering geology. This book deals with both the principles as well as practices of engineering geology. The aim of the book is to provide input regarding most of the frontier areas of geology.

Target Audience

The role of engineering geology in the career of civil engineers is of prime importance because of the tremendous rate of infrastructure development taking place and the investments made by the Government and local bodies. This book will serve as a basic course material for undergraduate students of civil engineering, graduate students of geology and applied geology, and field practitioners.

Salient Features

- Comprehensive coverage on mineralogy, petrology and geophysical investigations
- Coverage on emerging trends—Remote Sensing and GIS
- Student-friendly chapter design including chapter introduction, summary, key terms with definitions, review questions and multiple-choice questions
- Well-labeled self-explanatory illustrations with 3D views, wherever required, for better comprehension of topics
- Colour plates to support the text for better understanding
- **Terminology** at the end of each chapter to explain important terms, allowing unobstructed flow of text
- A set of **Viva-Voce Questions with Answers** given at the end of the book to help students face practical examinations
- Rich pedagogy includes:
  - 250 Figures
  - 16 Plates
  - 150 Exercise Questions, covering the theory discussed

- 120 Multiple-Choice Questions to help readers have a quick check on the knowledge gained

Chapter Organization

The text is divided in 16 chapters. A brief synopsis of each chapter is given below.

Chapter 1 presents an introduction of geology, its various disciplines and the importance of different aspects of engineering geology. Since all the building and construction materials are either taken from the surface or interior of the Earth, the Earth and its interior are introduced in **Chapter 2**. Magma, which is the primary source of formation of igneous rocks, is discussed next in **Chapter 3**. The occurrence of minerals, their physical and optical properties, and their importance are described in **Chapter 4**, which is on mineralogy.

Knowledge about the origin, texture and structure of various types of rocks—igneous, sedimentary and metamorphic—without which safe design and construction of structures is not possible, is the most important part of engineering geology, and is dealt with in **Chapters 5**, **6** and **7** respectively. **Chapter 8**, includes the deformation of rocks; folds, faults and joints. A know-how of these deformations help plan proper location of a civil-engineering structure. Engineering properties of different types of rocks and their suitability for different civil-engineering structures are dealt with in **Chapter 9**. The geological and hydrological investigations for civil-engineering structures like dams, tunnels and bridges, have also been described in this chapter.

The geological actions and effects of different natural agencies such as rivers, winds and glaciers are described in **Chapter 10**. Natural disasters, e.g. earthquakes and landslides, which may cause catastrophes and total destruction, and loss of lives are covered in **Chapters 11** and **12** respectively. The sites prone to such disasters need special design considerations and, therefore, have a great bearing on site selection for civil-engineering projects. A study of groundwater, its occurrence, distribution and movement is essential because it is an important natural resource at one hand. But, at the same time, it is also responsible for geological hazards like triggering of landslides, distress in tunnels, etc. These are discussed in **Chapter 13**.

Geophysical investigations for different types of subsurface exploration of natural resources have been described in **Chapter 14**. An introduction to applications of Remote Sensing and Geo-informatics in geological sciences is presented in **Chapter 15**. Determination of physical and optical properties for minerals and rocks in the laboratory is covered in **Chapter 16.** The chapter also includes preparation and study of outcrops and geological maps, and topographic maps.

Online Learning Center

The comprehensive OLC can be accessed at *http://www.mhhe.com/duggal/eg* and contains the following material:

- ***For Students***
  - Sample chapter
  - Interactive quizzes
- ***For Faculty***
  - Lecture PowerPoint slides

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Feedback

Constructive criticisms and suggestions for future improvements are always welcome.

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chapter 1

Engineering Geology: An Introduction

1.1 INTRODUCTION

The planet Earth is in a constant state of change due to the geological processes. They modify the Earth's surface by causing erosion and destruction of existing rocks; deposition and formation of new sediments in the seabeds; creation of new rocks underground and thereby subsequently affecting further deformation to them with time, adding to the complexity of ground conditions. The driving force for all these geological processes is the energy from the hot interior of the Earth.

Geology is the science that deals with the origin, age, composition, internal structure, surface features and history of the Earth. It includes the processes taking place inside the Earth, discovering its mineral wealth, and techniques to preserve the Earth. It also deals with the evolution and modifications of various surface features like mountains, rivers, coastlines, etc. Geology may also be defined as an applied science to advance our understanding of the processes that can result in natural disasters such as earthquakes, tsunamis, landslides, floods, etc. Therefore, it may be said that geology is the study of the Earth.

The application of geology to civil engineering projects is known as 'engineering geology'. It may be defined as the application of geological data, techniques, and principles for the study of

1. Naturally occurring rock and soil materials, and surface and sub-surface fluids
2. Interaction of introduced materials and processes with the geologic environment, and geological factors affecting the planning, design, construction, operation and maintenance of engineering structures
3. Recognition, protection, development and remediation of groundwater resources

Application of the geologic sciences to engineering practices ensures that the geological factors affecting the location, design, construction, operation and maintenance of engineering works are recognized and adequately provided for. The significance of site selection for dams, reservoirs, tunnels, airports, etc., cannot be over-emphasized. Further, groundwater exploration, watershed development and groundwater pollution, which are covered in the water resource engineering, also require some knowledge of the geology. Furthermore, problems associated with identification of sites prone to earthquakes and landslides, and their solutions also need a sound knowledge of geology.

Precise geological survey for important projects is carried out by geologists to foresee and solve the site-specific problems. However, civil engineers also must have a sound knowledge of geology to appreciate and understand the geological reports prepared by geologists, and use the data for solving the site specific problems. The principal objective of acquiring an in-depth knowledge of geology is to prevent disasters, protect and save life, as well as design structures against damage caused by geologic conditions.

Although the traces of know-how of geology in its rudimentary form, are available to the ancient mankind, but specific application of the science of geology is supposed to have originated in the eighteenth century. Probably it started with excavations in rocks and kinds of soil, speculations were made about the origin and nature of rocks, and relationships between similar rocks at other places were correlated. However, in the later nineteenth century, both engineering and geology advanced to refinement. In the early twentieth century, with the developments in soil mechanics, the importance of geology became apparent and gained importance in planning, design and construction of civil engineering projects. In due course of time, failure of structures emphasized expert assessment of geological conditions for big civil engineering projects and necessitated the employment of geologists to provide expert opinion. It must be remembered that a lack of knowledge about the nature of the ground conditions may cost lives, money, and result in the consequential delay in completing the project. Also, the success of a civil engineering project is totally dependent on the findings based upon geological investigations.

1.2 SCOPE OF ENGINEERING GEOLOGY

The objective of engineering geology is to meet the requirement of an engineering project, and involves the study of rock types and the structures associated with them. As defined in the previous section, engineering geology deals with the application of geology for a safe, stable and economic design and the construction of a civil engineering projects. For a civil engineer, therefore knowledge of the fundamentals of engineering geology is as essential as those of mechanics, strength of materials, theory of structures, etc. The knowledge of the geology of an area and geological features in planning, design and construction of civil engineering projects is not only desirable but essential as well.

Most civil engineering projects either involve excavation of soil and rocks, and/or involve loading the Earth by building structures on it. The excavated rocks may form part of the project, e.g. reservoir, or may be used as construction material. Geologists work hand-in-hand with civil engineers for the site selection and ground treatment for important civil engineering projects such as dams, reservoirs, tunnels, etc. Study of engineering geology is important for the reasons to follow:

1. It enables a geologist to understand the nature of geological information that is essential for the safe design and construction of a civil engineering project. Further, he is responsible for interpreting site specific geological data and for providing conceptual models representing the morphology, geological structures and classification of the rock units.
2. It enables a civil engineer to understand engineering implications of certain conditions related to the area of construction, which are essentially geological in nature. Further, he develops an appreciation of the relevance and importance of geologic observations and interpretations.

It may be noted that a civil engineer is neither expected nor required to undertake geological investigations of the area. However, he/she must be capable of understanding, analyzing and critically discussing a geological report of the area prepared by a geologist. With adequate knowledge of engineering geology, a civil engineer becomes capable of deriving maximum useful information pertaining to the geological conditions of the project site. In fact, while executing the construction, the task of a geologist is to specify the probable difficulties and the civil engineer is supposed to overcome them. The scope of engineering geology with reference to projects such as dams, tunnels, tube railways, water resource development, town and regional planning, etc., can not be overemphasized. Some of the applications of engineering geology are presented in the sections to follow.

1.3 INFRASTRUCTURE DEVELOPMENT

Some of the important civil engineering projects that are indicators of the prosperity and economic growth of a country are power plants, multi-storey buildings, dams and reservoirs, aerodromes and airports, embankments and retaining structures; and linear structures e.g. highways, bridges, tube railways, tunnels, irrigational and navigational canals and water bodies, pipelines for oil, gas and water transport, etc. The feasibility, planning, design, economy, and the safety of the project may depend on the geological conditions of the site of construction. Therefore for planning, design and construction of civil engineering projects, the geological information about the site of construction (or excavation) and about the excavated natural materials of construction is of great importance.

1.3.1 Planning

During the planning stage of a civil engineering project, there may be several possible optional sites/routes. The objective of the engineering geologic studies is to give a comparative evaluation of all the options so as to confirm the most feasible and optimum one. However, for proper planning of an engineering project the information related to topography, hydrology and geology of the area form the base for deriving economy and achieving intended serviceability and life time safety, and making it cost effective.

❑ *Topography*

Topographic maps providing details of relief features of the probable sites for the project are prepared, if not available. The relative pros and cons of the probable proposed sites are studied. From the topographic maps, the presence and nature of slopes, size, contours, depths of valleys and gorges, and the rate of change of elevation in various directions are determined. These parameters then help to decide the most suitable site for construction.

❑ *Geology*

The geological maps of different scales for the proposed site are useful in depicting the petrological character and structural behaviour of rock types. From these maps, information regarding the fracturing and displacement of the site rocks undergone in the past can be understood. Furthermore, the information related to availability of construction materials in the area can also be had. The information with regards to the location and the limit of exploratory operations (location of test boreholes, trial pits, etc.) for subsurface investigations, ground improvements, etc., is decided, based upon the geological maps.

❑ *Hydrology*

Surface water and groundwater have great bearing over the stability and cost of engineering structures. Hydrological maps are useful in establishing the distribution and geometry of the surface water channels, their occurrence and depth below the surface of the Earth. Such data is of great importance in proper planning of most civil engineering projects.

1.3.2 Design

In most cases, the geological characters and conditions finally dictate the engineering design of the project. For example, if a choice is to be made for the type of dam amongst earthen, gravity and arch dams, the geological conditions of the site will govern. The profile of the gorge or the valley, the strength of the rocks at the base and on the embankments need very thorough testing and analysis before deciding the final size, shape and other design parameters of the dam.

Some of the geological characters that have a direct or indirect bearing upon the design of a proposed project, in general, are the following:

1. The existence of hard bed rocks and their depth and inclination with the surface.
2. The mechanical properties along and across the site of the proposed project. The important properties are compressive strength, shear strength, transverse strength, modulus of elasticity, porosity and permeability, resistance to decay and disintegration.
3. Presence, nature and distribution pattern of planes of structural weakness—joints, faults, folds, cleavage, schistosity and lineation, etc.

4. The position of groundwater table in its totality including points of recharge and discharge and variations during different periods of the year. This also governs the stability of foundations for civil engineering structures.
5. Seismic character of the area and prediction about future seismicity.

1.3.3 Construction

For the execution of civil engineering projects, geological background is of great importance. Selection of appropriate construction materials derived from the natural bedrocks requires geological base. Desired durability and expected life of structures can be ensured from the knowledge of mineralogy and petrology of the natural materials such as sand, gravel, crushed rocks and soil.

In geologically sensitive areas, such as coastal belts, seismic zones, and permafrost regions, an in-depth knowledge of geological history of the project area is a must.

In coastal areas, behaviour of rocks towards waves, currents and marine environment must be fully understood, both at the planning stage and during the execution of the work. This may require special types of construction and construction techniques.

In regions of high seismicity, since lightweight structures are preferable, the weight of construction materials becomes a crucial factor. Geological knowledge is of great importance in handling problems concerned with earthquakes and landslides. Furthermore, in earthquake prone areas, the soil type is of utmost importance; some of the soils liquefy under strong ground motions.

In permafrost regions, the soil remains permanently frozen up to a certain depth, all the time. This presents problems that can be solved only by a proper understanding of the ground below.

Construction of underground projects e.g. tunnels require a thorough knowledge of the geological characters and the settings of rocks that may be encountered. The same type of rock may behave differently under different natural rock settings. Rocks, being anisotropic in character, do not behave according to empirical thumb rules. Therefore, stability of a structure constructed on rocks, or through rocks, or with aggregate from rocks depends considerably on the understanding of the nature of rocks.

1.4 WATER RESOURCES DEVELOPMENT

In the area of water resources engineering, projects ranging from groundwater exploration to watershed development, groundwater pollution and groundwater conservation, all require a sound geological understanding of the area under consideration. Studies concerned with reservoir-induced seismicity to understand the side effects are of utmost importance in constructing large dams.

Water resources comprise of the surface water and the groundwater. To access and manage these resources, geology of the area plays a vital role. The water-bearing properties of rock bodies, (aquifers), and factors that influence storage, movement and yield of water from aquifers are essentially geological problems.

They require thorough geological knowledge about the disposition of strata for designing a dependable water supply project. The knowledge of sub-surface soil, rocks, folds, faults, joints and lineaments is essential for an estimation of infiltration/recharge of the surface run-off.

Water is depleting fast and becoming most sought for the survival of mankind. Scientists, technologists and engineers all are equally concerned to explore new resources and means to conserve the existing ones. Geological information is of fundamental importance in the exploration and exploitation of water resources of a region for surface and sub-surface reserves of water.

For surface water resource, which is in the form of river system, the details of lineaments and nature of rocks govern the flow of surface run-off. Different rocks have different permeability and water absorption capacity. The siltation of river system is also influenced by the geology of the river course. There are several major and minor basins which have huge reserves of surface water as well as groundwater. The water resource estimation and its management are carried out basin-wise. The problems related to the quality and quantity of water is governed by the nature of soil/rocks in the basin. The geogenic contamination of water in particular basins are controlled by the nature of rocks and minerals. Therefore, it is necessary to understand the geology of the particular basin of interest.

To manage the water resource in the form of groundwater, the role of the rain water harvesting has become the most important technique of water conservation. Since, it involves the principles of sub-surface infiltration/recharge, the different soils and rocks have to be understood properly to make the sub-surface recharge effective. Hence, a proper understanding of sub-surface geology is necessary before attempting the rain water harvesting project.

Another approach to address the expected future scarcity of water involves finding out ways and means for utilizing frozen waters spread over millions of square kilometer areas in mountains and in Polar Regions in the form of glacial ice. This has opened up a field of importance for the water resource engineers in the near future.

1.5 TOWN PLANNING AND REGIONAL PLANNING

Towns grow during the passage of time. The need for education, employment and business are some of the factors for the migration of people from remote and rural areas to urban areas. A town planner is concerned with the utilization of land in the best and most aesthetic manner to meet the social needs of the people in different areas. The town planner must be capable of fully understanding the state of equilibrium already achieved between the surface features and the prevailing environment and also their intricate relations with each other.

Increase of population in metros and other industrial hubs necessitates gradual advances over the natural lands within and outside the existing towns and cities. Migration of people from other parts of the country require construction of additional housing facilities, community buildings, commercial complexes, water-supply projects, roads, metros and so on.

The suitability of a particular site for an identified project, from an engineering point of view, is decided by civil engineers in consultation with an engineering geologist. But primarily, it is the town planner who must have a background of geology so as to judicially make a decision regarding allocation of lands for different requirements; every meter of land taken out from the natural system for any construction activity will affect the system as a whole. A change affected in the natural set up of an area due to a proposed new project consequently leads to a series of changes in the adjoining and even distant area. However, the new area so developed should not introduce any major element of disequilibria in the natural set up.

1.6 DISCIPLINES INVOLVED IN ENGINEERING GEOLOGY

Most civil engineering projects such as dams, tunnels, bridges, sky-scrappers, etc., require a knowledge of Earth and applied aspects of geology during their planning, design, construction phases, and environmental impact analysis. This involves several geological disciplines such as *Mineralogy*—consisting in identification of different types of minerals and study of their physical and optical properties; *Petrology*—dealing with different types of rocks; *Structural geology*—concerned with structures of rocks; *Physical geology*—involving natural forces that bring about changes upon the Earth's surface; *Geomorphology*—study of the effects of weathering (physical disintegration, chemical decomposition, and biological activity) and subsequent erosion due to natural agencies such as sea, river, wind, and moving glaciers; and *Hydrology*—study of water resources. These are described in detail in the chapters to follow. Since application of remote sensing in the field of geology is gaining popularity because of the inherent advantages of the technique, a chapter is introduced at the end.

Summary

This chapter discusses the role and importance of geology for civil engineers. Various disciplines of geology involved in site selection for safe and economical construction of civil engineering projects are introduced. Engineering geology deals with the rocks and soils that make the foundation of various civil engineering structures. It also provides information and properties of various valuable stones to be used aesthetically and economically as construction materials.

The importance of a geologist and civil engineer for safe and reliable construction of civil engineering projects is presented. The role of engineering geology in the development of infrastructure is discussed.

Terminology

Aquifer These are water-bearing strata capable of holding and transmitting water.

Contour A line connecting points of same elevation (height).

Embankments These are human-made mounds of earth or stones built to confine the flow of water in any drainage or stream, or to support a road or railway.

Geogenic Contamination The contamination caused by leaching of rocks or soil.

Hydrology Comprises of the study of water resources, both the groundwater and surface water of the Earth. It involves the study of distribution, conservation and use of the water of the Earth and its atmosphere.

Permafrost Region The regions at or below the freezing point of water for at least three years. Most of the areas near the North and South poles fall in this category.

Rock Anisotropy Different behaviour of rocks along different axes is known as rock anisotropy. Most common rock-forming minerals are anisotropic, i.e. they have different physical and mechanical properties along different axes, and are responsible for rock anisotropy.

Topography Consists of the study of surface shape and features on the Earth's surface. It is concerned with local details including relief (quantitative measurement of vertical elevation change in a landscape) and natural and artificial features. Topography involves the recording of the relief of terrain, the 3-D quality of the surface and the identification of landforms (mounds, plateau, hill, valley and water-bodies).

Exercises

1. (a) Define geology. Why should civil engineers study geology?
   (b) What are the main disciplines of geology that a civil engineer must have a knowledge of?

2. (a) What is engineering geology and how is it relevant to civil engineering?
   (b) At what stage of the project engineering geological studies must be carried out?

3. Lack of attention to geological aspects may lead to hazard. Comment!

Multiple-Choice Questions

1. Knowledge of geology is important for civil engineers to understand
(a) the geological reports prepared by the geologist
(b) to prevent disasters
(c) the sub-surface water availability
(d) all the above

2. During surveying for a civil engineering project, topographic maps are prepared for:
(a) specifying the site location
(b) understanding relief features of the probable site
(c) specifying the structural behaviour of rock types
(d) depicting petrological characters of rock types

3. Which of the following is not covered in geomorphology?
(a) Physical disintegration of rocks
(b) Structures of rocks
(c) Sub-surface water
(d) Hydrology

4. Which of the following is matched correctly?

(a) Geology	Human body
(b) Hydrology	Valleys, gorges and other landforms
(c) Topography	Slopes, contours, etc.
(d) Seismology	Fold, faults and joints

5. Which of the following is not matched correctly?

(Branch of Geology)	(Deals with)
(a) Petrology	Types of rocks
(b) Physical	Natural forces bring changes
(c) Geomorphology	Landforms due to natural agencies
(d) Structural geology	Groundwater condition

Answers to MCQs

1. (d) 2. (b) 3. (a) 4. (c) 5. (d)

chapter 2

The Earth—Its Origin and Properties

2.1 INTRODUCTION

Our solar system consists of nine planets (the Earth being one of them), and their satellites, revolving around the central star, the sun. Our solar system is a very small part of the galaxy, also called *Milky Way,* that consists of many stars. Such innumerable galaxies form the universe. Apart from the nine planets, the other planetary bodies in our solar system are termed as asteroids—the minor planets, meteorites—small particles from asteroids and comets, ranging from small grains to 1 meter width, and, satellites—the celestial bodies' orbiting planets. As the planets move around the sun in the same direction and in almost elliptical orbits, and since these lie in the same plane, it indicates that the origin of the Earth is certainly related to the solar system. The planets are located at different distances from the sun and are classified as *terrestrial* or *inner* planets—Mercury, Venus, Mars and the Earth, and, *outer* or *major* planets—Jupiter, Saturn, Uranus, Neptune and Pluto. Mercury is nearest to the sun with the fastest orbital motion of 48 km/s and requires 88 days to complete one revolution, while Pluto is the most distant planet with an orbital speed of 5 km/s and requires 248 years to complete one revolution. The Earth, however, is the only known planet with favourable conditions for the sustenance of life.

The members of the inner planet group are smaller in size than the members of the outer planet group; the latter ones known as *giants*. Moreover the inner planets are made up of rocks and metals and are quite dense (4×10^{-3} kg/m^3), while the outer planets have a smaller density and are made up of ice and gases. For example, the density of Saturn is even less than water. It may be noted that the high density of planets indicates that they consist of silicates and metals and the low density of the planets is an indication that they are composed mostly of hydrogen, helium, water, ammonia, etc., besides having rocky cores, like the sun.

The interest of geologists is to explore the formation of our solar system so as to understand the formation of the Earth. The *nebular hypothesis*, the most scientific accepted explanation for how the Earth was formed, is presented in the following section, together with, some other popular hypotheses. It must be taken note that a *hypothesis*—a tentative explanation based on data collected through observations and experiments—is credited only after it has survived repeated challenges and critically analyzed by the scientists, and is then called a *theory*.

2.2 ORIGIN OF THE EARTH

Knowledge of the Earth as of today raises questions about the processes that have formed it—about its history. Scientific literature is full of hypotheses put forward from time to time regarding the origin of the solar system. Most of the earlier hypotheses about the solar system lost their importance gradually with time, since these were based on either unconvincing logic or incomplete information. However, some of them appeared to be convincing and interesting. Most theories explained a few of the fundamental truths, but failed to completely or partially explain the other regularities. Till date, there is no theory which can be considered to have universal acceptance. An ideal theory would be the one that will explain satisfactorily all the truths about the solar system as a whole. Since the astronomers and scientists keep on continuously working to modify the hypotheses proposed from time to time to be safer, the term hypothesis has been used in the following sub-sections.

It is impossible to predict the formation of the Earth. Although a number of hypotheses exist, but some of the more accepted by a large number of scientists and at the same time objected by an equally larger number of thinkers are presented briefly. However, note must be taken of the origin of the solar system and that of the Earth is yet without any final agreement within the scientists and geologists.

2.2.1 The Nebular Hypothesis

This hypothesis is the first scientific explanation proposed by a German philosopher, Immanuel Kant, and the French mathematician Laplace in the 1970s. It was suggested that the origin of the solar system could be traced to rotating clouds of gas and dust. Several such clouds were named *nebulae*. The materials forming the clouds were identified as gases (hydrogen and helium) that make up a small fraction of the sun, and dust particles which are chemically similar to the materials found on the Earth. The formation of the solar system was attributed to the force of gravity, i.e. the force of attraction between pieces of matter because of their mass. This diffused, slowly rotating nebula contracted under the force of gravity. The contraction in turn accelerated the rotation of the particles, and consequently the nebula got flattened into a disc shape. Under the pull of gravity, matter began to drift towards the centre, accumulating into the proto-sun; the precursor of our present sun. The material in the proto-sun got pressed under its own weight, and became dense and hot. The internal temperature of the proto-sun rose to millions of degrees, at which point nuclear fusion began.

Although most of the matter in the original nebula was concentrated in the proto-sun, a disc of gas and dust, called the *solar nebula*, remained to envelop it. The solar nebula grew hot as it flattened into a disc, becoming hotter in the inner region, where more of the matter accumulated, than in the less dense outer regions

(Plate 1). Once formed, the disc began to cool and many of the gases condensed. According to the nebular hypothesis, the planetary system is considered to have evolved from this originally hot, rarefied, disc-shaped rotating, gaseous cloud, which surrounded the proto-sun. From this original nebular mass, the planets were supposed to have been formed in the following manner:

1. The nebular mass originally rotated along its axis like a solid body with a characteristic feature that the outer parts of the nebular disc moved faster than the inner parts.
2. Somewhere during the rotation, the gas lost energy by radiation. The original nebular mass cooled and contracted simultaneously, and consequently the nebula contracted inwards. Its rotational speed about its own axis increased in accordance to the law of conservation of angular momentum. This resulted in bulging out of nebula in the equatorial zone.
3. Due to cooling and contraction, the outer parts of nebular mass started rotating still faster, so that eventually the centrifugal force equaled the gravitational force of attraction acting inwards. This resulted in successive rings of gaseous material to spin off from the central nebular mass by centrifugal force, at equatorial belt.
4. The broken nebular masses remained at the points where did they break. The rest of the gases, however, continued to contract.
5. The process of cooling and contraction continued, and several successive rings of gaseous materials were ejected off from the central mass.
6. These condensed gaseous rings ultimately formed gaseous agglomerations as a result of prolonged cooling and contraction. These agglomerations continued to revolve around the sun and finally condensed into the planets; the Earth being one of them.

The explanation of fundamental regularities by nebular hypothesis is as follows:

(a) Planets formed in the above manner would have circular orbits around the sun.
(b) All the planets would revolve in one and the same direction, the direction of rotation of the original nebula.
(c) The orbits of planets would lie in the same plane, which is the plane of the equator of the primeval nebula.

However, with the rapid development of astronomy, geophysics and geology in the nineteenth century, some errors were revealed in this hypothesis. It failed to explain some of the other fundamental regularities like distribution of angular momentum and differentiation of planetary bodies into heavier-smaller inner planets and lighter-bigger voluminous outer planets. Moreover, the process of condensation of highly rarefied gas into rings, rather than its dissipating into space, is believed to be quite hypothetical and has been put to question.

2.2.2 The Tidal Hypothesis

This hypothesis got popularity in the first half of the twentieth century. Jeans, a British astronomer, postulated in 1925 that the solar system was formed because of the passage of another major star very close to the sun. The attraction of this star caused a sharp disturbance in the balance of the internal layers of the sun. An enormous stream of matter was ejected from the sun which, later by division and subsequent condensation, gave rise to all planets and the solar system (Plate 2). The explanation given was as follows:

1. It was postulated that a very large-sized star progressively approached close to the sun. Due to the gravitational pull of the passing star, a gaseous tide was raised on the surface of the sun. The tide increased in size as the star approached progressively closer to the sun.
2. With the passage of the star away from the sun, the gaseous tide was separated. The separated gaseous filament, of spindle shape with maximum thickness at the middle, was supposed to have been dragged by the passing star for some distance in the space.
3. Ultimately, when the pull decreased, the filament was left behind revolving around the sun and gradually breaking down into ten pieces.
4. Nine of these pieces were supposed to get condensed into planets. These planets kept rotating around the parent sun.
5. The remaining one further broke into small pieces and formed the group of planetoids.

The tidal hypothesis explains, to some extent, the distribution of angular momentum condition, but failed to explain the following:

(a) The possibility of the passage of two stars in space as postulated in the tidal hypothesis is considered very rare. In fact, in space the stars are appreciably far apart from each other and the passing of one star nearer to another and the probability of exerting a dragging influence is the least.

(b) The hot gaseous mass which pulled away from the sun instead of forming planets would have dissipated in the space. Under the postulated conditions of tidal attraction, material at exceedingly high temperatures (about one million degree celcius) would have gushed out from the interior of the primary sun. Such a type of gaseous material would have easily dispersed in space rather than remaining around the sun to form planetary agglomerations.

(c) The hypothesis could not give a satisfactory explanation about the vast dimensions of the ultimately developed solar system. If the passing star was to succeed in tearing some matter out of the sun, it would have to pass through the immediate vicinity of the sun; the distances of the planets from the sun are known to be thousand times greater than its diameter.

(d) The hypothesis actually fails to explain completely even the condition of angular momentum.

2.2.3 The Gas-Dust Cloud Hypothesis

The hypothesis propounded in the recent past that planets have evolved out of a cold cloud of gas and dust, appears to be more appealing and convincing. The original idea was placed in 1943 by a German physicist, Weizsacker, and a Soviet mathematician, Q J Schmidt. Subsequently, in due course of time, different modifications to this hypothesis were presented.

❑ *Weizsacker's Hypothesis*

The German physicist C F Von Weizsacker (1943) proposed a modification of the nebular hypothesis. He expressed the two possibilities. First, the sun was formed through the condensation of fine particles of dense interstellar clouds of gases and dust, and a large part of this interstellar matter remained in the form of a giant cloud. Another possibility is that the sun entered into an extensive nebulae cloud. In any case, the sun was assumed to be surrounded by a thin, flat rapidly rotating cloud of dust and gas particles, termed as *proto-planetary cloud*. As a result of frictional forces developed during its revolution around the sun, a disc-shaped appearance was acquired by the cloud (Plate 3). This cloud was considered to have much a larger quantity of hydrogen and helium. As such, the mass of this nebular cloud was assumed to be about one tenth of that of the sun. The gradual accretion of the floating dust particles in the nebular disc gave rise to the formation of the planets. This hypothesis suggests a cold origin of the Earth.

❑ *Schmidt's Hypothesis*

The hypothesis presented by Q J Schmidt is almost similar to that of Weizsacker's hypothesis for the origin of planets and is as follows. Many important facts that have been explained by him appear to have a sound basis. In fact, a difference in details of the evolutionary process has been introduced.

He assumed that moving in the galaxy through gases and dust, the sun attracted part of them and got surrounded by a cloud of this substance. The dust particles composing the cloud moved in it, in all the directions with small random velocities, because of their friction with the gaseous part. Because of the random velocities, the dust particles collected in the equatorial plane of the cloud. Such assemblies of dust particles gave birth to an equatorial disc of dust.

In the disc, dust particles agglomerated in many bodies of smaller sizes. This agglomeration could have been caused either by mutual uniting of the particles (the smaller particles joining the larger ones), or because of tendency of the particles to establish local gravitational stability, or by both of these processes. The planets were thus gradually formed in the cloud. These proto-planets rotated around the sun in circular orbits and in the plane of the original sun. With their gradual growth in size, they acquired masses capable of exerting strong gravitational pulls on each other and this caused slight irregularities in their original circular orbits, making them slightly elliptical and inclined. Further growth of the planetary bodies continued as a result of collisions with other fragments and the present planets are just grown up pre-planetary asteroid like bodies.

The part of the cloud closer to the sun was subjected to intense heat. The nearest planets such as Mercury, Venus, Earth, etc., are, therefore, small in size and consist of dense matter like rock, metal and little gaseous remains. The distant planets such as Jupiter, Saturn, Uranus, etc., are of enormous size and consist of gaseous and volatile substances.

The hypothesis explained the interplanetary distance as well. While the proto-planetary bodies that were close to the sun received matter from smaller distances (keeping their angular momentum low), the bodies away from the sun received matter from farther sources, thereby causing an addition to their angular momentum. This change in the angular momentum resulted in moving away of the proto-planetary bodies from orbits of the outer planets.

Note Although, Schmidth's hypothesis explains a great deal about the formation of planets, but is as yet unable to explain the formation of all heavenly bodies.

❑ *Kuiper Hypothesis*

Gerald Kuiper, an American astronomer, suggested in 1951 a modification to Weizsacker's hypothesis. He suggested that condensation in the nebulous ring took place earlier than the condensation of the sun. As the nebula cooled, it contracted and divided into a number of separate clouds or proto-planets. The proto-planetary cloud divided itself into such massive agglomerations that these were almost touching each other during their earlier rotation around the sun. Further, it was assumed that this division of the dust cloud into proto-planets was accompanied by a considerable loss of mass that was blown away by solar winds of radiations. Kuiper considered the formation of the giant planets by the process of the removal of excess mass rather than their growth due to accretion of dust cloud material as suggested by Weizascker. As the proto-planets contracted, the satellites were formed close to the planets through a similar process.

❑ *Hoyle's Magnetic Theory*

In 1958, Prof. F Hoyle propounded his hypothesis about the origin of planets. The origin of the proto-planetary cloud was created in the process of differentiation of the sun from an original nebular matter that had undergone condensation. According to him, the cloud was created in the process of differentiation of the sun from an original nebular matter that had been undergoing contraction. The fast rotation of the nebular mass caused the separation of the nebular matter into the sun and the proto-planetary cloud. However, due to magnetic coupling between the sun and the gaseous cloud, the process of separation soon came to an end. The aggregation of the particles in the gaseous cloud gave rise to the planets.

2.3 THE PLANET EARTH

It is believed that about 20 million years after the formation of the Earth, due to some violent and giant impact of planetesimals or by some large body, enough heat was generated which caused about 30 to 65 per cent of the Earth to melt. Consequently, the lighter materials floated to the outer layers of the Earth and gases from the interior initiated to escape. This eventually led to the formation of the atmosphere and oceans. The outer layers of the Earth so formed were termed *Magma Ocean*. It is believed that the interior of the Earth, too, would have heated to a soft state allowing movement of its contents. This would have resulted in sinking of heavier materials to the interior, and rising of lighter materials towards the surface. Along with the rising materials, the heat that was brought to the surface must have radiated to the space. Gradually, the Earth cooled, solidified and was transformed into a differentiated (zoned) planet.

The shape of the Earth is commonly described as a spheroid. It has an equatorial diameter of 12757.776 km and a polar diameter of 12,713.824 km having a difference of 43.952 km. The Earth shows an equatorial bulge and a slight flattening at the poles. It has a mean density of 5.517 gm/cm^3, volume of 1.083×10^{27} cm^3 and mass of 5.975×10^{27} g. At present, the Earth is the only planet known to sustain life in the family of the solar system. However, recent studies of Mars indicate that possibilities of life on that planet cannot be entirely ruled out.

The planet Earth is generally differentiated into three parts—the atmosphere, the lithosphere, and the hydrosphere. However, biosphere has also been described in the sub-section to follow since it explains life on the planet Earth. A brief about the characteristics of the different parts of the planet Earth is presented in the sections to follow.

2.4 THE ATMOSPHERE

Atmosphere is the outer gaseous envelope extending up to 700 km beyond the Earth's surface and is energized by the sun. The survival of the life processes is associated with it. The atmosphere makes only about one-millionth part of the total mass of the Earth. Of the total mass of the atmosphere, 99 per cent is within the height of about 32 km from the surface of the Earth and is held around the planet due to gravitational pull of the Earth. The atmosphere has a layered structure. The different layers of the atmosphere are distinguished from each other on the basis of change in composition (chemical), temperature (thermal), and degree of ionization and so on.

2.4.1 Composition of the Atmosphere

Chemically, the atmosphere is made up of a mechanical mixture of gases commonly known as *air*. It has a fairly uniform composition and homogeneous structure which is given in Table 2.1.

Table 2.1 *Chemical composition of atmosphere (dry air)*

Component	*Volume Percentage*
Nitrogen	78.08
Oxygen	20.94
Argon	00.93
Carbon dioxide	00.03
Others (Ne, He, Kr, Xe, etc.)	00.003

On the basis of chemical composition, the atmosphere is divided into two layers: the homosphere and the heterosphere (Plate 4). Up to an altitude of about 90 km, the chemical composition of the atmosphere is almost uniform with regards to three major gases—nitrogen, oxygen and argon. In addition to these, noble gases such as neon, crypton and xenon are also present. This layer is generally referred to as *homosphere.* Beyond 90 km altitude, the composition of the atmosphere begins to change with progressive increase in the lighter gases. This part of the atmosphere is known as *heterosphere*. Here, the molecular oxygen is strongly dissociated and the atomic oxygen is an important constituent of the atmosphere. Helium and hydrogen are also found in this region. The composition of atmosphere in the heterosphere varies from place to place.

Although nitrogen and oxygen comprise most of the volume of atmosphere, climatically these are of little consequence. Nitrogen mainly serves as diluents or dissolvers and gets fixed into the soil. It regulates combustion as well. Oxygen present in the atmosphere combines with all the elements and is most combustible. Carbon dioxide absorbs heat and, therefore, allows the lower atmosphere to get warmed up by heat radiations from the sun and the Earth. Moreover, it is the most useful component in the photosynthesis process of green plants. The role of ozone present in the atmosphere is to absorb ultra-violet rays from the sun and protect life on the Earth. The water vapour and dust particles present in the atmosphere are the important variables of weather and climate and affect their stability. Nearly 90 per cent of water vapour lies in the lower 6 km of the atmosphere and holds the solid dust particles, salts, etc., in suspension. These components of matter act as a hygroscopic nucleus with positive charge and entrap the negatively charged water particles to produce clouds. The microscopic dust particles in the upper layer of the atmosphere scatter incoming solar rays and absorb all colours, except blue; the sky thus appears blue. The larger particles are responsible for red and orange colours at sunrise and sunset, respectively.

2.4.2 Structure of the Atmosphere

The atmosphere shows an interesting variation in temperature with an increase in height from the surface of the Earth (Plate 4). At some levels above the Earth's surface, the temperature starts falling with an increase in height, whereas at still some higher levels it remains constant and, and at further other higher levels it starts rising again. Consequently, the curve for the variation of temperature of the atmosphere above the surface of the Earth is zigzag. The homosphere is divided into three layers (Plate 4) based on its thermal character—troposphere, stratosphere, and mesosphere. The heterosphere is a layered thermosphere consisting of ionosphere and exosphere, extending above the mesopause, continuing to the edge of space. These atmospheric layers are described as follows.

❑ *Troposphere*

Troposphere is the lowermost layer of the atmosphere, starting from the surface of the Earth and extending on an average to a height of 11 km. The upper boundary of the troposphere is termed as *tropopause*. It lies at about 6–8 km above the poles and at about18 km around the equatorial regions.

Since a strong turbulence and thorough mixing of gases occur in this layer, it is termed *troposphere*. The troposphere contains almost nine-tenths of the total mass of the atmosphere. Most of the weather formation or meteorological processes on the Earth are due to this layer of gases. In this layer the temperature decreases vertically at a rate of 6.3°C/km, called *normal lapse rate*, up to tropopause, resulting in minimum temperatures of –60°C. This temperature decreases with altitude because the atmosphere gets heated by the radiated heat from the Earth's surface.

❑ *Stratosphere*

Stratosphere is a layer of the atmosphere that starts from the tropopause and extends up to an average altitude of 50 km. It contains almost the entire concentration of the ozone gas. The ozone layer starts at a height of 10 km above the Earth's surface and continues up to 35 km, referred to as *ozonosphere,* with a maximum concentration of ozone between 20–25 km. The ozone layer is responsible for life on the Earth; it absorbs a good proportion of the solar radiation, and shields the Earth from dangerous ultraviolet rays coming from the sun. In this process, the ozone gas gets heated, and consequently the temperatures in the upper regions of the atmospheric rise. The upper boundary of the stratosphere is called *stratopause*. At stratopause, the temperature rises to 0°C.

The stratosphere differs from the troposphere in the following respects:

1. It contains almost the entire concentration of ozone gas in the form of ozone layer.
2. The temperature is constant for a height of 20 km above the tropopause. Thereafter, the temperature starts increasing with the altitude. It is due to the presence of ozone gas in this layer which absorbs sunlight and gets heated.
3. The stratosphere has a layered structure and there is no significant mixing or turbulence of gases.
4. Since water vapour is not present in this layer, clouds do not form here, resulting in the finest visibility. The lower stratosphere, therefore, provides the best flying conditions for jet aircrafts.

❑ *Mesosphere*

Mesosphere is the layer of atmosphere extending from 50 km to about 90 km in altitude. It is characterized with a rapid decrease in temperature with increase in altitude. Minimum temperatures of –90°C can reach at the upper limit of mesosphere; the *mesopause*.

❑ *Thermosphere*

Thermosphere is the zone that starts at about 90 km and extends up to 500 km and beyond. In this zone, temperature rises once again and reaches 1000°C and above. Since the individual gas particles in thermosphere are separated by considerable distances, thermosphere is very rarefied in nature. Despite being at such a high temperature, these particles are not of concern to a space traveler because of being in insignificant concentration. However, it is the solar radiation at these heights which is of concern. The upper limit of thermosphere is called *thermopause*. Thermosphere has distinct layers of nitrogen, oxygen, helium and hydrogen at an average altitude of 200 km, 1100 km, 2600 km and 9600 km respectively from the surface of the Earth.

❑ *Ionosphere*

Ionosphere is a special region recognized within the atmosphere that reflects long radio waves. It starts from 90 km and extends upwards to variable heights up to 400 km. It is characterized by a continuous increase in temperature. Atmospheric gases at these heights absorb a great part of solar radiation coming to the Earth. Consequently, the gases break up into ions or electrically charged particles. Since this part of the atmosphere is made up entirely of ions, it is known as *ionosphere*. However, the degree of ionization is not uniform throughout the ionosphere.

On the basis of the degree of ionization, there are five layers in this zone. The most strongly ionized layer is located at the base of ionosphere and is called *D-layer*. It is also sometimes referred as the *Kennelly–Heavisiside layer* after the names of its discoverers.

Exosphere is the region of atmosphere beyond 700 km. It is believed to be an extremely rarefied, low-density and high-temperature region with minimum atomic collusions.

Note The structure of the atmosphere is being constantly investigated and monitored by remote sensing techniques and the information is being gathered about the physical, chemical, electrical, thermal and other properties of the atmosphere. The exact boundaries and nature of various atmospheric layers described above are under constant revision.

2.5 THE LITHOSPHERE

Lithosphere is the stony part of the Earth and in a broader sense includes all the solid materials composing the Earth from surface downwards. The body of the Earth is subdivided into three specific layers or zones as shown in Fig. 2.1—the crust, the mantle and the core and are introduced as follows. They are further detailed in sections 2.9 to 2.11. The term *lithosphere*, however, is understood to include only the uppermost shell of the Earth, the crust and only that part of the mantle up to which the material exists in a definite solid state.

❑ *Crust*

It is the outermost solid shell of the Earth which has varying thickness at different locations. For example, the thickness under the oceans ranges from 5 to 10 km; under the continents between 30 to 35 km; and under the mountains 70 to 100 km. The crust, therefore, constitutes just an insignificant part of the Earth when compared with the radius of the Earth (6378 km, on an average). Materials forming the Earth become quite different in properties at the base of the crust.

❑ *Mantle*

It is the zone that starts after the crust and continues up to a depth of 2900 km. It is made up of extremely basic material called *ultra-basic*, very rich in iron and magnesium but quite poor in silica. This zone is characterized with high density increasing with depth. The material of the mantle is believed to be variably viscous in nature and the overlying crust-blocks virtually float over it at a very slow rate.

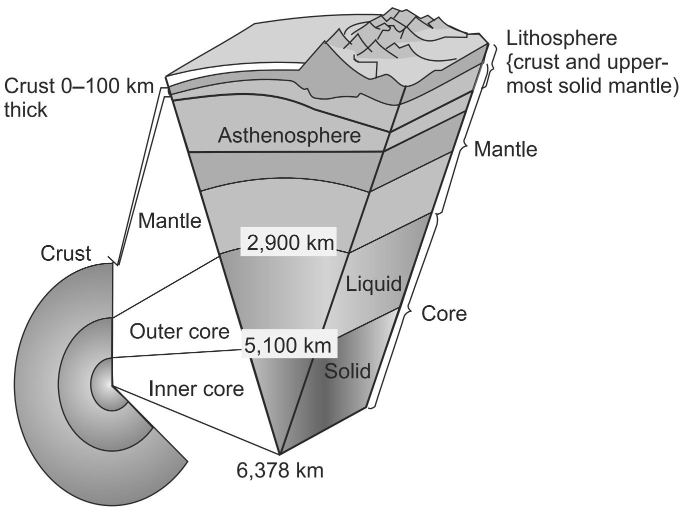

Fig. 2.1 *Internal structure of the Earth*

❑ *Core*

It is the third and the innermost structural shell of the Earth. The boundary between the mantle and the core is at a depth of about 2900 km below the surface. The core extends right up to the center of the Earth, at a depth of 6378 km. The liquidlike core extends from a depth of 2900 km to about 4800 km and is often termed as *outer core.* The *inner core* starts from 4800 km and extends up to 6370 km. It is of unknown nature but is definitely in a solid state and with properties resembling to a metallic body.

2.6 THE HYDROSPHERE

It is a collective term for all the natural water bodies occurring on or below the surface of the Earth. Although hydrosphere makes only 0.03 percent of mass of the Earth, its relevance to the existence of life can hardly be over-emphasized. More than 97 per cent of the hydrosphere is made up of huge surface bodies of saline water called *seas* and *oceans*. The five oceans—the Pacific, the Atlantic, the Indian, the Arctic and the Antarctic ocean—and their associated extensions called seas and *bays* together cover more than 70 per cent of the surface of the Earth. Rivers and lakes that spread over hundreds of thousands square kilometers are other constituents of the hydrosphere. Huge bodies of frozen water, the ice and snow, together that make up the glaciers, are also one of the major components of hydrosphere. Water occurring in aquifers, cavities and cracks of the rocks, called *groundwater*, form another important part of the hydrosphere.

On the basis of present state of knowledge, hydrosphere is a feature unique to our planet only. Although, the origin and development of the hydrosphere is yet not completely resolved, but was definitely not there at the time of origin of the Earth.

2.7 THE BIOSPHERE

This term is sometimes used to express the collective life form, as it exists on the surface and under-water as well. The biosphere depends for its existence on the three zones of the planet: the lithosphere, the atmosphere and the hydrosphere. The biosphere is also responsible for many geological processes that have been going on the planet since the evolution of life. The formation of coal deposits and extensive oil reserves cannot be explained without the existence of biosphere.

2.8 INTERNAL STRUCTURE OF THE EARTH

The real interior of the Earth is nowhere exposed to direct observations. With the presently available expertise and technical skills, exploration can be done only up to a few kilometers in depth, below the surface of the Earth. Therefore, it is usual to resort to the indirect geophysical methods for detailed information about the interior of the Earth. The section to follow is based on the evidences yielded by indirect geophysical methods, such as those by the study of seismic waves released during earthquakes, nuclear shocks, etc.

A major change in the velocity of seismic waves at some specific depths below the surface in numerous records reveals and indicates a change in the nature of medium (material) at that particular depth, known as *seismic discontinuity*. Such a discontinuity is considered to be of fundamental importance in the interpretation of the internal structure of the Earth. The two most significant seismic discontinuities are: the crust-mantle (Mohorovicic discontinuity) and the mantle-core discontinuity (Gutenberg discontinuity), demarcating three major internal zones of the Earth—the crust, the mantle and the core. These discontinuities are described below.

❑ *The Mohorovicic Discontinuity*

It is the first major discontinuity in the seismic records and is named after its discoverer, A Mohorovicic. It has been identified, in the seismic records, at depths of 30–40 km below the continents, 5–10 km below the oceans and 60–70 km below the mountains.

Both the P- and S-waves on reaching these depths are found to undergo a sharp increase in their velocity. The P-waves attain a velocity of 7.75 km/s as against their original velocity of 5.4 km/s in the immediately overlying layer. Similarly, the S-waves traveling at 3.35 km/s attain velocity of 4.35 km/s at this junction. Thus, the Mohorovicic discontinuity marks the lower limit of the skin of the Earth commonly known as crust. The Mohorovicic discontinuity is also referred as *M-discontinuity* or simply as *Moho.* The material below Moho forms a nearly homogeneous zone till a depth of 2900 km is reached, whereafter another striking change is observed in the quality of the material on the basis of the seismic waves reaching there.

❑ *The Mantle-Core Discontinuity*

The seismic waves that cross the Mohorovicic discontinuity continue to travel downwards with almost gradual and uniform increase in their velocity. At a depth of 2900 km below the surface, another major discontinuity is observed in the records of the seismic waves.

At this depth, the P-waves become very sluggish and suffer a decrease in velocity from 13.64 km/s to as low as 8.1 km/s. The S-waves are practically stopped from going deeper into the Earth after this depth. This discontinuity is known as the *mantle-core discontinuity*. The zone of the Earth lying between Mohorvicic discontinuity and the mantle-core discontinuity is called mantle. The mantel-core discontinuity demarcates the end of mantle and also the beginning of a third major zone of the Earth, the core.

In every major earthquake, P- and S-waves are recorded at all the stations lying between the epicenter and 142° arc distance (11,000 km). However, only P-waves are found to reappear between 105° and 142° arc distances (11,000–16,000 km). There is, thus, a *shadow zone* free from P- and S-waves in the record of each deep-seated earthquake. The shadow zone indicates the existence of a zone made up of material of completely different nature compared with that of the upper two zones of the Earth. This zone starts at a depth of about 2900 km and continues up to the center of the Earth (6378 km).

From the foregoing discussion, it is evident that the two discontinuities divide the Earth into three well-defined zones: the crust, the mantle and the core. In each of these zones, there are records of significant variations on the basis of which each zone can be further subdivided into different layers with definite characteristics. Figure 2.2 shows the refraction of primary and secondary earthquake waves inside the Earth. A simplified seismogram is shown in Fig. 2.3.

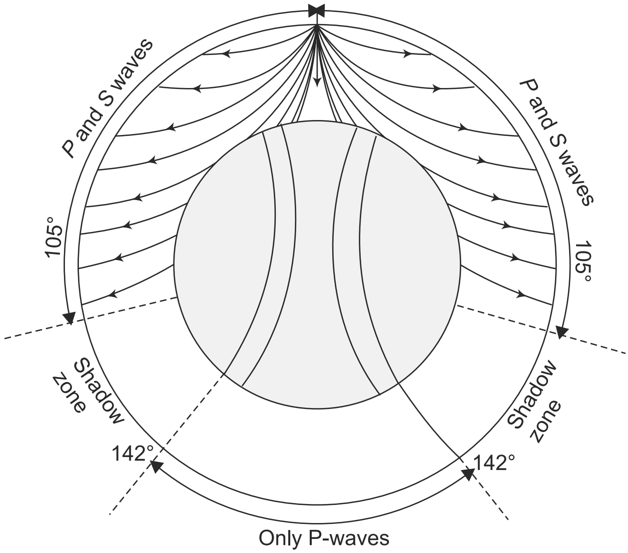

Fig. 2.2 *Refraction of primary and secondary earthquake waves inside the Earth*

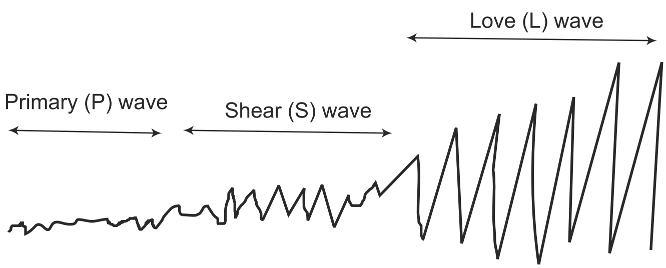

Fig. 2.3 *Simplified seismogram showing primary, shear and love waves*

2.9 THE CRUST

The uppermost shell of the Earth, about 40 km in thickness and containing relatively lighter materials with low melting temperatures is known as crust. The lower boundary of the crust is marked by the M-discontinuity.

❑ *Chemical Composition of the Crust*

The chemical composition of the crust is as follows.

- **Silica (SiO_2)** It is the most dominant component in the Earth crust and is more than 50% by volume in the oceanic crust and above 62% in the continental crust.

- **Alumina (Al_2O_3)** It varies between 13 to 16%.

- **Other Components** These are iron oxide (Fe_2O_3): 8%; lime (CaO): 6%; sodium oxide: 4%; magnesium oxide: 4%; potassium oxide: 2.5%; and titanium oxide: 2%.

The solid aggregate that makes the crust of the Earth is called *rock*. The crust is made up of different types of rocks—the igneous, the sedimentary, and the metamorphic. The crust of the continental regions is divided into two layers: the *sial*—the upper layer rich in silica and alumina, of sp. gr. 2.65 and granitic in character; and *sima*—the lower layer rich in silica and magnesia, of sp. gr. 3.0 and basaltic in character. It may be noted that under oceans, only sima layer is found.

❑ *Thickness of Crust*

Study of seismic waves reveals the following details about the thickness of the crust.

■ **Mountainous Areas** Under the Himalayas, the crust is believed to be 70–100 km thick; under the Hindukush Mountains it is 60 km thick; and under the Andes it is 75 km thick.

■ **Continental Areas** Thickness of the crust in continents varies from 30 to 40 km. However, along the continental slopes, thickness of the crust shows considerable variation. The Continental Crust is further distinguished into three layers: *A, B* and *C*.

The *A* or the *upper layer* is 2–10 km thick and of low density (2.2 g/cc). It is mostly made up of sedimentary rocks. In this layer, the P-wave velocity ranges from 1.8 to 5.0 km/s.

The *B* or the *middle layer* is relatively dense (2.4–2.6 g/cc). The seismic waves attain velocities of 5–6.2 km/s. This layer is also known as the *granite layer*. It is made up mostly of granites, gneisses and other igneous and metamorphic rocks. At places, it acquires a thickness of 20 km or even more. In fact, at many places in the world, it is the *B* layer of the crust, which is exposed on the surface because the overlying *A* layer has been eroded by prolonged weathering action. Since granite layer is mostly made up of silicates of aluminum and potassium, it is also sometimes referred to as *sial* (Si = silica, Al = alumina) layer.

The *C* layer is the *lowermost layer* of the continental crust and has a density of 2.8 to 3.3 g/cc in which P-waves attain as high a velocity as 6 to 7.6 km/s. This layer is also referred as *basaltic layer* and acquires a thickness of 25 to 40 km under the continents. It is predominantly made up of basic minerals (rich in magnesium silicates) and hence is sometimes also known as *sima* (Si for silica and Ma for magnesium).

■ **Oceanic Areas** The crust below the oceans varies in thickness from a maximum of 19 km to as low as a value of 5 km in deep oceans. The oceanic crust is generally the extension of *C* layer of the continental crust that makes the top layer of the oceans in most cases; *A* and *B* layers being practically absent. The oceanic crust is estimated to have a volume of 2.54×10^9 cc with an average density of 3.00 g/cc.

2.10 THE MANTLE

Mantle is a region that is the bulk of the semi-solid Earth. It lies between the crust and core. It starts from M-discontinuity and continues up to a depth of 2900 km. The mantle is the material left in the middle zone after most of the heavy material sank and the light matter rose towards the surface. It is made up of extremely basic material called *ultra-basic*, very rich in iron and magnesium but quite poor in silica. This zone is characterized with high density increasing with depth. The density in the mantle rises from 3.3 g/cc from just below the crust to about 5.7 g/cc at the base of the mantle. The material of the mantle is believed to be variably viscous in nature and the overlying crust-blocks virtually float over it at a very slow rate. The exact nature of the mantle is as yet incompletely understood. It has been subdivided into upper mantle and lower mantle. The boundary between the two mantle layers lies at 900–1000 km below the Earth surface. The upper mantle is further sub-divided into two layers of 400 and 600 km thicknesses respectively.

Most of the important geological processes such as volcanism, seismic activity and formation of mountains (orogeny[*]) are supposed to originate in the mantle. Indirect observations reveal that the mantle has a complex layered structure differentiated into upper mantle, middle mantle and lower mantle.

Recent studies indicate that a part of the upper mantle, from 100 km to 500 km depth, is in a plastic state rather than the solid state. This zone has been named as *asthenosphere*, believed to be located entirely in the upper mantle. It is the source of most volcanic activities of the Earth.

2.11 THE CORE

Core is the innermost concentric shell of the Earth. The boundary of the core begins at a depth of about 2900 km from the surface and extends up to the centre of the Earth.

Indirect observations indicate that the core can be classified as the outer core and the inner core. The outer core comprises the region from a depth of 2900 km to 4800 km below the Earth surface and behaves more like a liquid. The inner core, with a thickness of around 1790 km, is believed to be a solid metallic body. There are significant variations in the density of material immediately outside and inside of the core. At the base of the mantle, density is inferred as 5.7 g/cc that jumps to 9.9 g/cc at the top of the core. Despite such a high density, the outer core is supposed to be in the liquid state. The density reaches a value of 12.7 g/cc at the boundary of the inner core and becomes 13.0 g/cc at the centre of the Earth.

Core is supposed to be chiefly made up of iron and nickel, based on seismological evidences. Velocities of P-waves recorded in the core bear close

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* is the primary mechanism by which mountains are built on continents. Orogens develop while a continental plate crumples and is pushed upwards to form mountain ranges, and involves a great range of geological processes collectively called *orogenesis*.

resemblance to those recorded for nickel iron alloys. Other non-seismological grounds suggesting a nickel iron core of the Earth are the following:

- **The high density of the Earth as a Planet** It is fairly established that the mean density of the Earth is 5.517 g/cc. The density of the rocks of the crust is 2.7 g/cc. The density for the materials of the mantle is also found to range from 3.3 to 5.7 g/cc. Hence, all calculations suggest a density of 12 g/cc for the material of the core. This density is comparable to alloys of nickel and iron.

- **The Composition of Meteorites** Meteorites are considered the wandering fragments of planetary matter. Most of these are made up of ferruginous composition, with iron being an important metal in them.

Note It is argued by many that the iron meteorites are actually fragments from the core of a star or planet-like body of the Solar system that has suffered disintegration during the process of its evolution. As such, the core of the Earth can also be assumed to have a similar composition.

2.12 AGE OF THE EARTH

The exact prediction about the age of the Earth has always been a question and a matter of anxiety and research. Till recently, various methods used in attempts to estimate the age of the Earth were based on a variety of criteria and appeared unconvincing and unreliable. However, the discovery of radioactivity in the twentieth century led to refined predictions regarding the age of the Earth.

While Charles Darwin estimated the age of the Earth about 57 million years on the basis of the separation of the moon from the Earth, Kelvin estimated it to be around 20–40 million years on the basis of cooling of the Earth. Another crude approach was based on the rate of sedimentation and thickness of the Earth. But this approach was rejected in a short interval of time since the rate of sedimentation is different in different parts of the globe. Theory of evolution was applied in an endeavour to compute the time since the origin of organic life. However, the concept of organic evolution was also not acceptable to estimate the age of the Earth. Astronomical data such as changes in the eccentricity of the Earth, periods of perihelion and aphelion, and shifts of the solar system within the Milky Way were also made use of in calculating the age of the Earth. The studies of Helmholtz revealed that the Earth is as old as 22 million years on the basis of emission of heat from the sun. However, all these methods resulted in varying and unreliable estimates of the age of the Earth.

The radiometric dating technique is considered to be the principal and a convincing source of information about the absolute age of the Earth. All rocks and minerals contain long-lived radioactive elements that were incorporated into the Earth when the solar system was formed. Spontaneous breakdown or decay of atomic nuclei is termed as radioactive decay that forms the basis of radiometric dating methods. The technique consists in the measurement of the radioactive material that the rock contains or the amount of natural atomic fission that has occurred in the rock. The method is based on the fact that a radioactive isotope of an element changes into an isotope of another element at a fixed rate. Each radioactive element has its own rate, expressed in terms of its half-life. Some of the examples of radioisotopes (Table 2.2) are as follows.

Table 2.2 *Radioactive parent elements used to date rocks and minerals*

Radioisotope	*Half-life*	*Stable isotope*
Uranium-238	4.47 billion years	Lead-206
Uranium-235	0.7 billion years	Lead-207
Thorium-232	14.1 billion years	Lead-208
Rubidium-87	47.0 billion years	Strontium-87
Rhenium-187	43.0 billion years	Osmium-187
Potassium-40	1.27 billion years	Argon-40
C-14	5730 years	C-12

As of today, the best known techniques are the Uranium-lead dating, Potassium-argon dating and Radiocarbon dating. The most commonly used radioisotope for the purpose of determining the age of the Earth is Uranium-238. It changes into a series of other radioisotopes before a stable (non-radioactive) isotope is formed. Since the rate at which Uranium-238 becomes lead-206 is known, the age of the rock that contains Uranium-238 can be determined from the ratio of Uranium-238 to lead-206. Since potassium occurs very widely in the rocks, its radioactive decay (which leads to formation of argon) can be used to its advantage for calculating the age of the Earth by determining the potassium-argon ratio. Radiocarbon dating uses the decay of C-14 (unstable isotope) to C-12 (stable isotope) for determining the age of organic materials. When an organism dies, it contains a ratio of C-14 to C-12, but as the C-14 decays with no possibility of replenishment, the ratio decreases at a regular rate (the half life of C-14). The measurement of C-14 decay provides an indication of the age of any carbon based material.

The age of the Earth predicted by this method is at least 2.0 billion years. Thereafter, addition of the geochemical concept with radioactive minerals, give an estimate of the age of the Earth to about 4.6 billion years. This data has been validated from the radioactive dating of meteorites, the fragments of asteroids, which fell on the Earth in the past.

Note

Since the oldest rocks of the Earth have been recycled and destroyed due to the plate tectonics and since the Earth and the other slid bodies, such as meteorites, in the solar system are assumed to be formed at the same time, the meteorites can be very well considered for validation of the age of the Earth.

Summary

This chapter is about the Earth, its origin and interior. The nebular, tidal, and gas-dust cloud hypotheses have been presented. Since the interior of the Earth is inaccessible, based on the seismological evidences, the interior of the Earth is explained. Properties of the interior of the planet Earth and the three major segments—the core, the mantle and the crust—is presented in details. The internal structure of the Earth and the two discontinuities—the mohorovicic (crust-mantle discontinuities) and Gutenberg (mantle-core)—are described. The atmosphere which is an important part of Earth environment has been elaborated by its composition and structure. The chapter also encompasses the different methods to predict the age of the Earth. This chapter also provides an overview about the Earth and its different environments.

Terminology

Astronomer	A scientist who studies about space and celestial bodies.
Basin	It is a depression or synclinal structure in which sedimentation take place over the periods.
Discontinuity	Defines a surface inside the Earth after which a sudden change of physical properties at particular depth occurs.
Geological Structures	The structures which are originated in rocks by deformation. Examples: fold, fault and joints.
Geophysical Method	The method through which the sub-surface features are diagnosed like density of material, water pore spaces and other properties below the Earth.
Interstellar	When matter exists in the space between the star system and galaxy.
Magma Ocean	The area where magma is quite huge.
Meteorites	These are chunks of rocks or metal that fall to the Earth from space and are known as shooting stars.
Morphology	This deals with the study of different types of shapes.
Petrology	This is branch of geology which deals with the study of different rocks like igneous, sedimentary and metamorphic rocks.
Planetesimals	These are large sized planets/bodies theorized to have coalesced after condensing from concentrations of diffuse matter in the space. Within the solar nebula, dust and ice particles embedded in gases moved occasionally, colliding and merging. Through this process, called accretion, the microscopic particles formed larger bodies that eventually became planetesimals.
P-Wave	It is type of earthquake waves and also known as primary wave which travels in the entire medium and reaches first on the Earth's surface.

Radioisotopes These isotopes are characterized with radioactive decay. Their existence is measured in half lives, which is how long it takes half of the isotope be lost.

Run-off The flow of water on ground surface which does not infiltrate below ground surface.

Seismicity The frequency or magnitude of earthquake activity in a given area. It refers to the geographic and historical distribution of earthquakes.

S-Wave Type of earthquake waves and also known as secondary wave or shear wave. They displace the ground perpendicular to the direction of propagation..

Exercises

1. Give a brief account of origin of the solar system.
2. How did the Earth form? How old is it? Why is radiometric dating supposed to be the most accurate method for estimating the age of the Earth?
3. (a) Enumerate the various hypothesis of the origin of the Earth. Describe the Nebular hypothesis.
   (b) What are the major differences between the inner core and outer core of the Earth?
4. (a) With the help of a neat sketch describe the interior of the Earth.
   (b) What are the major characteristics of crust, mantle and core?
5. (a) State the reason for the differentiation of the Earth. What was the result?
   (b) How does the chemical composition of the Earth's crust differ from the core?
6. What are the systems of the components of planet the Earth? What are the sources driving the system?
7. What is isostasy? Give some of its evidences.
8. (a) Briefly describe the following:
   i. Atmosphere ii. Hydrosphere iii. Lithosphere
   (b) Describe the classification of atmospheric layers based on thermal variation.
9. (a) Discuss how layering of the Earth's interior can be explained on the basis of indirect observations.
   (b) Describe how seismic waves are useful in delineating subdivision of the Earth's interior.
10. (a) How is the atmosphere held to the Earth? State the major constituents of clean dry air of atmosphere.
    (b) State the role of water vapour and dust particles in atmospheric processes.
    (c) Describe the structure of the atmosphere and the main characteristics of each layer.
11. Write short notes on the following:
    (a) Tidal hypothesis
    (b) Solar system
    (c) Mohorovicic discontinuity
    (d) Radiometric dating

12. Write short notes on following:
   (a) Isostasy
   (b) Age of the Earth
   (c) Continental drift
   (d) Gas-dust cloud hypothesis

13. Write short notes on the following:
   (a) Biosphere
   (b) Ionosphere
   (c) Ozone layer
   (d) Chemical composition of the atmosphere

15. Write short notes on the following:
   (a) Composition of atmosphere
   (b) Structure of atmosphere
   (c) Interior of the Earth
   (d) Origin of the Earth

16. Differentiate between the following:
   (a) Mohorovicic discontinuity and mantle core discontinuity
   (b) Hypothesis and theory
   (c) Inner planets and outer planets
   (d) Body waves and surface waves
   (e) Homosphere and heterosphere

Multiple-Choice Questions

1. Density inside the Earth is maximum in
   (a) crust (b) mantle
   (c) core (d) oceanic ridge

2. The troposphere is boundary between
   (a) troposphere and homosphere
   (b) mesosphere and hetrosphere
   (c) mesosphere and thermosphere
   (d) troposphere and mesosphere

3. The altitude line between troposphere and hemisphere is
   (a) 20 km (b) 30 km
   (c) 40 km (d) 50 km

4. Atmosphere has maximum concentration of following gases:
   (a) Nitrogen (b) Oxygen
   (c) Carbon di oxide (d) Argon

5. Mental is characterized by following elements:
   (a) Si (b) Mg
   (c) Ni (d) Fe

6. Mohorovisic is discontinuity that exists inside the Earth between
   (a) crust and mantle (b) mantle and core
   (c) core and crust (d) crust and asthenosphere

7. Core is characterized by
(a) high density and liquid phase
(b) low density and solid phase
(c) high density and semi-solid phase
(d) low density and semi-solid phase

8. Which of the following instrument rates the intensity of an earthquake?
(a) Seismograph (b) Modified Mercalli scale
(c) Richter scale (d) Sonograph

9. Age of Earth is
(a) 4.6 billion years (b) 4.6 million years
(c) 3.2 billion years (d) 3.2 million years

10. The nebular hypothesis for origin of Earth is based on
(a) cloud and dust (b) water vapour and dust
(c) stars and planets (d) sun and other stars

Answers to MCQs

1. (c) 2. (a) 3. (a) 4. (a) 5. (b) 6. (a) 7. (c) 8. (a)
9. (a) 10. (a)

chapter 3

Magma

3.1 INTRODUCTION

The hot, molten rock material occurring naturally below the surface of the Earth is called *magma*. It is a mixture of semi-molten rock, volatiles and solids, and is a complex high temperature fluid-substance. Magma, a semi-solid material, forms at great depths below the surface of the Earth. The reasons attributed to the state of magma are the rise in temperature with depth and occurrence of radioactive materials. They are not necessarily completely molten, for they may contain a certain amount of growing crystals and fragments of surrounding rocks as well. Magma is a source for the origin of all kinds of igneous rocks. Enriched with gases, particularly volatile matters, when magma erupts through weak Earth surface (volcanoes), it is known as *lava*. Since lava comes out on the surface of the Earth through volcanoes, it is a thoroughly studied material, while magma is not so much within the study scope, as it is inside the Earth at great depths.

The molten magma starts crystallizing whenever there is change in the physical environment, e.g. fall in temperature or pressure due to its upward movement. Cooling and crystallization of magma starts and ends up with the formation of igneous rocks. Further, since magma/lava is a mobile melt, its movement depends upon its density and viscosity. Highly viscous magma is less mobile (atoms move slowly), generates small crystals, and gives a finer structure in the igneous rock. On the other hand, coarser structure is generated, in case magma has low viscosity. The solid and gaseous fractions, however, form only a small part (around 15% by weight) of the magma or lava, which are predominantly made up of liquid material.

3.2 ORIGIN OF MAGMA

Magma is originated by two processes, the partial melting of the Earth crust and anataxis, which may take place either separately or simultaneously.

❑ *Partial Melting*

Temperature, pressure, and composition of rocks are responsible for the partial melting of solid crust, which consists of different rocks to form magma. Melting of the rocks starts whenever there is increase in temperature and pressure. This rise in temperature and pressure may individually be by radioactive decay, collision of plates and movement along major fault planes, or by their combined effects. Gradually, with time, the volume of the molten rock material increases.

In this process, some solid rocks change to liquid form while the others remain unchanged; rocks are composed of different types of minerals, have different melting points and physiochemical properties. When enough rock is melted, the small globules of melt (generally occurring in between mineral grains) link up and soften the rock. Due to high pressures within the Earth, even a small fraction of partial melting may be enough to cause the melt to be squeezed from its source. Melts can stay in place long enough to melt to 20% or even 35%, but are rarely melted in an excess of 50%. It is because eventually, the molten rock mass becomes a crystal and melt amalgamation. The degree of partial melting is critical for determining the type of magma produced. The degree of partial melting can be estimated by considering the relative enrichment of incompatible elements versus compatible elements. Incompatible elements commonly include potassium, barium, cesium and rubidium.

Rock types produced by small degrees of partial melting in the Earth's mantle are typically alkaline (high aluminum to silica ratio). Primitive melts of this composition form lamprophyre, lamproite, kimberlite and sometimes nepheline-bearing mafic rocks such as alkali basalts and carbonatite. Pegmatite may also be produced by low degrees of partial melting of the crust. Some granite composition magmas are eutectic (or cotectic) melts. They may be produced by low to high degrees of partial melting of the crust, as well as by fractional crystallization. At high degrees of partial melting of the crust, granitoids such as tonalite, granodiorite and monzonite can be produced; but other mechanisms, for example anataxis, are typically important in producing them.

❑ *Anataxis*

Anataxis is a process for generation of magmatic melt at a smaller scale. In this process too, the partial melting of only metamorphic rocks take place which later solidifies as igneous rock. In order to have partial melting in the middle to lower continental crust, the continental geotherm must be steepened towards much higher temperatures. The minimum temperature needed to produce partial melting in meta-sedimentary rocks is about 650°C. Under these conditions, water saturated metapelites produce a melt of granite composition. The remaining metamorphic rock and the solidified igneous rock give a new rock, known as *migmatities*. Anataxis, however, also indirectly accelerates the process of partial melting of rocks in lithosphere.

3.3 COMPOSITION OF MAGMA

Since magma is too hot to collect the samples for its chemical analysis, the igneous rocks are tested to identify the chemical composition of magma. The testing of the rock samples reveal that magma contains an average of 99.25 per cent, oxides of silicon, aluminium, iron, calcium, sodium, potassium, magnesium and titanium. Water and volatiles are held in solution in magmas by high pressure. It is, however, held that quite a few volatile components escape from the magma, prior to or during the process of formation of rocks from the magma and hence are not represented in the rocks crystallized at the end. This implies that the exact chemical composition of the magma can not be identified.

Regarding physico-chemical constitution of the magma, it is believed that a few constituents are always dominating in the molten state. Further, the magmatic constituents may be divided into two groups. The first group consists of volatile gases, e.g., hydrogen sulphide, carbon dioxide and sulphur dioxide are characterized by high-vapor pressure. The other group consists of non-volatile gases such as oxygen, nitrogen and hydrogen.

Magma may be classified as silicic magma (rhyolitic magma), intermediate magma (andesitic magma) and basaltic magma (mafic magma). The silicic magma is composed of silica content more than 66% with a temperature range of 600–800°C. It is thick and possesses high viscosity and gas content. The intermediate magma is composed of silica content between 55–65% with a temperature range of 800–1000°C. Basaltic magma contains silica content between 45–55% with a temperature range of 1000–1200°C. It has low viscosity and gas content. Typical chemical compositions of basaltic magma and silicic magma are given in Tables 3.1 and 3.2.

Note Magma with silica content less than 45% is known as *ultra-mafic magma*.

Table 3.1 *Typical chemical composition of basaltic magma as weight percentage*

SiO_2	50	TiO_2	0.67
Al_2O_3	27.33	FeO	9.33
MgO	8.00	CaO	9.33
Na_2O	4	K_2O	0.67
H_2O	0.67		

Table 3.2 *Typical chemical composition of silicic magma as weight percentage*

SiO_2	67.2	Al_2O_3	13.5
Fe_2O_3	2.4	FeO	3.5
CaO	5.0	MgO	2.5
Na_2O	3.0	K_2O	2.9

Magma may also be classified as *acidic magma* and *basic magma*. While the acidic magma is rich in Si, Na and K, the basic magma is rich in Ca, Mg and Fe. The acidic magma produces acidic rocks such as granites, rhyolites, etc., and the basic magma produces basic rocks such as gabbro, basalt, etc.

3.4 PROPERTIES OF MAGMA

Magma occurs in a semi-solid state under pressure inside the Earth, and is in liquid state when it erupts out on the surface of the Earth. Following properties of magma are of interest:

❑ *Density*

Density of magma varies from 2.18 to 2.80 g/cc. It is controlled by composition, temperature and pressure besides the molecular concentration, which are the basic and primary properties of magma. Different constituents in magma may be present in varying molecular concentrations; some making 50–70% ratio and others 30%, and still others as small as 10% and 5% and so on in the melt. Other conditions remaining the same, the components present in smaller concentrations may form smaller crystals.

❑ *Viscosity*

The higher viscosity diminishes the rate of diffusion of molecules towards the centers of crystallization and thus growth of crystals is reduced. In highly viscous magmas, the density of small sized crystals formed may be more as those compared with mobile magmas; the mobile magmas may contain only fewer crystals of bigger dimensions.

3.5 CRYSTALLIZATION OF MAGMA

Magma may either come out through volcanic eruption or may crystallize within the crust or the mantle. The process of crystallization consists in the development/ genesis of crystals from molten magma. The processes involved are differentiation and assimilation. Crystallization of magma is governed by a number of factors like molecular concentration, viscosity, rate of cooling of the melt, and local environmental conditions. To understand the crystallization process, which itself is quite complex, it is essential to understand the uni-component, bi-component and multi-component systems.

❑ *Uni-component System*

In a uni-component system, a single mineral from the molten magma is crystallized, at a particular time. Crystallization of augite, as shown in Fig. 3.1, is an example of the system. The zone of slow crystallization is called the *metastabl*e stage and that for rapid crystallization the *labile* stage. Slow cooling of magma allows both the stages for longer period and yields holocrystalline (coarse-grained crystals). When these two stages pass in a shorter period, the crystallization is faster and yields holohaline (fine-grained crystals).

❑ *Bi-component System*

In a bi-component system, the melting point of any one component is lowered down to variable extent. In this system, two minerals are crystallized simultaneously at eutectic point. This phenomenon is illustrated in Fig. 3.2. A and B are the two end members of the bi-component system and melting points of A and B are respectively denoted by T_A and T_B. The eutectic point is determined by the point E corresponding to the composition of A_{40} and $B_{60,}$ while the eutectic temperature is given by the point T_E.

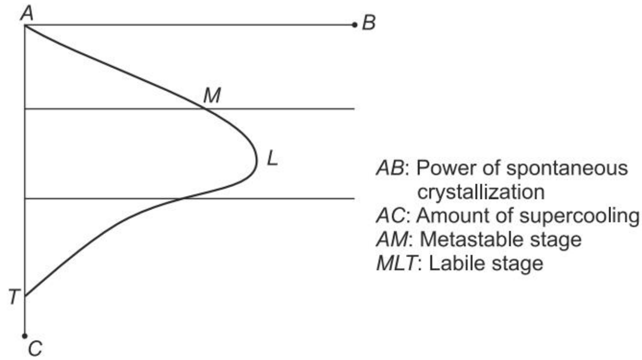


Fig. 3.1 *Uni-component system showing crystallization of mineral augite*

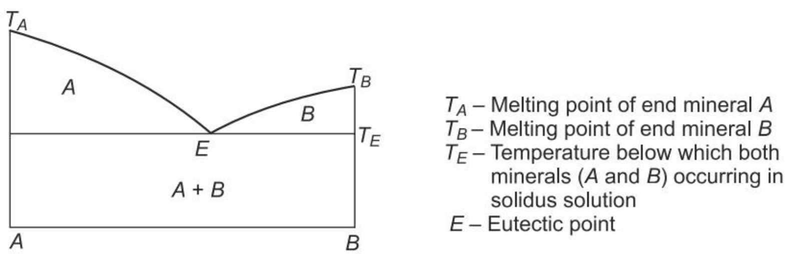


Fig. 3.2 *Bi-component system showing crystallization of minerals foresterite and olivine*

❑ *Tri-component System*

Tri-component system of magma crystallization is also known as Ternary system. In this system, three binary systems are involved in which any two of them are mutually connected by eutectic relation. This system is represented in Fig. 3.3. In the tri-component system of crystallization, the triangle *PQR* represents three pure components placed at the vertices of the triangle. *P*, *Q* and *R* are end minerals and any two of the remaining are mutually connected by eutectic relation. The ternary eutectic is represented by point $E_{PQ/PR/QR}$.

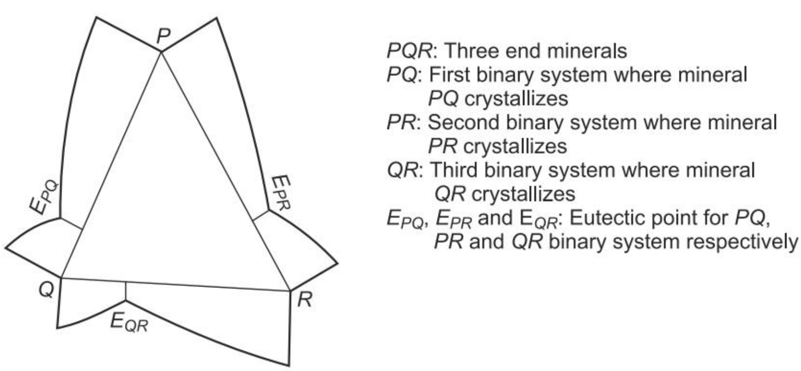


Fig. 3.3 *Tri-component (ternary) system showing crystallization of three independent binary systems*

3.5.1 Differentiation

It is the process by which an originally homogeneous and uniform magma splits into different types of igneous rocks. Differentiation is brought about due to the fact that different minerals crystallize at different temperatures. The differentiation can take place before, during or even after the partial crystallization of minerals in a magmatic melt.

Differentiation prior to crystallization is based on the assumption that it is due to liquid immiscibility. This involves separation of liquid phases of contrasting composition in the parent magma. Subsequent crystallization in these immiscible layers results in the formation of different igneous rocks, reflecting the composition of those layers. Though theoretically this is quite sound and possible, but since the phenomenon of liquid immiscibility is insignificant to cause differentiation on such a major scale as observed in igneous rocks, it has always been questionable.

The concept of differentiation during crystallization involves localization of the process of crystallization and by localized accumulation of crystals. In the first case, crystallization starts only at favourable locations, which can be the cooling margins of a magmatic body. This involves the diffusion of the particular molecules towards the crystallization regions and corresponding deficiency of the remaining melt. Consequently, minerals of early crystallization will be differentiated or separated from those of later crystallization. The process involves a considerable amount of molecular diffusion or convection currents. This type of diffusion is supposed to be an effective process, but whether it could be held responsible for bringing out differentiation on a large scale is questionable.

Differentiation after crystallization is possible in many ways of which *gravitational* and *filtration* differentiations are the more accepted processes.

❑ *Gravitational Differentiation*

Gravitational differentiation involves the sinking or setting of earlier formed crystals under the influence of gravity. The process is controlled by factors like specific gravity, shape and size of crystals on the one hand and viscosity of the melt on the other hand. Heavier and uniformly shaped crystals sink easily and quickly in lighter and less viscous melts.

❑ *Filtration Differentiation*

In this process, the solid phase and the crystals are separated from the liquid phase, the melt, through the operation of lateral stresses. The process involves squeezing out of the liquid from the crystallizing melt and is known as *filter pressing*. The squeezed out liquid may be injected into rocks farther away from the original source and crystallize there, giving rise to new types of rocks.

3.5.2 Assimilation

The process of incorporation of the foreign materials, generally from the host rock into the magmatic melts, is termed *assimilation*. This may lead to a change in the chemical composition of the magma, which on cooling may give rise to different types of rocks. The assimilation, therefore, is also thought as a process that can bring about the diversity in the character of igneous rocks. The process of assimilation cannot, however, be considered only to explain diversity of igneous rocks. It is so because the capacity of most of the magmas to digest the foreign materials is generally limited, being, at the best, up to ten per cent of their own mass.

From the foregoing, it may be said that the origin of igneous rocks is a complicated question. These rocks are thought to have been formed from a single parent or primary magma, basaltic in composition, and originally homogeneous and uniform in nature. From this parent basaltic magma, diverse types of igneous rocks are assumed to have evolved through the process of differentiation which might have been brought out by one or more of the processes like liquid immiscibility, fractional crystallization, gravitational differentiation and filtration differentiation. Much importance is attached to the role of volatile constituents in the magma; their presence in reasonable concentration influences the crystallization process and differentiation to a great extent.

3.5.3 Factors Affecting Crystallization

The principle involved in the formation of igneous rocks from magma or lava is that of crystallization—the formation of solid crystals from a cooling melt, with the change in its physico-chemical condition. Crystallization explains a well-defined atomic arrangement in the solid form of magma resulting from a cooling melt. The magma is supposed to pass through stages of nucleation which is followed by the growth of crystals around these nuclei. The process is quite complicated and is controlled by a number of conditions. It results in the formation of minerals of different compositions that ultimately make up the cooled solid mass, the igneous rock. Crystallization is invariably linked with cooling of magma, and therefore, it starts from the outer margins of a magmatic body, which are to cool first. Crystallization centers are established in the cooling mass at different locations; different molecules are attracted from the melt to the nearby respective centers. Thus, the crystals start growing and enlarging.

During the process of crystallization, the grain size of the ultimate rock is governed by the following factors.

❑ *Rate of Cooling*

Magma, that remains deep underground, cools slowly and results in the formation of coarse-grained crystals with well-defined shapes and faces. Such magma allows completely crystalline igneous rocks. On the other hand, if the rate of cooling is high, the grain size of the crystals would be finer. This is because molecules of various constituents dispersed throughout a melt require sufficient time to move towards their respective centers of crystallization. When this time is not available, the resulting crystals contain only fewer molecules and hence remain small in size. In glass, for instance, cooling may take place at such a fast rate that the molecules do not virtually find time to develop centers of crystallization or to move towards them; the resulting solid is therefore practically without any crystallization or atomic arrangement. Contrary to it, the slow rate cooling of magma yields bigger grains called porphyroblasts like in rocks such as pegmatites and quartz-reef.

❑ *Molecular Concentration*

Different constituents in magma may be present in varying molecular concentrations. Some of them may have 50–70% ratio and others, 30% and still others, as small as 10% and 5%, and so on. Other conditions remaining the same, the components present in smaller concentrations may make smaller crystals.

❑ *Viscosity*

Higher viscosity diminishes the rate of diffusion of molecules towards the centers of crystallization and thus the growth of crystals is reduced. In highly viscous magmas, the density of small-sized crystals may be more as compared to mobile magmas that may contain only fewer crystals of bigger dimensions.

3.6 MOVEMENT OF MAGMA

Magma develops and moves within the mantle or crust when the temperature and pressure conditions are conducive to the molten state. Magma raises toward the Earth's surface when it is less dense than the surrounding rock or weak structural zones are available. The locales where magma accumulates are called *magma-chambers*. Magma can remain in a chamber until it cools and crystallizes forming plutonic rocks, e.g. granite, gabbro, etc. It may also erupt as a volcano, or move into another magma chamber depending upon its density and proximity of weak zones. When magma erupts on the surface of the Earth, it forms volcanic rocks, e.g. basalt, andesite, etc.

The existence of magma beneath the surface and its movement is established from two factors; first the temperature gradient and second, the volcanic eruptions. The temperature of the Earth increases telescopically with depth, on an average, with the rate of 30°C/km. With such a rise of temperature, the Earth may be assumed to be in a molten form at certain depths. Similarly, huge amount of lava have poured out from various volcanoes over time. Many volcanoes are still active and erupt from time to time. The magma/lava that comes from within the Earth requires some source for huge outpouring. Hence, the existence of magma in pockets/places below the surface of the Earth in the form of magma-chambers is accepted.

3.7 LAVA AND LAVA FLOWS

A molten rock below the surface of the Earth that rises in the volcanic vents is known as magma. After the eruption from a volcano (Plate 5), it is called lava. Lava is red hot when it pours on the surface of the Earth and soon changes to dark red, grey, or black in colour as it cools and solidifies. When magma erupts on the Earth's surface from fissures, it separates at low pressures into incandescent lava and a gaseous phase. The gases are liberated either quietly or explosively. The gases escape quietly in case of thin lavas, while in the case of thick lavas the gases build-up tremendous pressure, and escape with explosive noise.

While eruption, the magma which is in a semisolid state becomes in liquid state during its flow on the Earth surface, and is known as *lava flow* (Plate 5). These are streams of non-explosively erupted molten material from a volcano moving down-slope. During the course of their flow, the temperature falls from within outwards until solidification takes place. Generally, flow within a lava stream is laminar. The distance traveled by a lava flow depends on the effusion rate, fluidity of lava, steepness of the slope, channel geometry and obstructions in the flow path. The lava flows are tabular in shape and may range in thicknesses from a few meters to several hundred meters. The lavas cover a very large area before solidifying and the repeated eruptions of magma lead to the formation of considerably thick rocks.

There are many types of lava flows; but the most common types are *ropy lava* (Plate 6), and *blocky lava* (Plate 6). Ropy lava also known as *table lava* is formed by rapid cooling of magma on the Earth's surface. It is generally composed of basic minerals and lower silica concentration. Ropy lava is characterized by its smooth surface and consists of many layers. The floors so formed range between 10 to 30 m. They flow out so fast that the vast volume of Basalt is discharged over an enormous area. Blocky lava on the other hand is characterized by its rough surface and consists of only a few layers. It is formed by the slow cooling of magma on the Earth's surface. Blocky lava is generally composed of acidic minerals and higher silica concentration.

Lava flows on lands may cause extensive damage by burning or burying everything in their path. But, because of their typically slow rate of movement and the modern forecasting techniques, they are not a threat to the human life. However, lava flows may be responsible for fires in case they enter forests and floods if lava flow moves on to snow or ice.

3.8 REACTION SERIES

In the mixed crystal system, an earlier formed mineral reacts with the melt and forms a new mineral. These two minerals form a reaction pair. In the process, a number of minerals may relate in this manner and when arranged in a proper order, they form a reaction series (Fig. 3.4). During cooling of the molten rock material, minerals of basic composition crystallize first. Then minerals rich in silica crystallize. Excess silica that remains at the end of the crystallization period forms quartz.

To establish the order of crystallization, experimental studies were performed by N L Bowen using artificially prepared silicate melts broadly corresponding to basaltic magma. The crystallization under laboratory conditions is considered to represent the order of crystallization of minerals in magmatic melts in a general way. The Bowen's reaction series is further distinguished into two types, the *continuous series* and the *discontinuous series*.

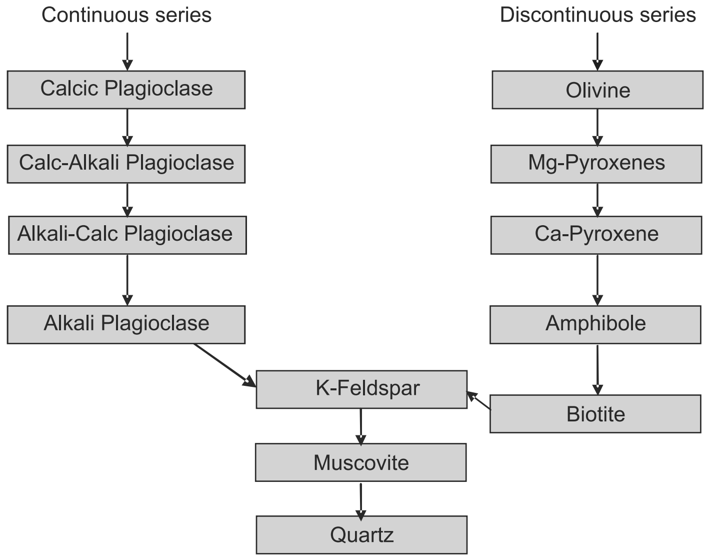


Fig. 3.4 *Bowen's reaction series*

❑ *Continuous Series*

In this series, the atomic structure of the new minerals remains the same. There is only minor change in the chemical composition of the minerals so formed. The best example of a continuous series is that of plagioclase feldspar, which gradually changes from calcic to sodium feldspar.

❑ *Discontinuous Series*

In this series, new minerals with different chemical composition and different atomic structures are formed, and that too at a particular temperature. The Olivine-Biotite series is an example of discontinuous series.

The Bowen reaction series is shown graphically in Fig. 3.4. As shown in the figure, the rocks to crystallize first are ultrabasic, followed by basic and acidic rocks. The three minerals shown at the end, the feldspar, the muscovite mica and the quartz, indicate the fact that from a melt, these three minerals will form towards the last stages of crystallization and they do not react with the remaining melt, if any.

Summary

Magma, after its crystallization and consolidation, is a source for the origin of primary rocks. This chapter includes the different factors like partial melting and antaxis which are responsible for the genesis of magma. The physico-chemical composition of magma and its different types such as silicic and basaltic types have been discussed in this chapter. Properties of magma, viz. density and viscosity, have also been described. Crystallization of magma in different component systems like uni-component, bi-component and tri-component systems of crystallization have been described in detail. Differentiation and assimilation of magma, which are important components of magma crystallization, have been discussed.

Factors affecting the rate of crystallisation which ultimately control factors for the development of shape and size of mineral grains are discussed. Movement of magma is controlled by number of factors and has been briefly described. The lava, its basic nature, movement and types have been presented. The chapter ends with the reaction series, known as Bowen's reaction series, which explains the sequence of mineral crystallization.

Terminology

Carbonatite It is an intrusive or extrusive igneous rock. The mineralogical composition of carbonatite mainly consists of carbonate minerals (greater than 50 per cent). Carbonatites may be confused with marble, and therefore require geochemical verification. They usually occur as small plugs within zoned alkali intrusive complexes, or as dikes, sills, breccias, and veins. They are, almost exclusively, associated with continental rift-related tectonic settings.

Eutectic Point The temperature at which two or more minerals crystallize together.

Filter Pressing When there is a high concentration of crystals the liquid could be forced out of the spaces between crystals by some kind of tectonic squeezing. Consequently the liquid moves into a fracture or other free space, leaving the crystals behind.

Fissures These are minor fractures which are developed in the minerals or rocks by tectonic and non-tectonic forces.

Granitoid It is an igneous rock similar to granite in mineralogical composition and textural behaviour.

Incandescent Lava Fire pit which is characterized by lavaflow particularly nearby crater is called incandescent lava.

Kimberlite It is an igneous rock characterized with plutonic texture and are formed deep within the mantle. It is composed of dark coloured minerals like hornblende, olivine and plagioclase. Kimberlite is the host rock for diamond. Kimberlite occurs in the Earth's crust in vertical structures known as kimberlite pipes, igneous dykes and sills. Kimberlite pipes are the most important source of mined diamonds.

Laminar Flow The flow of lava which has unidirectional flow without any turbulence is called laminar flow.

Pegmatite It is an igneous rock characterized by coarse-grained structure and is composed of orthoclase, quartz, muscovite and tourmaline. Most pegmatites are composed of quartz, feldspar and mica; in essence it is granite. Crystal size is the most striking feature of pegmatites, with crystals usually over 5 cm in size. Individual crystals over 10 meters across have also been found. The world's largest crystal is within a pegmatite. Rarer intermediate composition and mafic pegmatites containing amphibole, Ca-plagioclase feldspar, pyroxene and other minerals are found in recrystallized zones.

Exercises

1. (a) What is magmatic differentiation? Describe the origin of magma and its classification.
(b) Describe the process that brings about differentiation of magma.

2. (a) Describe the process of crystallization of magma consisting largely of two constituents.
(b) Explain the reaction series of Bowen.

3. Explain how the lava/magma is helpful to justify the structure of the interior of the Earth.

4. Describe about the crystallization of magma with an illustration of the Bowen reaction series.

5. Write short notes on following:
(a) Assimilation
(b) Lava flows
(c) Properties of magma
(d) Composition and movement of magma

6. Differentiate between the following:
(a) Lava and Magma
(b) Migmatite and pegmatite
(c) Ropy lava and blocky lava
(d) Differentiation and assimilation of magma

Multiple-Choice Questions

1. Which of the following types of rock is produced by magma that cools deep below the Earth's crust?
(a) Extrusive igneous (b) Intrusive igneous
(c) Foliated metamorphic (d) Sedimentary

2. The rate of cooling of magma or lava is reflected by
(a) mineralogy (b) texture
(c) colour (d) density

3. The temperature (at least a minimum estimate) from which the melt cooled is reflected by
(a) mineralogy (b) texture
(c) colour (d) density

4. Where would you expect to find the largest crystals in a lava flow?
(a) Near the top surface of the flow
(b) In the centre of the flow

(c) Near the bottom of the flow
(d) The crystals would have the same grain size throughout the flow

5. According to the Bowen's reaction series, which of the following pair of phases are likely to be incompatible?
(a) Quartz and alkali feldspar
(b) Ca-plagioclase and olivine
(c) Quartz and olivine
(d) Na-plagioclase and amphibole

6. The last mineral (assuming that the composition is appropriate) to crystallize from magma is
(a) plagioclase (b) olivine
(c) quartz (d) pyroxene

7. What type of magma forms at mid-ocean ridge?
(a) Basalt (b) Andesite
(c) Ultramafic (d) Granite

8. During crystallization of magma, the plagioclase feldspar
(a) is replaced by quartz (b) is replaced by pyroxene
(c) becomes richer in calcium (d) becomes richer in sodium

9. Which mineral is not part of the discontinuous reaction series?
(a) Plagioclase (b) Olivine
(c) Pyroxene (d) Amphibole

10. Which of the following minerals crystallizes first from a basaltic magma?
(a) Quartz (b) Biotite
(c) Pyroxene (d) Olivine

Answers to MCQs

1. (b) 2. (b) 3. (a) 4. (c) 5. (a) 6. (c) 7. (c) 8. (d)
9. (a) 10. (d)

chapter 4

Mineralogy

4.1 INTRODUCTION

A mineral is a substance or chemical compound that is normally crystalline and that has been formed as a result of geological processes. *Mineral* may also be defined as a naturally and inorganically occurring substance that is solid (with exceptions of metallic mercury and water), stable at room temperature, has definite physical properties and specific chemical composition (but not necessarily fixed), can be represented by a chemical formula and has an ordered atomic structure. Minerals possess a set of constant physical properties. Therefore, they can be described by various physical properties which relate to their chemical composition. Difference in chemical composition and crystal structure distinguish their various species. However, determination of crystal structure and chemical composition requires extensive laboratory tests and therefore for field identification of minerals, the physical properties are utilized. It may also be taken note that the physical and chemical properties of the minerals are influenced by the mineral's geological environment of formation.

As of today, there are about 4,900 known mineral species, and with the progress of research one or two elements are added every year. Over 2,000 minerals have been found in the Earth's crust and only less than 10 accounts for over 90 per cent of the Earth's crust. All the minerals in turn are made of atoms of chemical elements. Despite so many naturally occurring elements, the most common Earth's crust forming elements in decreasing order of their abundance are oxygen, silicon, aluminium, iron, calcium, sodium, potassium and magnesium. Of these silicon and oxygen are the most abundant elements which combine to form the mineral silicate group known as *silicates*.

The branch of geology in which the study of minerals is carried out is called *mineralogy*. It is founded on the principles of crystallography and to the microscopic study of rock sections. The importance of types of rocks—an aggregate of minerals or non-minerals having no specific chemical composition—for civil engineers can not be overemphasized. Since rocks are differentiated from each other essentially on the basis of mineralogical composition, a systematic study of minerals becomes all the more important.

4.2 FORMATION OF MINERALS

The processes that are responsible for the genesis of minerals are: solidification—hot molten magma solidifies through cooling; sublimation—wherein the gaseous form of minerals are formed through evaporation and precipitation; recrystalization—in which minerals are formed due to recrystalization during metamorphism; and evaporation—wherein the materials dissolved in water solution crystallize on precipitation under suitable geo-environmental conditions. These processes are described as follows.

❑ *Solidification of Magma*

The magma is a natural hot melt with great variation in its chemical composition, original temperature, viscosity and related physical and chemical properties. The magma continues in the molten state, until surrounding physiochemical environment changes. The factors such as temperature, pressure and viscosity and their changes are responsible for the crystallization of minerals and formation of mineral grains in solid form. The presence of some catalytic substances like water vapours, carbon dioxide, sulphur dioxide, chlorine, fluorine and boric acid greatly facilitates the process of formation of minerals from the magma and enhance the process of crystallization. They accelerate the mobility of the magma and the transfer of molecules dispersed throughout the melt to the centers of crystallization. These catalytic substances are called *mineralizers*. The process of crystallization and mineralization has been discussed in the previous chapter.

The process of genesis of minerals in which hot, molten magma solidifies through cooling is known as *solidification*. This is the most common method of formation of minerals and is also known as *crystallization.* From the partial melting of crust, molten magma is derived which cools down to form minerals. The composition and physical properties of minerals are governed by the rate of cooling and surrounding geological environment. Since the crust is dominated with the alumino-silicates, the most common minerals are silica and feldspar rich in general, and quartz in particular. However, there are a few quite rare and precious minerals also that are derived from residual magma. The examples of such minerals are diamond, ruby, sapphire and aquamarine.

❑ *Sublimation*

This process is generally associated with volcanism and fumaroles. In the process of sublimation, the mineral is formed through evaporation and precipitation directly from gaseous state, because of the sudden cooling of the vapours emanating from volcanoes or fumaroles. Since the emanating gases are only about 2% of magma, very little minerals are derived from it. However, sublimation is rather a rare process.

Sublimation may occur either near dormant or active volcanoes. The examples of minerals formed by this process through dormant volcanoes are gypsum and halite (table salt). Native sulphur and pumice like minerals are derived from the active volcanoes. While native sulphur and pumice are of common occurrence in the volcanic regions of Andaman and Nicobar islands (India), Japan, Mexico and Italy. Sylvite (KCl) is another mineral which commonly occurs around volcanoes in Germany, Poland and Italy.

❑ *Recrystallization*

Recrystallization is a phenomena in which the mineral grains which have been already crystallized are placed for recrystallization due to changes in pressure and temperature (i.e. metamorphism). Since the melting point for each mineral is fixed, the minerals try to stabilize again due to change in temperature and pressure at its original melting point. Consequently, there is a change in the atomic structures of the minerals with or without a change in their chemical composition. The new minerals derived so from the exiting minerals are grouped into three polymorphic silicates the kyanite, the andalusite and sillimanite. All the three polymorphic silicates have same empirical formula $Al_2Si_2O_8$ but with different atomic structures. These minerals are produced as a result of high-to-medium temperature and pressure, affecting the originally alumina-rich minerals. Examples of recrystallization are chlorite and other retrograde minerals.

Similarly, minerals of chlorite group (alumino silicates of Mg, Fe, Ni and Cr, etc.) provide examples of *alteration products* from original silicates of broadly similar chemical composition but of metamorphic origin. The change in their case is brought about at moderate to low temperatures, primarily under the influence of chemically active fluids. Some examples of alternation products are *penninite*, *clinocore* and *pro-chlorite* minerals.

❑ *Evaporation*

In the process of evaporation, the materials dissolved in water solution precipitate under suitable geo-environmental conditions. Some of the examples of minerals formed in the process of evaporation are *gypsum* and *anhydrite*. The waters of rivers, springs, lakes, seas and oceans contain dissolved salts in variable concentrations. From such natural solutions, minerals may be formed in quite good abundance through the processes as evaporation and precipitation. Sodium chloride, the common salt, is actually a mineral called *halite* and is the best example of evaporates. It crystallizes in cubic system and forms easily and abundantly when the sea water or lake water collected in shallow ponds starts saturating with progressive evaporation. This mineral is found naturally (rock salt) and also produced by evaporating salty sea water in specially prepared salt fields.

Anhydrite ($CaSO_4$) and Gypsum ($CaSO_4.2H_2O$) provide examples of another group of minerals formed from solutions by the process of evaporation. Calcite ($CaCO_3$), that often forms features of fantastic shapes in limestone caves the world over, is also a mineral precipitated from carbonate rich solutions due to the loss of CO_2.

In most cases, however, calcite may be of a different origin: organic as in limestones and recrystallized as in marbles.

4.3 CRYSTAL GEOMETRY

The crystal form of a mineral is the outward expression of the molecular structure, which is dependent on the state of equilibrium due to the interatomic forces. Crystal geometry which is also known as crystal morphology deals with faces and forms of crystal. A crystal possesses following three types of symmetry.

❑ *Plane of Symmetry*

It divides crystal into two halves such that one half of the crystal is the mirror image of other. A crystal may have more than one plane of symmetry or even devoid of it.

❑ *Centre of Symmetry*

It is central point about which every face and edge of crystal is matched by one parallel to it on the opposite side of the crystal.

❑ *Axis of Symmetry*

It is a line or an axis through a crystal about which the crystal can be rotated to bring it into an identical position a number of times in the course of one revolution. Such axis is termed diad (two fold), trid (three fold), tetrad (four fold) and hexa (six fold). For example, if during the course of full rotation of 360° about an axis of symmetry, the crystal is brought into an identical position six times, the axis is hexa.

4.4 CRYSTAL SYSTEM

Crystal system is a system in which the relationship between plane of symmetry and crystallographic axis and faces is studied. There are thirty two combinations of symmetry elements belonging to six major crystal systems having possible plane and axis of symmetry. Their symmetry elements are given in Table 4.1. These systems are as follows.

❑ *Cubic System (Isometric)*

In the cubic system of crystal, there are three axes of equal length and perpendicular to each other (Fig.4.1 (a)). This is exemplified by galena.

❑ *Tetragonal System*

The crystal system is recognized by three orthogonal axes perpendicular to each other in which two are of equal length and third, the vertical axis, is the longest (Fig. 4.1 (b)). Example is zircon.

❑ *Orthorhombic System*

These are the crystal system characterized by three unequal axes perpendicular to each other (Fig. 4.1(c)). Example is barites.

❑ *Hexagonal System*

The crystal system is characterized by three equal axes at 120° and fourth axis perpendicular to the existing three equal axes and by its longer length (Fig. 4.1 (d)). Example is quartz.

❑ *Monoclinic System*

The monoclinic crystal system is characterized by three unequal axes out of which two axes are perpendicular to each other and the third axis is inclined (Fig. 4.1 (e)). Examples are gypsum and orthoclase.

❑ *Triclinic System*

The triclinic crystal system is characterized by three unequal axes inclined to each other (Fig. 4.1 (f)). Examples are albite and microcline.

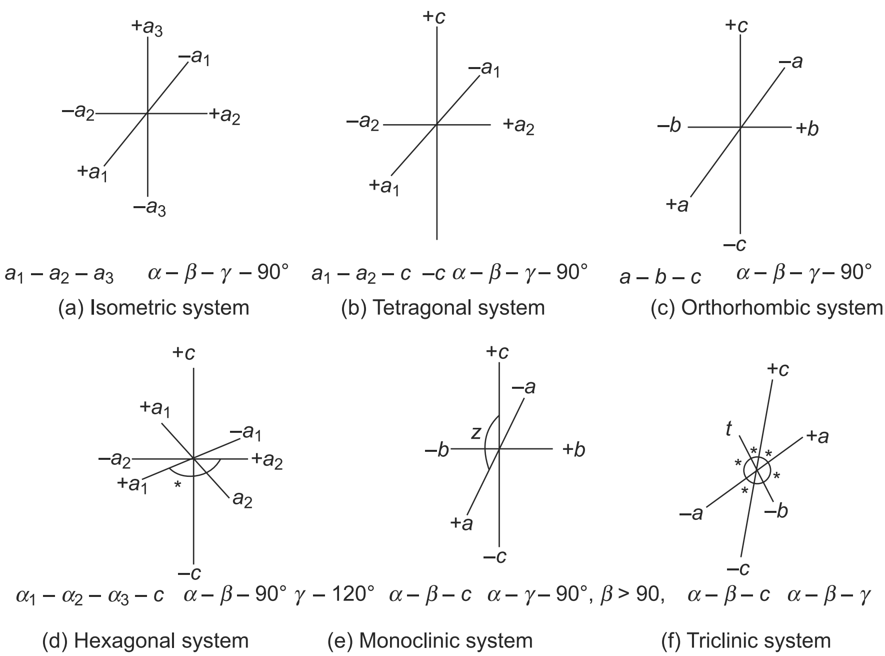


Fig. 4.1 *Crystal systems; axes and their mutual relationship*

Table 4.1 *Relationship between crystal system and axis of symmetry*

System	*No. of Plane of symmetry*	*No. of existing axes of symmetry*				
		Binary axes	*Trigonal axes*	*Tetragonal axes*	*Hexagonal axes*	*Name of Minerals*
Isometric or Cubic System	09	6	4	3	Nil	Pyrite, Galena, Magnetite and Fluorite
Tetragonal	05	4	Nil	1	Nil	Zircon, Rutile, Chalcopyrite.
Hexagonal	7	7	Nil	Nil	1	Quartz, Corundum, Beryl, Tourmaline, Calcite and Haematite
Orthorhombic	3	3	Nil	Nil	Nil	Topaz, Barytes, Stibnite and Sulphur

(*Contd.*)

Table 4.1 *(Contd.)*

Monoclinic	1	1	Nil	Nil	Nil	Gypsum, Orthoclase and Pyroxene
Triclinic	Nil	Nil	Nil	Nil	Nil	Albite, Kyanite, Microcline and Anorthite

4.5 PHYSICAL PROPERTIES OF MINERALS

Physical properties of minerals can be identified by inspection of hand-held specimens in the field or by studying their optical properties (in the laboratory) by a polarized microscope. While the physical properties can be readily and roughly identified by the hand-held specimens, the correct identification can be made only with the polarized microscope. This is achieved by viewing the minerals in groundmass or the thin slices of rocks under polarized light. Since minerals are composed of different elements, they certainly pose different physical properties. Furthermore, each property, to a degree, is diagnostic and all minerals possess some distinctive features that allow for their identification. This makes it necessary to understand and have a knowledge about all the possible physical properties that may help to identify and differentiate minerals and they are as follows.

❑ *Colour*

Colour for some minerals becomes a diagnostic property and is produced due to transmission or reflectance of light by it. In other words, the absorption of certain wavelengths of light by atoms making up the crystal produce different colours of mineral that is seen on its surface by the naked eye. The true colour of mineral is vitiated, however, due to the presence of even minute quantities of impurities present in it. Therefore, one specimen of mineral may display gradation of colour or different colours, making the colour a general property rather than a specific property. Some minerals display a fairly constant colour, e.g. galena (lead grey), but for most minerals, the colour is variable. Pure quartz is transparent, but impurities may yield colours like pink, red or black. Since the colour is always observed by the naked eye, the name of the colour may slightly vary from individual to individual. Hence, the colour of the mineral shown in majority should be taken into consideration.

Note Minerals exist in nearly every imaginable colour, and frequently any single mineral can be found in many different colors. Variations of this type make the identification of a mineral by color alone not to be a safe proposition.

❑ *Streak*

It is the colour of powdered mineral and is a more reliable and consistent indicator than the body colour of the mineral. The mineral is scraped, knifed or rubbed across a streak plate, made up of unglazed hard porcelain, and is seen by observing any mark left. Harder minerals than streak plate do not yield any colour of the powder. It is a diagnostic property for certain ore minerals, e.g. haematite, the streak of which is cherry red, but its colour is steel grey or iron-black.

❑ *Lustre*

It is the reflectance from mineral surface in ordinary light. Lustre depends upon the arrangement of mineral grains along crystal axis. Broadly, the types of lustre observed in minerals may be metallic or sub-metallic or nonmetallic. These are described as follows.

■ **Metallic** When a mineral resembles the shining surface of polished metals, the lustre is called metallic, e.g. the minerals galena and pyrite have metallic lustre. It is mainly used to describe mineral ores.

■ **Sub-metallic** When a mineral resembles imperfect lustre (less brilliant) of metals, the luster is called sub-metallic. For example, the minerals columbite and magnetite have sub-metallic lustre. It is mainly used to describe ore minerals and opaque minerals.

■ **Nonmetallic** The examples of non-metallic lustres are vitreous, pearly, admantine, greasy, resinous and earthy. These are as follows.

- *Vitreous* When a mineral resembles the lustre of broken glass; the most common example is that of quartz. It is mainly observed in silicate minerals.
- *Pearly* It is the lustre exhibited by pearls. Some of the examples of minerals displaying pearly lustre are muscovite and calcite.
- *Admantine* When a mineral has a brilliant shining resemblance like a diamond, it is termed as admantine lustre; the mineral, e.g. is psilomilane.
- *Greasy* Mineral that shines like oil is known to have a greasy lustre. For example talc, nephaline, etc., have a greasy lustre.
- *Resinous* When minerals exhibit a lustre like resin, they are called to have resinous lustre. The example of such a mineral is sphalerite.
- *Earthy* When a mineral has no shine but looks like soil in its appearance, the lustre is called earthy or dull; the most common examples are the lustre of kaolin and magnesite.

❑ *Cleavage*

The tendency of a mineral to break along a certain definite direction and yield almost a smooth plane surface is called *cleavage*. Cleavage is an indicator of the difference in strength between atomic bonds of the mineral. It is pervasive (repetition) in nature and occurs along different crystal axis in different minerals. Cleavage is a diagnostic property for certain minerals. It is denoted as perfect or imperfect and also somewhere as a set of cleavage. If the mineral shows a distinct cleavage, it is called perfect and when indistinct it is called imperfect. For example, calcite shows perfect cleavage and has three sets of cleavage. Minerals will typically either have no cleavage, or may have cleavage along one, two or three or even more planes of weaknesses. Minerals that have well-developed cleavage include micas as well as halite and galena.

❑ *Fracture*

The breaking of a mineral in a direction other than that of cleavage is known as *fracture*. Fracture, which is also a description of the breakage of mineral, is often confused with cleavage. It may be taken note that while cleavage is a direct product of the atomic arrangement; fracture does not follow internal planes of weakness. The commonly encountered form of fractures is: *even*—plane and smooth surface; *uneven*—rough surface; *conchoidal*—curved surface (glass); *hackly*—surface studded with jagged elevations and depressions; and *splintery*—breaking in fibres (asbestos, wood).

❑ *Hardness*

It is a property of mineral that shows resistance of its surface to abrasion or scratching. Hardness of mineral depends upon the internal arrangement of mineral grains and atomic structures. There is no exact measure of mineral strength; therefore, only relative scales of hardness have been developed. Hardness is graded as relative hardness by rubbing the mineral with another of an unknown hardness. Moho's scale of hardness is most commonly used and is an accepted scale to assign a numerical value. The scale consists of ten minerals arranged in the order of increasing hardness from 1 to 10. The Moho's scale is
Talc: 1, Gypsum: 2, Calcite: 3, Flourite: 4, Apatite: 5, Orthoclase: 6, Quartz: 7, Topaz: 8, Corundam: 9 and Diamond 10.

Notes

1. This wide range in hardness allows for the recognition of some minerals that might otherwise have similar physical properties.
2. As an example quartz has the hardness value of 7 in Mohs scale.
3. The only common mineral that has hardness greater than 7 is garnet; the other minerals with hardness value greater than 7 are semi-precious or precious stones.

❑ *Specific Gravity*

It is a physical property of mineral and is defined as a ratio of weight of mineral in air to its weight in water. Since it is a relative value, it is determined experimentally. The specific gravity of common silicate minerals is about 2.65. This implies that they are 2.65 times as heavy as water. Specific gravity depends upon the chemical composition and atomic arrangements, and is governed by the nature of atomic arrangements.

Notes

1. Specific gravity alone is not a diagnostic property but along with any other diagnostic property, it becomes important.
2. The examples of low specific gravity minerals are silicates, carbonates, (2.2 to 4) etc., whereas native metallic elements such as pure copper, gold etc. are the examples of high specific gravity (> 7). Metallic ores such as sulphides and oxides have medium specific gravities between 4.5 and 7.5.

4.6 OPTICAL PROPERTIES

Optical mineralogy is the study of minerals and rocks made by measuring their optical properties. Most of the rock and mineral samples are prepared as thin sections for study in the laboratory with a petrological microscope. Optical mineralogy is used to identify the mineralogical composition of rocks in order to reveal their origin and evolution.

In the identification of minerals, a proper study of their optical properties is of great value. Precise and specific identification of minerals can be made conveniently with reference to their optical properties alone, as studied under special type of microscope known as polarizing Petrological Microscope. The optical properties of minerals which are studied under microscope may be categorized in two parts:

(a) Optical properties under polarized light when the light is passed through the polarizer only; analyzer (nicol prism) is not inserted. The optical properties of minerals which can be studied are colour, pleochroism, shape, cleavage and relief.

(b) When the light is passed through the polarizer and analyzer is inserted, the light is partially absorbed and reflected by the minerals. By this process, the optical properties like extinction angle, twinning, relief etc. are studied.

❑ *Principle of Polarized Light*

A ray of ordinary light travels in straight lines, in all the directions. However, this light which travels in all the directions is not that useful for the optical study of minerals. It is because the absorbance and reflectance of the light varies in different directions. Polarized light that travels in a particular direction is used to its advantage for the study of different optical properties of the minerals.

Although ordinary light is utilized for the study of some of the optical properties of the minerals, but most of the optical properties are best studied with the help of polarized light. In case of polarized light the vibrations are not allowed to take place along all the planes, but these are confined necessarily to one specified plane only. This phenomenon of confinement of the vibrations along one particular plane only is known as polarization and the specific plane along which such vibrations are allowed to take place is defined as the plane of polarization. A ray of light may be polarized, at least partially, when it is subjected to reflection or refraction and completely, when it undergoes what is known as double refraction.

4.6.1 Optical Properties of Minerals Studied Under Polarized Light

❑ *Colour*

Minerals may be colourless, weakly coloured or strongly coloured. Often, the colour of a mineral in hand specimen and in thin section have the same nomenclature (e.g., red minerals will be red in both views, green minerals will be green in both views, etc.), although the colour in thin section is typically not as intense. Sometimes colour in thin section does not match colour in hand specimen, especially for dark coloured minerals. For example, hornblende is generally black when viewed in hand specimen, while in thin section it is likely to appear in various shades of brown or green. The different colours in hand specimen and thin section is because of following two reasons:

1. The colour seen in thin section is the colour of transmitted light; the colour in hand specimen is the colour of reflected light.
2. Plane polarized light is used while viewing minerals in thin section. When a mineral grain is heterogeneous (has not the same composition everywhere), it may exhibit patchy colour (different colours in different places) in thin section. Examples are different varieties of garnet.

❑ *Pleochroism*

Pleochroism is defined as the characteristic by virtue of which a mineral may exhibit variation in its colour with changes in the plane of vibration, within the mineral under polarized light. The phenomenon of pleochroism is to be ascribed to different absorption of the components of white light within a mineral, along its different vibration directions. Pleochroism is often found to be a characteristic feature of some of the common rock-forming minerals; the examples being biotite and hornblende.

When examined in ordinary non-polarised light, this phenomenon cannot be observed since, in such case, the mineral would exhibit an average colour due to light rays vibrating along all the vibration direction within it. Amorphous minerals and those which crystallize in isometric system are necessarily non-pleochroic due to their uniformity in atomic structure in all directions. Uniaxial minerals may but do not necessarily always show what is known as dichroism (i.e., variation in colour between two extremes only corresponding to the two dissimilar direction of vibration in them), while biaxial minerals only are capable of exhibiting true pleochroism since only such minerals have two dissimilar absorption of light.

❑ *Shape*

Minerals occur in different shapes which are not easily identified in hand specimen. When mineral's shape is studied under microscope through thin section, it is very easy to identify the shapes of minerals. Shapes of minerals are categorized on the basis development of their faces and classed as euhedral (all the faces are well developed and smooth), subhedral (some faces are developed and some are not developed) and anhedral (none of the faces are developed and are rough).

❑ *Cleavage*

It is observed under polarized light and number of sets of cleavage is determined. Each weak plane has particular direction and repetitive in nature. Examples are two sets of cleavage in biotite (perpendicular to each other) and hornblend (diagonal to each other).

❑ *Refractive Index*

If an analyzer is inserted in such a position that it is crossed relatively to the polarizer the field of view will be dark where there are no minerals, or where the light passes through isotropic substances such as glass, liquids and cubic crystals. All other crystalline bodies, being doubly refracting, will appear bright in some position as the stage is rotated. The only exception to this rule is provided by sections which are perpendicular to the optic axes of crystals. These remain dark or nearly dark during a whole rotation. It is verified by the study of medium (Canada balsam) by lowering the objective. If the field converges towards centre by lowering the objective, it is said that refractive index (R.I) of medium is higher than mineral and vice-versa, e.g., calcite has property of double refraction.

❑ *Relief*

Relief is a function of the difference of refractive indices of a crystal and its surroundings. The effect of relief is to make the mineral to differ from its surroundings. Most thin sections consist of a basal glass slide (1.1 5 mm thick), a cover glass (0.17 mm thick) and mineral or rock chip (0.03 mm thick) sandwiched between these glasses and glued with Canada Balsam (CB) of RI=1.537. Relief is examined with the observation in the difference of brightness of mineral and Canada balsam. When the boundary of mineral is darker than its central part, the mineral is said to have high relief.

4.6.2 Optical Properties of Minerals Studied Under Cross Nicol

❑ *Extinction*

When the mineral absorbs maximum light along a particular direction the mineral becomes dark. This phenomenon takes place only in anisotropic mineral. The angle is measured through rotating stage of microscope graduated with 360°. Extinction angle is difference between the angles when the same crystal of mineral becomes darkest and brightest during rotation of stage; For example hornblende has 39° extinction while augite has 45°.

❑ *Twinning*

It is optical property of mineral in which alternative dark and bright bands appear in a single crystal of particular mineral. It is due to absorbance and reflectance of light simultaneously along optic axis of mineral. Examples are microcline and albite.

Crystal twinning occurs when two separate crystals share some of the same crystal lattice points in a symmetrical manner. The result is an intergrowth of two separate crystals in a variety of specific configurations. A twin boundary or composition surface separates the two crystals. Crystallographers classify twinned crystals by a number of twin laws. These twin laws are specific to the crystal system. The type of twinning can be a diagnostic tool in mineral identification. Twinning can often be a problem in X-ray crystallography, as a twinned crystal does not produce a simple diffraction pattern.

Simple twinned crystals may be contact twins or penetration twins. Contact twins share a single composition surface often appearing as mirror images across the boundary. Plagioclase, quartz, gypsum, and spinel often exhibit contact twinning. Merohedral twinning occurs when the lattices of the contact twins superimpose in three dimensions, such as by relative rotation of one twin from the other, e.g., metazeunerite. In penetration twins the individual crystals have the appearance of passing through each other in a symmetrical manner. Orthoclase, staurolite, pyrite, and fluorite often show penetration twinning.

If several twin crystal parts are aligned by the same twin law they are referred to as multiple or repeated twins. If these multiple twins are aligned in parallel they are called polysynthetic twins. When the multiple twins are not parallel they are cyclic twins. Albite, calcite, and pyrite often show polysynthetic twinning. Closely spaced polysynthetic twinning is often observed as striations or fine parallel lines on the crystal face. Rutile, aragonite, cerussite, and chrysoberyl often exhibit cyclic twinning, typically in a radiating pattern.

❏ *Birefrengence*

Birefringence is the optical property of mineral having a refractive index that depends on the polarization and direction of propagation of light. These optically anisotropic materials are said to be birefringent (or birefractive). The birefringence is often quantified as the maximum difference between refractive indices exhibited by the material. Crystals with asymmetric crystal structures are often birefringent.

Birefringence is responsible for the phenomenon of double refraction whereby a ray of light, when incident upon a birefringent material, is split by polarization into two rays taking slightly different paths. This effect was first described by a Danish scientist Rasmus Bartholin in 1669, who observed it in calcite, a crystal having one of the strongest birefringence. However it was not until the 19th century that Augustin-Jean Fresnel correctly described the phenomenon in terms of polarization, understanding light as a wave with field components in transverse polarizations (perpendicular to the direction of the wave vector).

$$\text{Birefringence} = R_i - R_o$$

where R_e = refractive index for extraordinary ray and, R_o = refractive index for ordinary ray.

For example quartz has biferengence +0.009 and, beryl has -0.045.

❏ *Twinkling*

In anisotropic minerals where more than one refractive index are present, relief changes with respect to the crystallographic orientation. This effect is most obvious with minerals having large difference in their RI's. As an example, for calcite with R.I of 1.486 (< 1.537, the R.I of CB) and of moderate relief (0.051) and that with R.I of 1.658 (> 1.537, the R.I of CB) and high relief (0.121) will produce twinkling. This phenomenon is known as twinkling.

4.7 CLASSIFICATION OF MINERALS

On the basis of application/use, minerals are broadly classified as rock-forming minerals and the ore-forming minerals. The rock-forming minerals are those that are found in abundance in the rocks of the Earth's crust while ore-forming minerals are not, but have economical value. Study of rock-forming minerals is important from a civil engineering view point, whereas in-depth knowledge of ore forming minerals is important for metallurgical and mining engineers, and mineralogical professionals.

4.7.1 Ore-Forming Minerals

These minerals are formed from the solidification of magma or recrystallization. Sulphides of common elements occurring in rock-forming minerals are classified as ore-forming minerals. It may be noted that the economically exploitable minerals like galena, pyrite, chalcopyrite, etc., are also called ore-forming minerals.

4.7.2 Rock-Forming Minerals

The great bulk of rocks of the Earth crust are formed by only a few (not more than one hundred) minerals and are grouped together as rock forming minerals. Amongst these minerals, about 25 or so make up almost 99.5 per cent of the rocks. Therefore, practical identification of most common rocks requires study of a limited number of minerals making the job of a practicing engineer quite simple. Since silicates, oxides and carbonates groups of minerals are the most common rock-forming minerals; these are discussed in the sections to follow.

4.8 SILICATE GROUP

About eighty per cent of the Earth's crust is made up of silicates and free silica. Among the silicate group, the total number of minerals known to occur in nature may easily approach to about one thousand species. A great majority of them are quite rare in occurrence. Since it is one of the biggest groups of minerals, even a little knowledge about important aspects of this group will be quite useful. The important aspects of the silicate group of minerals are as follows. Further, the descriptive study of the important minerals of this group is presented in Appendices 1 to 4, while Appendices 5 to 7 explain nonsilicate minerals.

4.8.1 Chemical Composition

Most common silicate minerals are made up chiefly of a few of the following nine elements: Na, K, Al, Ca, Mg, Fe, Li, Si and O with some of the other elements in traces. Notwithstanding the fewer elements that go to make up the silicates, the variety and complexity of chemical composition of silicates still remains the most challenging assignment for a chemical mineralogist. In some cases, it may be impracticable to express the chemical composition of a silicate by a simple formula.

4.8.2 Atomic Structure

As a result of studies using latest techniques like X-ray defraction (XRD) and X-ray flouroscence (XRF), a vast amount of information has been collected about the general constitution of silicates. The scope of the book limits discussion about the atomic structure of silicates. Only most important conclusions are mentioned below:

All silicates are a repetition of a fundamental silicon–oxygen tetrahedron, represented by $[SiO_4]^{4-}$. The shape of the tetrahedron is described by very small Si^{4+} ion (cation) situated in the centre and surrounded on the four sides by relatively big, five times in size, oxygen ions (anions) as shown in Fig. 4.2. Further, the dimensions of this unit cell of silicon–oxygen tetrahedron are constant. This fundamental unit which is repetitive is linked and joined in different ways, giving rise to different types of silicate structures.

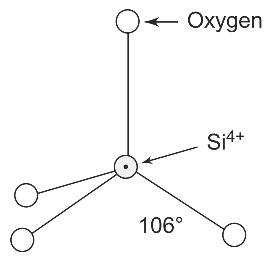


Fig. 4.2 *Silicon-Oxygen tetrahedron*

❑ *Independent Tetrahedra*

A unit $[S_iO_4]^{4-}$ has four negative charges. Hence, it has the capacity to exist as an isolated or independent tetrahedron, provided these four negative charges are balanced by four positive ions of other metals. This actually happens in nature in orthosilicates. Thus, zircon and magnesium, which have four and two valencies respectively, easily combine with an independent tetrahedral $[S_iO_4]^{4-}$ giving rise to a zirconium silicate ($ZrSiO_4$). Sometimes, more than one (two, three or four) elements may combine with an independent tetrahedron to satisfy the four negative valencies that gives rise to different types of minerals.

❑ *Doubly Linked Tetrahedra*

In some cases, SiO_2 may first get linked together in such a way that one oxygen atom is held common between the two cells (Fig. 4.3). The net negative charge left in the two joint tetrahedral is 6(O–Si–O–Si–O) and the formula for such a coupled tetrahedral is $[Si_2O_7]^{6-}$. In fact, it is known as Si_2O_7 group. This double tetrahedron is also capable of independent existence when its six negative charges are satisfied by an equal number of positive metallic elements.

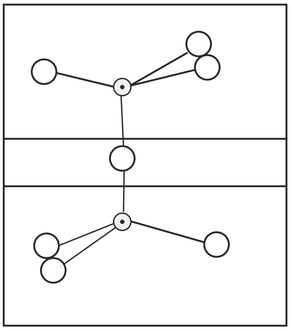


Fig. 4.3 *Double tetrahedra*

❑ *Complex-Linked Tetrahedra*

In some cases, three, four and six tetrahedral may be linked together in such a way that they form closed ring-type structures (Fig. 4.4).

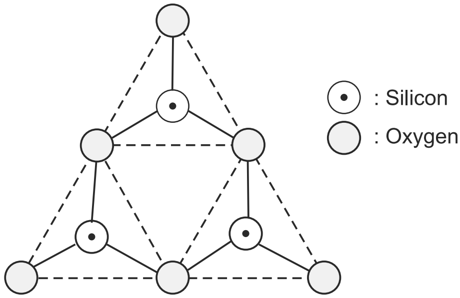


Fig. 4.4 *Complex linked tetrahedra*

4.8.3 Structural Forms

The single tetrahedron and the double-linked tetrahedron as described above may in themselves be repeated in space in a variety of ways giving rise to different structural forms in the silicate minerals. Among these structural forms, the following are of common occurrence.

❑ ***The Sheet Structure***

A two-dimensional continuation of silicon tetrahedron commonly results in a layered sheet structure; here, three oxygen ions are shared. It is characterized by linking of the tetrahedrons in such a way that all the three apexes of one tetrahedron are linked with one adjoining tetrahedron resulting ultimately into a hexagonal pattern repeated lengthwise and breadthwise (Fig. 4.5).

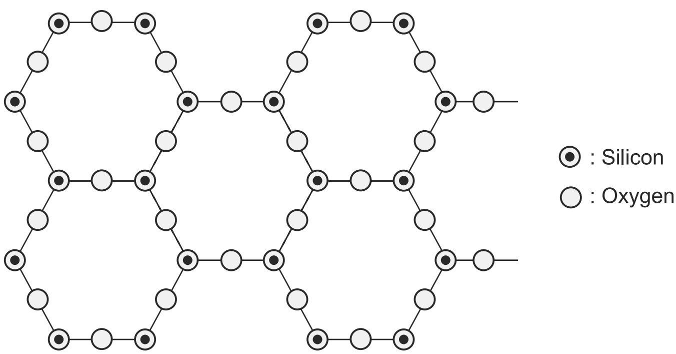


Fig. 4.5 *Sheet structure*

Such sheets may be linked with other identical sheets resting above or below through metallic ions resulting in a considerably weaker bond. This is the most characteristic atomic structure of flaky, platy and lamellar minerals like micas, chlorites and clay minerals.

❑ ***The Network Structure***

This is also known as the *framework* structure. In this type of structure, the silicon-oxygen tetrahedron are so arranged that they form a three-dimensional network. In such a network, oxygen ions at all the four corners are shared, each oxygen ion being shared by two adjacent tetrahedra. The examples are feldspars and quartz (Fig. 4.3).

❑ *The Chain Structure*

It results from a single-dimension continuation, wherein each tetrahedron is linked to an adjacent tetrahedron (one on the right and the other on the left) by sharing the two corners; here two oxygens are shared. In other words each silicon ion holds three oxygen ions in accordance with a general formula R [SiO_3]. This is the characteristic structure of the pyroxene group of silicates and is commonly referred as single-chain structure (Fig. 4.6).

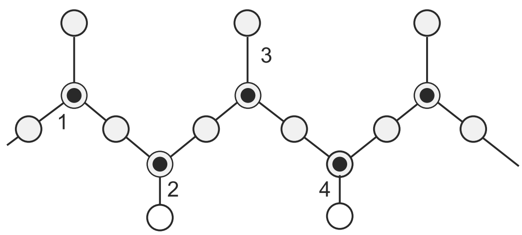


Fig. 4.6 *Single-chain structure*

A double-chain dimensional continuation is also possible according to formula $[Si_4O_{11}]^{6-}$. The amphibole groups of minerals have been found to exhibit this type of structure (Fig. 4.7). These will have six, eight and twelve free negative charges to be satisfied. Their formulae are expressed respectively as: $[Si_3O_9]^{6-}$, $[Si_4O_{12}]^{8-}$ and, $[Si_6O_{18}]^{12-}$. A large number of complex silicates have more than two fundamental tetrehedra linked together in this manner.

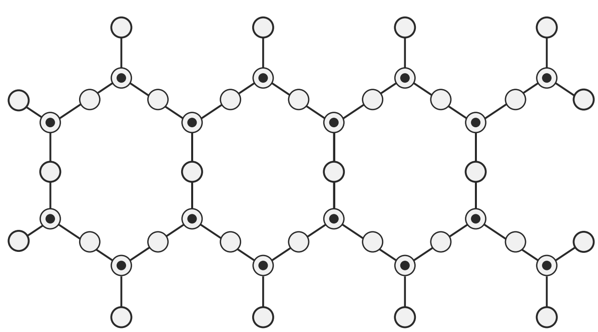


Fig. 4.7 *Double-chain structure*

4.9 THE FELDSPAR GROUP

Feldspars, the most prominent group of minerals, makes more than 50% (by weight) crust of the Earth up to a depth of 30 km. These occur chiefly in the igneous rocks (more than 60 %) but also form a good proportion of their metamorphic derivatives, and in some sedimentary rocks like arkose and greywacks (varieties of sandstone). The group comprises about a dozen of minerals of which 3 to 4 are the most common in rocks.

4.9.1 Chemical Composition

Feldspars are chiefly alumino-silicates of Na, K and Ca also referred to as alumo-silicates. These are represented with a general formula WZ_4O_8 in which W denotes Na, K, Ca and Ba, and Z denotes Si and Al. The Si:Al shows a variation from 3:1 to 1:1. Some examples of chemical composition of feldspar minerals are $NaAlSi_3O_8$ (albite), $KAlSi_3O_8$ (orthoclase) and $CaAl_2Si_2O_8$ (anorthite). Some of the metals that may be present in feldspars, either in appreciable quantities or in traces are barium, lithium and rubidium. An important character of the chemical constitution of feldspars is to occur in iso-morphous series as described in Section 4.9.4.

4.9.2 Atomic Structure

Feldspars show a continuous three-dimensional network type of structure, at atomic level, in which the $[SiO_4]^{4-}$ tetrahedra are linked at all the corners. Each of the oxygen ions is shared by two adjacent tetrahedra. The $[SiO_4]^{4-}$ tetrahedra are accompanied in this network by $[AlO_4]^{5-}$ tetrahedra, making the feldspars complex, three-dimensional framework of the above two types of tetrahedra. The resulting network is negatively charged and these negative charges are balanced by the presence of positively charged K, Na, Ca and Ba, etc.

4.9.3 Crystallization

The feldspar groups of minerals crystallize only in two crystallographic systems: the monoclinic and triclinic. The plagioclase division of feldspars, however, crystallizes only in the triclinic system.

4.9.4 Classification

Feldspars are classified on the basis of the chemical composition and mode of crystallization.

Based on chemical composition feldspars fall into two main groups: the *potash* feldspars and the *soda lime* feldspars.

The common minerals of the potash feldspars are orthoclase ($KAlSi_3O_8$), sanidine ($KAlSi_3O_8$) and microcline ($KAlSi_3O_8$) and that of soda-lime feldspars are albite ($NaAlSi_3O_8$) and anorthite ($CaAl_2Si_2O_6$). These are also called *plagioclase felaspars* and consist of an isomorphous series of the following six feldspars, with the two components albite and anorthite as the end members.

1. Albite	2. Labradoirte	3. Oligoclase
4. Bytwonite	5. Andesine	6. Anorthite

The above series is also known as the *albite-anorthite series*.

Based on the mode of crystallization, feldspars fall into the following two crystal systems.

Monoclinic Feldspars	*Triclinic Feldspars*
1. Orthoclase (K Al Si_3 O_8)	1. Microcline (K Al Si_3 O_8)
2. Sanidine (K, Na) $(Al\ Si)_4$ O_8	2. Albite-Anorthite series (six minerals)

4.9.5 Physical Properties

In addition to their close relationship in chemical composition, crystallography and atomic constitution, feldspar group of minerals exhibit a broad similarity and closeness in their physical characters as well. Differentiation of one variety from the other requires usually very thorough microscopic examination. These are generally light in colour because of the absence of Fe and Mg, low specific gravity (generally around 2.6), a double cleavage and a hardness varying between 6–6.5. The lustre is vitreous, and the colour white, grey, pink or green.

4.9.6 Description

Among the feldspar group, the common mineral species as rock-forming minerals are described in Appendix 1.

4.10 PYROXENE GROUP

The pyroxene group of minerals form another set of important rock-forming minerals. They occur in good abundance in the dark-coloured igneous and metamorphic rocks. Among the ferro-magnesium minerals, pyroxenes occupy first place as a rock forming group. A11 the minerals of this group are closely related in their atomic constitution, crystallization and general physical properties.

4.10.1 Chemical Composition

Pyroxenes are essentially ferro-magnesium silicates with other elements as calcium, sodium, aluminium and lithium present in varying amounts in different varieties. In its simplest form, the chemical composition of pyroxenes may be represented by the formula $RSiO_3$ with R representing Ca, Na, Al and Li, etc. The most important chemical character of the pyroxenes is the Si : O ratio which is 1 : 3 and is explained by their atomic constitution.

4.10.2 Atomic Structure

The pyroxenes show the single-chain structure of silicates. In this type of constitution, the fundamental silicon-oxygen tetrahedron are linked together by sharing the two corners (one on the right and the other on the left). In other words, one oxygen atom is shared between two adjacent $[SiO_4]^{4-}$ giving rise to the typical prismatic cleavage of the group. The lateral bonding of the tetrahedra so disposed is achieved by Ca, Mg and other positive ions (Fig. 4.8).

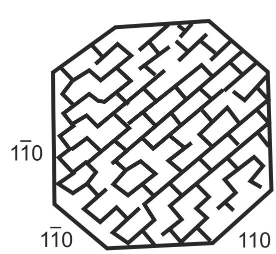


Fig. 4.8 *Cleavage in pyroxene*

4.10.3 Crystallization

Pyroxenes crystallize in two systems, the orthorhormbic and monoclinic. The cleavage angles in pyroxenes are 87° and 93° and form a distinct feature of pyroxenes.

4.10.4 Classification

Pyroxenes are commonly classified on the basis of their crystallization in the following two groups, viz. orthorhombic and monoclinic.

- **Orthorhombic Pyroxenes**
  1. Enstatite $MgSiO_3$
  2. Hypersthene $(Fe, Mg) SiO_3$
- **Monoclinic Pyroxenes**
  1. Clinoenstatite $MgSiO_3$
  2. Clinohypersthene $(Fe, Mg) SiO_3$
  3. Diopside $CaMgSi_2O_6$ or $CaMg (SiO_3)_2$
  4. Hedenberguite $CaFeSi_2O_6$ or $Ca (SiO_3)_2$
  5. Augite Complex silicate of Ca, Mg, Fe and Al
  6. Acmite (Aegirine) $NaFe (SiO_3)_2$
  7. Jaedite $NaAl (SiO_3)_2$
  8. Spodumene $LiAl (SiO_3)_2$

4.10.5 Physical Properties

The Pyroxene minerals as listed above exhibit similar physical properties of their identical atomic constitution. They are generally dark in colour, their hardness varying between 5 to 6 and sp. gravity from 3 to 3.3. Pyroxene crystals are generally short and stout. Prismatic cleavage is prominent in most cases.

4.10.6 Descriptive

The members of pyroxene group are of very common occurrence in the rocks and their description is given in Appendix 2.

4.11 AMPHIBOLE GROUP

This group of minerals is regarded as a parallel to the pyroxene group because most minerals of this group show a striking resemblance to the pyroxene minerals in most of the properties.

4.11.1 Chemical Composition

Amphibole minerals are meta-silicates with a Si : O ratio of 4 : 11. The metallic ions present in amphiboles are Ca, Mg, Fe and some times Mn, Na, K and OH. Presence of OH ion which may be replaced by F and Cl is another peculiarity of chemical composition. The general chemical formula: $[Si_4O_{11}][OH]_2$ forms the basis for combination with the metallic ions. There is a possibility of a good degree of substitution between various ions such as Al, Mg, Fe, Ca, Na and K, OH and F and so on, giving rise to a variety of amphibole minerals.

4.11.2 Atomic Structure

There is a basic difference in the atomic constitution of pyroxenes and amphiboles. In amphiboles, the $[SiO_4]^{4-}$ tetrahedra are linked in double chain and for this reason the amphiboles are more complex in their chemical constitution (Fig. 4.9).

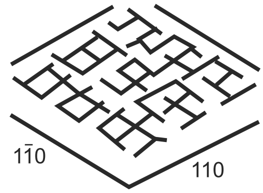


Fig. 4.9 *Cleavage in amphiboles*

4.11.3 Crystallization

Most important members of amphibole group crystallize in two crystal systems, the orthorhombic and monoclinic. The amphibole crystals are generally long, slender and prismatic; these are sometimes fibrous in habit. The cleavage angle in amphiboles is 124° and 56°.

4.11.4 Classification

Amphiboles are commonly divided in two groups on the basis of their crystallization, the orthorhombic amphiboles and monoclinic amphiboles.

The example of orthorhombic amphiboles is anthophyllite [Mg Fe $(Si_4O_{11})(OH)_2$], and that of monoclinic amphiboles are tremolite [$Ca_2Mg_5(Si_4O_{11})_2(OH)_2$]. Some important minerals of amphibole group are

Actinolit	[$Ca_2(MgFe)_5(Si_4O_{11})_2(OH)_2$],
Hornblende	[$Ca_2Na(MgFe)_4(AlFe)\{(Si,Al)_4O_{11}\}_2(OH)_2$],
Glaucophane	$Na_2(MgFe_3,Al_2[(SiAl)_{44}O_{11}]_2[OH,F]_2$

4.11.5 Physical Properties

Despite wide variation in their chemical composition, amphiboles show quite a few common physical characters due to their atomic structure. Thus, all of them crystallize in only two crystal systems. Most amphiboles are dark in colour, have a hardness ranging between 5 to 6 and specific gravity between 2.8 to 3.6. Their crystals are elongated, slender and often fibrous in nature.

4.11.6 Descriptive

The members of the amphibole group are of very common occurrence in the rocks and their description is given in Appendix 3.

4.12 COMPARATIVE STUDY OF PYROXENES AND AMPHIBOLES

Among the most common rock-forming minerals, the pyroxenes and amphiboles are very special since they are essential constituents of most igneous and metamorphic rocks, apart from the minerals quartz and feldspar. The prominent minerals of these two groups show so many similarities that often their identification on mere physical characteristics becomes quite difficult. It is, therefore, important to be familiar with these minerals resembling closely and with the characters that make them distinct from each other. The characteristics that bring about difference in pyroxenes and amphiboles are given in Table 4.2.

Table 4.2 *Comparison of pyroxenes and amphiboles*

Character		*Pyroxenes*		*Amphiboles*
1. Crystallization	1.	Crystallize in orthorhombic and monoclinic systems	1.	Crystallize in orthorhombic and monoclinic systems.
	2.	Crystals are commonly short and stout	2.	Crystals are commonly long and elongated
2. Cleavage	1.	Perfect, prismatic	1.	Perfect, prismatic.
	2.	Cleavage angle is 87° and 93°)	2.	Cleavage angle is 124° and 56°.
3. Physical properties	1.	H = 5–6	1.	H = 5–6
	2.	Sp. Gr. = 3.0–3.5	2.	Sp. Gr. = 2.5–3.5
	3.	Colour = Grey, black and other dark shades	3.	Colour = Grey to black and other dark shades.
4. Atomic structure	1.	Silicon-Oxygen tetrahedral linked together in single chain structure	1.	Silicon-oxygen tetrahedra linked together in double chain structure.
5. Chemical composition		Metasilicates with general formula of $R.SiO_3$ where R = Ca, Mg, Fe and Al, etc.		Broadly speaking, metasilicates but with a hydroxyl group in the lattice making the general formula: $R\ (Si_4O_{11})\ (OH)_2$ where R = Ca, Mg, Fe, Al, etc.
6. Cross section		In cross section under microscope the typical pyroxene minerals (e.g. augite) appear octagonal with almost right angled cleavage		In cross section under microscope the typical amphibole minerals (e.g. horn-blende) appear hexagonal with cleavage angle of 124° and 56°

4.13 MICA GROUP

Minerals of the mica group are characterized with the presence of a micaceous structure (cleavage) by virtue of which these can be split into very thin sheets along one direction. This micaceous cleavage is explained by their atomic constitution: they consist of $[SiO_4]^{4-}$ tetrahedra linked at three of their corners and extending in two dimensions. This is called sheet structure. These sheets are held together in pairs by metallic ions (e.g. K ion in muscovite, Mg or Fe ion in biotite, etc.). But due to the metallic ions, the resulting bond is the weakest and hence, there is an imminent cleavage present in micas.

Besides feldspars, pyroxenes and amphiboles, micas are very common rock-forming minerals, constituting approximately 4% of the Earth's crust. Despite great variation in their chemical composition, mica minerals are easily grouped together because of their similar atomic structure.

4.13.1 Chemical Composition

The mica group of minerals show a great variation in their chemical composition. Broadly speaking, they are mainly silicates of aluminium and potassium containing one or more of hydroxyl group of magnesium, aluminium, sodium and lithium. Because of the almost invariable presence of the hydroxyl group, all the micas yield water when heated in a closed test tube. In view of their very complex chemical composition, the formulae given for different mica minerals are considered only approximate.

4.13.2 Atomic Structure

Micas are characterized with a sheet structure in atomic constitution. In sheet structure, the basic unit of silicates, $[SiO_4]^{4-}$ tetrahedra are linked at all their three corners (oxygen ion) resulting in Si:O ratio of 2:5. Such a linkage when extended in two directions results in sheets of $[SiO_4]^{4-}$ tetrahedra. Two such sheets are so placed one above another that their vertices point inwards towards each other. It is here that they are mutually cross-linked with a metallic ion, commonly Al or Mg. Other groups, especially the hydroxyl group, are also incorporated in between these cross links (Fig. 4.5).

4.13.3 Crystallization

Most important members of the mica group crystallize in a monoclinic system only. However, some less important members crystallize in a triclinic system also.

It is typical of mica crystals that they apparently show a higher symmetry elements (as if they were belonging to orthorhombic or hexagonal systems). The crystals show cleavage angles of 60° and 120°. Because of atomic constitution, micas show excellent basal cleavage. A six-rayed percussion figure is sometimes obtained when a plate of mica (hexagonal) is struck with a blunt pointed tool in central part.

4.13.4 Classification

Micas are generally divided into two groups based on their colour/chemical composition as light or dark micas.

- **Light Micas** The varieties of light mica are
  1. Muscovite KAl_2 $(AlSi_2O_{10})$ $(OH)_2$ Potash mica
  2. Paragonite Na Al_2 $(AlSiO_{10})$ $(OH)_2$ Sodium mica
  3. Lepidolite KLiAl (Si_4O_{10}) $(OH)_2$ Lithium mica
- **Dark Micas** The varieties of dark mica are
  1. Biotite K (Mg, Fe), $(AlSi_3O_{10})$ $(OH)_2$ Fe–, Mg–Mica
  2. Phlogopite K, $Mg_3(A1_3Si_3O_{10})(OH)_2$Mg–Mica

4.13.5 Physical Properties

The properties that are common to all the minerals of the mica group are perfect basal cleavage, low hardness (between 2–3), vitreous lustre and platy habits of the crystals.

4.13.6 Occurrence

The members of the mica group are of very common occurrence in the rocks and their description is given in Appendix 4.

4.14 OXIDE MINERALS

Next to silicate minerals, oxide minerals occupy an important position in the list of rock forming minerals. Some of them are important as nonmetallic refractory minerals (e.g. quartz, corundum, spinel and rutile). Some other oxide minerals of metals are very important ore minerals, e.g. haematite, magnetite (iron), cuprite (copper), zincite (zinc), cassiterite (tin) and bauxite (aluminium). A few more common oxide minerals are described in Appendix 5.

4.14.1 Polymorphous Transformation

Quartz, when heated, transforms into high-temperature modifications as follows:

$$\text{Quartz} \xrightarrow{870°\text{C}} \text{Tridymite} \xrightarrow{1470°\text{C}} \text{Cristobalite} \xrightarrow{1713°\text{C}} \text{Melt}$$

The variety named quartz itself has two polymorphs, α-quartz and β-quartz. Identification of the exact type of quartz (into α and β) requires thorough investigations of the mode of formation of mineral as observed by its place of occurrence and also type of symmetry.

4.14.2 Varieties

Common pure quartz is a colourless, transparent mineral. Presence of even a trace of an impurity may give it a characteristic colour and hence a variety. A few common types of quartz distinguished on this basis are as follows.

1.	Amethyst	Purple or violet
2.	Smoky	Dark to light brown, even black
3.	Milky	Pure white and opaque
4.	Rose red	Colour is attributed to the presence of titanium

In many cases, crystallization of pure silica to quartz remains incomplete due to interruption in the process for one reason or another. Silica occurring in these cryptocrystalline varieties, although close in composition and physical properties to quartz, is named differently. A few common varieties of cryptocrystalline silica are as follows:

1.	Chalcedony	Lustre waxy, commonly translucent, generally massive
2.	Agate	Often banded, opaque and massive
3.	Onyx	A regularly banded agate having alternating and evenly placed layers of different colour

4.	Flint	A dull opaque variety of chalcedony breaking with a characteristic conchoidal fracture
5.	Jasper	A dull red, yellow and almost amorphous variety of silica

4.14.3 Occurrence

Quartz and its varieties occur in all types of rocks; igneous, sedimentary and metamorphic. In igneous rocks, quartz makes up bulk of acidic varieties. In sedimentary rocks, quartz makes up sandstones and ortho-quartzites. Loose sands consist mostly of quartz grains. The metamorphic rocks like gneisses and schists contain good proportion of quartz in some cases. A metamorphic rock named quartzite is entirely made up of quartz.

4.15 CARBONATE GROUP

A few carbonate minerals are important as rock-forming minerals in sedimentary and metamorphic rocks. These include calcite, dolomite and magnesite. These minerals are derived from the process of sedimentation and recrystallization.

4.15.1 Chemical Composition

In chemical composition, minerals of carbonate group are essentially carbonate $(CO_3)^{-2}$ with other bases as calcium and magnesium which is replaced by each other under suitable environmental condition. In its simplest form, the chemical composition of carbonates may be represented by the formula: RCO_3 with R representing Ca and Mg.

4.15.2 Atomic Structure

The carbonate ion is the simplest oxocarbon anion. It consists of one carbon atom surrounded by three oxygen atoms, in a trigonal planar arrangement which carries two negative charge. It is the conjugate base of the hydrogen carbonate (bicarbonate) ion, HCO_3^-, which is the conjugate base of H_2CO_3, carbonic acid. The structure of carbonate ion has two (long) single bonds to negative oxygen atoms, and one (short) double bond to a neutral oxygen.

4.15.3 Crystallization

The carbonate group of minerals are formed mainly from the precipitation of lime rich solution or recrystallization under metamorphism.

4.15.4 Physical Properties

The carbonate minerals exhibit similar physical properties in case of their identical atomic constitution. They are generally light in colour, their hardness varies between 3 to 4 and specific gravity from 2.5–3.5. Carbonate minerals are generally tabular and massive. Two to three sets of cleavage is prominent in most cases.

4.15.5 Occurrence

The members of carbonate group are of very common occurrence in the rocks and hence deserve individual description. They are given in Appendix 6.

4.16 SULPHIDE GROUP

The sulphide minerals are important as ore-forming minerals in igneous rocks and are limited to sedimentary and metamorphic rocks. These include pyrite, chalcopyrite, pyrolusite, etc. These minerals are derived from the process of solidification of magmatic fluids.

4.16.1 Chemical Composition

In chemical composition, minerals of sulphide group are essentially sulphide $(S)^{-2}$ with other bases as copper, iron, manganese and magnesium, etc., which is replaced with each other under suitable environmental conditions. In its simplest form, the chemical composition of sulphides may be represented by the formula: RS_2 with R representing Cu, Fe and Mn, etc.

4.16.2 Atomic Structure

The sulphide ion is the simplest anion. It consists of two sulphur atom surrounded by one base element like copper or iron in a isometric crystal system in which sulphur carries two negative charge. These two negative charged atoms of sulphide [S] are linked with single bond and another smaller bond which combines with positive ion like copper or iron.

4.16.3 Crystallization

The sulphide group of minerals are formed mainly from the solidification of magmatic fluids which is sulphide rich. All the sulphide group of minerals are ore-forming minerals. Igneous rocks are the main source for sulphide group of minerals.

4.16.4 Physical Properties

The sulphide minerals exhibit similar physical properties of their identical atomic constitution. They are generally dark in colour, their hardness varies between 4 to 5 and specific gravity from 4–6. Sulphide minerals are generally of cubic crystals and massive. Two sets of cleavage is prominent in most cases.

4.16.5 Occurrence

Members of the sulphide group are of very common occurrence in the rocks and hence deserve individual description. The same has been described in Appendix 7.

Summary

Minerals are naturally occurring solid substances with crystalline structures and are of inorganic origin having fixed chemical composition. Since these are naturally occurring, the products of industrial or commercial processes are not considered true minerals. Also, since they are solid substances with a crystalline structure, the atoms within the solid are arranged in a geometric pattern that is unique to that mineral. Thus, altering the structure in any way will result in the creation of a new mineral. Additionally, substances formed from the other phases of matter, liquid and gas, are not minerals. For that reason, water ice from a glacier is a mineral, while liquid water, steam, and ice cubes are not. Further, minerals are not organic compounds such as amino acids, or enzymes. However, many organic processes result in the formation of minerals. For instance, seashells are made of minerals, as are coral reefs and the bones and teeth of animals. Finally, minerals have a definite chemical composition. It is, therefore, possible to write a chemical formula for any mineral.

Importantly, the chemical composition of a mineral is an integral part of its definition. However, some chemical variation is allowed. Natural impurities are common in minerals, as is the tendency for one element to slip into the crystalline structure in place of some other element. Substitutions of these types do not cause a change in the mineral name as long as the replacements make up only a small percentage of the total structure.

Large numbers of minerals having different chemical composition and crystal structures occur in the nature. Among these minerals, physical properties being different for different minerals having similar chemical composition and crystal structures are kept together. These are known as group of minerals. Important group of minerals like silicate, oxide, sulphide and carbonate etc. and their characteristics have been described in the chapter. Minerals falling under different group and their properties have been elaborated in Appendices (I to VII).

Terminology

$1\bar{1}0$	Face with bar means that face has been intersected by middle axis.
110	Faces of crystal resembles like prism.
Diagnostic Properties	The specific physical properties of minerals which are unique for identification are called diagnostic properties.
Fumarole	It is a vent in the Earth's surface from which steam and volcanic gases are emitted. Fumaroles are often present on active volcanoes during periods of relative quiet between eruptions.
Gemstone	The mineral which is used as gem after polishing and cutting is known as gemstone.
Magnetic Polarity	When the mineral is characterized by magnetic normal and reversal, it is known as magnetic polarity.

Malleability	When mineral can be flattened after hammering, the property is known as malleability.
Ore-Forming Mineral	The mineral which is economically exploitable is known as ore-forming mineral.
Rock-Forming Mineral	The mineral which is not economically exploited but makes the bulk composition of rocks is known as rock-forming mineral.
Set of Cleavage	The direction along which the mineral breaks and if the property is pervasive in that direction, it is known as set of cleavage.
Silicon Tetrahedral	When one silicon atom is bonded with four numbers of oxygen that form the unit for silicate structures is known as silicon tetrahedral.
Tenacity	When the mineral changes its shape and forms due to mechanical changes, it is called tenacity.

Exercises

1. What is a mineral? Explain the origin of minerals and their classification.

2. (a) Explain how crystal structures are different for the oxide and mica groups.
(b) Explain the crystal structure of the mica-group minerals.

3. (a) Explain the different causes to have different colour and hardness of minerals.
(b) Explain the different process of mineral genesis.

4. Describe how the hardness of minerals are dependent upon the atomic and crystal structures.

5. Write short notes on the following:
(a) Physical properties of minerals
(b) Difference between pyroxene and amphibole groups
(c) Describe the atomic structures and physical properties of the silicate group

6. (a) Briefly explain the crystal systems along with their examples.
(b) Define the axis of symmetry and elaborate the role of axis of symmetry in classification of crystallographic system.

7. (a) Describe the different optical properties of minerals studied under polarized light, and non-polarized light.
(b) Which group of minerals is most common in occurrence and describe its characteristics.

8. Write short notes on the following:
(a) Sheet structure
(b) Double tetrahedral silicate structure
(c) Crystalline and amorphous substances

9. Differentiate between the following:
(a) Uniaxial and biaxial minerals
(b) Isotropic and anisotropic minerals
(c) Rock-forming and ore-forming minerals
(d) Sublimation and evaporation

Multiple-Choice Questions

1. Which of the following mineral has silica tetrahedra arranged in three-dimensional networks?
(a) Olivine (b) Halite
(c) Feldspar (d) Mica

2. Which of the following mineral is most likely to split into thin sheets?
(a) Mica (b) Halite
(c) Orthoclase (d) Quartz

3. Which of the following mineral is most likely to split into splintery fragments?
(a) Sheet silicate (b) Double chain silicate
(c) Silicate with single tetrahedra (d) Framework silicate

4. Chain silicates include
(a) clays and micas (b) amphiboles and pyroxenes
(c) feldspars and quartz (d) olivine and garnet

5. Which of the following mineral has the lowest hardness?
(a) Flourite (b) Quartz
(c) Topaz (d) Gypsum

6. Olivine is an example of which of the following crystal structure?
(a) Double-chain silicate (b) Chain silicate
(c) Silicate with double tetrahedra (d) Framework silicate

7. The property that causes quartz to break along smoothly curvy surfaces is
(a) lustre (b) specific gravity
(c) cleavage (d) fracture

8. The single most important group of minerals in abundance is
(a) silicates (b) carbonates
(c) oxides (d) sulfites

9. Which of the following is the diagonostic physical property of calcite?
(a) Hardness (b) Colour
(c) Lustre (d) Specific gravity

10. Amphibole and pyroxene are examples of
(a) sheet silicate (b) chain silicate
(c) silicate with single tetrahedra (d) framework silicate

Answers to MCQs

1. (c) 2. (a) 3. (d) 4. (b) 5. (d) 6. (b) 7. (d) 8. (a)
9. (a) 10. (b)

chapter 5

Rocks I: Igneous Rocks

5.1 INTRODUCTION

The branch of geology that deals with formation of rocks, their classification and occurrence is known as *petrology*. Since the strength and the suitability of rocks dictate its selection for a particular application, knowledge of petrology is of utmost importance for town planners, architects and civil engineers. A town planner and an architect must be able to assess the nature of the rocks that are going to form the base, as well as the environment of the entire construction project proposed in a given area. A professional civil engineer, involved in design and construction of civil engineering projects, has to deal with rocks and its aggregates at various stages of the project. Engineers must, therefore, have very sound knowledge about the inherent properties of different types of rocks.

Rock may be defined as natural, solid and massive aggregation of minerals forming the crust of the Earth. Generally they are abundant and constitute about 90% of the rock by volume, and are called *essential minerals*. Typically, some of the rocks are formed of one mineral only, e.g. quartzite (quartz) and marble (calcite). The characteristics of the essential minerals and the way these minerals are arranged in a rock, influence the properties of the rock and its mechanical behavior. The minerals whose presence is insignificant are called *accessory minerals*.

It has already been mentioned in Chapter 3 that on the basis of their origin, rocks are broadly classified into three groups: the igneous rocks, the sedimentary rocks and the metamorphic rocks. Igneous rock is supposed to be formed first due to the solidification of molten magma/lava and the other types are transformed from it. In due course of time, erosion of the existing igneous rocks takes place, the sediments are deposited in basins which form sedimentary rocks. These sedimentary rocks, under gradual increase in temperature and pressure, change into metamorphic rocks. Further under continued rise in temperature and pressure, the metamorphic rocks melt and give rise to molten magma which in turn changes again into igneous rocks. Therefore, this cycle is also called *rock cycle*. Rock cycle (Fig. 5.1) explains about the transformation of igneous, sedimentary and metamorphic rocks from one type to another.

An attempt has been made to describe the essential features of the different types of igneous rocks, their mode of formation and occurrence, composition, texture, structure, and classification of igneous rocks in this chapter, and those of sedimentary rocks and metamorphic rocks in Chapter 6 and Chapter 7, respectively. A few rock types, which are commonly used in various civil structures, have also been described.

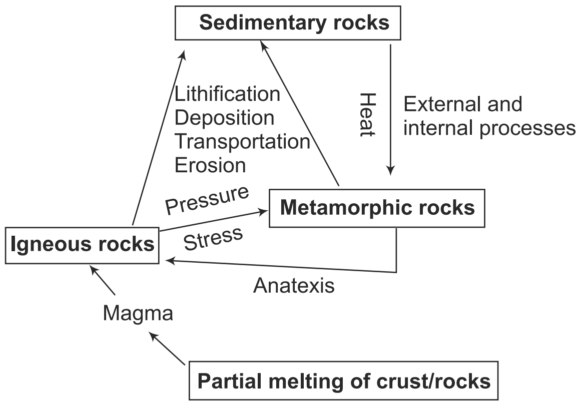


Fig. 5.1 *The rock cycle*

5.2 ORIGIN AND OCCURRENCE OF IGNEOUS ROCKS

Rocks that have formed from an originally hot molten material, through the process of cooling and crystallization are defined as *igneous rocks*. The hot molten material occurring naturally below the surface of the Earth is called *magma* and is called *lava* when erupted through volcanoes. Igneous rocks are supposed to form after crystallization and consolidation of magma or lava. The origin and formation of magma has already been described in Section 3.5.

Magma/lava is predominantly semi-solid in nature. The solid and gaseous fractions, however, form only a small part of the magma/lava. Magma can exist as a melt, as long as physical and chemical environment surrounding it remains unchanged. But as and when there is a change in one or more of these conditions (e.g. fall in temperature or pressure due to its upward movement), cooling and crystallizations of magma may start and end up with the formation of an igneous rock (Fig. 5.2). The resulting rock is termed as *intrusive* in case the magma cools, crystallizes and consolidates beneath the surface of the Earth, e.g. plutonic and hypabyssal rocks (Plate 9); and if the magma erupts over the Earth's surface as lavaflows, the rock formed is termed as *extrusive rocks* (the examples are of volcanic rocks).

Since igneous rocks exist in so many varieties, it becomes important to classify them scientifically for their study and engineering applications. Before discussing the existing classification systems, it is necessary to know about their composition—chemical as well as mineralogical; mode of occurrence and texture. These are discussed in the sections to follow:

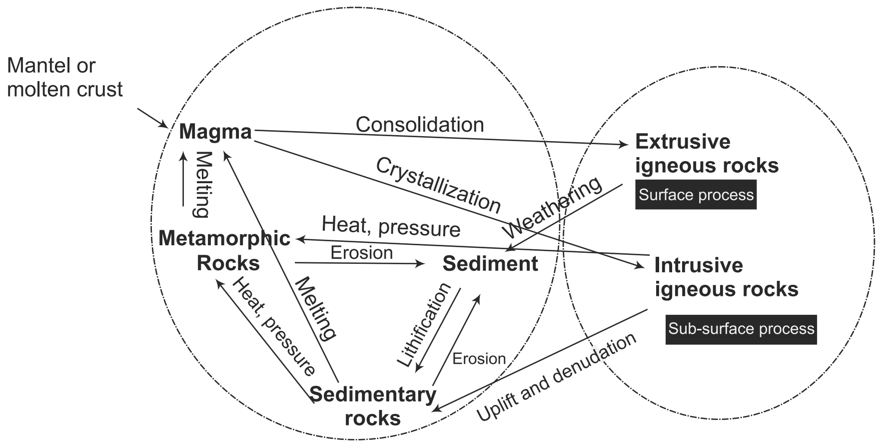


Fig. 5.2 *Rock cycle of igneous rocks*

5.3 COMPOSITION OF IGNEOUS ROCKS

Igneous rocks can be distinguished on the basis of their chemical composition, mineralogical composition and texture. Although chemical composition can not be determined in the field, it can be estimated, based on the essential minerals of a rock specimen. The chemical and mineralogical components of igneous rocks are described as follows and textures are presented in the section to follow.

Chemical composition of igneous rocks usually is indicated by the minerals of the rock and shows great variation. Silica in the rock is supposed to be the chief constituent with iron, magnesia and lime in large or small quantities. One of the ways to classify igneous rocks may be therefore the amount of silica present in the rock, and accordingly the rocks are classified as *acidic*, *basic*, *intermediate*, and *ultrabasic*. However, since the chemical composition for classification of rocks does not address the mode of occurrence and texture of rock bodies, it is not that significant. Moreover, the process of chemical analysis of rocks is a lengthy, time-taking and cumbersome exercise requiring too much sophistication.

It is well known that only a few essential minerals make the igneous rocks, and are called *rock-forming minerals*. Important minerals like silica and feldspar are taken into consideration for classification of igneous rocks, besides basic minerals like olivine, hornblende and plagioclase. The mineralogical components take into account the amount of quartz (SiO_2) and the composition of feldspar minerals (K, Na, Ca). The major mineralogical components of igneous rocks may be grouped into felsic (from feldspar and silica) and mafic (from magnesium and ferrous iron) varieties. The *felsic minerals* include quartz, feldspars (plagioclase and alkali feldspar), felspathoids (nepheline and leucite), and muscovite. These are light in colour and have low density. The *mafic minerals* include olivine, pyroxenes, amphiboles, and biotites, all of which are dark in colour and are heavier in density. Accessory minerals present in igneous rocks in minor amounts include monazite, allanite, apatite, garnets, magnetite, titanite, spinel, and zircon. Glass may be a major phase in some volcanic rocks but, when crystallizes, is usually found in minor amounts.

The mineralogical composition, on the other hand, is supposed to be a very convenient basis for classifying the rocks as they can be readily identified and their relative proportions can be ascertained accurately. On the basis of mineralogical composition, the categories that result are *felsic*—rich in feldspars and quartz, *mafic*—rich in divine (magnesium and iron with less silica), *intermediate*—between felsic (acidic) and mafic (basic), and *ultramafic* (also called ultrabasic; quartz content is less than 45% with little or no feldspar).

5.4 TEXTURES OF IGNEOUS ROCKS

The size, shape and arrangement of the crystals of the constituents composing the igneous rock define the property known as *texture*. Texture is determined primarily by how the magma or lava is cooled and on the crystallization system. The importance of texture lies in the fact that the mineral grains bear a record of the energy changes involved in the rock-forming process and the environmental conditions existing when the rock originated. Igneous rocks having essentially the same chemical and mineralogical composition may have different textures, and in such cases it is their texture that provides most of the information about how each rock was formed. It is pertinent to note that the texture can be studied with the help of a microscope only.

5.4.1 Controlling Factors for Texture

The texture of igneous rocks is a function of: degree of crystallization, i.e. crystallanity of magma/lava; size of grains (or crystals), i.e. granularity, and, fabric, which includes shape of crystals and, mutual relationship of different mineralogical constituents in a rock. These are discussed as follows.

❑ *Degree of Crystallization*

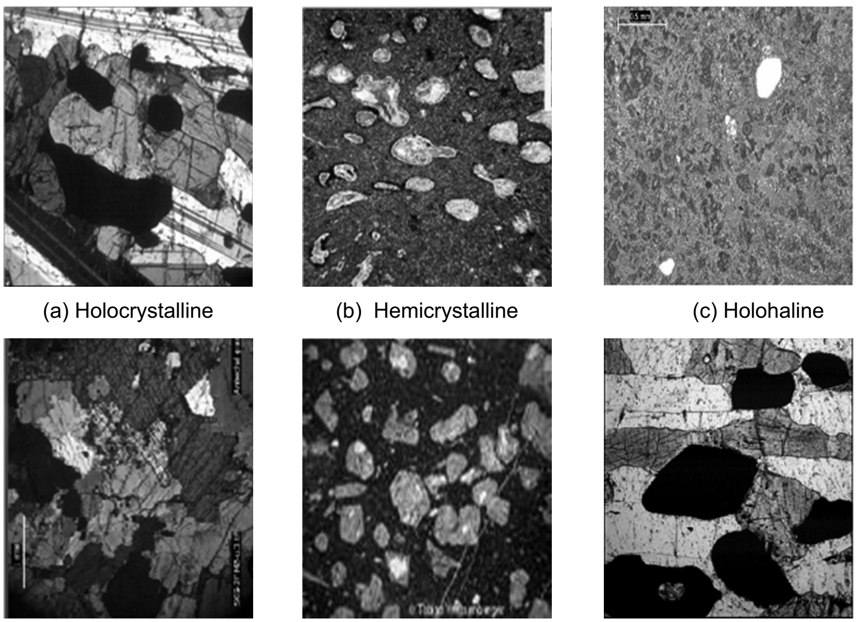
The type of texture in a given igneous rock primarily depends upon the degree of crystallization, granularity and groundmass. The grain size of igneous rocks depends on the rate of cooling of magma; slower the rate of cooling; coarser is the grain size of rock. The constituent minerals may be either distinctly crystallized (the minerals can be readily recognized), or be poorly crystallized, or be even glassy or noncrystallized. The resulting rock texture may be characterized as follows.

■ **Holocrystalline** When most of the constituent minerals are well crystallized, and have bigger grains, the texture is known as holocrystalline [Fig. 5.3(a)].

■ **Hemicrystalline** When some of the minerals have good crystals and embedded in glassy groundmass, the texture is termed as hemicrystalline or merocrystalline [Fig. 5.3(b)].

■ **Holohaline** When all the constituents are very fine in size, and glassy or non-crystalline in nature, the texture is known as holohaline [Fig. 5.3(c)].

> ***Note*** Rocks with holocrystalline texture are also referred to as *phaneritic* and those with holohyaline texture are referred to as *aphanitic*.



(a) Holocrystalline (b) Hemicrystalline (c) Holohaline

(d) Allotriomorphic (e) Panidiomorphic (f) Hypidiomorphic

Fig. 5.3 *Textures of igneous rocks based on degree of crystallization/shape of crystals*

❑ *Granularity (Size)*

Crystallized igneous rocks show a variety of grain sizes and arrangements of crystals. *Granularity* refers to the grain size of the various minerals present in the igneous rock. The grain size is taken as the average diameter of the dominant grain in the rock. Accordingly, the rock texture is described as coarse, medium or fine grained. Granularity of igneous rocks depends on the rate of cooling of the magma (most important factor), pressure, composition, viscosity and movement of the magma.

When the minerals of igneous rocks are too small to be distinguished with an unaided eye, the rock is termed as *aphanitic,* whereas if the individual minerals are visible to the naked eye, these are termed as *phaneritic*. The examples of texture of phaneritic rocks are coarse grained, medium grained and fine grained textures; and those of aphanitic rocks are microcrystalline and cryptocrystalline textures. The other parameter of texture grain size and shape are explained as follows:

■ **Coarse Grained** The texture is called coarse grained, when the average grain size is more than 5 mm in diameter; the constituent minerals can be easily identified with an unaided eye. Most intrusive igneous rocks exhibit coarse-grained textures.

■ **Medium Grained** The texture is called medium grained, when the average grain size lies between 5 to 1 mm in diameter; magnifying lens will often be required to identify all the constituent mineral components.

■ **Fine Grained** The texture is called fine grained, when the average grain size is less than 1 mm in diameter; the constituent mineral grains can be identified only with the help of a microscope. Most extrusive rocks are fine grained.

❑ *Shape of Crystals*

Shape of the crystals refers to the degree of development of crystal faces, i.e. the degree of perfection in the form of the crystals of the individual minerals. The crystal shapes are described as *euhedral* (the grains show well developed faces, i.e. the crystal is bounded by crystal faces), *subhedral* (the crystal faces are partly developed) and *anhedral* (grains with no developed crystal faces, often due to other crystals interfering with their growth). Development of faces of mineral grains depends upon the rate of cooling, composition and type of crystallization. An igneous rock may contain crystals of any type in a predominating proportion as described above, and accordingly its texture is defined as follows:

■ **Alltromorphic** When most of the crystals are anhedral [Fig. 5.3(d)]. Examples are some aplites.

■ **Panidiomorphic** When most of the crystals are euhedral [Fig. 5.3 (e)]. The example is lamprophyres.

■ **Hypidiomorphic** When a rock contains crystals of all the categories, euhedral, subhedral and anhedral, but with subhedral in domination [Fig. 5.3(f)]. The examples are granites and syenites.

❑ *Mutual Relation of Grains*

The texture is termed *equigranular* when all the component minerals are of approximately equal dimensions and *inequigranular* when some minerals in the rock are exceptionally larger or smaller than the others.

5.4.2 Types of Textures

Some of the important textures exhibited by the igneous rocks are equigranular, inequigranular, intergranular, directive and intergrowth. These are described as follows.

❑ *Equigranular Texture*

Igneous rocks with constituent crystals more or less equal in size are described as having *equigranular texture*. This texture is exhibited by granites and felsites and is accordingly referred to as granitic or felsic texture.

■ **Granitic Texture** The constituents are either all coarse grained or all medium grained and the crystals are euhedral to subhedral.

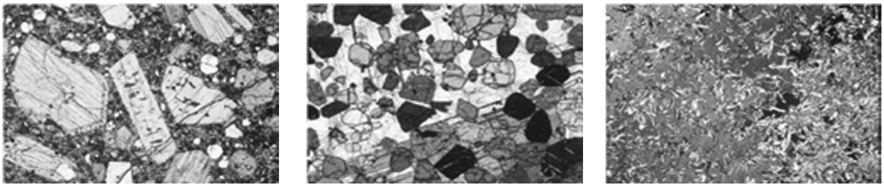
■ **Felsic Texture** The rock is microgranular with cryptocrystalline matter. Felsic textures may also be described as panidiomorphic (most grains are euhedral).

❑ *Inequigranular Texture*

The texture of igneous rocks with considerable difference in their relative grain size is termed as *inequigranular texture*. *Porphyritic* [Fig. 5.4(a)] and *poiklitic* [(Fig. 5.4(b)] textures are the examples.

■ **Porphyritic Texture** Porphyritic texture is characterized by the presence of a few conspicuously large sized crystals (the phenocrysts) which are embedded in a fine-grained ground mass. This texture implies two-stage cooling—an early stage of slow cooling in which the phenocrysts grow, followed by a later stage of rapid cooling that forms the groundmass.

■ **Poikilitic Texture** Poikilitic texture is characterized with the presence of fine-grained crystals within the body of large size crystals. When the host mineral is augite and the inclusions are of plagioclase feldspars, the poiklitic texture is called *ophitic texture* [Fig. 5.4(c)]; for example gabbro. When the growth of plagioclase is limited and partially enclosed in the grain of augite, the texture is called *subophitic*, the example being basalt.



(a) Porphyritic (granite) (b) Poiklitic (syenite) (c) Ophitic (gabbro)

Fig. 5.4 *Inequigranular texture of igneous rocks*

❑ *Intergranular Texture*

In some igneous rocks, the arrangement of crystals are formed in such a way that a network of triangular or polygonal spaces is left in between them. When the interspaces get filled subsequently by crystalline or glassy masses of other minerals during the process of rock formation, the texture produced is called *intergranular* (Fig. 5.5). However, if the material filling the spaces is glassy in nature, the texture is specifically termed *intersertal*. Anhedral crystals of a mineral occupy spaces between sub-euhedral

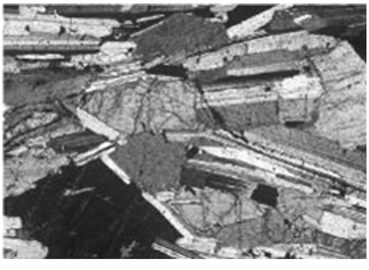
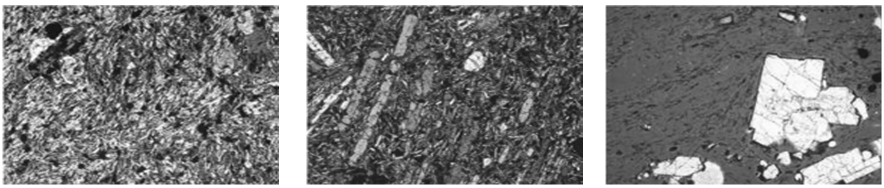


Fig. 5.5 *Intergranular texture of igneous rock (perthite)*

crystals of another mineral. In basalts and similar rocks, clinopyroxene fills gaps between plagioclase.

❑ *Directive Texture*

Textures that are produced during consolidation of lavas are known as *directive textures* (Fig. 5.6). The directive texture may be trachytic, trachytoid or hyalopilitic.



(a) Trachytic (b) Trachytoid (c) Hyalopilitic

Fig. 5.6 *Directive textures of igneous rock*

■ **Trachytic Texture** It is characterized by certain feldspathic lavas and is recognized by a parallel arrangement of feldspar crystals [Fig. 5.6(a)].

■ **Trachytoid Texture** It is characterized by the presence of well developed feldspar crystals with preferred orientation in groundmass of glass [Fig. 5.6(b)].

■ **Hyalopilitic Texture** It is characterized by the presence of phenocryst of feldspar in groundmass of glass [Fig. 5.6(c)].

■ **Myrmekite Texture** It is produced by an intergrowth of quartz and plagioclase feldspar where quartz occurs as blobs or drops in plagioclase.

■ **Graphic Texture** It results from an intergrowth of quartz and orthoclase feldspar.

■ **Xenolithic Texture** Occurrence of foreign rock fragments within an igneous rock gives rise to xenolithic texture. The xenoliths are said to be *cognate* when they are genetically related to enclosing rocks and *accidental*, when they are fragments of country-rocks without having any genetic relation with the enclosing rock.

❑ *Intergrowth Texture*

In case two or more minerals crystallize simultaneously in a limited space during the formation of the igneous rocks, the resulting crystals may get mixed up or intergrow. When a crystal of one mineral appears to be completely embedded within a crystal of another mineral, the texture is known as *intergrowth texture*. The examples of intergrowth textures are *graphic* (Fig. 5.7) characterized by irregular intergrowth of two minerals visible with the naked

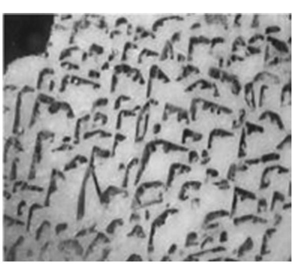


Fig. 5.7 *Intergrowth texture (graphic)*

eye and; *micrographic*—the graphic intergrowths that are visible only under the microscope. The micrographic textures are further divided as *granophyric*—graphic intergrowth of quartz and alkali feldspar and *myrmekitic*—graphic intergrowths of plagioclase and quartz.

5.5 STRUCTURES OF IGNEOUS ROCKS

The structures of igneous rocks are large scale features that are developed in the body of an extrusion or intrusion, giving rise to conspicuous shapes or forms. These are dependent on several factors like composition of magma, viscosity of magma, temperature and pressure at which cooling and consolidation takes place, and presence of gases and volatiles that are present. They may be so well developed as to be recognized with the naked eye or may become apparent only under a microscope, thus termed *microstructures*.

5.5.1 Types of Structures

The mobility of the magma/lava is responsible for a variety of structures that the ultimate rock acquires. The structures of igneous rocks are classified as mega-structures, minor-structures and micro-structures. Some of the examples of the structures of igneous rocks are as follows.

❑ *Mega Structures*

These are usually formed when the magma comes on the surface (i.e. in the extrusive rocks), and include the following:

■ **Vesicular, Amygdaloidal and Scoriaceous Structures** When lavas heavily charged with gases and other volatiles are erupted on the surface, the gaseous constituent's escapes from the magma as there is a decrease in the pressure. Thus, near the top of flows, empty cavities of variable dimensions are formed. The individual openings are known as *vesicles* and the structure as a whole is known as *vesicular structure*. If, however, the vesicles thus formed are subsequently filled in with some low-temperature secondary minerals, such as calcite-zeolite, chalcedony, etc., these infillings are called *amygdales* and the structures are termed *amygdaloidal structures*. While a *vesicular structure* is when the cavities make up less than 50% of the rock, the *scoriaceous structure* is dark-coloured rock with > 50% vesicles.

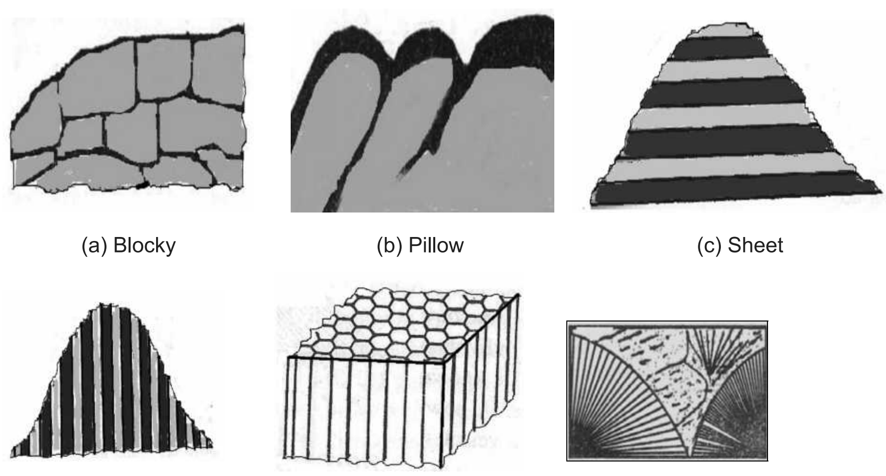
■ **Lava-drain Tunnels** Sometimes while the upper surface of the lava consolidates, the interior may still remain fluid. When the enclosed fluid lava drains out through some weak spots lying at the periphery of the flow, the resulting structure is known as lava-drain tunnel.

■ **Flow Structure** Subsequent to eruption of lava upon the surface, the viscous varieties flow from one place to the other with great difficulty and in their attempt to do so, the dissimilar patches within the lava are drawn out in the form of elongated lenticels. Sometimes, the already crystallized particles within the magma are arranged parallel to the direction of flow of the lava. They naturally indicate the direction of flowing of the mass, prior to its consolidation. These are known as flow structure or *directional structure*.

■ **Blocky and Ropy Lava Structures** Lavas of acidic composition, due to their high viscosity, do not flow to greater distances, and after solidification are found to offer a very rough surface. Such lavaflows are known as block lava; the surface structure is termed *blocky structure* [Fig. 5.8(a)]. On the other hand, lavas of basic composition are quite mobile because of their low viscosity and they can flow to greater distances and after solidification offers very smooth surface. Such lavaflows are known as ropy lava; and the surface structure is known as *ropy* or *pahoehoe structure*. They have been discussed in detail in Chapter 3.

■ **Pillow Structure** It is found in certain extrusive igneous rocks. It indicates extrusion of lava into rain-soaked air, beneath ice-sheets, under water logged sediments or in sea water and crystallized. Pillow structure is characterized by discontinuous pillow-shaped masses, piled one upon another, ranging in size from a few centimeters to a meter or more in the largest dimension. The pillows are close fitting, with the concavities of one matching the convexities of the next. Grain sizes within the pillow usually increase toward the interior. Spaces between pillows are not common. When present, spaces are filled with scoriaceous material, with clastic sediments, or with material of the same composition as the pillows. It is a typical structure of rocks formed from mobile basaltic lava. The rock is usually basaltic. Spilites, a lava rich in albite (i.e. sodium rich), characteristically exhibit pillow structure [Fig. 5.8(b)].

■ **Sheet Structure** The development of one set of well defined joints sometimes brings about a slicing effect on the massive igneous rock body. If all such slices are horizontal, the structure is said to be sheet structure [Fig. 5.8(c)].



(a) Blocky (b) Pillow (c) Sheet

(d) Platy (e) Columnar (f) Spherulitic

Fig. 5.8 *Lava structures of igneous rocks*

■ **Platy Structure** This is also due to the development of different sets of joints, which gives rise to only plates of the rock mass, after consolidation of magma/lava. Such a feature is known as platy structure [Fig. 5.8(d)].

■ **Columnar Structure** As a consequence of contraction due to cooling, a few sets of vertical joints develop. Such joints bring about the formation of columns, which may be square, rectangular, rhombic or hexagonal in outline [Fig. 5.8(e)].

❑ *Minor Structures*

These structures are formed in the fluid stage of the magma (i.e. in the intrusive rocks) and include the following:

■ **Primary Foliation** Sometimes, few plutonic rocks are characterized by foliation resulting from the parallel arrangement of platy and ellipsoidal mineral grains.

■ **Banding in Rocks** These are also known as *layered rocks* consisting of alternating bands of different composition. It may result from lamellar flow, from settling of minerals from a crystallized magma or from successive injections.

■ **Schlieren** These are somewhat wavy, streaky, irregular sheets, usually lacking sharp contact with the surrounding igneous rocks. They may be altered inclusions, segregation or may represent concentration of residual fluids into layers in a rock that had otherwise crystallized.

❑ *Micro Structures*

These are formed due to reaction between already solidified crystals and the rest of the magma and include the following:

■ **Spherulitic Structure** It is characterized by spherical bodies from microscopic size to meters in diameter formed in volcanic glass. Its essential feature is the simultaneous crystallization of fibres, composed of feldspar and quartz, with radiating arrangement about a common centre. It is a common structure of acidic volcanic and hypabyssal rocks. The structure results during crystallization of saturated lava or magma [Fig. 5.8(f)].

■ **Orbicular Structure** These are spherical segregations consisting of concentric shells of different mineral composition and texture, which occasionally occurs in plutonic rock usually granitic in composition. These rocks have a unique appearance due to orbicules–concentrically layered, spheroidal structures, probably formed through nucleation around a grain in a cooling magma chamber. The rock mass appears as if composed of ball-like aggregations. Each ball is in turn composed of concentric shells of different minerals (Fig. 5.9). The occurrences of orbicular structure are usually very rare.

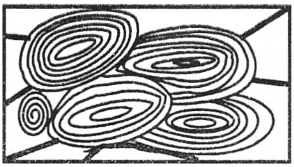
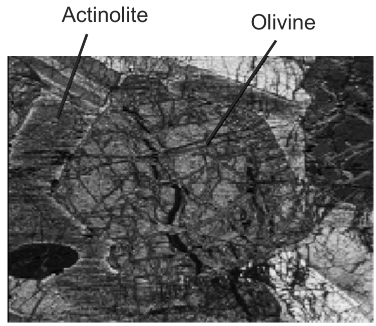


Fig. 5.9 *Orbicular structure*

■ **Reaction Rim Structure** It is formed by steady cooling of magma and having different compositions. When the reaction between an already crystallized mineral and the rest of the magma is incomplete, the corroded crystals (in centre) are found surrounded by the products of reaction i.e. some new mineral. Such zones are known as *reaction rim*. When the reaction rims are produced by primary magmatic reaction, they are known as *corona structures* (Fig. 5.10), and *kelyphitic borders* when secondary. It must be noted that since reaction rim can be observed under microscope as well as with the naked eye, it can therefore be classed as texture or structure.



Olivine: original mineral
Actinolite: surrounding the reaction product

Fig. 5.10 *Corona structure*

5.6 FORMS OF IGNEOUS ROCK BODIES

Igneous rocks are formed either on the ground surface or below it. They are formed when the melted rock, called magma, deep within the earth becomes trapped in small pockets. As these pockets of magma cool slowly underground, the igneous rocks are formed. Igneous rocks are also formed when volcanoes erupt, causing the magma to rise above the Earth's surface. When magma errupts above the Earth, it is called lava. Igneous rocks are formed as the lava cools down above ground. Ultimate form acquired by an igneous mass on cooling depends on the following three factors.

1. Structural disposition of the host rock, also called the country rock, viscosity of the magma/lava
2. Environment in which the injection of magma or eruption of lava takes place
3. Composition of the magma/lava.

The rock bodies may be extrusive (consolidated over the Earth's surface) or intrusive (consolidated beneath the Earth's surface).

5.6.1 Igneous Extrusions

The igneous extrusions generally occur as widely spread extensive flows cover enormous area and the existing topography. These lava flows form solid sheets of rocks on cooling. Generally, the sheets may occur as layers laid one above another, but however there may be layers of other sedimentary materials deposited during the volcanic emissions alternatively. These layers are called *intertrappean layers*. The total thickness of volcanic layers may be even many hundreds of meters. The different flows may be distinguishable from one to another by the presence of intertrappean beds or be completely welded together without any visible zone of separation. Some of the forms of igneous extrusions have been shown in Figs 5.7 to 5.9.

5.6.2 Igneous Intrusions

The intrusive igneous rock bodies are divided into two broad classes: *concordant* and *discordant*. These are shown in Fig. 5.11.

5.6.3 Concordant Bodies

The intrusions in which the magma has been injected and cooled along or parallel-to the structural planes of the host rocks are grouped as concordant bodies [Fig. 5.11(a)]. The bedding planes in the sedimentary formations and cleavage planes in metamorphic rocks define such planes. Some of the important concordant forms are sills, phacoliths, lopoliths and laccoliths.

❑ *Sills*

Rising magma follows the path of least resistance. If this path includes a bedding plane, which separates layers of sedimentary rock, magma may be injected between those layers to form a *sill* or *sheet*—a tabular intrusive body parallel to, or concordant with, the layering (Fig. 5.12). Therefore, these may be defined as igneous shallow intrusions injected showing a concordant relationship with the rocks that they intrude. Sills range from a few centimetres

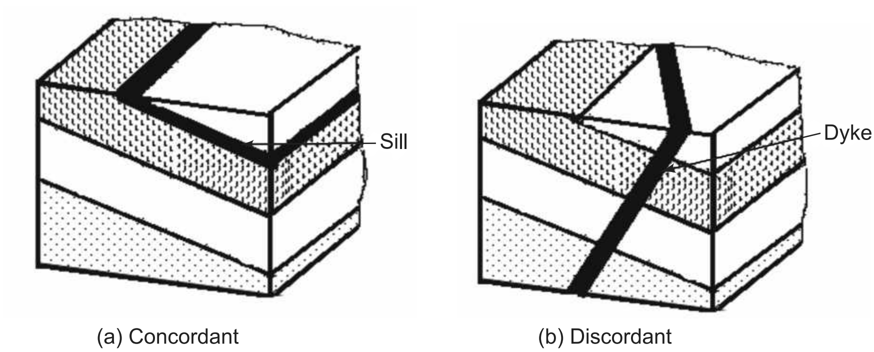


Fig. 5.11 *Forms of igneous rocks*

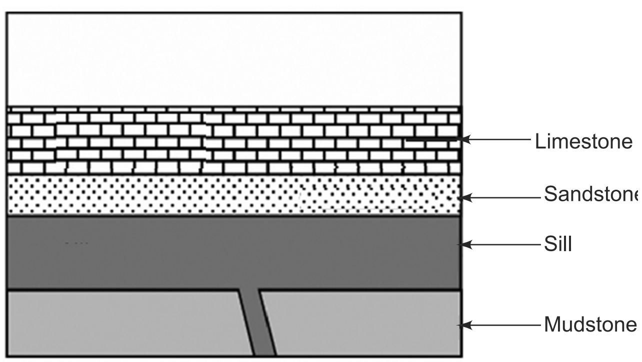


Fig. 5.12 *Sill*

to hundreds of metres thick and can extend laterally for several kilometres, i.e., they have relatively small thickness as compared with their width and length. Moreover, this body commonly thins out or tapers along its outer margins. Sills usually are fed by dikes, but these may not be exposed in the field. The most common rocks composing the sills are intermediate and basic igneous rocks like syenites and gabbros. They may show aphanitic and porphyritic textures.

The type of sills may be *simple*—single intrusion of magma, *multiple*—two or more injections of magma of same kind, *composite*—two or more injections of magma of different kinds *differentiated*—sheet like injection of magma with segregation of minerals or, interformational—sheet like injection of magma along or in between the planes of unconformity.

❑ *Phacoliths*

These are concordant, small sized intrusives that occupy positions in the troughs and crests of bends called *folds*. More specifically, it is a typically lens-shaped body that occupies either the crest of an anticline or the trough of a syncline (Fig. 5.13). As regards to their origin, it is thought that when magma is injected into a folded sequence of rocks, without exerting much pressure. A phacolith thus has both a curved floor and roof, magma having been intruded into rocks that were already folded. It is also called saddle and reef type of igneous form.

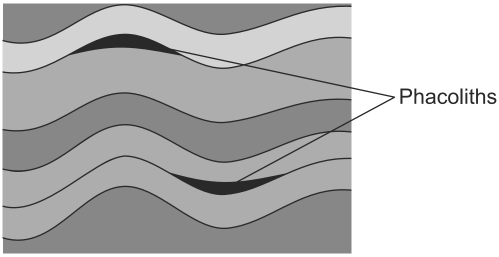


Fig. 5.13 *Phacoliths*

❑ *Lopoliths*

Igneous intrusions, which are relatively small plutons, usually show a concave downward upper surface. This shape may have resulted from the reduction in volume that occurs when magmas crystallize, with the weight of the overlying rocks causing collapse into the space once occupied by the magma when it had a larger volume as a liquid (Fig. 5.14). They may form huge bodies of consolidated magma, often many kilometres long and thousands of meters thick. It is believed that the origin of the lopoliths is due to the simultaneous formation of structural basin and injection of magma.

❑ *Laccoliths*

These are concordant types of somewhat large intrusions that result in the uplift and folding of the preexisting rocks above the intrusion. A laccolith has a flat floor and domed roof, the roof having been arched by the pressure of incoming magma. Laccoliths are formed when highly viscous magma is injected between layers of sedimentary rocks and is unable to flow and spread for greater distances. Hence, it gets collected in the form of a heap about the orifice of eruption as the magma is injected with sufficient pressure (Fig. 5.15). Bysmaliths are the laccoliths in which the overlying strata get ultimately fractured at the top of the dome because of continuous injections from below.

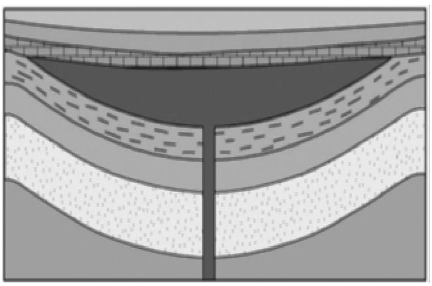


Fig. 5.14 *Lopolith (dark shaded)*

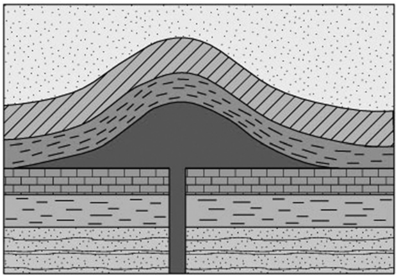


Fig. 5.15 *Laccoliths (dark shaded)*

5.6.4 Discordant Bodies

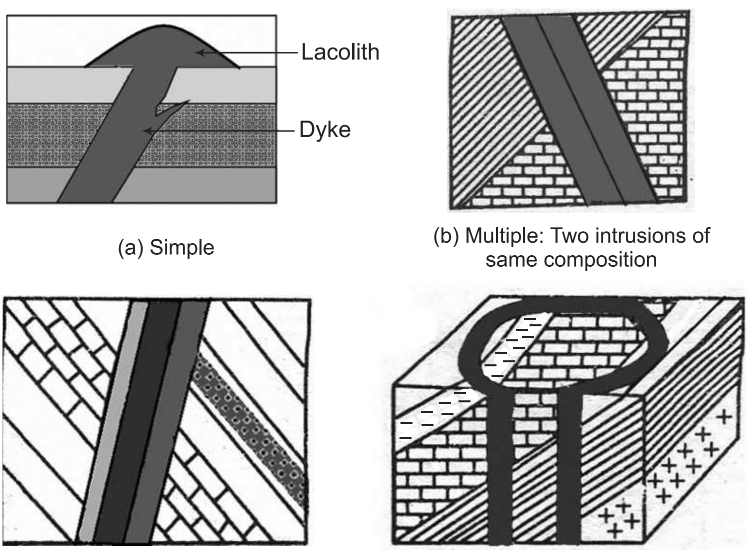
These are the intrusive bodies that have been injected into the strata without being influenced by their structural disposition (dip and strike) and traverse across preexisting structures as shown in Fig. 5.11(b). Dykes, batholiths and volcanic necks are some of the important discordant intrusions. Plate 10 shows the various discordant bodies and the concordant body.

❑ *Dykes*

These are small (< 20 m wide) shallow intrusions (the columnar bodies of igneous rocks) that show a discordant relationship to the rocks in which they intrude. They cut across the bedding plane or cleavage planes and similar structures (Plate 9). They commonly outcrop in nearly straight lines over short distances, but exceptionally may run for many kilometres across the country. Dykes may occur as isolated bodies or may occur as swarms of dikes emanating from a large intrusive body at depth. Dykes commonly have a fine to medium-grained texture.

Dykes are generally made up of hypabyssal rocks like dolerites, porphyries and lamprophyres, showing all the textures. A dike forms when magma enters a fracture and cools. The emplacement of dikes is controlled by fracture systems within the surrounding rock. They commonly radiate from ancient volcanic necks and thus reflect the stresses associated with volcanic activity. They may be only a few centimeters or many hundreds of metres thick, and in length they may be a few metres to several kilometres. Dykes generally tend to occur in groups and therefore these are termed *dyke-set*. When the number of dykes occurring in a limited area is quite large, it is called a *dyke swarm*.

Dykes are classified as simple, multiple, composite and differentiated dykes. Cone sheets and ring dykes are special types of dykes. Cone sheets are assemblages of dyke like injections, which are generally inclined towards common centres. Their outcrops are accurate in outline and their inclination is generally between 30°–40°. The outer sheets tend to dip more gently as compared to the inner ones. Sometimes, upward pressure from a magma chamber produces circular or elliptical fracture systems, in which injected magma forms ring dikes. Large ring dikes can be as much as 25 km in diameter and thousands of meters deep. These may be arranged in concentric series, each separated from the other by a screen of country rock. Figure 5.16 shows some of the types of dykes.



(a) Simple

(b) Multiple: Two intrusions of same composition

(c) Composite: Three intrusions of different composition

(d) Ring dyke

Fig. 5.16 *Types of dykes*

❑ *Batholiths*

These are large intrusive bodies that display both the concordant and discordant relations with the country rock (Plate 9). These are crystallized at considerable depth below the Earth's surface and exposed only by erosion. Batholiths are usually so large that their bottoms are rarely exposed. To be classed as batholiths, the igneous mass should be greater than 100 square kilometres in area and its depth should not be traceable. Sometimes they are composed of several smaller intrusions.

When the surface area is less than 100 km^2, the batholith is called *stock*. Stocks may have been feeders for volcanic eruptions, but because large amounts of erosion are required to expose a stock or batholith, the associated volcanic rocks are rarely exposed. A stock with a roughly circular outline is called *boss*. Minor projections of igneous masses from the roofs of batholiths, stocks and bosses are called apophyses. Although batholiths may be made of any type of igneous rock, a majority of batholiths show predominantly granitic composition.

❑ *Volcanic Neck*

A volcanic neck forms when magma solidifies in a pipe-like conduit through which lava reaches the surface (Plate 10).

5.7 CLASSIFICATION OF IGNEOUS ROCKS

Classification of igneous rocks is not an easy task. It is so because igneous rocks represent a continuum in nature (whether mineralogically or chemically), making their classification rather artificial. Nevertheless, classifications are needed to improve communication between scientists. There are a number of ways the igneous rocks are classified. Some of the important parameters considered for classification of igneous rocks are as follows.

5.7.1 On the Basis of Mode of Occurrence

The igneous rocks may be classed as intrusive and extrusive rocks. The intrusive rocks are those formed by the crystallization of the magma within the Earth's crust, and are termed *plutonic* or *hypabyssal*, depending upon the size and depth of the rock inside the Earth. However, when magma is erupted as lava on the Earth's surface and gets solidified, the rock is termed as *extrusive rock*; the examples are those of volcanic rocks. The igneous rocks are described as follows.

❑ *Plutonic Rocks*

These are the igneous rocks that are formed at considerable depths, generally 7–10 km below the surface of the Earth (Plate 10). A very slow rate of cooling at these depths results in coarse-grained rocks. These rocks get exposed on the surface of the Earth as a consequence of erosion of the overlying strata. Granite, syenite and gabbro are a few examples of plutonic rocks.

❑ *Hypabyssal Rocks*

These igneous rocks are formed at intermediate depths, generally up to 2 km below the surface of the Earth (Plate 10). The hypabyssal rocks exhibit mixed characteristics of volcanic and plutonic rocks. Porphyries of various compositions are examples of hypabyssal rocks. These rocks are characterized by medium grains.

❑ *Volcanic Rocks*

The igneous rocks that are formed on the surface of the Earth by cooling and crystallization of lava erupted from volcanoes are known as volcanic rocks (Plate 10). Since the lava cools down at a very fast rate (compared to magma), the grain size of the crystals formed is very fine, often microscopic. Further, cooling of lava may take place on the surface or under the waters of seas and oceans; the latter process being more common. The examples are Deccan Traps of India spread over more than four lakh square kilometres in Peninsular India; and the Pir-Panjal Traps in Kashmir Himalayas are the example.

5.7.2 On the Basis of Mineralo-Chemical Composition

To classify igneous rocks on the basis of chemical composition, the availability of bulk rock chemical analyses is required. The classification is needed for many volcanic rocks that are either too fine-grained to allow for proper identification of their mineralogy, or contain considerable amounts of glass. The igneous rocks may be classified on the basis of relative abundance of the rock-forming minerals. In terms of the percentage of silica, igneous rocks are classed as acidic, intermediate, basic and ultra-basic rocks.

❑ *Acidic Rocks*

Acidic Rocks also known as *oversaturated rocks* (contain excess of silica to crystallize as quartz), the rocks are rich in silica (> 66%) and have very little ferromagnesian minerals. The common constituents are quartz, alkali feldspar and mica. Acidic rocks are also called *felsic* rocks. These are generally light to medium in colour and have low specific gravity (about 2.7). The example rocks are granites and syenites.

❑ *Intermediate Rocks*

These rocks contain silica between 55 to 66%. The examples of these rocks are pegmatite and syenite. These rocks are characterized by their light colour and medium- to coarse-grained texture.

❑ *Basic Rocks*

These rocks contain silica content between 45 to 55%. These rocks essentially contain dark ferromagnesian minerals and feldspar in significant proportion also. Basic rocks are also called *mafic* rocks. These are generally dark in colour and have high specific gravity (about 3.2). The examples of these rocks are basalt and gabbro.

Note The intermediate and basic rocks together are also classed as saturated basic rocks. These rocks have just sufficient silica to form stable silicate minerals and have no free quartz.

❑ *Ultra-basic Rocks*

In ultra-basic rocks, also known as *undersaturated rocks* (contain insufficient silica so that unsaturated minerals like olivine, nepheline, etc., may be present), silica is present in negligible quantity (< 45%) and quartz is rare. The rocks are rich in ferromagnesian minerals containing high iron and magnesium like olivine. The unsaturated minerals like leucite, nepheline, sodalite, olivine, etc., make these rocks. The example rocks are peridotite and dunite.

5.7.3 On the Basis of Mineralogical Composition

Mineralogical classification is regarded as an easy and most accurate method. The mineralogical composition of most of the igneous rocks can be determined quite accurately, megascopically or by making thin rock sections and studying them under the microscope. Since the mineralogical composition of an igneous rock is an expression of the chemical composition of the parent magma and cooling history of the rock, it therefore forms a sound basis for classifying the igneous rocks.

On the basis of mineralogical composition, the rocks may be classified as felsic, intermediate, mafic and ultramafic. This has been covered in Section 5.7.6.

5.7.4 On the Basis of Colour Index

It is a convention to broadly assess the sum of the coloured minerals in a rock and express it in percentage terms of total mineralogical composition, which gives the colour index of the mineral. This is a very simple classification used by field geologists, and depends on estimating the volume percentage of the dark-coloured (mafic) minerals in the rock. The rock divisions into four groups on the basis of colour index are given in Table 5.1.

Table 5.1 *Rock divisions on colour index*

S. No.	*Rock Division*	*Colour Index*	*Examples*
1.	Leucocratic	1–30	Granite
2.	Mesocratic	31–60	Lamprophyre
3.	Melanocratic	61–90	Gabbro
4.	Hypermelanic	>90	Peridotite

Note Igneous rocks which are excessively rich in mafic minerals with a colour index above 90 and are also termed as *hypermelanic*.

5.7.5 On the Basis of Texture

This is a megascopic or microscopic classification. Textures are used as a secondary criterion for the classification of igneous rocks. Based on the texture, igneous rocks may be classified as follows.

❑ *Phanerites*

Large crystals that are clearly visible to the eye with or without a 10-power (10 X) hand lens. The entire rock is made up of large crystals which are generally ½ mm to 5 mm in size (coarse-grained; average grain size greater than 5 mm); no fine matrix material is present. This texture forms by the slow cooling of magma deep underground in the plutonic environment.

❑ *Aphanites*

These are the crystals that cannot be seen by the eye with or without a 10-power hand lens. The entire rock is made up of small crystals, which are generally less than ½ mm in size. This texture results from the rapid cooling in volcanic or hypabyssal (shallow subsurface) environments.

❑ *Glasses*

Glass results from cooling that is so fast that minerals do not have a chance to crystallize. This may happen when magma or lava comes into quick contact with much cooler materials near the Earth's surface. Glasses may be defined as rocks of zero grain size. These are sometimes referred as *supercooled liquids*. Pure volcanic glass is known as *obsidian*. The non-crystalline (glassy) structure of the rock, in which no minerals are present, is termed glassy texture.

5.7.6 Tabular Classification

To facilitate field geologists and engineers, who are rather concerned more with a practical classification system than a theoretical one, igneous rocks may be classified on the basis of chemical composition, mineralogical composition and depth of occurrence. Table 5.2 shows the modern classification of igneous rocks.

Table 5.2 *Tabular classification of igneous rocks*

Mode of Occurrence	Silica % + Mineralogical composition			
	Quartz + Orthoclase	Quartz + Albite	Honblende + Olivine ± Quartz	
	$SiO_2 > 66\%$	66–55%	55–45%	< 45%
	Acidic	***Intermediate***	***Basic***	***Ultrabasic***
Volcanic	Rhyolite	Trachyte	Basalt	Dunite
Hypabyssal	Syenite	Microdiorite	Dolerite	Microperidotitite
Plutonic	Granite	Diorite	Gabbro	Peridotite

The essential features of the tabular classification are as follows:

1. Each class of the above rocks is subdivided into rock subclasses according to the relative abundance of rock-forming mineral assemblages of: quartz and feldspars; feldspars; feldspars and felspathoids and; ferro-magnesian minerals.
2. Silica content is also an important governing factor for classification of igneous rocks.
3. The igneous rocks are first classed based on their mode of occurrence as indicated by their textural and structural features: plutonic, hypabyssal and volcanic.

5.8 IMPORTANT IGNEOUS ROCKS AND THEIR CHARACTERIZATION

Important characters of a few of the common igneous rocks are described as follows for a ready reference. Engineering properties of these rocks have been dealt with in detail in Chapter 9.

5.8.1 Granite

Granite is a plutonic acidic igneous rock which is generally derived at deeper depth. It is one of the most common igneous rocks found on the Earth.

❑ *Mineralogical Composition*

Granite is mainly composed of quartz and feldspar with biotite and hornblend. The colour of different granites is derived by the presence of feldspar, i.e. albite and orthoclase. Microcline and tourmaline may also be present as an accessory mineral.

❑ *Texture*

The texture of granite depends upon the mineral composition as well as their mutual relationship. Granite shows porphyritic as well as intergrowth texture, depending upon the abundance of quartz to feldspar.

❑ *Occurrence*

Granites generally occur in the crust of the Earth and one of the most abundant igneous rock. They are mainly situated as deep-seated intrusive bodies like sills, and batholiths. Granites are exposed on the surface as an outcrop after erosion activities.

❑ *Megascopic Identification*

Granites may be identified in hand specimens by their

(i) Light-coloured (leucocratic) appearance such as grey, pink, brownish and yellowish. Some of the shades may take brilliant polish to make it eminently suitable as a decorative building stone,

(ii) Coarse- to medium-grained and nonlayered texture, and

(iii) Abundance of quartz and feldspar (orthoclase) as essential minerals and tourmaline and hornblende as accessary minerals.

❑ *Use*

Granites are widely used in building materials as decorative stones, both as exterior and interiors. Different types of granites are also used for geological studies.

❑ *Origin*

There are two thoughts related to the genesis of granite– 1. simple crystallization of molten magma and, 2. due to partial melting of existing rocks, i.e. anatexis.

5.8.2 Diorite

Diorite is an intermediate and plutonic igneous rock which is characterized by intermediate characters between granite and rhyolite. Silica lies between 52 to 66 per cent.

❑ *Mineralogical Composition*

Diorites are typically rich in feldspar plagioclase of sodic group (e.g. albite). Besides plagioclase and alkali feldspars, diorites also contain accessory minerals like hornblende, biotite and some pyroxenes. Quartz is uncommon in diorite; but sometimes if it is present, it would be called as quartz-diorite.

❑ *Texture*

The texture generally observed in diorite varies from coarse- to medium-grained and has holocrystalline arrangement of different mineral grains. It shows ineguigranular texture, particularly panidiomorphic texture.

❑ *Occurrence*

Diorite commonly occurs as small intrusive bodies like dikes, sills, stocks and other irregular intrusive masses. They also get formed at the margins of bigger igneous masses called igneous pluton. It is found as hypabyssal rock.

❑ *Megasopic Identification*

Diorite may be identified in hand specimens by their

(i) Light-coloured (leucocratic) appearance such as grey, and yellowish. Some of the shades may take a brilliant polish to make it eminently suitable as a decorative building stone,
(ii) Medium to fine grained, and
(iii) Abundance of quartz and plagioclase (albite) as essential minerals and biotite and hornblende as accessory minerals.

❑ *Use*

Diorite is used in buildings as decorative stones and also as aggregate.

❑ *Origin*

It is originated due to the slow cooling of magma at intermediate depths.

5.8.3 Andesite

Andesite is volcanic igneous rock in which plagioclase feldspars (albite, andesine and labradorite) are the predominant constituents making the potash feldspar (orthoclase/microcline) only a subordinate member.

❑ *Mineralogical Composition*

It is constituted by plagioclase. Andesite may contain small amounts of quartz as well as biotite, hornblende, augite, olivine and hypersthene from the dark minerals giving them an overall greyish or darker appearance.

❑ *Occurrence*

Andesite occurs abundantly as volcanic rocks, next to basalts, and may also occur as crystallized lava flows of extensive dimensions.

❑ *Megasopic Identification*

Andesite may be identified in hand specimens by their

(i) Dark-coloured (mesococratic) appearance such as dark grey, and brown,
(ii) Fine grained, and
(iii) Abundance of quartz and andesine as essential minerals and biotite and hornblende as accessory minerals.

❑ *Use*

Polished blocks of andesite make it eminently suitable as a decorative building stone. Andesite is used in buildings as decorative stones and in the paint industry.

❑ *Origin*

Two modes of origin are suggested. First, it is crystallized from a simple crystallization process from magma, while a second thought is that it is derived from the reaction of wall rock.

5.8.4 Syenite

Syenite is a plutonic coarse-grained, intermediate type of rock. It is the plutonic equivalent of trachyte.

❑ *Mineralogical Composition*

Syenites mainly contain feldspars of which many types may occur simultaneously in the same rock or in different varieties. The most common feldspars of syenite are orthoclase and albite. Microcline, oligoclase and anorthite are also present in them as accessory minerals. In some syenites, the minerals like nepheline, and leucite are present. Common accessory minerals occurring in syenites are apatite, zircon, and sphene. Quartz is absent and rarely present as a minor accessory.

❑ *Texture*

Syenite shows textures coarse- to medium-grained textures, holocrystalline in nature and exhibit graphic, inter-grown or porphyritic relationship among its constituents.

❑ *Occurrence*

Syenite occurs in the plutonic stage of igneous activity when a suitable composition of magma is cooled down.

❑ *Megasopic Identification*

Syenite may be identified in hand specimens by their

(i) Light-coloured (lucocratic) appearance, such as light grey, and white,
(ii) Coarse grained, and
(iii) Orthoclase albite, and biotite as essential minerals and nepheline and hornblende as accessory mineral.

❑ *Use*

Syenite is used in buildings as decorative stones and also in the extraction of nephaline as mineral .

❑ *Origin*

The origin of syenite has been a long debate due to its variable composition and variation in mode of occurrence. A common association of nepheline syenite with syenite and limestones in various occurrences has suggested that syenite has been formed from silicic magma which has reacted with the associated limestone.

5.8.5 Gabbro

Gabbro is a coarse grained, plutonic basic rock.

❑ *Mineralogical Composition*

Plagioclase feldspars of lime and soda composition (e.g. labradorite and anorthite) are the chief constituents of gabbro. Besides these, the mafic minerals like augite, hornblende, olivine, biotite and iron oxides are common as accessory minerals.

❑ *Texture*

Gabbro shows inequigranular textures in which augite or olivine mineral encloses the plagioclase. The modal abundance of plagioclase is more than augite or olivine. Reaction rim is also well observed in gabbro.

❑ *Occurrence*

Gabbro occurs under plutonic condition and is associated with convergent plate margin.

❑ *Megasopic Identification*

Gabbro may be identified in hand specimens by its

(i) Dark-coloured (melanocratic) appearance, such as dark grey and dark brown. Some of the shades may take a brilliant polish to make it eminently suitable as a decorative building stone,
(ii) Coarse grained, and
(iii) Abundance of labradorite plagioclase and olivine/augite as essential minerals and quartz or biotite as an accessory mineral.

❑ *Use*

Gabbro is used in buildings as decorative stones and also in the extraction of plasioclase as mineral.

❑ *Origin*

It has originated due to the slow cooling of basic magma at deeper depth and is also associated with convergent plate boundaries.

5.8.6 Dolerite

Delorite is igneous, volcanic basic rock of typically hypabyssal origin. It may be regarded as an equivalent of gabbro of hypabysal origin and basalt of volcanic origin. It is sometimes also called *diabase*.

❑ *Composition*

Dolerite is predominantly made up of calcic plagioclase (e.g. anorthite and labradorite). Dark minerals like augite, olivine and iron oxide, etc., are also present in good proportions along with the plagioclase minerals.

❑ *Texture*

Ophitic texture is very common in which augite mineral encloses the plasoclase.

❑ *Occurrence*

Sills and dykes of doleritic composition have been recorded at many places associated with magmatic activity. In the Singhbhum region of south Bihar, many doleritic dykes traverse the Singhbhum granites.

❑ *Megasopic Identification*

Dolerite may be identified in hand specimens by their

(i) Dark-coloured (melanocratic) appearance, such as dark grey and dark brown. Some of the shades may take a brilliant polish to make it eminently suitable as a decorative building stone,

(ii) Medium grained, and

(iii) Abundance of labradorite plagioclase and olivine/augite as essential minerals and quartz or biotite as accessory mineral.

❑ *Use*

Dolerite is used in buildings as decorative stones and in the extraction of plasioclase as mineral.

❑ *Origin*

Dolerite has originated due to the slow cooling of basic magma at deeper depth and also associated with convergent plate boundaries.

5.8.7 Basalt

Basalt is a volcanic, igneous basic rock formed by rapid cooling from lava flows, either over the surface or underwater on oceanic floors.

❑ *Mineralogical Composition*

Basalts are commonly made up of calcic plagioclase feldspars (anorthite and labradorite) and a number of ferro-magnesian minerals like augite, hornblende, hypersthene, olivine, biotite and iron oxides, etc. In fact, many types of basalts are distinguished on the basis of the type and proportion of ferro-magnesian minerals in them.

❑ *Occurrence*

Basaltic rocks form extensive lava flows on the continents and also on the oceanic floors at divergent and convergent boundaries in almost all the regions of the world. In India, the Deccan Traps, which composes mainly basalt, are spread over more than four hundred thousand square kilometres in Maharashtra, Gujarat, Madhya Pradesh and adjoining parts of the Indian Peninsula.

❑ *Megasopic Identification*

Basalt may be identified in hand specimens by their

(i) Dark-coloured (melanocratic) appearance, such as dark grey and black appearance,
(ii) Fine grained, and
(iii) Abundance of labradorite plagioclase and olivine/augite as essential minerals and quartz or hornblende as an accessory mineral. Zeolite mineral is also generally associated with basalt after solidification.

❑ *Use*

Basalt is used in buildings as decorative stones and in the extraction of zeolite as mineral.

❑ *Origin*

It has originated due to rapid cooling of basic magma on surface of the Earth and is also associated with divergent plate boundaries.

5.8.8 Pegmatite

Pegmatite is an exceptionally coarse grained igneous rock formed from hydrothermal solutions emanating from magmas that get cooled and crystallized in cavities and cracks around magmatic intrusions.

❑ *Mineralogical Composition*

Pegmatites exhibit great variation in their mineral composition. The granite-pegmatites contain alkali feldspars (like orthoclase and microcline) and quartz as the dominant minerals. A variety of other minerals like tourmaline, micas (muscovite and biotite), topaz, fluorite, spodumene, beryl, cassiterite, wolframite, columbite and tantalite, etc., occur in different pegmatites.

❑ *Texture and Structure*

Pegmatites do not show any special textures and structures, except that they are invariably coarse grained and mostly inequigranular. In many pegmatites, the so-called complex pegmatites, a zonal structure is commonly observed. In such cases, different minerals of pegmatite occur in different zones, starting from the periphery and proceeding towards the centre. In a five-zoned pegmatite, for instance, the outermost zone is made up of muscovite and feldspar, the second zone is of quartz and feldspar, third zone of microcline and fourth of quartz. The central zone is ploymineralic containing albite and spodumene besides quartz and mica.

❑ *Occurrence*

Pegmatite occurs in fissures and cracks in existing igneous and metamorphic rocks as a later phase of magma crystallizes and solidified in cracks. Pegmatites are very common in Bihar, Jharkhand, Chhatisgarh, MP and Rajasthan.

❑ *Megasopic Identification*

Pegmatite may be identified in hand specimens by their

(i) Light-coloured (lucoocratic) appearance, such as light grey and white appearance,
(ii) Very coarse grained, and
(iii) Abundance of quartz, orthoclase, tourmaline, plagioclase, mica as essential minerals and microcline, hornblende as accessory minerals.

❑ *Use*

These rocks are used for their containing big-sized crystals of minerals. Some of these crystals may be gems and other precious minerals.

❑ *Origin*

No single mode of origin can be assigned to them. At present, two modes of origin are broadly suggested. Pegmatites have been formed from magmatic melts towards the end of the process of crystallization. The hydrothermal fractions left behind at this stage are capable of taking in solution all metallic and nonmetallic components by virtue of their temperature, pressure and chemical reactivity. Most of the granite- and syenite-pegmatites are believed to have formed through this mode.

5.8.9 Lamprophyre

Lamprophyres form a group of igneous rocks that typically occur as dykes and sills.

❑ *Texture*

Panidiomrphic (in which most of crystals show a perfect outline), fine grained and holocrystalline.

❑ *Mineralogical Compositlon*

Lamprophyres show a great variation in their mineralogical composition. Mostly they are rich in ferro-magnesian silicates. Important minerals forming lamprophyres are biotite, augite and other pyroxenes, hornblende and other amphiboles, feldspars and olivine.

❑ *Structure*

Lamprophyre does not show any special textures and structures, except that they are invariably coarse grained and mostly inequigranular.

❑ *Occurrence*

Lamprophyres occur in fissures and cracks in existing igneous and metamorphic rocks as the later phase of magma crystallizes and gets solidified in cracks. Pegmatities are very common in Bihar, Jharkhand, Chhatisgarh, MP and Rajasthan.

❑ *Megasopic Identification*

Pegmatite may be identified in hand specimens by their

(i) Light-coloured (lucoocratic) appearance, such as light grey and white appearance,
(ii) Very coarse grained, and
(iii) Abundance of quartz, orthoclase, tourmaline, plagioclase, mica as essential minerals and microcline, hornblende as accessory minerals.

❑ *Uses*

These rocks are used for their containing big-sized crystals of minerals. Some of these crystals may be gems and other precious minerals.

❑ *Origin*

It is originated from anatexis, i.e. process of partial melting and recrystallization.

5.8.10 Peridotite

The peridotite rock is an ultra-mafic, coarse grained, plutonic igneous rocks.

❑ *Mineralogical Composition*

It is highly rich in a ferro-magnesian mineral like olivine and augite, which has a composition of $(Mg,Fe)SiO_4$. This is characterized by a low silica index; (when silica is less than 45%). It is also characterized by the presence of much more darker minerals which give melanocratic appearance.

❑ *Texture*

Peridotites are generally massive and coarse grained in texture.

❑ *Occurrence*

Peridotites occur in form of sills and dykes of moderate size and are found at deeper depth.

❑ *Uses*

Peridotites are not common igneous rocks, but it is a suitable rock to replace the basalt and dolerite for giving dark appearance in building exteriors. The olivine and augite minerals are also extracted from this rock.

❑ *Origin*

The origin of peridotite is mainly due to the crystallization of basic magma, and sometimes it may also be derived by hydrothermal fluids rich in magnesium and iron.

5.9 ENGINEERING IMPORTANCE OF IGNEOUS ROCKS

The igneous rocks are typically impervious, hard and strong and form very strong foundations for most of civil engineering projects such as dams and reservoirs. Many of the igneous rocks are used extensively as materials for construction. Granites, syenites and dolerites possess very high crushing strength and are therefore supposed to be most suitable for construction works. Although, basalts and other dark coloured igneous rocks are equally strong, these are recommended for use in foundation of structures and roads only. Until traversed by joints, these rocks are the best for tunnels.

Some of the igneous rocks like peridotites and pegmatites are very valuable; they may contain many valuable minerals of much economic worth. Moreover, their minerals and chemistry give information about the composition of the mantle, from which some igneous rocks are extracted, and the temperature and pressure conditions that allowed this formation, and/or of other pre-existing rock that melted.

Summary

Igneous rocks are formed by the cooling and crystallization of a silicate melt (dominated by oxygen and silicon, with a variety of other metals). The molten rock material from which igneous rocks form is called magma. It is in fact a melt and is assumed to get formed at great depths below the surface of the Earth; it is not possible to see magma at its place of occurrence. Magma, which is in molten state, may include already formed crystals and dissolved gases. The causes attributed to the formation of magma are the rise in temperature with depth and occurrence of radioactive minerals. The magmas when reach the Earth's surface are referred to as *lava*. Lava is, however, a thoroughly studied material that has poured out occasionally from volcanoes in many regions of the world which confirms existence of the magma below the surface.

The various kinds of igneous rocks can be distinguished by their chemical composition, mineral composition, mode of occurrence and texture. The chemical and mineralogical composition of igneous rocks is discussed with their limitations in the light of classification of igneous rocks. Texture and its types are described. Texture is the way the minerals in the rock look like and relate to each other. The controlling factors resulting in various textures are discussed in detail.

The intrusive and extrusive rocks have been described. The intrusive rocks are formed beneath the surface of Earth and cool down slowly inside the crust. Generally, rocks with phaneritic textures have minerals of coarse to intermediate grain size. If these rocks form at very shallow depths they may be called hypabyssal, and porphyritic textures are developed (e.g. dykes and sills). If they form at considerable depth, they are called plutonic rocks and the respective rock bodies may be called stocks, or batholiths, or plutons. The extrusive rocks are those that make it to the surface of the Earth in molten state, tend to cool quickly, and have therefore typically small crystals. These are the volcanic rocks formed by the eruption of magma on the surface of Earth. The resulting textures aphanitic and glassy have been explained. These textures are typical of volcanic rocks. Gas bubbles (pressure drop at eruption) may give rise to vesicular structures. Pyroclastic textures formed from ashfalls and ashflows are also discussed.

Bodies of igneous rocks vary in variety of shapes and sizes. Forms of igneous rock bodies, both the intrusive and extrusives, have been discussed. Rock bodies that cool beneath the surface described as plutons, and discordant and concordant bodies are described. The classification of rocks on the basis of mode of occurrence, chemical composition, minerals present, and colour index are presented. The chapter ends with the discussion about the classification systems of igneous rocks followed with the details of various types of igneous rocks used in civil engineering construction works.

Terminology

Accessory Minerals Those minerals which are present in very small amounts (< 10% by volume), and can normally be ignored when naming the rock. However, it may be useful in the name to note the presence of a particular accessory mineral in a rock, particularly if that mineral is not normally associated with that particular rock type, and this can be done by adding the mineral name as a prefix e.g. quartz gabbro.

Batholith A large igneous discordant structure, often many kilometres across.

Countryrock The rock (of any kind) that has been invaded by an igneous mass.

Dike A sheetlike body that fills a fracture that cuts across other rocks.

Essential Minerals Those minerals which are necessary to the naming of the rock, but may only be present in minor quantities, e.g. quartz and feldspar in granite.

Fabric The texture and structure of an igneous rock together define the fabric of the rock.

Laccolith A concordant igneous structure resembling a saucer (roughly lens shaped).

Plutons Rock bodies that cool beneath the surface of the Earth are generally described as *plutons*.

Rock cycle The phenomenon of the transformation of igneous, sedimentary and metamorphic rocks from one type to another is known as rock cycle.

Sill A sheet like injection of magma between layers of sedimentary or metamorphic rock.

Structures The features of igneous rocks that are developed on a large scale in the body of igneous rocks that give rise to conspicuous shapes or forms.

Texture The size, shape and arrangement of the crystals of the constituents composing the body of the igneous rock define the property known as *texture*. Texture describes the way the minerals in the rock look like and relate to each other (large *vs* small; ideal crystal shapes or irregular grains, etc.), and is in large parts influenced by the cooling history of the magma.

Exercises

1. Define petrology. How is a rock defined? Classify the igneous rocks on the basis of their mode of origin.
2. (a) Define structure and texture of igneous rocks.
   (b) On what basis are igneous rocks classified?
3. (a) How are igneous rocks formed? What are their characteristics?
   (b) Describe briefly the rock cycle with the help of a neat sketch.
4. (a) Classify igneous rocks into various groups. Give the tabular classification of igneous rocks. What parameters are considered for this classification?
   (b) What are extrusive and intrusive igneous rocks? Describe their salient features.
5. Describe briefly various textures found in igneous rocks. What is the importance of each of them?
6. Enumerate the uses of different igneous rocks in Civil Engineering projects. Why are volcanic rocks fine grained?
7. Give an account of the classification of igneous rocks. Which of these classifications is most suitable for field engineers and why?
8. What are the various textures of igneous rocks? Explain them with neat sketches.
9. Enumerate the important igneous rocks. Give a brief account of their distinguishing characteristics.
10. Write short notes on the following:
    (a) Dyke and sill
    (b) Reaction rim
    (c) Batholith
    (d) Cone-sheet
11. Differentiate between the following:
    (a) Directive and intergrowth textures
    (b) Ophitic and Sub-ophitic textures
    (c) Concordant and discordant structures
    (d) Phacolith and laccolith
    (e) Granite and basalt
    (f) Dyke and sill
    (g) Essential and accessory minerals
    (h) Trachyte and rhyolite

Multiple-Choice Questions

1. Mineralogical composition of granite is
(a) quartz, feldspar and biotite
(b) quartz, hornblende and biotite
(c) feldspar, hornblende and olivine
(d) quartz, biotite and tourmaline

2. Mineralogical composition of basalt is
(a) quartz, feldspar and biotite
(b) augite, olivine and plagioclase
(c) quartz, olivine and hornblende
(d) hornblende, olivine and biotite

3. Texture observed in gabbro is
(a) directive (b) panidiomorphic
(c) intergrowth (d) ophitic

4. Texture observed in granite is generally
(a) poikilitic (b) inequigranular
(c) equigranular (d) subophitic

5. The discordant igneous structure in igneous rock is
(a) sill (b) phacolith
(c) lacolith (d) batholith

6. The concordant structure in igneous rock is
(a) sill (b) dyke
(c) ring dyke (d) batholith

7. Granite is mostly used in
(a) building (b) flooring
(c) foundation (d) both building and flooring

8. Basalt is formed from
(a) magmatic emplacement (b) volcanism
(c) geothermal plumes (d) hydrothermal fluids

9. Volcanic equivalent of gabbro is
(a) dolerite (b) basalt
(c) granite (d) rhyolite

10. Plutonic equivalent of rhyolite is
(a) granite (b) basalt
(c) dolerite (d) rhyolite

11. Igneous rock is also known as
(a) primary rock (b) secondary rock
(c) tertiary rock (d) primary or secondary

12. Pegmatitite is
(a) acidic igneous rock (b) basic igneous rock
(c) ultramafic igneous rock (d) intermediate igneous rock

13. Consider the following with regards to corona and reaction rim in igneous rocks. These are
1. textures

2. structures
3. neither texture nor structure

Of the above

(a) only 1 is correct (b) only 2 is correct

(c) 1 and 2 both are correct (d) only 3 is correct

14. Consider the following with regards to tabular classification of igneous rocks.

1. Silica %
2. Mineralogical composition
3. Depth of origin

Of the above, the parameters considered are;

(a) 1 and 2 (b) 2 and 3

(c) 1 and 3 (d) 1, 2 and 3

15. Igneous rocks may be formed from

1. magma
2. lava
3. oil and compounds

Of the above

(a) Only 1 and 2 are correct (b) Only 2 and 3 are correct

(c) Only 1 and 3 are correct (d) Only 1 is correct

Answers to MCQs

1. (a)	2. (b)	3. (d)	4. (c)	5. (d)	6. (a)	7. (d)	8. (b)
9. (b)	10. (a)	11. (a)	12. (a)	13. (c)	14. (d)	15. (a)	

chapter 6

Rocks II: Sedimentary Rocks

6.1 INTRODUCTION

Sedimentary rocks forming the Earth's crust cover about 75% of the continental areas. Nearly 100% of the ocean floor is blanketed with at least a thin layer of sediment. One factor that all sedimentary rocks have in common is that they are deposited, in basin or low-lying area, and that is why they are characterized by *bedding* or *stratification*. In fact, the sediments of any particular time period form a distinct layer that is underlain by equally distinct layers of respectively older times as well as overlain by layers of younger times.

Sedimentary rocks may form mechanically, organically or chemically. They are formed in basins or sub-basins by deposition, consolidation and cementation of sediments. This involves mechanical weathering and erosion of pre-existing rocks, and disintegration, transportation and deposition of eroded materials in the basins facilitated by the natural agencies. Different agencies like rain, stream-flow, wave action, ocean circulation, wind and glaciers, therefore, play a vital role. As sediment accumulates with time (thousands of years), it becomes compacted and cemented, eventually forming sedimentary rock. Some common sedimentary rocks are shale, sandstone, limestone, and conglomerate. Apart from this process, sedimentary rocks are also formed due to leaching of chemicals (chemical weathering) through different types of organism which later on get compacted. Furthermore, biological action is also responsible for generation of sedimentary rocks like coral reefs or even coal deposits. Most sedimentary rocks are of secondary origin, in that they consist of material derived by the breakdown of pre-existing rocks.

Since sedimentary rocks are stratified, they facilitate deciphering the sequence of events that made today's Earth, if not reformed. In addition, the animals that lived during these time periods get preserved in their respective sediment units, which help to establish the changes of plant and animal communities through history. Since most of the Earth's exposed land surface consists of sediments and sedimentary rocks, these are more familiar than the igneous or metamorphic rocks. The importance of sedimentary rocks from the perspective of their use in civil engineering projects can not be overemphasized.

6.2 ORIGIN OF SEDIMENTARY ROCKS

The constituents of sedimentary rocks derived from the mechanical breakdown and chemical decay of pre-existing rocks, get compacted and cemented in due course of time, to form solid rock bodies. This may be explained with reference to the type and the source of the sediments and the depositional environment (Fig. 6.1). The sedimentary rocks may be formed in any of the following manner:

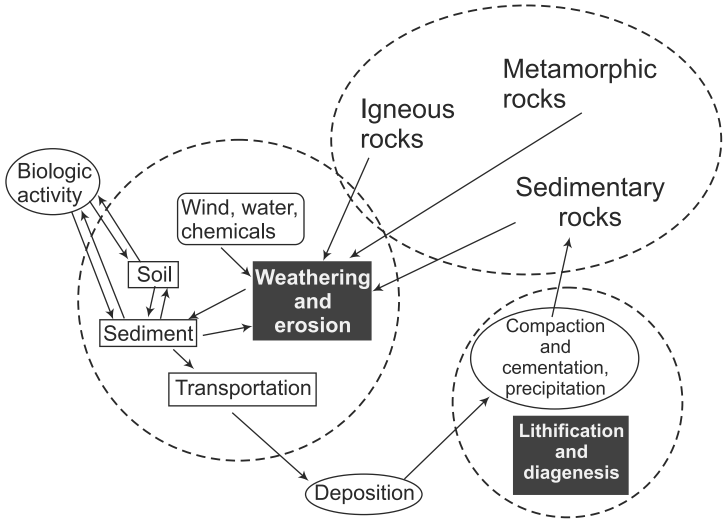


Fig. 6.1 *Rock cycle of sedimentary rocks*

1. The pre-existing rocks on the Earth's surface are eroded continually by natural processes. The sediments so produced get transported by the natural agencies to the basins where they are deposited. Sand grains dumped on the beach by the waves, silt dumped off the mouth of a river in a delta, glacial moraine deposits, landslide deposits, etc., are some examples. These deposited eroded-materials get compacted and consolidated, and finally transformed into a cohesive solid mass.
2. The sea and oceanic organisms perish in due course of time. The hard parts of these organisms accumulate at the floors of the water bodies, and gradually get compacted and converted into sedimentary rocks. For example corals (which are little animals) extract $CaCO_3$ from the ocean to make their skeletons which form a coral reef. When they die, their skeletons eventually crumble and collect on the bottom of the ocean to form a sedimentary rock.
3. Chemical processes–evaporation and precipitation–continually operate on the surface of water bodies. These processes result into solids that settle down in the water bodies containing dissolved salts, producing sedimentary rocks.

Note Many sedimentary rocks are a mixture of two or more of the above mentioned processes.

On the basis of their mode of formation, the sedimentary rocks are broadly grouped into three classes: mechanically formed rocks, also called *clastic rocks* or *terrigenous rocks*, organically formed rocks and chemically formed rocks; the latter two groups of rocks are termed as *non-clastic rocks*.

6.2.1 Formation of Clastic Rocks

Formation of clastic rocks involves weathering and erosion of the pre-existing rocks, and transportation, deposition, compaction and consolidation of the sediments. These processes are described as follows.

❑ *Weathering and Erosion*

The process of weathering and erosion is also termed *decay and disintegration*. It is the first step in the genesis of sedimentary rock. The original hard and coherent rock bodies are gradually broken down into smaller fragments, grains and particles by the climatic factors like temperature, humidity, etc. Besides climatic and atmospheric factors, there are different geological agencies like stream, wind and glaciers, responsible for disintegration of existing rocks. The disintegrated pre-existing solid rocks thus form a layer of loose, decayed rock debris, or soil, which accumulates near the source. This is called *sediment* or *detritus*. Hence, clastic rocks are often also termed *detrital rocks*.

Notes

1. The rate at which denudation takes place acts as a control on the rate of sedimentation, which in turn affects the character of a sediment.
2. The rate of denudation is not only determined by the agents at work, but also by the nature of the surface. The upland areas are more rapidly worn away than are lowlands. Each cycle of erosion is accompanied by a cycle of sedimentation.

❑ *Transportation of Sediments*

The process of accumulation of sediments at the site of deposition is called *sedimentation*. The sediments produced by weathering and erosion can then be transported by the natural agencies to a suitable place for transformation again into a rock mass.

The winds transport the sediments from ploughed fields, the deserts and the dry lands. These loads of sediments are dropped down wherever intercepted by rains. Running water is the most effective form of sediment transport. All streams and rivers carry sediment loads toward the sea. As clastic sediment is transported by a river, it is sorted and separated according to grain size and composition.

Large particles accumulate in high-energy environments as gravel, medium-sized grains are concentrated as sand, and finer material settles out as mud. The large particles are carried by rapidly moving streams with high amounts of kinetic energy; only small particles are transported by slowly moving streams. Ice, in the form of huge moving bodies called *glaciers,* also breaks the rocks along their bases and sides (in valley glaciers) and dumps the same at low lying areas, thereby making large volumes of the clastic load that is further transported by other agencies. The sediments are thus transported to seas and oceans where they get deposited.

Note The particles of which sedimentary rocks are composed have undergone varying amounts of transportation. The amount of transport together with the agent responsible plays an important role in determining the character of a sediment. Transport over short distances usually result in the unsorted sediment with an exception of beach sands. However, lengthier transport by water or wind, results in better sorted and reduced size material.

❑ *Deposition*

The sediments produced through weathering and erosion are transported to settling basins. Probably the most significant factor in the genesis of sedimentary rocks is the place where the sediment is deposited. The deposition of clastic material is controlled by the change in physical parameters of the transporting agency. These basins in which the sediments are deposited may be located in different environments such as on the continents, along the seashores or in the deep-sea environments. As such, sedimentary rocks formed in different environments will show different inherent characters. The continental environments may include the glacial deposits, the fluvial deposits, the glacio-fluvial deposits and the eolian deposits, each type giving rise to a definite type of sediment accumulation. In the marine deposits, some sediment may be dropped just along the sea-shore, or at some shallow depth within the sea or quite far away in the deep-sea environment. The depositional environment of a sedimentary rock is reflected in the physical, mineralogical, textural and structural characteristics of the rock. Deposition of non-clastic material, however, occurs *in situ* (at the place of erosion/weathering).

Notes

1. The sediments during their transport and deposition are subjected to sorting or grading according to their size, shape, and density. Consequently, these sediments get deposited in the form of layers in general.
2. The sediments deposited in the settling basins gradually get converted to cohesive and hard rock formations through the process known as *diagenesis*.

❑ *Diagenesis*

The process of transformation of loose sediments deposited in the basins to solid cohesive rock masses either under pressure or because of cementation is collectively known as *diagenesis*. It is also known as *lithification* or sometimes *consolidation*. It may be achieved by either welding or cementation.

The process of compaction of the sediments accumulated in the lower horizons of a basin due to the pressure exerted by the load of the overlying sediments is called *welding*. This results in squeezing out all or most of the water from in between the sediments. Consequently, the sediments are brought closer and closer and get consolidated virtually in a solid rock mass. In fact, the degree of packing of sediments in a sedimentary rock is broadly directly proportional to the load of the overlying sediments. *Cementation*, on the other hand, is the process by which loose grains or sediments in a basin get held together by a binding material of its own. The binding material may be derived from within the accumulated particles or the fluids The examples of cementing materials are silica, calcium carbonate, iron oxide, etc.

6.2.2 Formation of Non-clastic Rocks

❑ *Chemically Formed Rocks*

These non-clastic rocks are formed by recrystallization of mineral matters in solution. Water from rains, springs, streams, rivers, lakes and underground water bodies dissolves many compounds from the rocks with which it comes into contact. Generally, these dissolved salts are carried by the running water ultimately to the sea. Furthermore, the local water bodies may get saturated with one or the other dissolved salt. A stage may be reached when the dissolved salts get crystallized out either through evaporation or through precipitation. For examples, limestone may be formed by precipitation from carbonated water due to loss of carbon dioxide, and rock salt may be formed from sodium chloride rich seawater, merely by the process of continued evaporation in bays and lagoons. Chemically formed rocks may be thus of two types: precipitates and evaporites. Examples of non-clastic rocks are limestone, rock salt, gypsum, and anhydrite.

❑ *Organically Formed Rocks*

The rocks which are formed due to decomposition of biological or organic matter are known as *organic sedimentary rocks*. These rocks are formed in-situ with existence of suitable environmental condition including oxidation and reduction condition. Besides these conditions, temperature, pressure and time of burial are important for the formation of organic sedimentary rocks. These rocks are characterized by non-clastic textures and structures because the formation of these rocks occur in low energy condition. Coal, coral reef, etc., are the examples of such rocks.

6.3 DEPOSITIONAL ENVIRONMENTS

Sediments may accumulate at different places and in vastly different environments, also called *genetic environments*. The concept of formation of a sedimentary rock in a particular type of environment is explained by the term *facies* (Fig. 6.2). A small depositional area within a system creates a facie; a body of rock with distinct chemical, physical and biological characteristics created by the environment. The three main facies recognized with respect to the formation of sedimentary rocks are as follows.

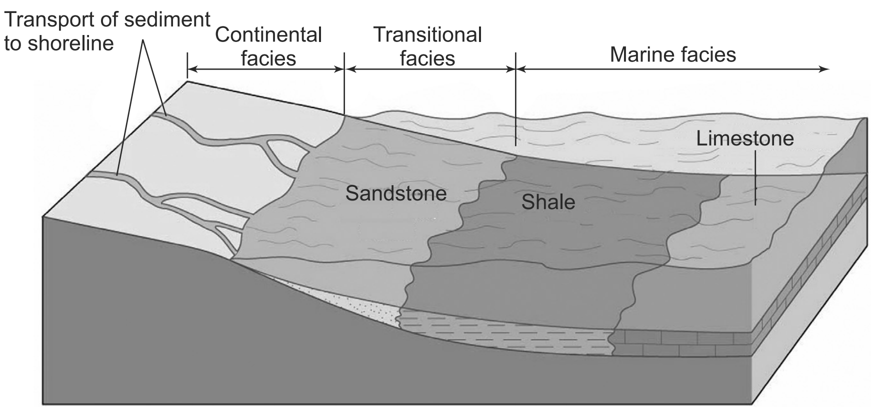


Fig. 6.2 *Facies of sedimentary rocks*

❑ *Continental Facies*

Some sedimentary rocks formed on the continents in lakes, rivers, streams and alluvial fans are known as *continental facies*. Coarse-grained rocks like breccia, conglomerates and soft sandstone are typical examples of rocks of continental facies. Some of the other examples are boulder clays of glacial origin and varved clays of lacustarine origin. The rocks of continental facies are, in general, relatively less dense, loosely packed, and often cemented and form good repository for groundwater.

❑ *Transitional Facies*

Some sedimentary rocks that may form by accumulation and compaction of sediments along the seashore, or on the continental shelf that remain partly submerged under sea are known as *transitional facies*. The examples are deltas, beaches, barrier islands, tidal flats, and lagoons. Many types of sandstone, siltstone and claystones are formed in the transitional facies.

❑ *Marine Facies*

All sedimentary rocks formed at sea floors and ocean floors are the marine facies. Marine systems include the shallow marine, which cover parts of the continental platform, reefs, submarine fans, and the floors of the deep-ocean basins. Many types of shales and limestones are formed in marine facies. There are several sedimentary rocks of marine facies hosting important minerals like iron and manganese nodules.

6.4 MINERALOGICAL COMPOSITION

Sedimentary rocks show great variation in their mineralogical composition. Since the rock subjected to erosion and weathering can be igneous or sedimentary or metamorphic, the type of sediment derived will vary greatly. The earlier crystallizing minerals of Bowen's Reaction Series (e.g. olivine, pyroxene and calcium-plagioclase) are not stable at the Earth's surface. Therefore, as time goes by and they are exposed, they break down and are dissolved. The chemicals that make them up are redistributed into minerals that are stable at Earth's surface conditions. On the other hand some igneous minerals, such as quartz and feldspars (base of Bowen's Reaction Series), are stable or at least very slow to breakdown. Detrital rocks are collections of these stable phases that are frequently cemented together by minerals precipitated in the interstices between the detrital grains. It is primarily for this reason that quartz becomes concentrated in sediment with progressive chemical weathering of rocks, whereas olivine, pyroxene and feldspar are preferentially removed. Sedimentary rocks may contain a few or host of minerals. Rocks containing one or two minerals only, e.g. limestones are very common. Rocks containing a host of minerals like clays and shales are also quite common. This variation can be explained on the basis of the following factors.

❑ *Nature of Gathering Ground*

The composition of sedimentary rock will depend upon the bulk composition of the existing rocks of the area over which the natural agents operate to derive the sediments.

❑ *Duration of Transport*

It defines the extent in terms of time and distance for which any load of sediments is transported from the original place of disintegration to the depositional basin. Sediments that are soft and fragile wear out easily whereas durable grains from the parent rock are often transported to the ultimate destination. Quartz is one example of a stable mineral and, hence, appears in most of sedimentary rocks.

❑ *Mixing up of Sediments*

The rocks formed along the seashore may have a complex mineralogical composition. It is so because the detritus carried up to that place by many long-distance streams, a variety of sediments may get mixed up by waves and currents before actual settling starts.

Note In spite of the factors mentioned above, the bulk composition of the most common sedimentary rocks is made up only of a few common rock forming minerals. The examples are quartz (sandstones, quartzites), calcite (limestones), feldspars (greywacks), gypsum and clay-minerals (shales).

❑ *Place of Mineral Formation*

The minerals that have been formed outside the basin of deposition, i.e., they have been brought there by natural agent of transport, are called *allogenic*. These are the detrial minerals, the examples being quartz, feldspar, amphiboles, pyroxenes, olivine and corundum. The minerals that have been formed within the basin of deposition are called *authigenic*. Commonly they are the result of chemical, biochemical, or biomechanical activity that takes place in the basin of deposition. Calcite, dolomite, anhydrite and gypsum are but a few examples of minerals of this group.

6.5 TEXTURES OF SEDIMENTARY ROCKS

Texture, along with composition and mode of formation, is used to classify sedimentary rocks and to determine their origin. The term *texture* describes the size, shape and mutual arrangement of minerals that make up the rocks. Sedimentary texture is concerned with the grain-size and its distribution, morphology and surface features of grains, and the fabric of the sediment. Sedimentary rocks show considerable variation in their texture. Chemical sedimentary rocks generally have a crystalline texture. Some of them, however, are formed of fragments, and their textures are dependent on the sizes, shapes and arrangement of these fragments. If the rock has been formed from organic debris then the fragments may consist of particles of shell or wood, but the texture can be described in the same terms as are used for other fragmented rocks. For any sedimentary rock, textural analysis involves a description of the following *textural elements*.

❑ *Nature of Grains*

A sedimentary rock may be partially or wholly composed of clastic (or, allogenic) grains, or of chemically formed (authigenic) or organically contributed components. Thus, the rock may show a clastic or non-clastic texture.

❑ *Size of Grains*

The size of grains is an important textural feature of a sedimentary rock. It is an indication of distance between its source and depositional areas. Moreover, it is an easily observed property which may be used to distinguish and classify the rock. The coarsest particles are deposited nearest to the source area, and most of the finest particles are carried in suspension to greater distances before they settle. An example is deposition of clay in very-very low energy environment. The grain size in the sedimentary rocks varies within wide limits. A description of the grain size and grain size variation (sorting) within a sedimentary rock is therefore essential. Five categories of sediments are recognized on the basis of grain size.

Very coarse-grained rocks	average grain size > 10 mm
Coarse-grained rocks	average grain size between 10 and 5 mm
Medium-grained rocks	average grain size between 5 and 1 mm
Fine-grained rocks	average grain size between 1 and 0.1 mm
Very fine-grained rocks	average grain size < 0.1 mm

❑ *Sorting*

A sedimentary rock is also described as well sorted, moderately well sorted, or poorly sorted according to its grain size variation.

To be well sorted, all the grains in a sample should be close to the average size of the grain. Beach and dune sands are typically well sorted. To be classed as poorly sorted, many of the grains should be much smaller or much larger than the average. Avalanche and glacier deposits are typically poorly sorted. Most sedimentary rocks contain grains of different sizes. The relative homogeneity of a rock is expressed as its degree of sorting, a well sorted rock consisting of similarly sized particles. In contrast, a poorly sorted rock has a wide range of particle sizes (that is, grades). The size of particles is determined by the strength of the currents that carry them. Stronger currents result in bigger grains. These size categories reflect the energy of the current and reveal about the environment. For example gravel suggests a strong, swift flowing stream in the mountains or a high energy surf zone, and clay suggests quiet waters like a swamp.

❑ *Shape of Grains*

The sediments making the rocks may be rounded, sub-rounded, angular or sub-angular, as shown in Fig. 6.3. The degree of roundness of grains is related to the amount of abrasion suffered during transport, and hence to distance travelled from their source before deposition. Roundness is related to the sharpness or curvature of edges and corners of grains. It is also dependent on the size and hardness of the grains and the impact of bigger grains on smaller grains. The degree of roundness is an important property in sand being used to make concrete, or for other engineering purposes. It also controls the permeability of rocks.

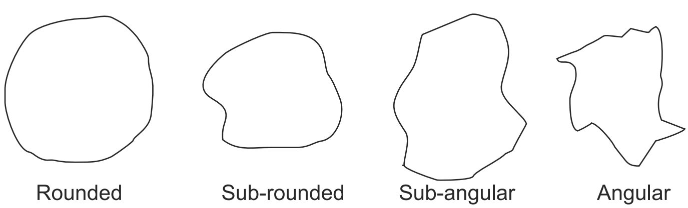


Fig. 6.3 *Shape of grains*

Breccias are made up mostly of rough and angular fragments indicating least transport and abrasion, Conglomerates are full of rounded and smooth-surfaced pebbles and gravels indicating a lot of transport and rubbing action during their transport before getting deposited and consolidated into a rock mass. Sand grains deposited from ice are normally more angular than those in river deposits, and the most rounded grains usually occur in sand dunes and coastal beaches.

Notes

1. Grain shape is an important clue to their origin. Lots of rounded, spherical grains in a rock indicate a long, high energy journey after removal of the grains from the source rock. Lots of angular, oddly shaped grains in a rock indicate proximity to the source rocks or a low energy medium of transport.
2. Sphericity defines the degree to which a particle or grain approaches the shape of a sphere. Equidimensional particles have a greater prospect of becoming spherical during transportation than other shapes of particles.
3. A positive correlation exists between sphericity and roundness, but other factors, notably particle size, planes of weakness, and particle composition, may have a marked influence on the final shape of the particle when it is finally deposited. Settling velocity will also influence the shape of the deposit.

❑ *Packing of Grains*

Packing describes the spatial density of the clasts in a rock. If the clasts are loosely packed, the resulting rock is described as *cement supported* or *matrix supported,* depending on whether the spaces between these clasts are partially or completely filled with mud or cement. On the other hand, a rock is described as *clast supported* or *grain supported* if its clasts are closely packed, so that they are in contact with one another. The degree of packing is generally related to the load of the overlying sediments during the process of deposition. Packing of grains also reflects about the parent rock and energy condition for deposited sedimentary rocks.

❑ *Porosity and Permeability*

The percentage volume of the pore spaces in a sedimentary rock is a measure of *porosity*. For example, a loosely packed shale (a clastic rock consisting of clay sized particles) may have a porosity of up to 50%. *Permeability* describes the amount of connected pore spaces in a rock. It is, therefore, a measure of the capacity of sedimentary rock to pass fluids through it. Both the porosity and permeability are essential for the evaluation of the suitability of a sedimentary rock to carry exploration works for oil, gas and water.

❑ *Fabric of Grains*

Fabric includes the description of grain size, sorting and grain shapes (Fig. 6.4). Besides these, fabric also includes the description of the orientation of particles (Fig. 6.5) in the rock, and their arrangement or packing. Sedimentary particles may be *randomly oriented*, or may show a *preferred orientation,* also known as *parallel orientation*. The latter may result from compaction of a group of sediments containing elongated particles resulting in their longest dimensions perpendicular to the compaction direction. Sedimentary rocks rarely have randomly oriented particles; the examples being conglomerate and breccias.

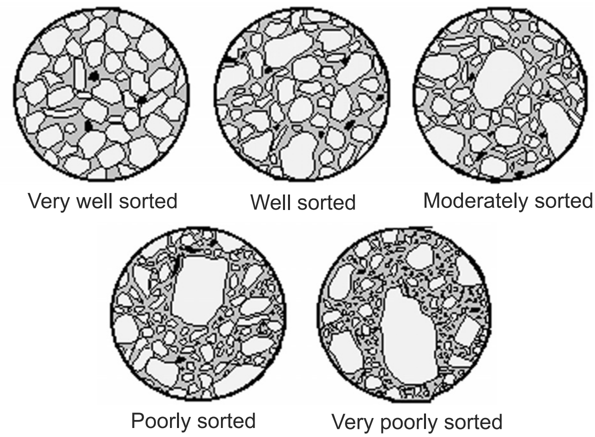


Fig. 6.4 *Fabric of grains*

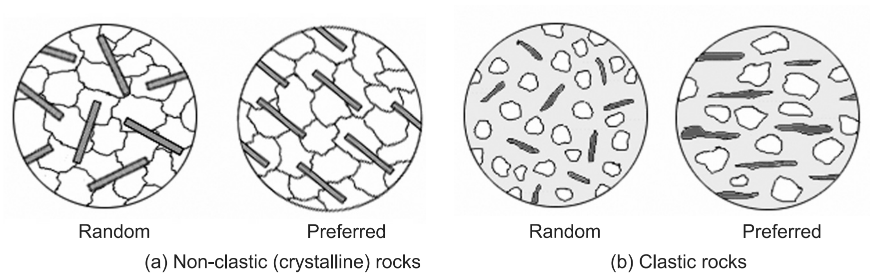


Fig. 6.5 *Orientation of grains*

Note A given sedimentary rock may contain mostly elongate particles. If all or most of the elongated particles are arranged in such a way that their longer axes lie in the same general direction, the rock is said to show a high degree of preferred orientation. This direction is generally indicative of the direction of flow of the current during the period of deposition.

❑ *Crystallization*

In sedimentary rocks of chemical origin, the texture is generally defined by the degree and nature of crystallized grains. Rocks may show perfectly interlocking grains, giving rise to *crystalline granular texture* or they may be made up of non-crystalline, colloidal particles when they are termed *amorphous*.

From this brief description of the textural elements of sedimentary rocks, it can be seen that sedimentary textures can be broadly grouped into two categories, the *clastic texture* and *non-clastic* (*crystalline*) *texture*. This plays a key role in the classification of sedimentary rocks.

■ **Clastic Textures** For characterizing the rock, description of clastic textures would include all the elements discussed above. The grains in the rocks are fragments of pre-existing rocks and minerals [Fig. 6.6 (a)]. It shows the signs of mechanical transport and deposition by currents of various kinds. Detrital sedimentary rocks are classified mainly on the basis of size along with uniformity of grain size and grain shape. These features help to determine the means by which these sediments were transported.

■ **Non-clastic (Crystalline) Textures** Applies mostly to rocks characterized by chemical or biochemical sedimentation. In addition to a description of the grain size, porosity and permeability, crystalline textures [Fig. 6.6 (b)] are often described as *granular* (macrocrystalline), *microcrystalline*, *cryptocrystalline* or *amorphous*. It is also necessary to establish the order of crystallization of the different authigenic minerals, and to identify any textures that may result from diagenetic processes as dissolution or replacement.

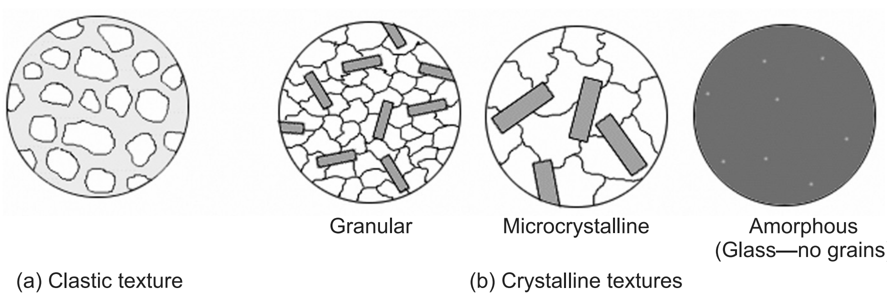


Fig. 6.6 *Texture based on degree and nature of crystallized grains*

6.6 STRUCTURES OF SEDIMENTARY ROCKS

The term 'structure' signifies some large-scale features developed in the rock masses during the process of their formation. These structures are called *primary structures.* Primary sedimentary structures provide key information about the conditions under which the sediment accumulated. Structures developed subsequently due to deformations are called *secondary structures* or sometimes *tectonic structures* also. The structures of sedimentary rocks are broadly classified as mechanical, chemical and organic structures.

6.6.1 Mechanical Structures

Also known as *primary structures*, these are the most commonly found structures in clastic sedimentary rocks. They develop due to physical processes operating at the time of deposition of the sediments. Some of the common mechanically developed structures of sedimentary rocks (Plate 11) are as follows.

❑ ***Stratification***

Almost all sediments are deposited horizontally, one layer on top of the other. These layers are termed *strata*, or simply *beds*. The planes separating the layers are called *planes of stratification*, or *bedding planes* and are the planes of weakness. Stratification thus implies a layered arrangement in a sedimentary rock. Stratification may develop very prominently and can be seen from a distance of kilometers or in other cases may have to be ascertained after close examination of the rock. The different layers may be similar or dissimilar in colour, composition, grain size and texture, and can be distinguished easily on the basis of these features. Since the interfaces between different layers are usually parallel, stratification is also termed *parallel bedding*. It is originated in the depositional stage with low and calm energy environment.

The thickness of each layer in a sedimentary formation may thus show great variation: from a few centimeters to many meters. Beds may extend laterally over distances as long as several meters to hundreds of kilometres, where they may pinch out or end abruptly against other rock types.

❑ *Lamination*

This is a layered structure similar to stratification, but with individual layers quite thin; generally less than 0.3 cm in thickness. Laminations are common in fine-grained sedimentary rocks like clays, mudstones and shales. The individual layers are called *laminae* and are parallel to the bedding plane. These are generally distinguished on the basis of colour difference and grain size. Lamination is originated due to low energy conditions and even during transportation.

❑ *Cross-bedding*

Cross-bedding is the type of stratification in which various layers lying one above another bear an irregular or inclined relationship to each other. This implies that the layers are not parallel to the bedding planes of the underlying or overlying units. Such a structure often results from deposition in a shallow-water environment or eolian deposits. Cross-beds form when wind or water currents flow across a sloping surface while sediment is being deposited. Therefore, rather than being deposited horizontally, the sediment is deposited at an angle equal to that of the slope.

Cross-bedding is common in sandstones deposited in deserts by the action of winds. It is also commonly found in sandstones and felspathic sandstones (or arkoses), which have been laid down in shallow water or deposited as dunes by the action of wind. Successive minor layers are formed as sand grains settle in the very slow moving deeper water at the downstream end of a sandbank or delta, and the sandbank grows in that direction. Each layer slopes downstream and is initially S-shaped; however, erosion of the top of the sand bank by the stream leaves the minor layering still curving tangentially towards the major bedding plane at its base, but truncated sharply at its junction with the upper bedding plane. In such an environment, the stream suffers repeated changes in direction of flow or the currents produced in the body of the water. The structure is sometimes referred as *false bedding* or *current bedding*.

❑ *Graded Bedding*

In some stratified rocks, the component sediments in each layer appear to be characteristically sorted and arranged according to their grain size, the coarsest being placed at the bottom and the finest at the top. Such an individual layer is said to be *graded*. When a rock is made of such graded layers, the structure is called *graded bedding*. Graded bedding results from rapid deposition of sediments from dense masses of water containing a mixture of sedimentary particles of different sizes which flow down-slope.

This type of stratification commonly is produced on the deep-ocean floor by turbidity currents, which transport sediment from the continental slope to adjacent deep oceans, forming bodies of rock called *turbidites*. Turbidity current is generated by turbid (muddy) water, which, being denser than the surrounding clear water sinks beneath it and moves rapidly down the continental slope. The denser, muddy water moves out along the bottom of the basin. As a turbidity current moves across the flat floor of a basin, its velocity at any given point gradually decreases. The coarsest sediment in the turbidity current is deposited first, followed by successively finer particles. After the turbid water ceases to move, the remaining suspended sediment in the water gradually settles out.

Notes

1. Turbidity currents are commonly generated by earthquakes or submarine landslides, during which mud, sand, and even gravel are transported downslope.
2. In a graded bedding, a sediment containing a wide range of grain sizes is sorted vertically such that there is a continuous gradation from coarse particles at the bottom of the sedimentary layer to fine grains at the top.
3. In both graded and cross bedding, the original top of the bed may be recognized from the asymmetry of the structure within the bed.

❑ *Mud Cracks*

These are structures that result from the desiccation of sediments. They are common structural features of many fine-grained sedimentary rocks, and show that the sedimentary environment was occasionally exposed to the air during deposition. These are typical of argillaceous sediments (clays or silts). The structure consists of polygonal or irregular cracks spread along the surface of an exposed sedimentary layer. Once these cracks are covered under further layers of mud, they get preserved in the body of the deposits. They can be seen once again with the erosion of overlying layers with the passage of time. The role of evaporation along with the fine grains of sediments is important for the formation of mud cracks.

Note

Mud cracks in rocks suggest that the original sediment was deposited in shallow lakes, on tidal flats, or on exposed stream banks.

❑ *Rain Prints*

These are irregular, small crater-shaped depressions seen on fine-grained dried sediments. These may get dried up and subsequently preserved under another layer of mud. The imprints become a part of the deposit.

Note Rain prints are sometimes preserved in some mudrocks.

❑ *Ripple Marks*

These are small wavelike structures of sand that develop on the surface of a layer of loose sand either in a desert, along a beach or on the bottom of the stream. The shapes of these ripples are a function of the current (or wind) direction and its intensity. They are defined as symmetrical or asymmetrical, wave-like undulations or irregularity in a layer. Ripple marks generally result from interplay of wind action and wave action during the process of deposition. The direction of shallow water current can easily be affected by strong winds blowing over the current: the fine sediments get dragged along with the currents because of the waves so generated and deposited as and where the waves become weaker. Another change in the direction of the current would create another layer of deposits in the opposite direction, and so on. Many ripple marks are preserved in rocks and provide information concerning the environment of deposition, such as depth of water, ancient current directions, and trends of ancient shorelines.

Notes

1. Ripple marks are characteristic of shallow water environment and also of eolian deposits.
2. The mud cracks, rain prints and ripple marks when encountered in sedimentary formations are taken as confirmatory evidence of the formation having been deposited in a shallow water environment.

6.6.2 Chemical Structures

Many sedimentary rocks are formed due to chemical processes such as evaporation, precipitation and re-crystallization. These rocks often show structures that are quite different from those found in clastic rocks (Plate 11). Following are some of the important types of chemical structures.

❑ *Concretionary Structure*

In this type of chemical structure, the sedimentary rock is made up of concretions of various shapes and dimensions. The individual concretions may be rounded, sub-rounded, rough or smooth and quite small or of quite appreciable size. When large number of such concretions are cemented or compacted together, the rock is said to show a *concretionary structure*.

The oolitic and pisolitic structures are examples of concretionary structures differentiated on the basis of size of the concretions. While in the oolitic structure, the concretions are of the size (0.1 to 1.0 mm), in the pisolitic structure, the individual size of a concretion is like that of a peanut. Limestones and bauxite show both these structures.

❑ *Nodular Structure*

This type of structure is seen in some limestones and is differentiated by the development of irregularly shaped nodules of chert, iron oxides, iron carbonates and clayey ironstones. Sometimes these nodules show an elongation or flattening, parallel to the bedding planes.

❑ *Geode Structure*

A geode is actually a hollow shell of rock, looks like a section of the Earth, the interior of which is lined with inwardly projecting crystals. Generally, the rock shell is made up of chalcedony and the inner encrustations are of quartz crystals. This type of structure is believed to result from crystallization of quartz crystals on the inner walls of an original cavity.

6.6.3 Organic Structures

These structures develop in the sedimentary rocks by the manner in which the organic source material gets accumulated and compacted to form a rock. The stromatolitic structure is the example of organic structures. The *stromatolitic structure* is produced by the presence of remains of algae—a kind of unicellular plant in the rocks.

6.7 CLASSIFICATION OF SEDIMENTARY ROCKS

In general, sedimentary rocks may be classified as clastic and non-clastic rocks on the basis of their mode of formation from detrial or chemical load. These groups are further subdivided on the basis of their grain size, composition and nature of the source material. Each of these groups includes a number of rock types identified on the basis of their constituent minerals. The rocks may also be classified on the basis of mineral composition as arkose, greywacke and arenite.

6.7.1 On the Basis of Mode of Formation

❑ *Clastic Rocks*

Rocks made up of fragmental material such as gravel, sand, silt, or clay are called *clastic rocks*, *mechanically formed rocks* or *detrital rocks*. These rocks are formed from weathering and erosion of pre-existing rocks and by subsequent transportation, deposition and diagenesis of the sediment. The term *clastic* comes from the Greek word *klastos,* meaning broken, and describes the broken and worn particles of rock and minerals that were carried to the sites of deposition by streams, wind, glaciers, and marine currents. The classification of the clastic rocks is based on the average grain size or grade of the sediments making the rock. The grading of clastic sediments is presented in Table 6.1. The gravels, sands, silts and clays may further be classified to lower limits of grain size.

Table 6.1 *Fourfold grading of clastic sediment*

Gravel	*Sand*	*Silt*	*Clay*
Grain size > 2.00 mm	2 mm and 1/16 mm	1/16 and 1/256 mm	<1/256 mm

■ **Gravel** Sediments and clastic fragments of rocks greater than 2 mm in size are termed as gravels. Boulders, cobbles and pebbles are the examples. The rocks composed of these fragments are known as *rudaceous rocks*.

1. *Boulders:* Grain size bigger than 256 mm
2. *Cobbles:* Grain size between 256–16 mm
3. *Pebbles:* Grain size between 16–2 mm

■ **Sand** Sediments that range between 2 mm and 1/16 mm are termed as sands. Sand may be further subdivided on the basis of grain-size as follows. The rocks composed of these fragments are known as *arnaceous rocks*.

1. *Coarse sand*: 2 mm to 1/2 mm
2. *Medium sand*: 1/2 mm to 1/4 mm
3. *Fine sand*: 1/4 mm to 1/16 mm

■ **Silt and Clay** Sediments that range between 1/16 mm to less than 1/256 mm form *argillaceous rocks*.

Note The grain size of clastic sedimentary rocks is controlled by the size of clasts present in the source and by the carrying capacity of the transporting medium.

❑ *Non-Clastic Rocks*

Non-clastic sedimentary rocks include both the *chemical* and *organic sedimentary rocks*. These rocks form from chemical components dissolved in the seawater by evaporation, precipitation and re-crystallization of minerals from seawater thereof, or from the breakdown of the shells and bones of sea creatures. These may also be formed by accumulation of remains of plant life followed by their compaction and consolidation. Sea animals such as coral produce calcium carbonate solutions that harden to form rock. As the chemicals that come from the mineral or biological precipitation, mix with sediments on the floor of the ocean or lake they crystallize and grow in the spaces around the sediment. When these crystals grow large enough to fill the spaces they harden and form a solid rock. The non-clastic rocks are sub-divided as chemically formed rocks and organically formed rocks.

■ **Chemically Formed Rocks** The chemically formed rocks are composed primarily of sediment precipitated from water. This type of rock forms when mineral constituents in solution become supersaturated and inorganically precipitate following evaporation or crystallization. These rocks are named according to the mineral present. This group includes the evaporites, the carbonates (limestones and dolostone), and the siliceous rocks. The subdivision of these rocks on the basis of their chemical composition is as follows.

- *Carbonate Deposits* These rocks are formed by the chemical precipitation of calcium carbonate from sea water. Limestones and dolomites are formed from sea waters rich in calcium carbonate; and magnesites are formed from seawater rich in magnesium carbonate.

- *Siliceous Deposits* These rocks are formed by precipitation of silica (SiO_2) from water. They commonly form from silica-secreting organisms such as diatoms, radiolarians, or some types of sponges. Examples of siliceous rocks are flint, chert, jasper and agate.

- *Ferruginous Deposits* These rocks form by the chemical precipitation of iron oxides. They can be extracted as a source (ore) of iron.

- *Evaporites* These may be treated as a distinct class of sedimentary rocks formed by the process of evaporation of seawater, such as bays and estuaries that got detached from the main sea. It is believed that loss of moisture from these bodies due to evaporation with passage of time increased the concentration of the salts to an extent that these salts separated out as rock masses. Some of the examples of evaporites are: rock salt, anhydrite, borates, rock sulphur and nitrate.

■ **Organically Formed Rocks** Also known as *biogenic* sedimentary rocks, these are formed predominantly from remains of organisms (life and death of organisms, particularly planktonic skelletal material, shells, bone materials, and other organic remains). Some of the more common organic rocks are as follows.

- *Carbonate Rocks* The carbonate sedimentary rocks are also formed through biochemical processes. They include the limestones and dolostones. The formation of these rocks is due to gradual accumulation and compaction of shells and skeletal bones of sea organisms like foraminifera, corals, crinoids and crustacea etc. Some of the examples are micrite (microcrystalline limestone), oolitic limestone, fossiliferous limestone, and stromatolites.

- *Carbonaceous Rocks* These rocks are composed of organic matter (mainly plant fragments). Because of this, they lack minerals (which must be inorganic, by definition). Wood gets accumulated in huge volumes in sedimentary basins. Bio-mechanical and bio-chemical processes convert the wood to various grades of coal.

- *Phosphatic Deposits* Most phosphate rocks are of chemical origin. Small volumes of phosphatic composition, called *guano*, are accumulations of excreta of some birds, containing high content of phosphate. When accumulated over a period of time, they form a rich source of phosphate salt.

o *Ferruginous Deposits* These are iron carbonate deposits. In fresh water lakes and swamps, bacteria reduce ferric oxide to ferrous oxide which finally precipitates as iron carbonate.

6.7.2 On the Basis of Mineral Composition

The minerals like quartz and feldspar are essential and primary constituents of sedimentary rocks. Rocks on the basis of mineral composition are classed as follows:

❑ ***Arkose***

The rock which is characterized by significant amount of feldspar (> 60%) with coarse grained quartz and other accessory minerals is called *arkose.* It is light in colour. This rock is formed when transportation of sediments is too little. Feldspar rich sandstone is the example.

❑ ***Greywacke***

The rock which is characterized by subordinate amount of feldspar (about 30%) with fine grained quartz and basic accessory minerals is called greywacke. This rock is formed when transportation of sediments is too much and energy condition is high. Fine grained angular and poorly sorted sandstone is the example.

❑ ***Arenite***

The rock which is characterized by subordinate amount of feldspar (about 30%) and dominant amount of quartz with coarse-grained character is called arenite. This rock is formed when transportation of sediments is considerable and formation of well sorted grains is there. It has negligible matrix. Coarse grained sandstone is the example.

6.8 IMPORTANT SEDIMENTARY ROCKS AND THEIR CHARACTERIZATION

Sedimentary rocks are most commonly used for making construction materials and foundations. Some of the more prominent rocks are described below and are shown in Plate 12.

6.8.1 Conglomerate

These are sedimentary rocks of clastic nature and are classed as *rudite*. Conglomerates consist of rounded pebble- or cobble-sized rock fragments, generally above 2 mm, set in a fine-grained matrix of sand or silt. After the fragments have been deposited, they are compacted by the sediments that pile up on top of them. Over very long periods of time, the fragments become cemented. The common cementing minerals are calcite, iron oxide, silica, gypsum or hardened clay. Most conglomerates are only crudely stratified and include beds and lenses of sandstone.

❑ *Types*

Conglomerates are generally distinguished as follows.

■ **On the Basis of Grain Size** Conglomerates are classed as boulder-conglomerate (> 256 mm); cobble-conglomerate (64–256 mm); and pebble-conglomerate (2–64 mm).

■ **On the Basis of Source** Conglomerates are classed as basal-conglomerates–consisting of gravels from advancing sea-waves deposited over subsiding land masses; glacial-conglomerates–consisting of gravels from glacial origin; volcanic-conglomerates–consisting of gravels of volcanic origin subsequently transported by river before their deposition and compaction or cementation. Because of longer transportation, the gravels get smoothened and polished.

■ **On the Basis of Lithology** Conglomerates are classed as oligomictic-conglomerates–consisting of gravels made up of quartz, chert and calcite; and polymictic-conglomerates–consisting of gravels derived from any type of rock, all cemented together.

❑ *Uses*

Conglomerates with fine matrix textures are used for ornamental works in buildings, monuments, grave stones, and as tiles. However, their use is limited due to the irregular grain sizes affecting durability. They act as reservoirs of groundwater, natural gas and petroleum.

❑ *Significance*

When the sediment is first deposited, there are lots of open spaces or pores. Cement can affect the amount of pore space that is left in a rock as it solidifies. Conglomerates usually have significant pore space and they are generally a good rock to act as a reservoir for ground water, natural gas and petroleum.

6.8.2 Breccia

Breccia, a mechanically formed sedimentary rock, is classed as *rudite*. These are conglomerates consisting of angular pebble- or cobble-sized rock fragments. The rock fragments are of heterogeneous composition and of variable mineral composition embedded in a fine matrix of clayey material. The angularity of the rock fragments indicates that they have not been transported over long distances. Breccia can be formed in sedimentary settings close to areas of high relief, such as on alluvial fans, along mountain stream valleys, material ejected from volcanoes, shattered rock in fault zones, areas of mass wasting, cavern collapse and land-sliding. On the basis of their source, commonly recognized breccias are as follows:

❑ *Basal Breccia*

It is formed when fragments of chert and other similar rocks in the coastal regions are got cemented by the fine mud brought by the advancing seawater.

❑ *Fault Breccia*

Also called *crush-breccia*, these are formed by the angular fragments produced while faulting, due to crushing effect of the block movements, and by their subsequent embedment in clay and other fine material.

❑ *Agglomeratic Breccia*

It is formed from angular and sub-angular fragments derived from volcanic eruptions.

> ***Note*** The difference between conglomerates and breccias is the roundness of the grains. In conglomerates, the grains are rounded and usually indicate that they have been transported or worked more than the angular grains found in breccias. Moreover, in breccias, the grains are large enough to be seen with the unaided eye.

6.8.3 Sandstone

Sandstones are mechanically formed sedimentary rocks and belong to an *arenaceous group*. Sandstone consists of sand sized particles cemented together through lithification into solid stone. The grain size of sandstone is 1/16 to 2 mm in diameter. Sandstone is made up mostly of quartz, probably because quartz is one of the most abundant minerals on Earth and is very durable; it resists weathering and chemical change. Silica, calcite, and iron oxides are the most common cementing minerals for sandstone. These minerals are deposited in the spaces between the sand grains by water, and over the course of millions of years, the minerals fill up all of the spaces.

The cementing materials can influence the durability, colour, porosity and usefulness of the stone. The particles of sand in most sandstone are cemented by calcite, quartz (silica), clays and gypsum. Silica cemented sandstone is very durable and hard. Calcite cemented sandstone is subject to acidic dissolution and is more easily eroded. Clay and gypsum cements, which are soft minerals, tend to produce much softer sandstone and the sand can sometimes be rubbed off in a person's hands. Sandstones have a variety of colours, depending upon the type of cementing material.

❑ *Composition*

Quartz (SiO_2) is the most common mineral making the sandstones. Quartz, feldspar, mica, garnet and magnetite may also occur in small proportions. The component grains may be cemented together by siliceous, calcareous, argillaceous or ferruginous in composition, or by welding by natural pressures from overlying sediments.

❑ *Texture*

The component grains of sandstones show a great variation in their size, shape and arrangement. The differences in texture, sorting, and rounding help geologists decipher the environmental conditions that formed the sandstone. The textures based on the grade of the component grains are given in Table 6.2. The shape and mutual arrangement of the component grains usually defines the engineering and other properties of sandstones. The properties such as porosity and permeability of these rocks generally help to decide their use in different situations.

Table 6.2 *Textures of sandstones*

Type	*Coarse grain*	*Medium grain*	*Fine grain*
Size–range	2 mm–0.5 mm	0.5 mm–0.25 mm	0.25 mm–0.10 mm

❑ *Colour*

Sandstones naturally occur in a variety of colours. However, red, brown, grey and white are the most common. While iron oxide as a cementing material results in red, brown and yellow shades; the presence of glauconite gives a greenish shade to the sandstones. These colours give sandstone its unique character and ornamental desirability. Coloured sandstone is usually intricately banded in multiple colours which enhance its aesthetic value.

❑ *Types*

Sandstones are distinguished on the basis of their composition and nature of the cementing material, and are as follows.

■ On the Basis of Cementing Material

- *Siliceous Sandstones* The cementing material is silica (SiO_2). The rock so formed is called *silsic sandstone*.

- *Calcareous Sandstones* Those varieties of sandstones in which carbonates of calcium and magnesium are the cementing materials are referred to as calcareous sandstones.

- *Argillaceous Sandstones* The cementing material is clay. These are the soft varieties of sandstone.

- *Ferruginous Sandstones* The cementing material is iron oxide examplified by banded heamatite jesper (BHJ) compound.

■ On the Basis of Mineralogical Composition

- *Arkose* It is exceptionally rich in feldspar minerals, at least 25 per cent, besides the main constituent quartz.

- *Greywacke* They contain a fine-grained muddy matrix of angular fragments of quartz and some feldspars embedded side by side with fragments of rocks like felsites, granites, shales, etc.

- *Flagstone* It is exceptionally rich in mica, which is dispersed in parallel or sub parallel layers. Mica being weak, its abundance and arrangement renders the stone weak and easily splitting. It is not recommended for load bearing structures.

o *Freestone* It is rich in quartz and does not contain bedding planes or any mica. Freestone is compact, dense, massive and quite strong. It is suitable for construction requiring high crushing strength.

❑ ***Uses***

Sandstones are very useful natural resources. Generally, sandstone is a very porous rock. It is the ideal rock for groundwater and oil reservoirs. They are the biggest source for materials of construction like building stones, pavement stones, road aggregate and aggregate for making concrete. Mined sandstone can be cut, polished and carved for use as ornamental rocks for buildings, monuments, grave stones, tiles, etc. Sandstone can also provide silica for glass production. Some mineral ores are found in sandstone. Uranium minerals are associated with sandstone deposits. Heavy minerals such as rutile, gold, diamonds and others can be found in sandstones from prehistoric placed deposits.

Note Conglomerates form in environments that are generally not too far from the source of the sediments and high in energy. The grains of a breccia are found even closer to the source of the sediments since they have not been rounded like the grains of a conglomerate. If the deposit is farther from the source, then the sediment is more likely to be sandstone with all the large grains left behind.

6.8.4 Shale

Shale is a fine-grained sedimentary rock that forms from the compaction of silt and clay-size mineral particles, commonly called *mud*. It belongs to an argillaceous group. Shale is similar to siltstone but with even finer grain size, less than 1/256 of a millimeter in diameter. Shale usually contains about 50% silt, 35% clay, and 15% non-clastic sediments. Many shales may also contain organic plant materials and fossils. Once deposited, the silt becomes compacted and cemented together into solid stone. Silica, calcite, and iron oxides are the most common cementing minerals for shale. These minerals are deposited in the spaces between the silt grains by water over the course of thousands or even millions of years.

Shales often contain fine laminations which helps impart fissility to the rock. *Lamination* means that the rock is made up of many thin layers. *Fissility* is the property that allows the rock to readily split into thin pieces along the laminations. Shales are often soft and can be scratched by a knife. The sediments that form shale are most likely deposited very gradually in non-turbulent, environments such as lakes, lagoons, flood plains, and deep-ocean basins.

❑ ***Composition***

Shale is a fine-grained, moderately to well sorted rock formed by the compaction of well rounded silt- and clay-sized grains. Accessory minerals like oxides of iron, carbonates, sulphide minerals and heavy mineral grains, and organic matter are also present. Silica and clay minerals together make more than 70% of shales in most cases.

❑ *Colour*

Many shales are black and rich in organic material that accumulated in a variety of quiet-water, low-oxygen environments, such as lagoons and seas. Red shales are coloured with iron oxide and suggest oxidizing conditions in the environments in which they accumulate, such as river floodplains, tidal flats, lakes, and well-mixed oceans.

❑ *Structures*

Laminations, ripple marks and some organic structures may be present. The laminae or the layers may range in thickness from 0.05 mm to 1.00 mm depending upon the environment of deposition.

❑ *Types*

Shales have been classified in varied ways.

■ On the Basis of Origin

o *Residual Shales* When the shale is made up of materials from erosion and weathering of pre-existing rocks followed by compaction and consolidation of the particles in adjoining basins.

o *Transported Shales* When the shale is made up of finer clastic materials, transported over long distances before settlement in basins of deposition.

o *Hybrid Shales* When the shale is made up of materials derived both from clastic sources and non-clastic (organic source).

■ On the Basis of Mineralogical Composition

o *Quartz Shales* These shales are rich in free quartz content.

o *Felspathic Shales* These shales predominate in feldspars and clay minerals

o *Chloritic Shales* These shales are rich in minerals of chlorite group and clay group.

o *Micaceous Shales* These shales are rich in muscovite mica and other flaky and platy minerals.

■ On the Basis of Predominant Group of Sediments

o *Siliceous Shales* Consist of considerable amount of silica

o *Calcareous Shales* Consist of considerable amount of calcium carbonate

o *Ferruginous Shales* Consist of considerable amount of iron oxide o *Carbonaceous Shales* Consist of considerable amount of organic matter. An example is oil shale

❑ *Formation*

Because of weathering, rocks break down into clay minerals and other small particles which often become part of the local soil. A rain storm or strong wind might wash tiny particles of soil from the land and into streams, making the streams muddy. When the stream slows down or enters a standing body of water such as a lake, swamp or ocean, the mud particles settle to the bottom. If undisturbed and buried, this accumulation of mud gets compacted due to overlying sediments that further results in squeezing out of water. Compacted mud that still retain 10–15% of moisture are lithologically termed as *clays*. If orientation within the particles takes place, the deposit attains the property of fissility; it becomes shale. This is how most shales are formed. However, if it gets compacted further and without any fissility, it may simply be a *mudstone* or *claystone*.

❑ *Uses*

Shale is used to manufacture bricks and tiles. Cement is another important construction material that is often made with shale. These are sources of alumina, paraffin and oil.

Notes

1. Shale is characterized by thinly, laminated layers, representing successive deposition of sediments.
2. Shale accounts for about 50% of all sedimentary rocks deposited on the Earth's surface.
3. Shales and the soils derived from them are some of the most troublesome materials to build upon. They are subject to changes in volume and competence that generally make them unreliable construction substrates.

6.8.5 Mudstone

These are fine-grained clastic rocks with grains less than 1/16 mm in diameter. Mudstones are formed from the compaction and cementation (lithification) of muddy sediments. They are the most abundant sedimentary rocks. They are usually soft and weather rapidly to form slopes, so relatively few fresh, unweathered exposures are found. They are frequently deposited in river floodplains and deltas and other shallow marine settings. Many mudstones also show evidence of burrowing by organisms. Clasts in mudstones tend to be more angular than those in sandstone.

Notes

1. A mudstone that contains very thin layers (laminae) is called *shale*.
2. The most common minerals in mudstones and shales are clays, quartz, chlorite and calcite. Shale is the most common sedimentary rock on the Earth.

6.8.6 Siltstone

Clastic sedimentary rocks consisting of silt-sized particles are termed siltstones. The most common minerals in siltstones are quartz, clays and chlorite.

6.8.7 Limestone

Limestone is by far the most abundant chemically precipitated rock. It is composed principally of calcium carbonate ($CaCO_3$—dominantly calcite), with subordinate proportions of magnesium carbonate. Magnesium oxide is a common impurity in most limestones; when its percentage exceeds 2 per cent, the rock is called *magnesian limestone*. Limestones are formed both chemically and organically.

❑ *Composition*

Pure limeston is invariably made up of mineral calcite ($CaCO_3$). In the limestone rock formations, however, presence of dolomite $CaMg(CO_3)_2$, quartz (SiO_2), feldspar minerals and silicon dioxide, iron oxides or carbonates, and aluminum oxide is rather a common feature.

❑ *Texture*

Limestones show a great variety of textures. The most important textural feature of limestones is their fossiliferous nature. Fossils in all stages of preservation may be found in limestones. Other varieties of limestones show dense arid compact texture; some may be loosely packed and highly porous, others may be compact and homogeneous. Concretionary texture is also common in limestones.

❑ *Types*

Broadly, limestones can be divided into two groups: *autochthonous*—formed by biogenic precipitation from sea waters; and *allochthonous*—formed from the precipitated calcareous sediments that have been transported from one place to another where they were finally deposited. Following are common types of limestones.

■ **Chalk** It is the purest form of limestone. It is porous, fine-grained and has an earthy texture and generally friable. Common colour of chalk is white. Some chalks may be exceptionally rich in the remains of foraminifera (very small sea organisms).

■ **Shelly Limestone** It has a rich assemblage of fully or partly preserved fossils. Shelly limestone is also called fossiliferous limestone. Those limestones that are made up of fragments of sea shells only, are termed coquina.

■ **Argillaceous Limestone** These limestones are impure limestones containing clay as major constituent and are of allochthonous origin. When the clay and calcium carbonates are present in almost equal proportions, the rock is known as *marl*.

■ **Kankar** It is a non-marine nodular or concretionary form of carbonate material formed by evaporation of sub-soil water, rich in calcium carbonate just near the soil surface.

■ **Oolite** Recent carbonate muds can accumulate in the oceans in thick layers that are destined for limestone formation. A limestone variety caused by swift currents that rolled carbonate mud into small beads that (once solidified) look like tiny eggs is called an oolite and is used for ornamental applications.

■ **Calc-Sinter (calc-tuffa)** It is white or light-colored calcareous rock ($CaCO_3$) deposited from carbonate-rich springs.

■ **Travertine** It is a type of limestone that forms in caves as a result of deposition of calcite from groundwater.

❑ *Formation*

Limestone is a very common sedimentary rock of biochemical origin. It is composed mostly of the mineral calcite. The calcite, in general, is derived from the remains of organisms such as brachiopods, bryozoa, crinoids and corals. These animals live on the bottom of the sea and when they die their shells accumulate into piles of shelly debris. This debris can then form beds of limestone. Some limestones may have been derived from non-biogenic calcite formation. Although some limestones are nearly pure calcite, there is often a large amount or sand or silt that is included in the shelly debris. Limestones form usually close to the source of shelly debris although some significant transport can occur. Great sources for limestone are coral reefs. The mechanically deposited limestones are formed by accumulation of particle of calcite derived from pre-existing rocks in the same way as those of any other clastic rock.

❑ *Uses*

Limestones are the primary source of lime for cements. Cement is considered one of the most important construction materials. It can be used as a building stone and road ballast, but is not quite as strong as sandstone. In metallurgical industries, it is used as a flux. Limestone is also used in chemical industries.

6.8.8 Dolostone

Dolostone, also called *dolomite*, is an evaporative sedimentary rock. It is a carbonate rock composed of the mineral dolomite, a calcium-magnesium carbonate [$CaMg(CO_3)_2$]. Ferrous iron is present in small proportions in some of its varieties. It is similar to limestone in general appearance, but reacts with acid only when powdered.

❑ *Texture*

Dolostone shows textures mostly similar to limestones. Some of its varieties are be coarsely crystalline, finely crystalline or show interlocking crystals.

❑ *Formation*

Dolostone may form by the reaction of magnesium-bearing groundwater with calcium carbonate in limestone. In most cases, they are formed from limestones by a simple process of replacement of Ca^{++} ions by Mg^{++} ions through the action of Mg^{++} ion-rich waters. This ionic replacement process is often termed *dolomitization*. The replacement may have started shortly after the deposition of limestone or quite subsequent to their compaction. Dolostone can also form by direct precipitation from seawater, however such environments are extremely rare. Direct precipitation of dolomites from magnesium rich waters occurs in association with gypsum, anhydrite and calcite. Since dolomite is less water soluble than calcite, it precipitates first, and is also more stable when water containing magnesium penetrates a limestone, resulting in the gradual conversion of a limestone bed into a dolomite bed.

Notes

1. Dolostone is so closely related to limestone in composition, texture, structure and physical properties that it may not always be easily possible to differentiate between the two rocks in hand specimens. A chemical analysis of the rock is required to establish the predominance of CaMg $(CO_3)_2$ over $CaCO_3$ to declare it a dolostone.
2. Dolostone forms when magnesium in pore water replaces some of the calcium present in limestone. For this reason, dolostone is often preceded by the formation of limestone deposits.
3. Dolostone forms very slowly and is rarely observed in modern depositional environments.

6.8.9 Coals

Coal, an organic sedimentary rock, is of biochemical origin. It is made up mostly of plant material and other organic matter, which accumulated in a swamp with stagnant, oxygen-deficient water. For coal to be formed these matters have to be remained buried for millions of years under elevated conditions of heat and pressure. The original raw material passes through many bio-mechanical and bio-chemical processes before it becomes a coal in technical terms. Although the chemical composition of coal changes from its organic origins, it often retains fossilized imprints of plant leaves, bark, wood, and organisms that lived during the time the organic materials were deposited.

❑ *Formation*

Coal forms from accumulations of organic matter, likely along the edges of shallow seas and lakes or rivers. Swampy areas that are episodically flooded are ideal conditions for coal formation. During non-flooding periods of time, thick accumulations of dead plant material pile up. As the water levels rise, the organic debris is covered by water, sand and soils. These covering materials can prevent the decay and transport of the organic debris. If left alone, the buried organic debris begins to go through the formation of coal series as more and more sand and silt accumulates above it. The compressed and/or heated organic debris begins driving off volatiles, leaving primarily carbon behind. The sand and soils form the rocks sandstone and shale. The process of coal formation thus involves a series of stages such as wastage of forests and transport of the wood material through different natural agencies to places of deposition, accumulation of the material in huge formations, its burial under clays and other matter and its compaction and consolidation under superimposed load.

Bio-chemical transformation of the organic matter so accumulated takes place under the influence of aerobic and anaerobic bacteria available at the place of deposition. The degree of processing results in different varieties of coal.

❑ *Types*

The deposited organic material goes through four main phase of coal formation, which are related to increasing heat and pressure. The main varieties of coal in order of increasing depth of burial are peat, lignite, bituminous and anthracite coal.

■ **Peat** It is porous mass of brownish plant fragments. Peat is the lowest grade coal that consists of slightly altered vegetable matter and may not be even considered as a coal. It has very low calorific value, high percentage of moisture and is rich in volatile matter.

■ **Lignite** It is also known as brown coal and forms the poorest grade of coal with calorific value ranging between 6300–8300 BTU. It is compact and massive in structure with specific gravity of 1.5 and hardness of 2.5. Some varieties of lignite may still show to a good extent the traces of original vegetable structure. It is often crumbly, relatively moist and powdery.

■ **Bituminous Coals** These form a broad group of common coals having essential properties varying within wide limits. It is dull to shiny and black and is sooty. The fixed carbon ranges between 69–78% and the calorific value between 9,500 to 14,000 BTU. Their common character is that they contain enough volatile matter, which makes them quite soft on heating, and they start agglomerating. Some of bituminous coals may contain volatile matter to such a high extent as 30% of their bulk. Some such coals are typically banded in structure.

■ **Anthracite Coal** It is considered the highest-grade coal with fixed carbon ranging between 92–98%. It is actually considered to be metamorphosed bitumenous coal. Anthracite coal has the highest calorific value in coals and burns almost without any smoke, as the volatile matter is negligible. It has a glassy luster, and is blackish and denser, may have a slight golden shine as well; has low density and is not sooty. It is largely used for heating domestically as it burns with little smoke.

■ **Graphite** It is essentially pure carbon and would actually be a higher grade of coal than anthracite, but is difficult to ignite and is rarely used for this purpose. Graphite forms from intense metamorphism and even igneous inclusion.

❑ *Uses*

Coals form all-purpose fuels, some varieties being more suitable for specific industrial uses.

Notes

1. It requires very specific environmental conditions for plant material to become coal. The organic material must be deposited in an anoxic (oxygen free) environment to prevent it from decomposing. Most coal beds originated in swampy and saturated environments.
2. Great deposits of coal, sandstone and shale are often found together in sequences, hundreds of meters thick.

6.8.10 Iron Ores

Most of the important iron ore deposits are found in sedimentary rocks. The iron ore beds occur interstratified in sedimentary rocks. Sedimentary iron deposits form from chemical reactions that combined iron and oxygen in marine and fresh waters, chiefly as chemical precipitates in the form of oxides, carbonates and silicates, e.g. haematite (Fe_2O_3) and magnetite (Fe_3O_4). Iron-ore deposits of sedimentary origin in India are at Singhbhum, Orissa, etc.

❑ *Formation*

It is believed that oceans on the Earth contained abundant dissolved iron and almost no dissolved oxygen about two billion years ago. The iron ore deposits began forming when the first organisms capable of photosynthesis began releasing oxygen into the waters. The abundant dissolved iron combined with this oxygen to produce hematite or magnetite, which got deposited on the sea floor in alternating bands with silica and sometimes shale. The banding might have resulted from seasonal changes in organism activity.

❑ *Uses*

Most of the iron produced is used to make steel. Steel is used to make beams and columns used in buildings, reinforcing rods for concrete, automobiles, locomotives, ships, furniture, paper clips, tools, etc.

6.8.11 Gypsum

Gypsum is an evaporite sedimentary rock composed of the mineral gypsum. It has a composition of $CaSO_4.2H_2O$. Gypsum is commonly fibrous (medium- to fine-grained) or granular and has low hardness. Its common colour is white but it may also occur in other shades such as yellow, red or dark grey, due to impurities present in the rock. Common sedimentary environments are desert lakes and marine areas with high evaporation rates.

❑ *Formation*

Rock gypsum is a chemical precipitate formed by the evaporation of concentrated solutions such as seawater. It collects in layers as calcium sulphate precipitated from water. Gypsum beds can be huge, although since it is somewhat water soluble, it is unstable at the surface, except in very arid regions. In many cases, gypsum occurs associated with rock salt bodies; although independent deposits of gypsum are also quite common.

❑ *Uses*

Gypsum finds extensive uses in industries, e.g. as a raw material in the manufacture of fertilizers; as an essential ingredient in the manufacture of cement, in the manufacture of Plaster of Paris, and as fire proofing component of gypsum boards.

Note *Anhydrite* is a granular aggregate of mineral anhydrite, $CaSO_4$, is genetically related to the mineral gypsum; hydration of anhydrite results in gypsum. These rocks are commonly associated in occurrence.

6.8.12 Rock Salt

It is an evaporite sedimentary rock composed of mineral *halite* (NaCl). It is also sometimes called *hellite*. Halite normally forms perfect cubes. The texture of rock salt varies from coarse-grained crystalline to fine-grained massive. The purest rock salt is white in colour. It may have other shades as well, such as grayish and pinkish due to presence of impurities. The pink colour comes from bacterial debris that has been trapped in the salt crystals. Rock salt is commonly associated with other evaporites. Its specific gravity is 2.1, and has a hardness of 2 on Moh's scale. Common sedimentary environments are desert lakes and marine areas with high evaporation rates where it is originated.

❑ *Formation*

Rock salt is believed to have been formed by the evaporation of concentrated saline seawater. It forms in places where seawater has been isolated from the ocean forming a lake. As the saltwater evaporates in the lake, the salt becomes concentrated in the remaining water. As the water continues to evaporate, the lake can no longer hold the same amount of salt. The salt precipitates out and is deposited as crystallized sodium chloride or salt.

❑ *Uses*

The most common use of halite is as food supplement. In cold climates, salt is used to control ice on roads and sidewalks. It is used to soften water and as an ore for sodium.

6.8.13 Chert

Chert is a chemical precipitate formed by groundwater. It is a sedimentary rock composed of micro- and crypto-crystalline silica. It is more common in occurrence compared to its other varieties such as flint. In a hand specimen, chert is hard, dense, and typically breaks like glass, but under a high-power microscope, it has a fibrous or granular texture. Chert is usually white in colour, however, shades of gray, tan, green, or red are also seen. It can be easily recognized by its high hardness. Chert possesses very fine grain size and conchoidal fracture.

Flint is the most common form of chert. It is often a dark, glassy, coloured rock of silicious composition that forms as nodules embedded in limestone. The dark colour of the chert comes from the organic matter it contains. Besides flint, the other forms of chert are jasper and agate. While jasper is a red variety of chert that gets its colour from iron oxide. Agate is a banded form of chert that may contain several different colours layered throughout the rock.

❑ *Formation*

Common sedimentary environments for the formation of chert are groundwater precipitate or deep-marine biogenic accumulations. Chert can develop as irregular nodules inside limestone or as distinct rock layers. Most cherts are hypothesized to originate from silica derived from one of three sources: solution in water, biochemical sediments, or lava flows and volcanic ash. Silicate materials can be precipitated out of a solution in marine waters, or produced as a byproduct of water dwelling organisms. Diatoms and radiolarians extract silica from their surroundings and use it to grow silica-rich skeletons. When these organisms die and settle to the bottom, their skeletons provide the silica source for the chert to develop. Large beds of chert have been found to develop in association with lava flows and volcanic ash. It is believed that the chert is produced by the decomposition of volcanic ash.

❑ *Uses*

Chert is a very hard rock that generally breaks along conchoidal fractures. Because it fractures to make sharp edges, it has been shaped by many ancient people to make arrowheads, spear points, knives and tools.

6.8.14 Tillite

Tillite is a clastic sedimentary rock. Tillite consists of consolidated masses of unweathered blocks (large, angular, detached rock bodies) and glacial till (unsorted and unstratified rock material deposited by glacial ice) in a rock flour (matrix or paste of unweathered rock). The component particles are unsorted and may be of any size including large boulders. The matrix, which comprises a large percentage of the rock, usually is dark gray to greenish black in colour and consists of angular quartz and feldspar grains and rock fragments in a very fine-grained paste. Only tillites formed from the till deposited by continental ice sheets have a good chance of being preserved in the geologic record.

6.9 APPLICATIONS

Apart from their scientific significance, the sedimentary rocks have been a controlling factor in the development of industry, society, and culture. Humans have used materials from sedimentary rocks since the Neolithic Age; flint and chert played an important role in the development of tools, arrowheads, and axes. These rocks are also used sometimes for decorative purposes which are cheaper than igneous and metamorphic rocks. The churches, forts and historical monuments in India are made from sedimentary rock, and the statues made by the artists of ancient Greece and Rome and during the Renaissance would have been impossible without limestone. Fully 85% to 90% of mineral products used by our society come from sedimentary rocks. Virtually, our entire store of petroleum, natural gas, coal, and fertilizer come from sedimentary rocks. Sand, gravel, and limestone are the raw materials for cement and aggregate. Sedimentary rocks are also important reservoirs for groundwater, and host important deposits of copper, uranium, lead, zinc, as well as gold and diamonds.

Summary

Sedimentary rocks are widespread on the continents, covering about 75% of the surface of the continents; they therefore form most of the landscape. Nearly 100% of the ocean floor is covered with at least a thin layer of sediment. In India, the sedimentary rocks have maximum areal coverage and duration of the origin. The basic materials for sedimentary rocks are derived from pre-existing igneous and metamorphic rocks. Processes of physical and chemical weathering break down these source materials into gravel, sand, or silt size that may be identifiable rock fragments; or new minerals produced by weathering processes, e.g. clays or dissolved salts in water bodies.

Detrital sediments, also known as clastic sediments, form by the fragmentation of the parent rock by weathering, followed by erosion or transportation of these fragments over variable distances to their place of deposition by natural agencies. Chemical sediments are precipitated from solution. The soluble material may eventually precipitate out of solution as a result of physical and/or chemical changes that take place to such solutions. Biological/organic sediments are sediments in which organisms were involved in their formation or deposition in one way or another. Most of these sediments form by a chemical process in which a living organism precipitates one or more minerals from solution to build its own shell or skeleton. When the organism dies, its soft tissue decays, leaving behind the skeleton to deposit in the middle of other chemical or detrital sediments. Alternatively, coarse biological debris may be transported and deposited elsewhere, giving rise to clastic sediment. One factor that all sedimentary rocks have in common is that they are deposited in basin, and this gives rise to their most noteworthy characteristic, that is, they are bedded or stratified. The most significant feature of sedimentary rocks is therefore the fact that they are stratified.

The textures and structures of sedimentary rocks which reflect about the depositional environment and energy condition prevailing at the time of deposition are also described. Different sedimentary structures like ripple marks, cross bedding, graded bedding, mud cracks, rain prints, track and trails in clastic rocks and their significance for analysis of different depositional environment has been described in detail. This chapter includes the classification of sedimentary rocks based on the basis of its origin, composition and size of grains. But the most common and general classification of sedimentary rocks is clastic and non-clastic which has been described in detail. The fundamental classification of sedimentary rocks is also presented.

The chapter categorically explains about the rocks like sandstone, boulders, conglomerate, shale and limestone, etc., which are of common use from a civil engineering point of view. The chapter ends with a brief about the importance of sedimentary rocks in the construction of civil structures like buildings, dams, roads, and bridges and even as raw material for manufacturing of cement.

Terminology

Aeoline It is a type of clastic sedimentary rock which is formed by sand grains by wind.

Bedding The smallest unit of a geological formation or stratigraphic rock series marked by well defined divisional planes (bedding planes) separating it from layers above and below.

Cross-bedding It is a type of stratification in which various layers lying one above another bear an irregular or inclined relationship to each other. Cross-beds form when wind or water currents flow across a sloping surface while sediment is being deposited. Cross-bedding is common in sandstones deposited in deserts by the action of winds.

Detritus The disintegrated and loosened material formed by weathering and erosion of pre-existing rocks and thereafter accumulated near the source is called *detritus*.

Detrital Rocks The clastic rocks are formed after transportation, sedimentation and lithification of detritus. These rocks are also termed *detrital rocks*.

Diagenesis The process of transformation (physical and chemical changes) of loose sediments deposited in the settlement basins to solid cohesive rock masses, either under pressure or because of cementation is collectively known as diagenesis.

Dune It is a mound or hillock of sand that lies behind the part of beach. It is common depositional feature near beaches and desert.

Facies Sediments may accumulate at different places and in vastly different environments. A small depositional area within a system creates a sedimentary facies. The concept of formation of a sedimentary rock in a particular type of environment is explained by the term facies.

Fissility Fissility is a term used to describe layered laminations formed by compression forces exerted over long-time periods. The property may be defined as the tendency of a rock to split into flat, shell-like fragments, parallel to bedding.

Fossil Fossil is generally used to refer to any evidence of former life (plant or animal).

Lamination This is a layered structure similar to stratification. In lamination, the individual layers are quite thin (generally less than 0.3 cm in thickness). Laminations are more common in fine-grained sedimentary rocks like clays, mudstones and shales. The individual layers are called *laminae* and are parallel to the bedding plane.

Lithification Sediment becomes sedimentary rock through lithification, which involves compaction and cementation. While compaction is caused due to pressure or weight of overlying sediments, cementation is due to the deposition of minerals in pore spaces from waters carrying ions in solution.

Non-clastic Sediments	These include materials that are not formed by the weathering and erosion of rock, but include sediments formed from precipitation directly from water or formed by accumulation of plant material and the skeletal remains of plankton, shells, bone or other biological materials *in situ*.
Permeability	The amount of connected pore spaces in a rock, and is therefore a measure of the capacity of a sedimentary rock to pass fluids through it.
Porosity	A measure of the percentage volume of the pore spaces in a sedimentary rock. For example, loosely packed shale may have a porosity of up to 50%.
Ripple Marks	A series of small wavy structures produced in sand by water currents or by wind.
Rock Flour	These are the minute particles of the common rock-forming minerals.
Sediment	It is the loose particulate material (clay, sand, gravel, etc.). Most sediment is derived from the weathering (breakdown) of pre-existing rocks. Some sediment is formed through chemical and biochemical processes acting in the depositional basin.
Sedimentary Depositional Environment	The combination of physical, chemical and biological processes associated with the deposition of a particular type of sediment. The characteristics of ancient sedimentary depositional environments are often preserved in sedimentary rocks.
Sorting	It is the process by which sedimentary particles of similar size, shape, or density are selected and separated from associated but dissimilar particles, by the agent of transportation (water and wind). It is a measure of the degree of separation of sediments into different size groups. Sorting is a function of the transporting agent as well as the depositional environment. Clastic sediments commonly have a variety of different sized material mixed together. A sediment with a narrow range of sizes is described as well sorted, and one with a very wide range of sizes is considered poorly sorted.
Stratification	Sediments are generally deposited horizontally, one layer on top of the other. A layered arrangement in a sedimentary rock is termed as stratification. The different layers may be similar or dissimilar in colour, composition, grains size and texture.
Texture	It describes the size, shape and arrangement of minerals that make up the rocks. Texture is an important aspect in the description of sedimentary rocks and can be useful in interpreting the mechanisms and environments of deposition.
Turbidity Flows	A turbid, dense current of sediments in suspension, moving along downslope and along the bottom of an ocean or a lake is termed as *turbidity flow*. As turbidity flows slow down, they drop their coarse sediment fractions first, and then finer sediments as the currents diminish, resulting in graded bedding.

Tufa Calcareous and siliceous rock deposits of springs, lakes, or groundwater are called *tufa*.

Weathering and Erosion The interaction between the elements of the atmosphere and the rocks exposed at Earth's surface. The atmospheric agents break down and decomposes pre-existing rocks and forms a layer of loose, decayed rock debris, or soil. The process of weathering and erosion is also termed as *decay and decomposition*.

Exercises

1. (a) Describe briefly the formation of sedimentary rocks.
(b) List the characteristics that distinguish sedimentary rocks from igneous and metamorphic rocks.
(c) What is probably the single most characteristic feature of sedimentary rocks?

2. (a) Describe the classification of sedimentary rocks and parameters considered for classification.
(b) Explain the importance of shape and size of grains in sedimentary rocks.

3. (a) How are the degree of sorting and the amount of rounding related to the transportation of sand grains?
(b) What is the principal mineral in sandstone? Why does this mineral dominate?

4. (a) List three categories of sedimentary environments. Provide examples for each category.
(b) What is the major difference between the various kinds of clastic sedimentary rocks?

5. (a) What is diagenesis? Give an example.
(b) Describe briefly the lithification of sedimentary rocks.

6. What is the mineral composition of limestone? How do limestones differ from clastic rocks?

7. (a) What are evaporite deposits? Name a rock that is evaporite.
(b) How do evaporites form? How are they different from clastic sedimentary rocks?

8. (a) What is the primary basis for distinguishing among various detrital sedimentary rocks?
(b) What is the primary basis for distinguishing among different chemical sedimentary rocks?

9. (a) Distinguish between clastic and nonclastic textures. What type of texture is common to all detrital sedimentary rocks?
(b) Distinguish between cross-bedding and graded bedding.

10. (a) Show with the help of neat sketches, the characteristics of stratification, cross-bedding, and graded bedding.
(b) Give a brief account of classification of sedimentary rocks.

11. What rock types form in the following sedimentary environments?
    (a) Delta (b) Eolian (c) Organic reef (d) Deep marine
12. Write short notes on the following:
    (a) Ripple marks
    (b) Delta structure
    (c) Greywackes
    (d) Stratification
13. Differentiate between the following:
    (a) Cross and graded beddings
    (b) Cement and matrix
    (c) Mud cracks and rain prints
14. (a) Why does shale often crumble easily?
    (b) Distinguish between conglomerate and breccia.
15. Each of the following statements describes one or more characteristics of a particular sedimentary rock. For each statement, name the sedimentary rock that is being described.
    (a) An evaporite used to make plaster.
    (b) A fine-grained detrital rock that exhibits fissility.
    (c) The primary example of an organic sedimentary rock.
    (d) The most abundant chemical sedimentary rock.
    (e) A variety of limestone composed of small spherical grains.

Multiple-Choice Questions

1. Clastic rock is formed from
   (a) lithification of transported grains
   (b) evaporation of seawater
   (c) transformation by heat
   (d) transformation by pressure
2. Shale refers to sedimentary rocks formed from
   (a) sand-sized material (b) buried plants
   (c) clay minerals (d) organic matters
3. Which one of the following is a biochemical sedimentary rock?
   (a) Sandstone (b) Coal
   (c) Shale (d) Conglomerate
4. Which of the following list of rocks is written in order of decreasing particle size?
   (a) Sandstone, siltstone, conglomerate (b) Sandstone, conglomerate, siltstone
   (c) Conglomerate, sandstone, siltstone (d) Siltstone, sandstone, conglomerate
5. Which of the following rock is deposited by chemical precipitation only?
   (a) Halite (b) Limestone
   (c) Dolostone (d) Coal

6. The layer of sedimentary rock in which the grain size changes vertically through the layer is known as

(a) cross-bedding (b) foliated
(c) graded bedding (d) bedding plane

7. Consider the following natural agencies involved in the formation process of sedimentary rocks.

1. Rivers 2. Wind
3. Ocean waves

Which of the above types of currents can transport sand grains?

(a) 1 and 2 (b) 2 and 3
(c) 3 and 1 (d) 1, 2, and 3

8. Consider the following sedimentary environments.

1. Alluvial 2. Beach
3. Desert 4. Glacial

In which of the above environment(s) are the sand deposits expected to be poorly sorted?

(a) 1 and 2 (b) 2 and 3
(c) 3 and 1 (d) 3 only

9. Which of the following process(es) takes place during the diagenesis of sedimentary rocks?

1. Compaction 2. Cementation
3. Lithification 4. Metamorphism

Of the above processes, the correct ones are:

(a) 1 and 2 only (b) 1, 2 and 3 only
(c) 3 and 4 only (d) 1, 2, 3 and 4

10. Consider the followings with regards to lithification of sedimentary rocks?

1. Compaction
2. Erosion
3. Cementation

Of the above processes, the correct ones are

(a) 1 and 2 only (b) 2 and 3 only
(c) 3 and 1only (d) 1, 2, and 3

Answers to MCQs

1. (a) 2. (c) 3. (b) 4. (c) 5. (a) 6. (c) 7. (d) 8. (d)
9. (b) 10. (c)

chapter 7

Rocks III: Metamorphic Rocks

7.1 INTRODUCTION

Metamorphic rocks form from pre-existing igneous, sedimentary and metamorphic rocks under the conditions of high temperature and pressure (higher than conditions of formation of starting material), or through the action of chemical alteration induced by very hot and chemically aggressive pore water. The original texture, composition and mineralogy of the parent rocks get changed in the new physico-chemical and/or tectonic conditions. The process responsible for this change is known as *metamorphism* and the resultant rock is called *metamorphic rock* (Fig. 7.1). Metamorphism generally occurs a few kilometres below the Earth's surface and extending into the upper mantle or along active plate tectonic boundaries. In these areas, temperatures can exceed 800°C and pressures can build up to 6 kbar (6000 times atmospheric pressure). The mineralogical and textural changes during metamorphism occur essentially in the solid state. It is so because if complete melting occurs, it will be the realm of igneous activity. The agents responsible to bring about these changes are heat, pressure and, chemically active fluid and gases.

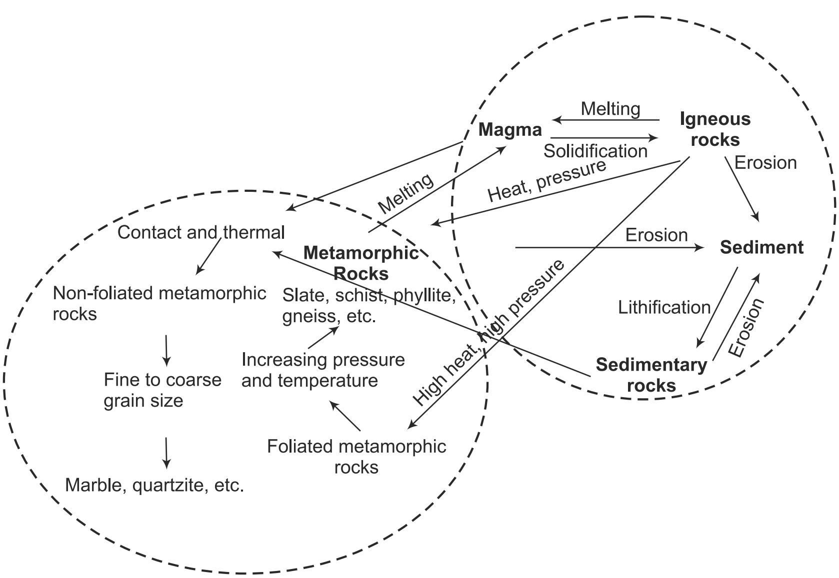


Fig. 7.1 *Metamorphic rock cycle*

The type of metamorphic rock that can form depends on the rock that is being metamorphozed, as well as the amount of pressure and heat to which the rock is exposed. Since varied temperature and pressures will produce different minerals, the exact type of metamorphic rock produced depends on the intensity of metamorphism. The grade of metamorphism can most often be determined by the minerals present in the metamorphic rock and the type of rock formed. Some of the more common metamorphic minerals include quartz, feldspar, biotite, muscovite, chlorite, garnet, tourmaline, calcite and amphibole.

Metamorphic rocks thus form when the precursor materials (igneous, sediment, etc.) are buried deep in the Earth's crust and are consequently brought into an environment of high temperature and are, therefore, most commonly encountered in the core zones of mountain belts (uplifted root zone), in old continental shields, and as the basement rock below the sediment veneer of stable continental platforms. The metamorphic rocks may also develop from the pre-existing rocks in the contact zones.

7.2 AGENTS OF METAMORPHISM

The agents responsible for metamorphism include heat, pressure (stress), chemically active fluids and gases, and other controlling factors, e.g. deformations. These may act to cause changes individually or in combination and create distinctive metamorphic environments. The changes occur to restore equilibrium of rocks subjected to an environment different from the one in which they are originally formed. A change in temperature, pressure, and composition of the environment or strong deformation, and their combination thereof cause alterations in mineral composition and texture of the rock. Importantly, these are changes that occur below the melting point of the rock. Thus, all metamorphic reactions involve solid-state transformations of minerals.

However, the degree of metamorphism and the contribution of each agent vary greatly from one environment to another. Metamorphism causes a series of changes in the texture and composition of a rock. While changes in pressure result in new textures, rise in temperature and chemically active fluids which bring changes in the mineral composition. The controlling parameters of metamorphism are discussed as follows:

7.2.1 Heat as a Metamorphic Agent

One of the most important factors driving metamorphism is heat. It provides the energy to drive chemical reactions that result in the recrystallization of existing minerals and/or the formation of new minerals. Heat affects especially the Earth materials that form in low-temperature environments in the following ways:

1. It promotes recrystallization of individual mineral grains in clays, fine-grained sediments, and some chemical precipitates. Higher temperatures enhance recrystallization where fine particles tend to coalesce into larger grains of the same mineralogical composition.

2. Heat may raise the temperature of a rock to the point that may cause the minerals to become chemically unstable. The constituent ions, in such a case, tend to arrange themselves into crystalline structures that are more stable in the new high-energy environment. Consequently, new minerals with stable configurations are created, having an overall composition roughly equivalent to that of the original material.

The temperature increases on an average of 15–30°C/km in the Earth's crust. Thus, rocks that formed at the Earth's surface will experience a gradual increase in temperature as they are taken to greater depths. Such environments include convergent plate boundaries where slabs of sediment-laden oceanic crust are being subducted. As a rock's temperature increases, its minerals may become unstable and react with other minerals to form new mineral assemblages that are stable under the new conditions. Crystal lattices are broken down and recreated using different combinations of ions and different atomic structures. As a result, new minerals appear.

Below 200°C, reaction rates are low, and most minerals will remain unchanged for millions of years. For rocks buried to a depth of about 8 km, where temperatures are about 200°C, clay minerals tend to become unstable and begin to recrystallize into new minerals, such as chlorite and muscovite that are stable in this environment. However, many silicate minerals, particularly those found in crystalline igneous rocks such as quartz and feldspar remain stable at these temperatures. As another example, if pressure is held constant at 2 kb and temperature increases, the mineral andalusite recrystallizes to sillimanite at about 600°C. When the sillimanite crystallizes, the bonding of atoms in the mineral is rearranged and new crystal forms result. If temperature continues to increase, the rock becomes partially molten at about 700°C, and layers of solid material mixed with layers of magma might form. Metamorphic changes in these minerals, therefore, generally occur at much greater depths.

Note It may be taken note of that different minerals remain in equilibrium at different temperatures. The minerals in a rock, therefore, provide a key to the temperatures at which the rock was metamorphozed.

7.2.2 Pressure as a Metamorphic Agent

An increase in pressure can be produced by deep burial of the rock (lithostatic pressure), or by directed (horizontal) pressure (stress) at convergent plate margins (subduction zones) or as oceanic crust thrusts deep into the mantle. Burial may be caused by prolonged sedimentation in a basin. This static pressure is associated with the existing temperature gradient within the Earth and causes significant changes in the properties of rocks that originally formed at the surface. An increase in pressure can drive chemical reactions to produce new minerals of higher density, because their atoms are more tightly packed and the minerals occupy less space.

While static uniform pressure is caused when rocks are buried deep beneath the Earth's surface, the directed pressure dominates at or near the Earth's surface where mountain building forces are active.

Lithostatic pressure is experienced uniformly by a metamorphic rock. That is, the rock is squeezed to the same degree in all directions. Thus, there is no preferred orientation to lithostatic pressure and there is no mechanical drive to rearrange crystals within a metamorphic rock. Conversely, directed pressure is the pressure of motion and action. Plate tectonics provide the underlying mechanical control for all forms of directed pressure. Thus, metamorphism is closely linked to the plate tectonic and many metamorphic rocks are the products of tectonic interactions.

Notes

1. Minerals tend to grow in the direction of the lowest pressure. Therefore in rocks that were subject to high pressures, the metamorphic minerals elongate perpendicular to the direction of highest pressure.
2. Since the pressures affect very large volumes (or regions) of rock, metamorphism that causes preferred orientations of minerals is also called *regional metamorphism*.
3. Temperature and confining pressure increase together in most environments where metamorphic rocks form. Metamorphism that takes place at low temperature and pressure is called *low-grade metamorphism*; high pressure and high temperature produce *high-grade metamorphism*.

7.2.3 Chemically Active Fluids and Gases as a Metamorphic Agent

Chemically active fluids and gases are also agents of metamorphism. They can be either fluid between crystals promoting chemical exchange within the rock resulting in recrystallization; or from intrusive igneous bodies that may circulate within the country rock resulting in contact metasomatism. The magmatic intrusions may release hot fluids and volatile gases that flow into the surrounding country rock producing metasomatic rocks. Consequently, minerals that are stable in the new chemical environment crystallize and form metamorphic rocks.

The movement of water and carbon dioxide plays a key role in the process of metamorphism. In metamorphic processes that involve an increase in temperature, many minerals that contain H_2O or CO_2 eventually break down, providing a separate fluid that migrates from one place to another. For example, at high temperatures, calcite ($CaCO_3$) and clay [$Al_2Si_2O_5(OH)_4$] break down to release CO_2 and H_2O fluids and other ions. Original crystals break down, and new crystals that form are stable under the changed metamorphic environment. If an ion becomes detached from a mineral's crystal structure, it may move with the fluid to some other place. The fluids move through tiny pore spaces, fractures, and along the margins of grains. The small amount of pore fluid transports material through the rock and allows it to rearrange into new mineral structures.

7.2.4 Deformation

The deformation of rock can also cause metamorphism. In many tectonic settings, there is *directed* or *differential stress* that acts to shorten and compress the rock, or lengthen and extend the rock. The differential stress is usually the result of horizontal compression at zones of plate convergence or collision. At high temperature or confining pressure, a rock becomes ductile and may be deformed slowly if such a differential stress is applied. At low pressure or rapid rates of deformation, mineral grains may be strongly sheared. Deformation reorients mineral grains and forms a new rock texture.

7.3 METAMORPHIC PROCESSES

During metamorphism, a series of changes in texture and mineral composition of the rock occur due to readjustment to new environmental conditions. Readjustment occurs because the minerals and pore fluids become unstable, and a new set of stable minerals or mineral assemblage will form under the new environment. Recrystallization, metasomatism, granulation and plastic deformation are the processes of metamorphism; the first two processes being the major ones.

❑ *Recrystallization*

With the rise in temperature, the intergranular water in the minerals is expelled. Consequently, some unstable minerals of comparatively low melting point will start to melt or dissolve into these pore fluids. Diffusion will then carry the dissolved materials to a nearby site of formation of a new metamorphic mineral. This process of local diffusion and reorganization of the rock into new minerals is called *recrystallization*.

❑ *Metasomatism*

When plenty of fluid is available (in case of fractures), then material can be imported from sources outside a particular rock body of specific composition, or can be exported to adjacent rock bodies. Thus, because of addition or removal of large quantities of mineral-bearing fluids, the overall rock composition will change. The process of change in the chemical composition by a loss or gain in certain elements is called *metasomatism*. It is also called conact metastomatism.

❑ *Granulation*

The process wherein rocks get shattered (fine fractures within the rock) under pressure without losing coherence and the large developed friction which causes melting of the rock is called *granulation*. During this process, the grains similar in shape and size come together due to change in temperature, pressure and deformation of existing rocks. This process is largely influenced by temperature and pressure than the deformational process.

❑ *Plastic Deformation*

A rock is said to be plastically deformed when on removal of the stress, it does not regain its shape. It depends upon pressure, temperature, mineral composition of rocks and moisture content. The content of fluid governs the degree of metamorphism under plastic deformation. When the limit of plastic deformation exceeds, the process of anatexis takes place. Plastic deformation may also generate temperature and pressure which can again aggravate the metamorphism.

7.4 CLASSIFICATION OF METAMORPHISM

There are many environments in which metamorphism occur. Most metamorphic rocks form either at convergent plate boundaries or in the vicinity of igneous intrusions. At convergent plate boundaries, crustal rocks are buried deep and experience high pressures and temperatures. Because of the moving plates, there is a direction of highest pressure and foliation typically develops. Metamorphism can also develop in the vicinity of igneous intrusions where the surrounding rocks are heated by the ascending hot magma. Following are some of the types of metamorphisms.

❑ *Cataclastic Metamorphism*

It is caused because of directed pressure (shear force) and results when rock bodies slide over each other along faults. Tectonic movements build up tremendous pressure (but temperature remains low) causing the rocks to grind and pulverize each other. Consequently, the rock gets crushed into small pieces and is deformed with formation of little new minerals. Directed pressures dominate at or near the Earth's surface in mountain belts where lateral forces, leading to mountain building, are in play. The rocks thus formed are cataclastic rocks with new textures; the examples being *fault braccia* and *mylonite.*

❑ *Dynamic Metamorphism*

This is also known as *clastic metamorphism* or *impact metamorphism* or *shock metamorphism* or *mechanical metamorphism* or *dislocation metamorphism*. This type of metamorphism occurs when rocks are subjected to extreme pressure very rapidly and increase in temperature is very little. When extraterrestrial objects (meteorites) strike the Earth's surface, they crash. Upon impact, the energy of the rapidly moving meteorite is transformed into heat energy and shock waves that pass through the surrounding rocks. The result is pulverized, shattered, and sometimes melted rock. The new rock is formed due to mechanical effects of flow with the growth of very little new minerals in the direction of flow. Stishovite and coesite, both are high pressure forms of quartz resulting from meteor impacts. Dynamic metamorphism may also be caused due to tectonics. The example of rock developed by dynamic metamorphism is slate, phyllite and schist. Dynamic metamorphism is produced on a comparatively small scale and is usually highly localized.

❑ *Contact Metamorphism*

Also called *thermal metamorphism*, it occurs around igneous intrusions. Thus, the principle factor controlling the alterations in the original rocks is temperature (heat). Temperatures in excess of 800°C can occur when magma intrudes into country rock. The rate at which chemical reactions take place during thermal metamorphism is exceedingly slow and depends on the rock types and temperatures involved. Typically, this kind of metamorphism is caused by moderate pressure and extreme heat that may last for a period of days to thousands of years. Since metamorphism is caused due to local heating of the rock by the intruded magma, in contact zones around igneous intrusions; as the magma cools it heats up the surrounding host rock. The host rock is hottest right near the contact and then the temperature gradually declines away from the intrusion. Parallel to the temperature decline, a progressive change of the mineral composition and texture of the rock can be found. Original rock textures can be altered, but they are seldom destroyed as in the case of regional metamorphism. The encircling zone of metamorphic rock around an intrusion is called *contact aureole*.

Notes

1. Contact metamorphism occurs adjacent to volcanoes in mountain belts and hot spots, and along divergent plate boundaries even near the hydrothermal deposits.
2. While small intrusions such as dikes and sills typically form aureoles only a few centimetres thick, large intrusions such as batholiths can produce aureoles that extend outward for several kilometres.

❑ *Hydrothermal Metamorphism*

Contact metamorphism can also occur in areas that are in contact with hot water (hydrothermal fluid). Also known as *metasomatism*, it occurs when hot, ion-rich fluids circulate through fissures and cracks developed in rocks and react with it. This process alters the overall chemical composition of the parent rock. In addition to chemically altering the host rocks, the ions contained in hydrothermal solutions sometimes precipitate to form a variety of economically important mineral deposits. The hot, volatile fluids may be derived from any of the following sources.

1. The fluids may consist of volatiles escaping directly from the intrusive magma.
2. The fluids may be composed of meteoric groundwater heated by the igneous intrusion.
3. An oceanic plate may be subsumed at a boundary between two plates; water may be transported along with it and may subsequently take part in the metamorphic processes.
4. Seawater may also seep into the crust as two oceanic plates move apart. As the seawater migrates, it reacts with the host rock. Large quantities of metals such as iron, cobalt, nickel, silver, gold, and copper are dissolved from the crust.

This type of metamorphism is closely associated with igneous activity, since it provides the heat required to circulate these ion-rich solutions.

❑ *Regional Metamorphism*

In this process, both the temperature (typically in the range of 300–800°C) and directed pressure (> 3 kilobar)/stress are dominant and must have been maintained over millions of years. This type of metamorphism is caused by burial deep in the crust (typically deeper than 5 km) and is associated with large scale deformation and mountain building. It is the most widespread form of metamorphism. An example of regional metamorphism of shale (sedimentary rock) to gneiss is shown in Fig. 7.2. Regional metamorphic rocks develop deep within convergent plate boundaries (subduction and collision zones), in the cores of mountain ranges, where confining pressure is high, differential stress is significant, and temperatures are generally elevated. Further, most regional metamorphic rocks are foliated, since they develop at convergent plate boundaries where differential stress is high.

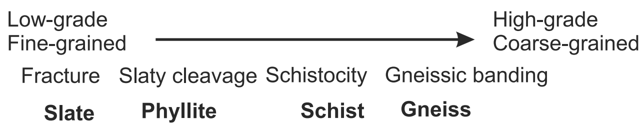


Fig. 7.2 *Schematic representation of regional metamorphism*

Temperature in the interior of the Earth's is dominant at considerable depths, and directed pressures dominate at or near the Earth's surface. When these two agents act together in the presence of hydrothermal fluids, the metamorphism of rocks occurs over wide areas. While heat causes recrystallization, the directed pressure is responsible for shearing and flow movements resulting in new structures. This type of metamorphism is also known as *dynamothermal metamorphism*. The example of such an environment is the occurrence of an igneous intrusion at shallow depth below the Earth's surface in a region where mountain building processes are in operation. The new minerals formed are flat, elongated and flaky with their shortest dimension parallel to the direction of the pressure (stress).

Rocks generally undergo changes in their texture when they experience regional metamorphism. Most of the time, this is a completely destructive process and little remains of the rock's original texture. In rare cases, regional metamorphism may not be so pervasive, and some of the original texture of a rock may be preserved. Metamorphozed sedimentary rocks containing bedding can retain imprints of sedimentary structures.

❑ *Plutonic Metamorphism*

In this type of metamorphism, both the uniform static pressure and temperature dominate. Plutonic metamorphism takes place at great depths underneath the Earth's surface. Since at high static pressure there will be a reduction in volume, there is a change in mineral composition and denser minerals are formed during recrystallization. Plutonic metamorphic rocks have an even-grained texture and are called *granulite*.

❑ *Retrograde Metamorphism*

Also known as *regressive metamorphism,* this occurs when high-temperature metamorphic mineral assemblages change to low temperature ones. Strong differential movement or hydrothermal activity is needed to cause retrograde metamorphism. The environment is similar to that prevalent during formation of igneous rocks. An example of retrograde metamorphism is change of mica-schist to chlorite-schist.

7.5 METAMORPHIC ZONES

Both the temperature and pressure increases with the depth beneath the surface of the Earth. The degree (grade) of metamorphism of a metamorphozed rock therefore varies with depth. In areas affected by metamorphism, there usually exist systematic variations in the mineralogy and texture of the rocks, and accordingly the depth-wise zones of metamorphism are classed on the basis of Grubennman's classification. These zones (Fig. 7.3) are as follows.

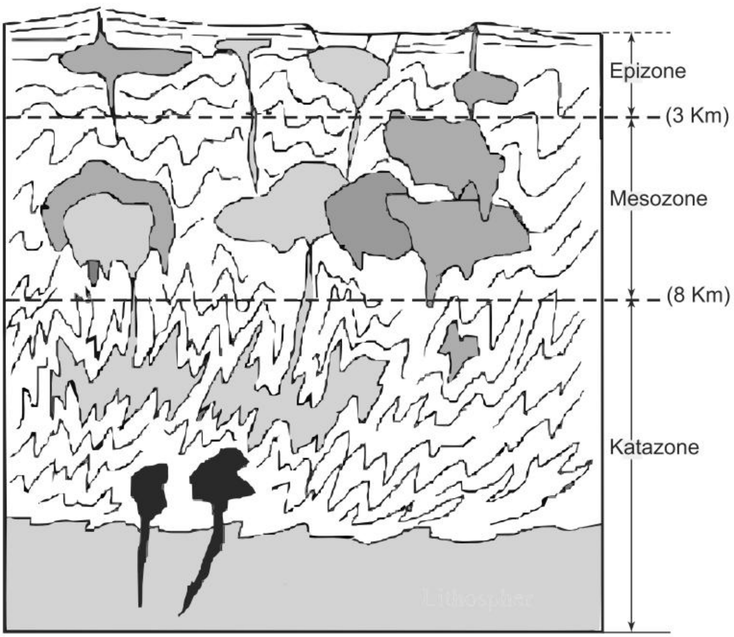


Fig. 7.3 *Depth-wise metamorphic zonation*

❑ *Epizone*

The zone of metamorphism that occurs near to the Earth's surface is called *epizone*. Here, conditions of cataclastic metamorphism prevail. Epizone is characterized by low-grade metamorphism, and minerals chlorite and biotite.

❑ *Mesozone*

The zone that lies below the epizone is termed *mesozone*. Here, the agents of metamorphism promote regional metamorphism. Mesozone is characterized by medium-grade metamorphism, and minerals staurolite and kyanite.

❑ *Katazone*

The lowest zone of metamorphism is known as *katazone*. Plutonic metamorphism takes place in this zone. Katazone is characterized by high-grade metamorphism, and minerals garnet and sillamanite.

7.6 METAMORPHIC FACIES

It is believed that groups of associated minerals, called *index minerals*, can be used to determine the pressures and temperatures at which rocks undergo metamorphism. This forms the concept of *metamorphic facies*, which often is used to classify metamorphic rocks. Rocks containing the same assemblage of minerals belong to the same metamorphic facies—implying that they formed in very similar metamorphic environments.

Presence of index minerals in metamorphic rocks denotes different types of facies. The metamorphic facies and their relationship with corresponding index minerals are given in Table 7.1.

Table 7.1 *Index minerals/rocks and their relationship with metamorphic facies*

S. No	*Index Mineral/Rock*	*Metamorphic Facies*
1.	Zeolite	Lowest grade
2.	Green-schist	Low grade
3.	Amphibolite	Medium to high grade
4.	Granulite	High grade
5.	Eclogite/Glucophane/Lawsonite	Highest grade

The name for each facies is based on the minerals that define them. For example, rocks of the zeolite facies are characterized by the mineral zeolites, chlorite, etc., and the green-schist facies consist of schists in which the green minerals chlorite, epidote, and serpentine are prominent. It should be noted that the name for each metamorphic facies refers to a metamorphic rock.

❑ *Application*

One of the most significant concepts to be drawn from the study of metamorphic rocks is the notion of metamorphic facies. By evaluating the changes in texture and composition within metamorphic rocks, it is possible to delineate regions of high- and low-grade metamorphism. That is, the geometries of similar metamorphic rocks provide insights to the processes of metamorphism. From the analysis of metamorphic facies, two inferences can be drawn.

1. Different kinds of metamorphic rocks are formed from different parent rocks at the same grade. Thus, compositional variation in the precursor rocks is inherited by the metamorphic rocks.
2. Different kinds of metamorphic rocks are formed from the same precursor at different metamorphic grades.

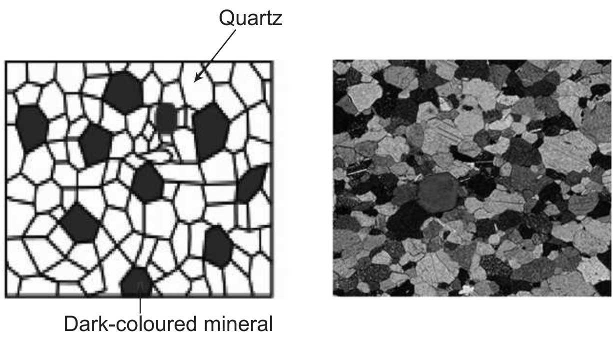
Note Metamorphic rocks are named by combining the most abundant minerals and the textural type, e.g. quartz-mica schist. In some cases, the prevalent colour of the rock may be used instead of a mineral name, particularly if such colour is due to a certain mineral, e.g. metamorphic rocks with chlorite tend to be greenish in colour, and, therefore, the name 'green-schist' is used instead of 'chlorite-schist'.

7.7 METAMORPHIC TEXTURES AND STRUCTURES

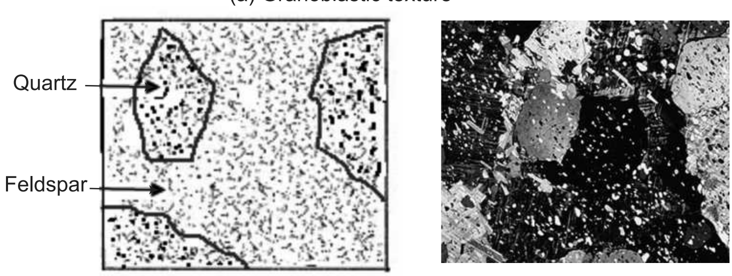
There are two basic types of texture for a metamorphic rock. Rocks which exhibit foliation are said to exhibit a *planar* or *foliated texture*. Planar texture can further be divided based on the type/degree of foliation. Rocks which do not show foliation are said to exhibit a *granular* or *non-foliated texture*. Metamorphic textures and structures distinguished on the basis of size, shape and orientation of the crystals and foliation are presented below.

❑ *On the Basis of Size, Shape and Orientation of Crystals*

Some of the important types of textures, as shown in Fig. 7.4, are as follows.



(a) Granoblastic texture



(b) Porphyroblastic texture

Fig. 7.4 *Metamorphic texture on the basis of grain shape and size*

■ **Granoblastic** This type of texture results from recrystallization of minerals and is similar to the holocrystalline texture of igneous rocks. In a crystalloblastic metamorphic rock, the texture may be *xenoblastic*—none of the minerals appear to have perfect crystal outline; *ideoblastic*—mineral grains have developed perfect crystal outline; and *granoblastic*—the mineral grains are equidimensional.

■ **Porphyroblastic** This type of texture is characterised by large crystals embedded in a fine grained groundmass. Porphyroblastic textures develop in a wide range of rock types and metamorphic environments when minerals in the parent rock recrystallize to form new minerals. During recrystallization, certain metamorphic minerals, including garnet, staurolite, and andalusite, invariably develop a small number of very large crystals. By contrast, minerals such as muscovite, biotite and quartz typically form a large number of very small grains.

■ **Palimpsest** When the remnant of the mineral composition and texture of the parent rock is preserved, the metamorphic texture is called *palimpsest*.

Notes

1. The term blastic or blast is commonly used as a suffix to represent the metamorphic equivalents of igneous textures of similar look.
2. Especially in the case of higher grade metamorphism, crystals can grow in the rocks that are considerably larger than the average grain size in the rock (garnets, staurolite). These large crystals are called porphyroblasts in analogy to porphyric crystals in igneous rocks.

❑ *On the Basis of Foliation*

The texture is classed as foliated and non-foliated.

■ **Foliated Texture** During metamorphism, new textures are developed besides formation of new minerals. The most common of these textures is *foliation*. Foliation refers to any planar (nearly flat) arrangement of mineral grains or structural features within a rock. The layered texture means that the minerals are aligned and grew under directed pressure (compressional stress). It is a fundamental characteristic of rock units that have been strongly folded and distorted. Under the changed conditions of temperature and pressure, new mineral grains as well as pre-existing mineral grains recrystallize, i.e. the grains grow and coarsen. Foliation comprises a segregation of particular minerals into different bands or contiguous lenticels that exhibit a common parallel orientation.

Rocks resulting from regional metamorphism generally display foliations. Examples of foliation include the parallel alignment of flattened mineral grains and pebbles; slaty cleavage where rocks can be easily split into thin, tabular slabs along parallel surfaces; the parallel alignment of platy and/or elongated minerals (schistosity); and compositional banding where the separation of dark and light minerals generate a layered appearance as shown in Fig. 7.5. These diverse types of foliation can form by

1. Rotation of platy and/or elongated mineral grains into a new orientation
2. Recrystallization of minerals to form new grains growing in the direction of preferred orientation
3. Changing the shape of equidimensional grains into elongated shapes that are aligned in a preferred orientation

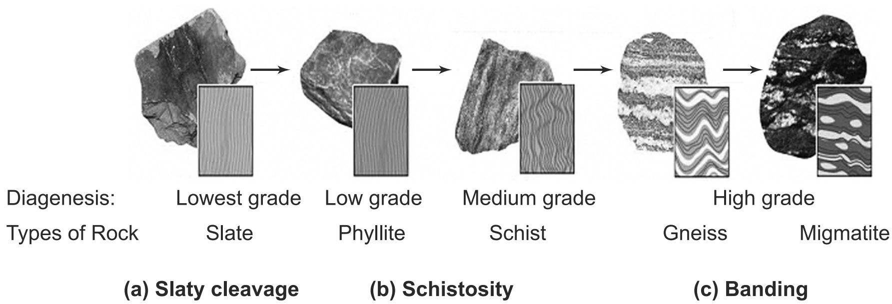


Fig. 7.5 *Gradual changes in rock texture due to temperature and pressure*

o *Slaty Cleavage* Also known as *rock cleavage,* it is developed in most metamorphic rocks but slates are the best example, hence termed 'slaty cleavage'. It is probably the most familiar type of preferred orientation (particularly of those belonging to the mica family) and occurs in rocks of low metamorphic grade and is characteristic of slates and phyllites. It is independent of bedding.

o *Schistosity* It develops in a rock when it is subjected to increased temperatures and stress that involves its reconstitution, which is brought about by localized solution of mineral material and recrystallization. The minute mica and chlorite grains in slate begin to grow many times larger. When these platy minerals grow large enough to be discernible with the unaided eye and exhibit a planar or layered structure, the rock is said to exhibit schistosity (Fig. 7.6). Rocks having this texture are referred to as *schist.*

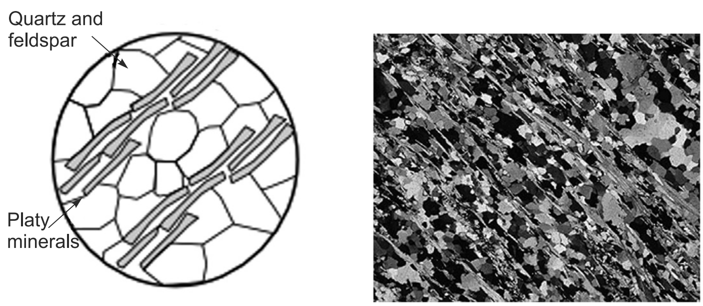


Fig. 7.6 *Schistose structure*

In addition to platy minerals, schist often contains deformed quartz and feldspar grains that appear as flat, or lens-shaped, grains hidden among the mica grains. The more abundant, flaky and tabular minerals are in such rocks, the more pronounced is the schistosity. However, the schistocity may disappear due to a change in high temperature and pressure, and rock deformation.

- *Gneissic Texture* During high-grade metamorphism, ion migrations can result in the segregation of minerals, giving the rock a banded appearance called *gneissic texture* (Fig. 7.7). A metamorphic rock with this texture is called *gneiss*. Gneisses do not usually split as easily as slates and some schists. Gneisses that do cleave, tend to break parallel to their foliation and expose mica-rich surfaces that resemble schist.

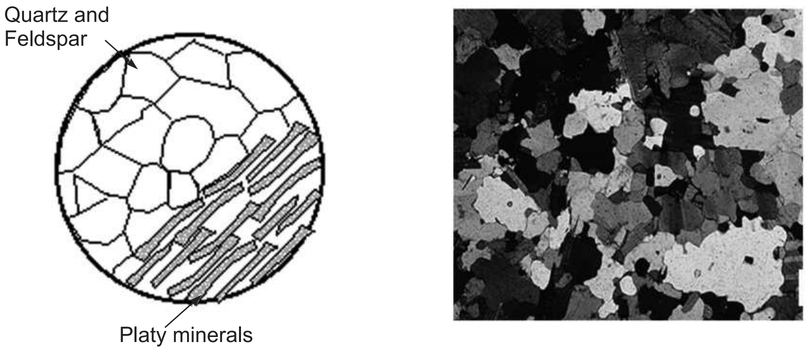


Fig. 7.7 *Gneissic structure*

❑ *Non-foliated Texture*

Metamorphic rocks can only be foliated if the composition of their parent rocks allows mica formation; those that do not are referred to as *non-foliated*. Non-foliated metamorphic rocks typically develop in environments where deformation is minimal and the parent rocks are composed of minerals that exhibit equidimensional crystals, such as quartz or calcite. They are also known as *granular metamorphic rocks*.

Contact metamorphism, and regional metamorphism of rocks that contain few platy minerals (e.g. mica and chlorite), produce rocks that do not display foliation. Some of the examples of such rocks are quartz sandstones transformed into quartzite [Fig. 7.8(a)], limestones transformed into marble [Fig. 7.8(b)] and basalt transformed into amphibolite. Hornfels is another non-foliated, fine-grained metamorphic rock. It occurs typically in metamorphic aureolas around intrusions (contact metamorphism).

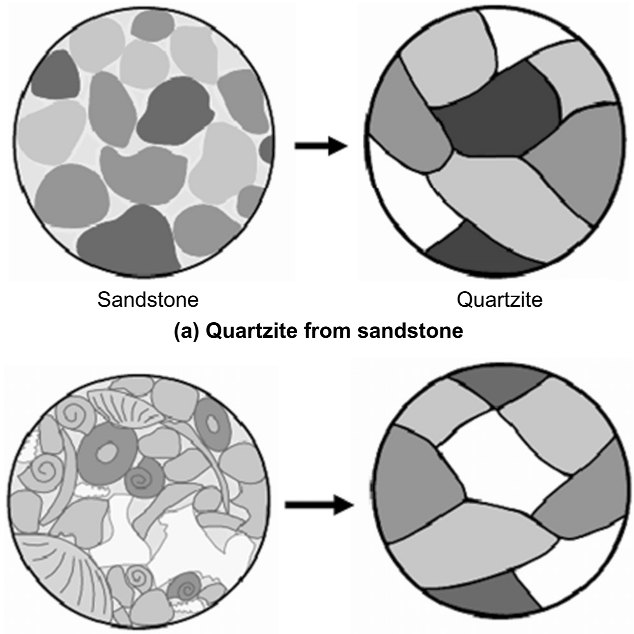


Fig. 7.8 *Non-foliated metamorphic rocks*

7.8 IMPORTANT METAMORPHIC ROCKS AND THEIR CHARACTERIZATION

Due to the variation in the kinds and degrees of metamorphism of the original rocks, many types of metamorphic rocks are formed. Since varied temperature and pressures will produce different minerals, the exact type of metamorphic rock produced depends on the intensity of metamorphism. The grade of metamorphism can most often be determined by the minerals present within the metamorphic rock and the type of rock formed. Some of the more common metamorphic minerals include quartz, feldspar, biotite, muscovite, chlorite, garnet, tourmaline, calcite and amphibole. The important metamorphic rocks (Plate 13) may be grouped under the headings of foliated and non-foliated rocks.

7.8.1 Foliated Rocks

Foliated rock is classified on the basis of the intensity of foliation, degree of mineral separation and crystal size, and is as follows.

❑ ***Slate***

The foliated metamorphic rock produced by low-grade metamorphism, generally of shale or mudstone, is called *slate*. Slates are foliated fine-grained rocks, but the platy minerals are so fine, that foliation is not normally obvious.

■ **Mineral Composition and Colour** The colour of slate depends on its mineral constituents. Black (carbonaceous) slate contains organic material, red slate gets its colour from iron oxide, and green slate usually contains chlorite.

■ **Texture and Structure** Slate is a very fine-grained (less than 0.5 mm) low-grade foliated rock composed of minute mica flakes that are too small to be visible. Thus, slate generally appears dull and closely resembles shale. It has a planar texture. A noteworthy characteristic of slate is its excellent rock cleavage, or tendency to break into flat slabs.

Slaty cleavage is produced by the parallel alignment of minute flakes of platy minerals, such as mica, chlorite, and talc. Zeolites also form in these low-grade rocks. Excellent foliation can develop in the shale, in which clay minerals are abundant and are easily altered to mica. In thick layers of quartz sandstone, however, the slaty cleavage plane is generally poorly developed.

■ **Origin** Slate is most often generated by the low-grade metamorphism of shale, mudstone, or siltstone. Regional metamorphism of volcanic ash also produces slate, which is normally dark in colour.

❑ *Schist*

Schists are medium- to high-grade metamorphic rocks containing mineral grains that are distinguishable with the unaided eye. They produce a planar structure because of their overlapping sub-parallel arrangement. Because the crystals are large enough to identify, schists are named on the basis of their dominant mineral or minerals. The foliation of schist differs from that of slate mainly in the size of the crystals. At least 50% of these minerals are platy in nature resulting in a distinctive foliated texture called *schistosity*. Because of the mica content, most schists split apart relatively easily, but splits are wavy rather than flat as seen in slates.

■ **Mineral Composition** Schists are medium-to coarse-grained metamorphic rocks in which platy minerals predominate. These flat components commonly include the micas (muscovite and biotite), which display a planar alignment that gives the rock its foliated texture. These rocks are commonly associated with appreciable amounts of other minerals, including micas, hornblende, talc, graphite, chlorite, and others. The mineral composition provides a basis for subdividing schists into many varieties, such as chlorite-schist, mica-schist, and amphibole-schist.

Notes

1. To indicate the composition, mineral names are used. For example, schists composed primarily of muscovite and biotite are called *mica-schist*.
2. Some common accessory minerals that occur as porphyroblasts include *garnet, staurolite,* and *sillimanite,* in which case the rock is called *garnet-mica schist, staurolite-mica schist,* and so forth.

■ **Texture and Structure** Schist is a strongly foliated rock ranging in texture from medium-grained to coarse-grained. Foliation results from the parallel arrangement of relatively large grains of platy minerals, such as mica and chlorite. The direction of elongation is also the direction along which the rock is weakest; thus, most schists easily split along this axis. It has a planar texture.

■ **Origin** Schists are one of the most abundant metamorphic rocks. Parent rocks include basalt, granite, shale, and tuff. Schists result from a higher grade of regional metamorphism than the type that produces slates.

❑ *Phyllite*

Phyllite is a metamorphic rock that represents a gradation in the degree of metamorphism between slate and schist. Its constituent platy minerals are larger than those in slate but not yet large enough to be readily identifiable with even hand lens. Although phyllite appears similar to slate, it can be easily distinguished from slate by its glossy sheen and sometimes with its wavy surface. Also the glossy sheen is the best means to distinguish a phyllite from a schist.

■ **Mineral Composition** Phyllites are normally medium- to coarse-grained, with visible grains of mica or other metamorphic minerals

■ **Texture and Structure** During the continued application of heat and pressure to slate, minute crystals of quartz, graphite, sericite, or chlorite grow, bestowing a distinctive sheen to the rock's foliations. This foliation manifests itself as a crinkly or wavy texture. Phyllite usually exhibits rock cleavage and is composed mainly of very fine crystals of either muscovite or chlorite, or both. Phyllite comes in a variety of colours depending upon the mineral composition. The two most common colors, green and golden yellow, contain respectively, the minerals chlorite and muscovite.

■ **Origin** Most phyllites form from rocks that were originally shales due to regional metamorphism.

❑ *Gneiss*

Gneiss is medium-to coarse-grained banded high-grade granular metamorphic rocks in which granular and elongated minerals predominate. Characteristically, it is identified by its alternating layers of light and dark minerals. During high-grade metamorphism the light and dark minerals separate, giving gneisses the characteristic of banded or layered appearance. These banded gneisses often exhibit evidence of deformation, including folds and sometimes faults. Some gneisses split along the layers of platy minerals, but most break in an irregular fashion.

■ **Mineral Composition** The most common minerals in gneiss are quartz, potash feldspar, and sodium-rich plagioclase feldspar. Most gneisses also contain some amounts of biotite, muscovite, and amphibole that develop a preferred orientation. Gneisses may include large crystals of accessory minerals such as garnet and staurolite. Gneisses made up primarily of dark minerals resembling basalt also occur. The composition of most gneisses is similar to that of granite.

■ **Texture and Structure** When struck with a rock hammer, gneiss generally fractures across the layers, or planes of foliation, where micas are abundant, it can break along the foliation. Gneissic layering can be highly contorted because of deformation during recrystallization. It has planar and banded texture.

■ **Origin** Most gneisses have a felsic composition and are often derived from granite or its equivalent, rhyolite. However, many form from the high-grade metamorphism of shale. In this instance, gneiss represents the last rock in the sequence of shale (slate, phyllite, schist, and gneiss).

Note Although, gneiss forms during high-grade metamorphism, and in some areas it grades into partially molten rock if the temperature of initial melting is reached. Such a rock that is partly igneous and partly metamorphic is known as *migmatite*. Migmatites are commonly deformed and have thin dikes or sills. The migmatites may even grade into completely igneous rocks, such as granite.

❑ ***Mylonite***

Mylonite is hard, fine-grained metamorphic rock with a streaked or weakly foliated texture formed by intense shearing. Less-deformed, larger grains may survive as relicts embedded in a sheared groundmass. Very fine-grained mylonite forms sheet like bodies that appear to be as structureless as chert. Mylonites form in shear zones in folded mountain belts and along transform fault plate boundaries.

7.8.2 Non-foliated Rocks

Non-foliated metamorphic rocks can either form by recrystallization in a uniform stress field or those that lack a foliation because they are made of minerals that are equant in shape and not platy like micas and chlorite. The major varieties of non-foliated metamorphic rocks are quartzite, marble and hornfels.

❑ ***Quartzite***

Quartzite is a very hard non-foliated metamorphic rock formed from quartz-rich sandstone. It is not foliated because quartz grains, the principal constituents, do not form platy crystals. The individual grains commonly form a tight mass, so the rock breaks across the grains as easily as it breaks around them. Pure quartzite is white or light-coloured, but iron oxide and other minerals often impart red, brown, green colours, while dark mineral grains may impart a grey colour.

Quartzite has granular texture. Under moderate- to high-grade metamorphism, the quartz grains in sandstone fuse or weld together by heat into an interlocking mosaic of crystals. The fusing of quartz grains in quartzites also makes them harder than quartz-rich sandstones where sand grains are loosely held together by cement. The recrystallization is so prominent that when broken, quartzite will split through the quartz grains rather than along their boundaries.

❑ *Marble*

Marble is a coarse, crystalline carbonate rock metamorphozed from limestone or dolostone. Pure marble is white and composed essentially of the mineral calcite. Because of its relative softness, marble is easy to cut and shape. The parent rock from which marble forms, often contains impurities that tend to colour the stone. Thus, marble can be pink, grey, green, or even black and may contain a variety of accessory minerals (chlorite, mica and garnet). Unfortunately, since marble is composed of calcium carbonate, it is readily attacked by acid rain.

■ **Mineral Composition** The purest marbles are snow white, but many marbles contain a small percentage of minerals other than calcite that were present in the original sedimentary rock. These impurities result in streaks or bands and, when abundant, may impart a variety of colours to the marble. Because of its colouration and softness, marble is a popular building and monument stone.

■ **Texture and Structure** Calcite, the major constituent of the parent rocks, is equidimensional, so marble is usually non-foliated. The grains are commonly large and compactly interlocked, forming a dense rock. Marble has a granular texture.

When marble forms from limestone interbedded with shales, it will appear banded and exhibit visible foliation. When deformed, these banded marbles may develop highly contorted mica-rich folds that give the rock a rather artistic design. Marbles and dolomitic marbles, like quartzite, are characterized by recrystallized, interlocking crystals of roughly equal size. Some marbles are less pure than others because the carbonate rocks that they formed from contained high concentrations of silt and clay. These impure substances frequently develop a weak foliation or schistosity upon metamorphism. These rocks are called *schistose marbles*.

■ **Origin** Most marbles occur in areas of regional metamorphism where metamorphozed sedimentary rocks include schists and phyllites. The majority of marbles are derived through the metamorphism of limestone, but dolomite and dolostone also produce marble if metamorphozed.

❑ *Hornfels*

Hornfel is a fine-grained, non-foliated metamorphic rock that is very hard, dense and dark coloured. A lack of differential stress is the main reason these rocks are non-foliated. Hornfels are generally gray-black in colour because they were essentially baked due to direct contact with a pluton or other reservoir of magma.

■ **Mineral Composition** Hornfels display a varied mineral composition. The common occurring minerals are feldspar, andalusite, cordierite, biotite and quartz.

■ **Texture and Structure** Generally, the texture of hornfels is granulose. These fine-grained rocks commonly lack pronounced foliation because of the low-grade of metamorphism. Low-grade metamorphism converts the minerals in mafic igneous rocks (plagioclase, pyroxene, and olivine) to new minerals such as chlorite, epidote and serpentine that are stable at low temperatures (about 200° to 450°C) and in the presence of water. Because these abundant minerals are characteristically green, metamorphozed mafic rocks such as basalt are called *green-stones.* In hornfels, platy minerals such as mica, can be present, but they have random orientations.

■ **Origin** Hornfels result from thermal metamorphism of the wall rocks around igneous intrusions. The parent rock is usually shale.

7.9 ENGINEERING IMPORTANCE OF METAMORPHIC ROCKS

Metamorphic rocks are an important source of building materials. Marble is commonly used as decorative building stone since prehistoric times. White marble is particularly prized as a stone from which to create monuments and statues, such as the famous Taj Mahal. Slate is very useful in building material and finds application in roof tiles, floor tiles, pool tables, blackboards, etc. Some schists contain the mineral *graphite,* which is used as pencil lead, graphite fibers (used in fishing rods), and lubricant (commonly for locks). Augen gneiss containing large porphroblasts of quartz, feldspar and/or garnet make very attractive building materials when polished, and are often used on the exteriors of office buildings.

Metamorphism of impure limestone produces talc, a very soft silicate mineral, that is an important mineral filler in paints, rubber, paper, asphalt, and cosmetics. High-grade marbles and granulites are important sources of sapphires and rubies. Low-grade metamorphism of ultramafic igneous rocks (dark igneous rocks composed mostly of magnesium and iron) produces serpentine, a group of sheet-silicate minerals (crysotile, lizardite, antigorite) that are the principal sources of asbestos. Many economic deposits of gold, copper, tungsten and iron occur in metamorphic rocks.

Summary

Metamorphic rocks form from pre-existing rocks, which undergo mineralogical, textural and structural changes. These alterations are brought about by changes that have taken place in the physical and chemical environments in which the rocks existed. The primary agents of metamorphism, which include heat, pressure (stress), and chemically active fluids give rise to their progressive transformation. This alteration essentially takes place in the solid state. Metamorphic rocks and associated igneous intrusions make up about 85% of the continental crust.

In metamorphic rocks, there exist zones of metamorphism characterized by systematic variations in the mineralogy and texture of the rocks. The degree, i.e. the grade of metamorphism of a metamorphozed rock, therefore, varies with depth. These differences are related to variations in the degree (grade) of metamorphism experienced in each metamorphic zone. The grade of metamorphism can most often be determined by the minerals present within the metamorphic rock and the type of rock formed.

The textures and structures of metamorphic rocks are described. During regional metamorphism, rocks typically display a preferred orientation called foliation in which their platy and elongated minerals are aligned. Foliation develops as platy or elongated minerals are rotated into parallel alignment, recrystallize to form new grains that exhibit a preferred orientation, or are plastically deformed into flattened grains that exhibit a planar alignment. Foliated and non-foliated textures and structures are described. Rock cleavage, schistosity and gneissosity are discussed.

Various important metamorphic rocks are described. Common foliated metamorphic rocks include slate, phyllite, various types of schists and gneiss. Non-foliated rocks include marble and quartzite. The type of metamorphic rock that can form depends on the rock that is being metamorphozed as well as the amount of pressure and heat to which the rock is exposed. Since varied temperature and pressures will produce different minerals, the exact type of metamorphic rock produced depends on the intensity of metamorphism.

Terminology

Anatexis It is the differential or partial melting of rocks under extreme conditions of temperature and pressure. Anatexis results from tectonism (regional metamorphism) because magmas typically carry too little heat to melt significant quantities of surrounding rocks while they continue to remain molten.

Differential Stress refers to higher pressure from one direction than in others. In some cases, the differential stress can result in shearing.

Equilibrium It is a state where the mineral assemblage is stable and does not change.

Foliation refers to flat or wavy planar (nearly flat)) arrangement of mineral grains or structural features within a rock. The resulting rock is foliated. Foliation frequently manifests itself as a visible sequence of layers, though it can also appear as alternating bands of light and dark minerals. Another term used for foliation is, therefore, *banding*.

Foliation is a fundamental characteristic of regionally metamorphozed rocks. In metamorphic environments, foliation is ultimately driven by compressional stresses that shorten rock units, causing mineral grains in pre-existing rocks to develop parallel, or nearly parallel alignments.

Gneiss During high-grade metamorphism, ion migrations can cause minerals to segregate into distinct layers or bands. Metamorphic rocks with a banded texture are called *gneiss*.

Grade is a term used in a relative sense to refer to the conditions of temperature and pressure to which a rock has been subjected.

Grade of Metamorphism	The degree or intensity of metamorphism to which the rock is affected is known as grade of metamorphism. It is expressed as very low, low, medium and high. For example, the mineral chlorite begins to form when temperatures are relatively low (< 200°C). Thus, rocks that contain chlorite (usually slates) are referred to as low-grade. By contrast, the mineral sillimanite only forms in very extreme environments where temperatures exceed 600°C and rocks containing it are considered high-grade.
Igneous Intrusion	Molten magma beneath the Earth's surface that moves through joints, fractures, and between the crystals of the solid rock of the crust and mantle is called igneous intrusion.
Metamorphic Facies	A facies is a grouping of metamorphic rocks of various compositions that have formed under the same grade of metamorphism.
Metamorphism	It is a process that leads to changes in the mineralogy, texture, and sometimes the chemical composition of rocks. Metamorphism takes place where pre-existing rock is subjected to a physical or chemical environment that is significantly different from that in which it initially formed. These include changes in temperature, pressure (stress), and the introduction of chemically active fluids. In response to these new conditions, the rock gradually changes, until a state of equilibrium with the new environment is reached.
Parent Rock	The rock that has undergone changes is called the parent rock. Parent rocks can be any of the three types of rocks: igneous, sedimentary, or metamorphic rocks which can be metamorphosed again.
Preferred Orientation	Any deviation from randomness in the distribution of crystallographic axis of minerals of rocks, produced by deformation and non-uniform stress during crystallization in metamorphic rocks.
Rock Cleavage	A type of foliation in which rocks split cleanly into thin, tabular slabs along surfaces, where platy minerals are aligned, when hit with a hammer.
Schistosity	A type of foliation defined by the parallel alignment of medium-to-coarse-grained platy minerals.
Sheen	The sheen is caused by the alignment of platy minerals that develops a pearly surface on the phyllite.

Exercises

1. (a) What is metamorphism? Discuss the various agents of metamorphism.
(b) Why is heat considered the most important agent of metamorphism?
(c) What role do chemically active fluids play in metamorphism?

2. Compare and contrast the characteristics of metamorphic rocks with those of igneous and sedimentary rocks.

3. Define foliation and explain the characteristics of following textures.
(a) Slaty cleavage (b) Schistosity
(c) Gneissic layering (d) Mylonitic texture

4. Make a generalized flowchart showing the origin of the common metamorphic rocks. Describe the major types of metamorphic rocks.
5. What are the major metamorphic facies? What are the factors that regulate them?
6. Distinguish between contact metamorphism and regional metamorphism. Discuss metasomatism.
7. Where does most hydrothermal metamorphism occur? Describe the metamorphic zones.
8. Distinguish between the following rocks.
   (a) Quartzite and marble
   (b) Marble and recrystallized limestone
   (c) Slate and phyllite
9. What important variables cause changes associated with
   (a) regional metamorphism?
   (b) contact metamorphism?
   (c) ocean ridge metamorphism?
10. Each of the following statements describes one or more characteristics of a particular metamorphic rock. For each statement, name the metamorphic rock that is being described.
   (a) Calcite-rich and often non-foliated
   (b) Loosely coherent rock composed of broken fragments that are formed along a fault zone
   (c) Represents a grade of metamorphism between slate and schist
   (d) Very fine-grained and foliated; excellent rock cleavage
   (e) Foliated and composed predominately of platy minerals
   (f) Composed of alternating bands of light and dark silicate minerals
11. Write short notes on the following.
   (a) Contact aureole
   (b) Granoblastic texture
   (c) Porphyroclastic texture
   (d) Foliation
   (e) Grades of metamorphism
12. Distinguish between the following.
   (a) Slaty cleavage and gneissic textures
   (b) Porphyroblastic and crystalloblastic textures
   (c) Epizone and mesozone
   (d) Cataclastic and dynamic metamorphisms

Multiple-Choice Questions

1. Which of the following rock is metamorphozed to marble?
   (a) Granite (b) Limestone
   (c) Sandstone (d) Slate

2. Changes in the bulk composition of the parent rock occur primarily as a result of which of the following agent of metamorphism?

(a) Pressure (b) Temperature
(c) Hydrothermal fluids (d) Deformation

3. What type of metamorphism is caused by high temperature and high pressure imposed over a large volume of crust?

(a) Burial (b) Contact
(c) Regional (d) Cataclastic

4. Which mineral is responsible for the strong foliation in schist?

(a) Mica (b) Calcite
(c) Quartz (d) Chlorite

5. Which of the following metamorphic rock cannot form from shale?

(a) Schist (b) Slate
(c) Phyllite (d) Marble

6. Which of the following index mineral forms at the highest metamorphic grade?

(a) Chlorite (b) Sillmanite
(c) Biotite (d) Garnet

7. By which of the following process, a metamorphic rock earlier metamorphozed under high-grade conditions is later metamorphozed under low-grade conditions.

(a) Metasomatism (b) Cataclasis
(c) Foliation (d) Retrograde metamorphism

8. The parallel alignment of mica in a metamorphic rock is an example of

(a) porphyroblasts (b) bedding
(c) metasomatism (d) foliation

9. Which of the following rock represents the highest metamorphic grade?

(a) Slate (b) Schist
(c) Phyllite (d) Gneiss

10. Metamorphic rocks with segregated light and dark minerals are called

(a) slate (b) schist
(c) gneiss (d) phyllite

11. Which of the following pair of metamorphic rock and parent rock is not matched correctly?

(a) Greenstone: Basalt
(b) Quartzite: Quartz arenite
(c) Schist: Shale
(d) Hornfels: Dolomite

12. Consider the following types of pressures.

1. Contact pressure
2. Directed pressure
3. Confining pressure

Which type of pressure(s) will result in the alignment of metamorphic minerals?

(a) Both 1 and 2 (b) Both 2 and 3
(c) Both 3 and 1 (d) Only 2

13. Consider action of heat, pressure and chemically active fluids on the pre-existing rocks. Which of the following will cause metamorphism?
1. A change in the chemical environment
2. An increase in temperature
3. An increase in pressure

(a) Both 1 and 2 (b) Both 2 and 3
(c) Both 3 and 1 (d) 1, 2 and 3

14. In which of the following settings can metamorphism occur.
1. Adjacent to igneous intrusions
2. Along faults
3. In subduction zones

(a) Both 1 and 2 (b) Both 2 and 3
(c) Both 3 and 1 (d) 1, 2 and 3

15. Consider the following rocks.
1. Slate
2. Schist
3. Shale
4. Phyllite

The code for correct increasing order of grade of metamorphism is
(a) 1, 3 and 4 (b) 3, 2 and 1
(c) 1, 4 and 2 (d) 1, 2 and 3

Answers to MCQs

1. (b)	2. (c)	3. (c)	4. (a)	5. (d)	6. (b)	7. (d)	8. (d)
9. (d)	10. (c)	11. (d)	12. (d)	13. (d)	14. (d)	15. (c)	

chapter 8

Rock Deformations

8.1 INTRODUCTION

The collective displacements of points in a body relative to an external reference frame are known as deformation. Deformation describes the transformations from some initial to some final geometry. *Rock deformation* may be defined as any change in the volume, shape and size of a rock body. Deformation of a rock body occurs in response to a force. A volume change of a rock that occurs when confining pressure increases is an example of rock deformation. The components of the deformation of a rock body are rotation, translation, distortion, and dilation. Some of the forms of rock deformation include folding, faulting, jointing and unconformity.

There are basically three types of forces—compression, tensional and shear—that can deform rocks. While *compressive forces* squeeze and shorten a body, the *tensional forces* stretch a body and pull it apart, and *shearing forces* push different parts of a body in opposite directions. When rocks deform in response to imposed stress, they exhibit strain, which is the differential change in size, shape, or volume of a material. Stress is a force per unit area or a force that acts on a surface. Rocks differ in their responses to stress, depending upon composition, conditions of temperature and confining pressure, and strain rate. Strain describes the changes of points in a body relative to each other, or, in other words the distortions a body undergoes.

The type of strain (deformation) that develops in a rock depends upon the nature of force. Compressive forces generate folding and faulting as a consequence of shortening. Compressive forces are common along convergent plate boundaries, resulting in mountain ranges. Tensional forces cause stretching and thinning of the rocks, usually accompanied by tensional faults. Tensional forces are common along extensional plate boundaries, such as mid-ocean ridges. Shearing forces cause rocks to slide horizontally past one another, such as along transform plate boundaries to produce extensive fault systems.

Another factor that determines how a rock deforms is *confining pressure*. Under confining pressure, forces push against a body in all directions. Consequently, the body is squeezed into itself. Confining pressures within the Earth are caused by the weight of the overlying rock pushing downward and from all sides. When an external force is applied to buried rocks under low confining pressure, such as near the surface of the Earth, the rock typically deforms by simple fracturing.

This is known as *brittle deformation*. Thus, in brittle deformation, a continuous force is applied to a rock and under the gradual increase in force, little change occurs in the rock until suddenly it fractures. At higher confining pressures, a similarly directed external force will cause the deeply buried rock to actually flow and deform without fracturing. This is known as *ductile deformation* and the rock is said to behave *plastically*. Thus, in ductile deformation, a gradually increasing force will cause the rock to undergo smooth and continuous plastic deformation. The rock will contort and change shape without fracturing. Rocks under low confining pressures near the Earth's surface, therefore, generally deform through *fracturing* and *faulting*. Rocks deep within the crust under high confining pressures deform by *folding*.

Rocks are defined as *brittle* or *ductile* on the basis of the way they are deformed by forces. However, regardless of intrinsic degrees of brittle or ductile qualities, all strained materials pass through three successive stages of deformation: elastic, ductile, and fracture (failure, or brittle deformation). Provided that the strain rate is sufficiently slow to allow minerals to accommodate structurally, minerals can adjust to applied stresses by a variety of mechanisms. The type of rock also determines the type of deformation. Under similar confining pressures, halite (rock salt) is more susceptible to ductile deformation than granite, which will more likely fracture. Since igneous and metamorphic rocks are stronger, they resist deformation to a greater extent than sedimentary rocks. Figure 8.1 shows a stress-strain curve for brittle and ductile rocks.

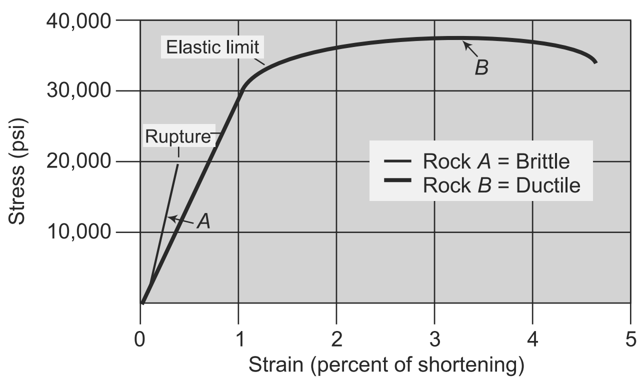


Fig. 8.1 *Stress-strain curve for brittle and ductile rocks*

Different types of rocks, viz. igneous, sedimentary and metamorphic have been described in the previous chapters. These rocks undergo changes under external forces over a period of time and are subjected to deformations. The external forces of different types and magnitudes act on rocks for different durations. The strain thus produced is governed by the intensity of stress and on the nature of rocks, i.e. whether the rocks are brittle or ductile. The cumulative affects of these factors lead to different types of geological structures. The type and extension of geological structures depend upon the nature of stress, lithological characteristics and time. The different geological structures produced due to rock deformations are fold, fault, joint and unconformity. This chapter presents and discusses the origin, classification and importance of geological structures for civil engineering projects.

8.2 FOLD

A fold is defined as a curvature or wavy form of rock produced by stress. The compression force is responsible for generation of fold. Folds result from the plastic deformation of rocks at low strain-rates usually under elevated temperature and pressure conditions. They are originated at micro level in which the dimension is less than few centimetres and only visible under a petrological microscope, while it can occur up to 100 km as a single fold exemplified by Himalayan orogeny. In this orogeny, two major plates have collided and larger folds were generated. Fold is more pronounced when the forces are acting laterally. The stress which is acting on a particular rock in opposite direction yields different types of fold. Before classifying folds, it is necessary to be conversant with different parts of a fold. The anatomy of folds is described as follows.

8.2.1 Anatomy of a Fold

The anatomy of a fold explains its different parts—the crest, limb, axial plane and axis of fold. These are described as follows and are shown in Figs 8.2 and 8.3.

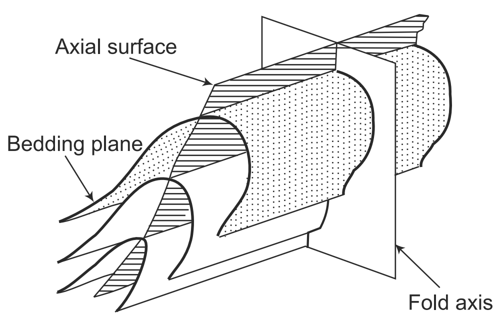


Fig. 8.2 *Morphology of a fold*

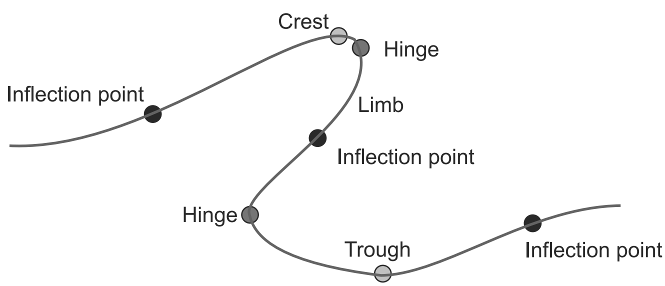


Fig. 8.3 *Basic terminology of a fold*

■ **Crest** The highest point of an anticline is termed 'crest'.

■ **Trough** The lowest point on a syncline is termed 'trough'.

■ **Limb** The curved part of the fold which runs in an opposite direction to each other is known as 'limb'. An individual fold has two limbs. Each limb is the part of a fold between a hinge surface and an inflection point.

■ **Axial Plane** The plane which divides the fold into two halves is called an axial plane. The axial plane may be vertical, inclined or horizontal. The axial plane of a fold is also an integral part and is taken into consideration for classification of folds.

■ **Fold Axis** The line that cuts the axial plane and intersects the horizontal plane is called the axis of fold. It is also called the *hinge line.*

■ **Hinge** A hinge is the point of maximum curvature in a folded surface. The intersection of the axial surface with a folded surface is known as hinge line.

8.2.2 Classification of Folds

The classification of folds is made on the basis of genesis and geometry. These two parameters are explained below.

❑ *On the Basis of Genesis of Fold*

Compressional forces are responsible for genesis of the folds. Folds can be categorized as anticline, syncline, drag fold and ptygmatic fold; and are described as follows.

■ **Anticline** The fold which is characterized by convex curvature, having opposite dip directions towards each other is known as anticline (Fig. 8.4). The anticline is characterized by older rocks in the centre and younger rocks in the periphery. This is produced due to compressive stress.

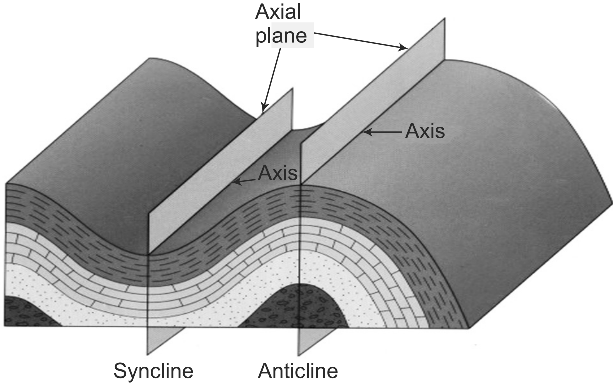


Fig. 8.4 *Fold structure (anticline and syncline)*

■ **Syncline** The fold which is characterized by a concave curvature, having dip directions towards the centre is known as syncline (Fig. 8.4). The syncline is characterized by older rocks in the periphery and younger rocks at the centre.

■ **Drag Fold** Drag fold is a minor fold which is developed due to stress in opposite directions and in an incompetent bed which is overlain and underlain by competent rocks (Fig. 8.5). The fold developed in sandstone lying between quartzite beds is an example.

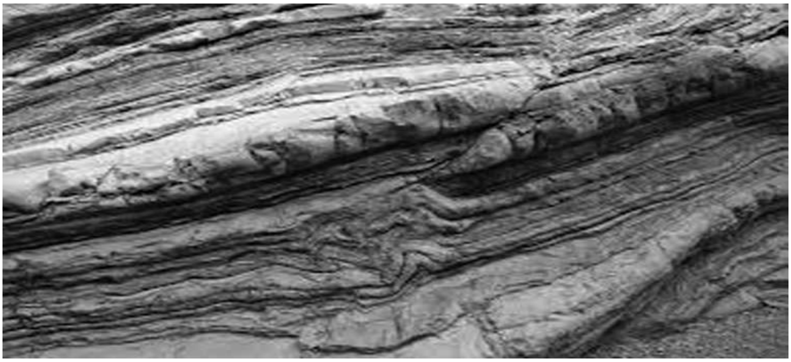


Fig. 8.5 *Development of drag folds in incompetent rocks, over and underlain by competent rocks*

■ **Ptygmatic Fold** Ptygmatic fold is the fold developed in fluid conditions or elastic condition of rocks. The geometry of fold, therefore, is very uneven and zig-zag (Fig. 8.6). The folds developed in certain rhyolites are examples.

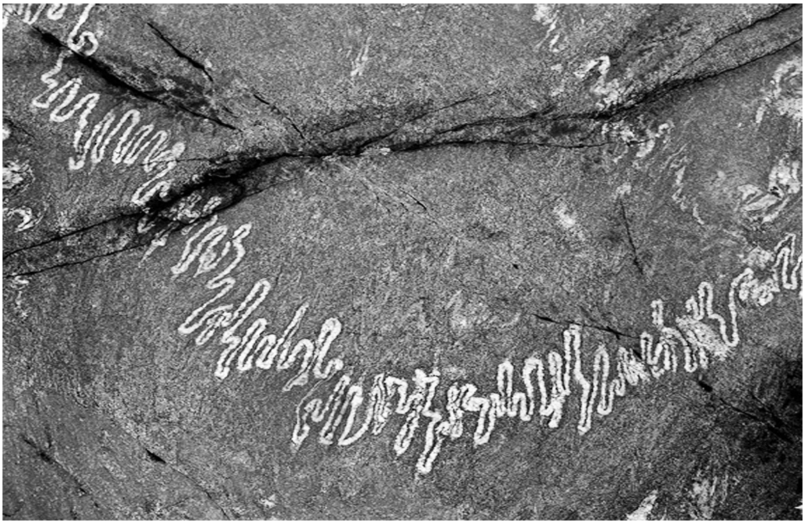


Fig. 8.6 *Ptygmatic folds developed in rocks during fluid state*

❑ *On the Basis of Geometry of Fold*

The geometry of fold comprises of limbs, axial plane and axis, which may be used to classify folds.

■ **On the Basis of Limb** The folds are classified as symmetrical folds and asymmetrical folds.

o *Symmetrical Fold* The symmetrical fold is characterized by equal lengths of limbs. The axial plane divides the fold in such a way that both the limbs are equal. Furthermore, the limbs are a mirror image to each other (Fig. 8.7).

o *Asymmetrical Fold* The asymmetrical fold is characterized by an unequal length of limbs. The axial plane divides the fold in such a way that both limbs are unequal. Furthermore, the limbs are not a mirror image to each other (Fig. 8.7).

o *Overtured Fold* In this fold one limb overrides the other limb of the same fold (Fig. 8.7). This is developed when compressional stress continues for longer duration and rocks do not have brittle nature.

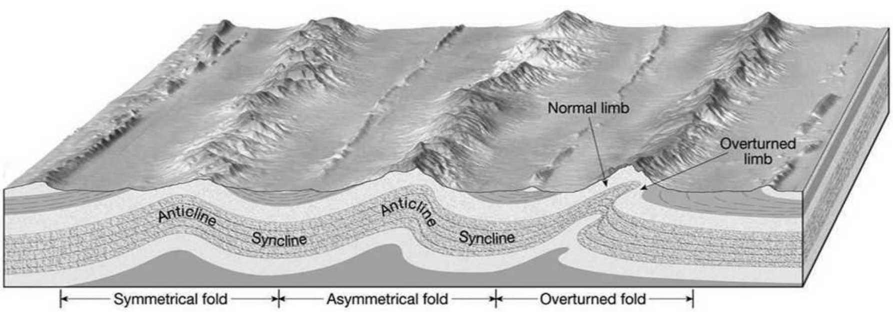


Fig. 8.7 *Symmetrical, asymmetrical and overturned fold*

■ **On the Basis of Pattern of Dip Direction of Beds** The folds are classified as dome and basin.

o *Dome* The fold which is characterized by a convex, dome-shaped structure with qua-qua versal dip (dip of beds diverting towards periphery from the centre). The older beds occur in centre and younger beds towards periphery [Fig. 8.8(a)]. It is a very suitable structure for salt deposit as well as for capping of oil and gas.

o *Basin* The fold which is characterized by a convex (basin) shaped structure with centroversal dip (dip diverting towards centre from periphery). The older beds occur in periphery and younger beds in the centre (Fig. 8.8). This is a suitable geological structure in which groundwater exploration should be targeted.

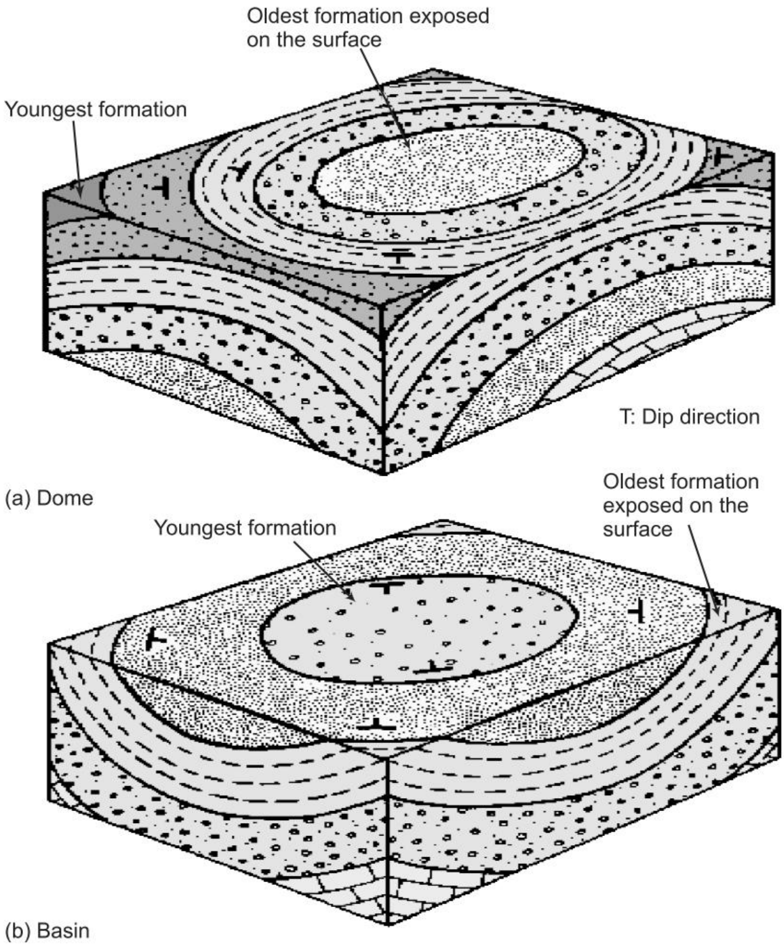


Fig. 8.8 *Dome and basin*

■ **On the Basis of Disposition of Axial Plane** It is a fact that axial plane is one of the most important part of a fold. Folds may be classified as inclined fold, recumbent fold and overturned fold and are defined as follows.

- *Inclined Fold* A fold in which the axial plane is inclined or the angle is less than 90° and more than 0° is called an inclined fold [Fig. 8.9(a)]. These folds are developed due to differential stress acting in different directions.

- *Overturned Fold* A fold in which the axial plane and limbs are inclined between 0–10°, and the distance between the axial plane limbs is very less is called overturned fold or overfold [Fig. 8.9(a)]. These folds are developed due to extensive stress acting in the opposite direction.

o *Recumbent Fold* A fold in which the axial plane is parallel to the horizontal, and in turn limbs are also parallel to the horizontal, is called a recumbent fold [Fig. 8.9(b)].

o *Isoclinal Fold* When the angles of both limbs of a fold with the axial plane are equal and the axial planes are parallel to each other [Fig. 8.9(c)].

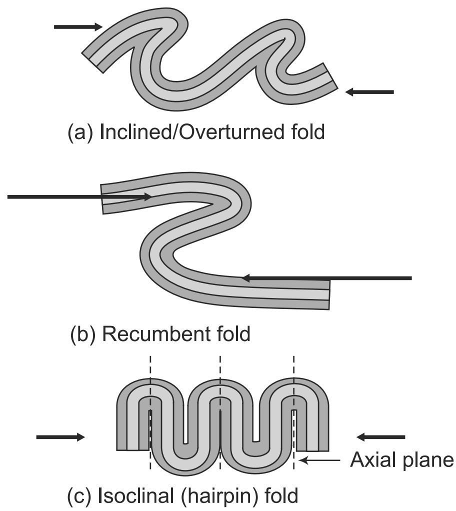


Fig. 8.9 *Folds on the basis of axial plane*

■ **On the Basis of Fold Axis** The axis of a fold has significant relevance for classifying folds. They are classified as plunging folds and non-plunging folds.

o *Plunging Fold* When the axis or hinge line of a fold is inclined with respect to the horizontal, the fold is known as a plunging fold [Fig. 8.10(a, b)]. The dip direction of anticline and syncline fold is marked on the map given below.

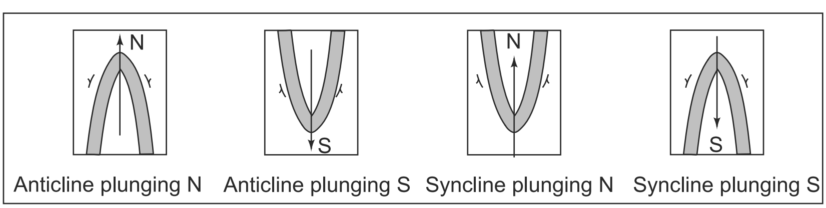


Fig. 8.10(a) *Different types of plunging folds*

o *Non-plunging Fold* When the axis of a fold is not inclined with respect to the horizontal, the fold is known as a non-plunging fold [Fig. 8.10 (a, b and c)]. In other words, when the axis of a fold is tangential then it becomes a non-plunging fold.

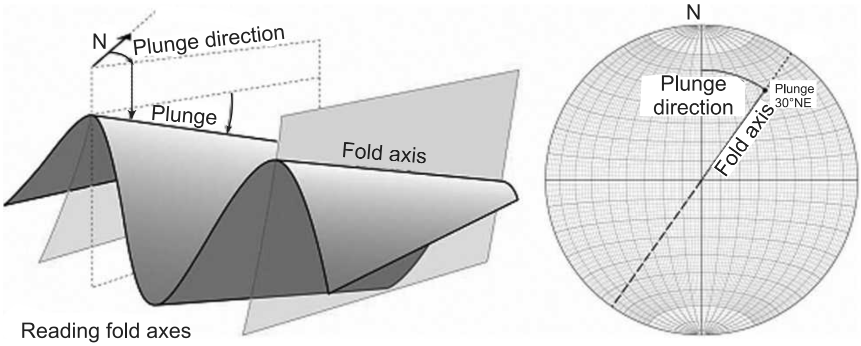


Fig. 8.10(b) *Concept of fold axis and its relationship with folding*

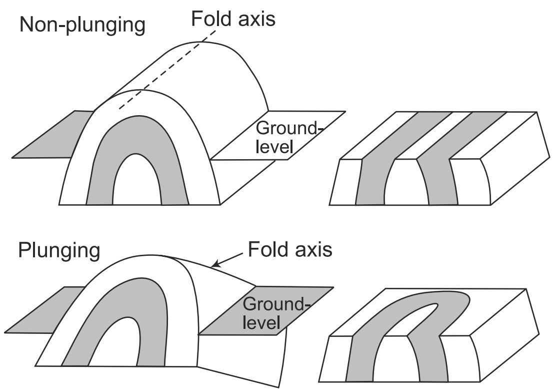


Fig. 8.10(c) *Plan and section view of non-plunging folds*

■ **On the Basis of Interlimb Angle** Angles made between two consecutive limbs joining the same inflection point is known as an *interlimb angle* (Fig. 8.11). The categorizations of folds based on an interlimb angle are given in Table 8.1, and their description is as follows.

Table 8.1 *Interlimb angle and corresponding types of folds*

Interlimb angle	*Type of fold*
180–120	Open
120–70	Gentle
70–30	Close
< 30	Tight
0	Isoclinal
< 0	Fan

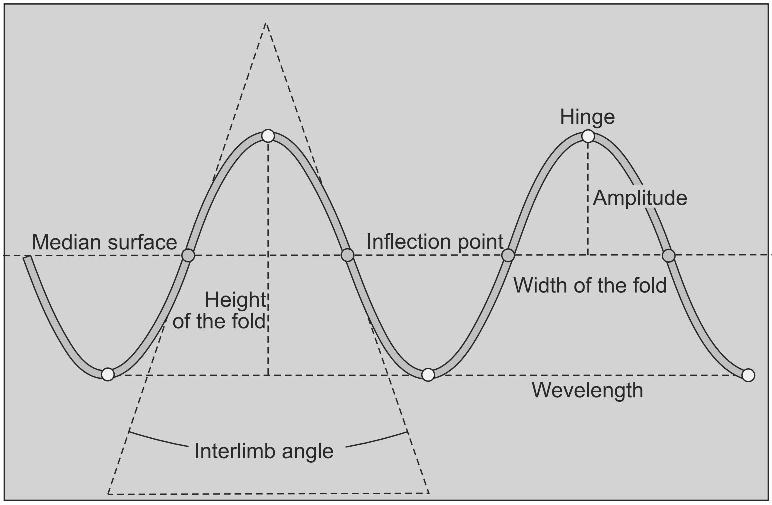


Fig. 8.11 *Concept of an interlimb angle*

- *Gentle Fold* The fold which is characterized by the interlimb angle between 180° and 120° is classed as gentle fold (Fig. 8.11). This type of fold is developed when stress is very low and the period of stress is very less.
- *Open Fold* The fold which is characterized by the interlimb angle between 120° to 70° is classed as open fold (Fig. 8.11). This type of fold is developed when stress is low and the period of stress is also less.
- *Close Fold* The fold which is characterized by the interlimb angle between 70° to 30° is classed as a close fold (Fig. 8.11). This type of fold is developed when stress is high and the period of stress is quite longer.
- *Tight Fold* The fold which is characterized by the inter limb angle between 30° to > 0° is classed as tight fold. This type of fold is developed when stress is very high and the period of stress is too long (Fig. 8.11).

8.2.3 Identification of a Fold in Field and Importance

It is already mentioned that geological structures like folds are originated due to compressional force or stresses. They are observed on the body of the rock formations, exposed on the ground surface (outcrop) and are therefore studied in field by traversing. The traverse is conducted along strike direction so that variation and extent of folds can be observed. During field work, the following parameters are observed to identify the fold and its nature.

1. The dip direction of beds should be opposite in direction when we proceed from one end to another end of a fold.
2. The repetition of rock beds along the direction of traverse.
3. *Curvature or dip of beds*: beds should not be horizontal as well as not sharply curved.

Note It is pertinent to note that an open fold under increasing strain may gradually convert to overturned fold then gradually to recumbent fold and subsequently faulting may take place as shown in Fig. 8.12.

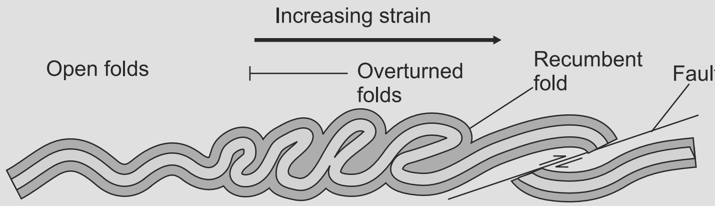


Fig. 8.12 *Development of fault from open fold*

8.3 FAULT

A fault is a planar fracture or discontinuity in a rock in the Earth's crust wherein the fractured rocks are displaced relative to one another. Typically, faults are associated with, or form, the boundaries between the Earth's tectonic plates. Faults range in size from micrometers to thousands of kilometres in length and tens of kilometres in depth, but they are generally much thinner than they are long or deep. In addition to variation in size and orientation, different faults can accommodate different styles of rock deformation, such as compression and extension.

The faults are originated mainly due to tectonic forces which have been active since very long in geological history. Rocks are very slowly, but continuously moving and changing shape. Because of friction and the rigidity of the rocks, they cannot glide or flow past each other. Consequently, stress builds up in rocks and when it reaches a level that exceeds the strain threshold, the accumulated potential energy is dissipated by the release of strain, which is focused into a plane along which relative motion is accommodated—the fault. The ductile lower crust and mantle accumulates deformation gradually via shearing, can melt and allow the rock to flow, whereas the brittle upper crust responds to large stresses by fracturing—instantaneous stress release—to cause motion along the fault. A fault in ductile rocks can also release stress instantaneously when the strain rate is too great. Energy released by instantaneous strain associated with rapid movement on active faults is the cause of most earthquakes.

The forces that may lead to faulting are tensional, compressional and shear. Fault generated may be horizontal, vertical or oblique. Furthermore, the fault may be active or inactive. In an active fault, the pieces of the Earth's crust along a fault move over time. The movement can occur in sudden jerks and can cause earthquakes. Inactive faults had movement along them at one time, but no longer move. Figure 8.13 shows the type of forces and their resulting effects.

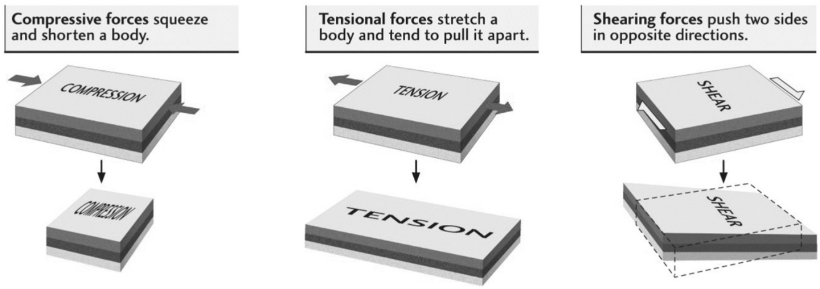


Fig. 8.13 *Different types of stress and their output as strain in different forms*

❑ *Tensional Force*

When the force acts in opposite directions from the centre of the rock formation, it is known as tensional force. The tensional force yields the normal type of fault [Fig. 8.14(a)].

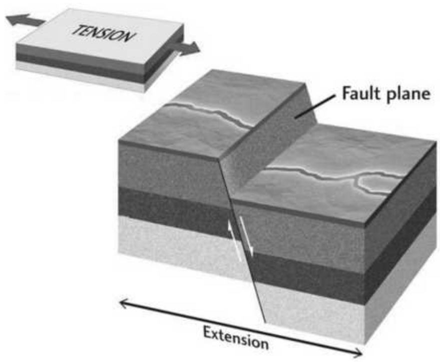


Fig. 8.14(a) *Normal fault due to tensional forces*

❑ *Compressional Force*

When the force acts in the same direction from the centre of the rock formation, it is known as compressional force. The compressional force yields the reverse type of fault under dip slip fault [Fig. 8.14(b)].

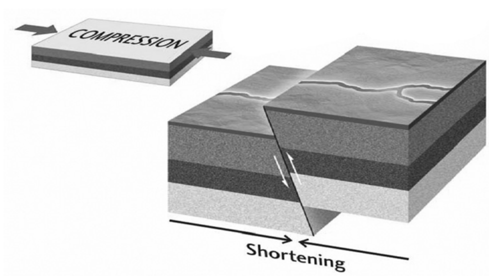


Fig. 8.14(b) *Compressional forces producing the reverse fault*

❑ *Shear Force*

When the force is parallel to horizontal direction and acts in opposite direction to each other, it is known as shear force [Fig. 8.14(c)]. This force yields a strike slip fault or oblique-slip fault.

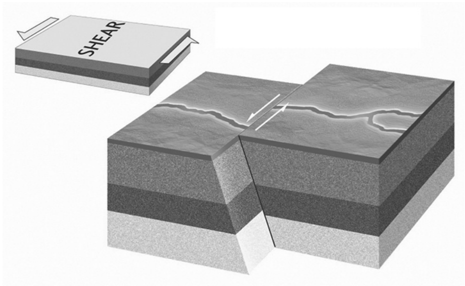


Fig. 8.14(c) *Strike-slip fault*

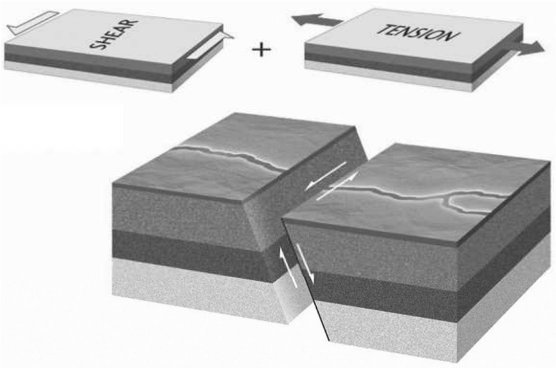


Fig. 8.14(d) *Oblique-slip fault*

8.3.1 Anatomy of a Fault

The different parts of the fault are fault plane, hade, net slip, throw and heave. These are shown in Fig. 8.15 and defined as follows.

■ **Fault Plane** It is the plane through which faulted blocks move upward and downward. The attitude of fault plane also contributes towards classification of fault.

■ **Hade** The angle made between fault plane and throw is known as hade.

■ **Slip** It is defined as the relative movement of geological features (beds) present on either side of a fault plane. It is a displacement vector. The net displacement of similar beds in any fault is called *net slip*. In measuring the horizontal or vertical separation, the *throw* of the fault is the vertical component of the dip and the *heave* of the fault is its horizontal component (Fig. 8.15).

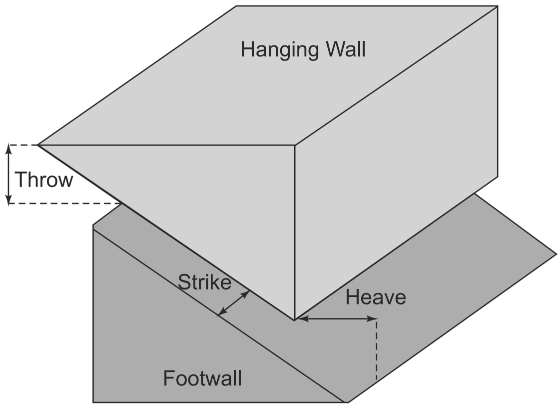


Fig. 8.15 *Different components of net slip*

8.3.2 Classification

Classification of faults depend upon few important parameters like nature of net slip, nature of movement of faulted blocks and relationship of attitude of fault plane with rock beds.

❑ *On the Basis of Movement of Footwall and Hanging Wall*

■ **Normal Fault** When the footwall moves upwards and the hanging wall moves downwards, the fault is known as normal fault [Fig. 8.16(a)]. It is produced when tensional force is quite large. Normal faulting usually occurs in regions with relatively high elevation such as plateaus.

■ **Reverse Fault** When the footwall moves downwards and hanging wall moves upwards, the fault is known as reverse fault [Fig. 8.16(b)]. It is produced when the compressional force is quite large. Reverse fault reflects compressive forces squeezing a region, and they are common in uplifting mountain ranges particularly in areas along the coast of many regions bordering the Pacific Ocean.

■ **Thrust Fault** It is a low angle (< 45°) reverse fault and generated when compressional force is added with shear force.

■ **Overthrust Fault** When the angle is < 10°, the reverse fault is generated when compressional force is added with shear force.

❑ *On the Basis of the Nature of Net Slip*

The faults may be classified as dip-slip, strike-slip and oblique-slip faults.

■ **Dip-Slip Fault** The fault in which the net slip is parallel to the dip direction of fault plane is known as dip-slip fault (Fig. 8.16).

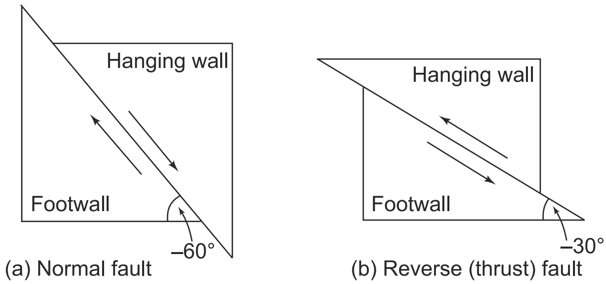


Fig. 8.16 *Dip-slip fault*

■ **Strike-Slip Fault** When the net slip is parallel to the strike direction of fault plane, it is known as strike-slip fault (Fig. 8.17). Strike-slip faulting indicates neither extension nor compression, but identifies regions where rocks are sliding past each other.

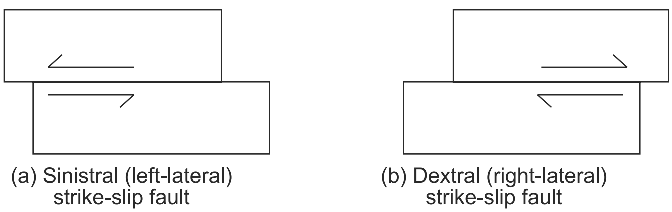


Fig. 8.17 *Strike-slip fault with two directional movements*

■ **Oblique-Slip Fault** The fault in which the net slip is neither parallel to the strike nor dip direction of fault plane is known as oblique-slip fault (Fig. 8.18).

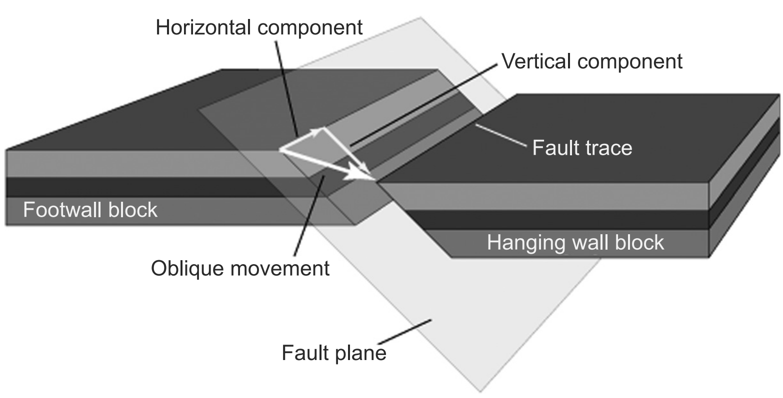


Fig. 8.18 *Oblique-slip fault*

❑ *On the Basis of Attitude of Fault Plane and its Relationship with Attitude of Beds*

Faults may be classified as dip fault, strike fault, oblique fault and bedding fault.

■ **Dip Fault** When a fault plane is parallel to the dip direction of involved beds, the fault is known as dip fault.

■ **Strike Fault** When a fault plane is parallel to the strike direction of involved beds, the fault is known as strike fault.

■ **Oblique Fault** When a fault plane is neither parallel to the dip and strike direction of involved beds rather oblique to it, the fault is known oblique fault.

■ **Bedding Fault** When a fault plane is parallel to the beddings involved in faulting, the fault is known as bedding fault.

8.3.3 Faults as Geological and Geotechnical Hazards

Faults create weak zones in different rocks or soils and destabilize the rocks and impair their strength. In geotechnical engineering, a fault often forms a discontinuity that may have a large influence on the mechanical behaviour (strength, deformation, etc.) of soil and rock masses, e.g. in a tunnel, foundation, or slope construction. The impact of faults can be critical in civil engineering projects for the following two reasons:

1. Locating buildings, tanks, and pipelines.
2. Assessing the seismic shaking and tsunami hazard to infrastructure and people in the vicinity.

The existence of major faults is responsible for the following geological and geotechnical hazards.

(a) During the construction of tunnel and bridge, the location and nature of fault is deciphered very accurately during the planning and construction. The fault plane should never be parallel to the axis of a tunnel or tangent to it. The abutment of a bridge warrants the delineation of a fault plane. Major or even minor faults destabilize the structures.

(b) During the construction of dams and reservoirs, the faults are very dangerous for the stability of a dam and accelerate the seepage from a reservoir. The location of a fault plane and its relationship with the axis of a dam has a strong bearing on the stability of a dam. The dams and reservoirs are not advisable in a faulted area. This has been explained in the next chapter.

(c) Genesis of Earthquakes: A major cause of an earthquake is considered tectonic, and faults are the main originating force for the generation of tremors inside the Earth. Movement of faulted blocks and their reactivation are the primary reasons for an earthquake and even the occurrence of volcanism.

Therefore, the identification of faults and its extension in time and space is very important before implementation of any civil project to have a safe, stable and reliable structure to serve its intended life.

8.3.4 Field Identification of Faults

It is essential to understand about the signatures of fault in field because the selection of sites for different civil structures will be governed by the location of the fault. Some important clues are mentioned here to identify the fault. The extension of faults in some cases can be measured when the length of a fault is in few meters. There are several clues which help in identification of faults. These features are as follows:

1. Valley running straight for a long distance, following a fault line which may be observed as straight line in arial photographs.
2. Disposition of older beds with younger beds is an evidence for the presence of a fault.
3. Presence of fault breccia and mylonites in a faulted area.
4. Dip direction of beds in area with fault are in the same direction.

To get the above information in field, a traverse is made along the strike direction. The dip of all the beds are measured and plotted on a map for its cross section.

8.4 JOINT

A joint is a fracture which has no displacement. Joints are developed in a rock due to stress and brittleness of the rock. Joints are mostly pervasive in nature. Typically, there is little to no lateral movement across joints, which makes it different from a fault—wherein one side of the rock slides laterally past the other.

Joints normally have a regular spacing related to either the mechanical properties of the individual rock or the thickness of the layer involved. Joints generally occur as sets, with each set consisting of joints sub-parallel to each other.

The shape of joints is not similar in all the types of joints. To understand, the attitude, orientation and genesis of joints is very important for its classification and impact on the construction of civil engineering projects. The genesis of joints is explained as below.

Joints in a rock are created due to tectonic stress as well as by rapid cooling and contraction of magmatic fluid. They form in solid, hard rock when stretched and its brittle strength is exceeded (the point at which it breaks). During this process, the rock fractures in a plane parallel to the maximum principal stress and perpendicular to the minimum principal stress (the direction in which the rock is being stretched). Consequently, a single sub-parallel joint set is developed. Continued deformation of the rock may lead to development of one or more additional joint sets. The presence of the first set of joints strongly affects the stress orientation in the rock layer, often causing subsequent sets to form at a high angle to the first set.

8.4.1 Anatomy of a Joint

The joints are characterized by a few important components like set of joint, orientation, roughness, frequency and aperture. These components are briefly described below.

❑ *Joint Set*

The joint sets are counted from the intersecting joint system. The particular set of joint has a single direction with repeated joints which are parallel to each other. The set of joints occur in nature from a single set to four and even rarely five sets (Fig. 8.19). When the number of joint sets is more than one, and the pattern of joint sets are different then it is called a *joint system*. The set of joints reflects about the nature of force and its intensity. Figure 8.19 depicts two sets of joints.

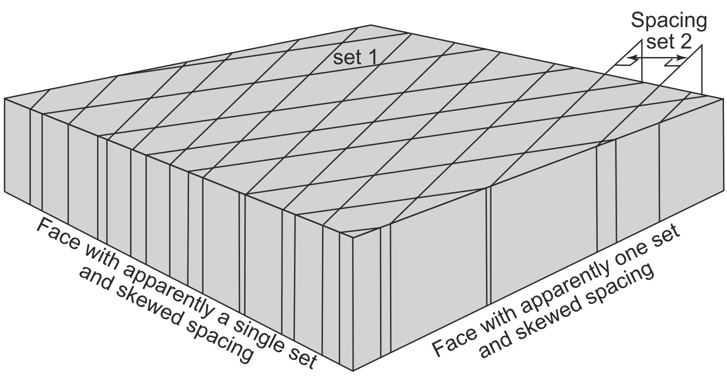


Fig. 8.19 *Joint set and pattern*

■ **Frequency** The number of joints per square metre is termed joint frequency. The measurement of the joint frequency is carried out in outcrop as well as drill core, in case of massive hard rocks.

■ **Spacing** It is the perpendicular distance between two adjacent joints. Spacing is a useful and important parameter in Rock Mass Rating (RMR). Harder rocks will have larger spacing than the incompetent or soft rock. The spacing between joints may vary from a few centimetres to even more than a metre.

■ **Orientation** The amount and direction of dip along strike makes the term orientation of joints. It is expressed as E-W and N-S. The orientation of joints is measured through a *Brunton compass* and plotted on a map with symbols. The mapping of joints should be carried out very carefully in case of civil engineering projects like tunnelling and dam construction because hair fractures which are part of joints even or not properly sealed during grouting. This phenomena weakens the rock mass and may destabilize the engineering structures.

8.4.2 Classification

❑ *On the Basis of Genesis and Orientation*

The joints are broadly classified as primary joint and secondary joint.

■ **Primary Joints** A joint that is developed at the time of formation of the rock is known as a primary joint. A joint which develops due to cooling, contraction and solidification of magma is the example. Primary joints may be classified as tensional and sheet joints.

- *Tensional Joints* These joints are formed in the rocks due to contraction of mineral grains during cooling of magma. The structures produced during the process of generation of these joints are columnar (Fig. 8.20). The joint sets developed in basalt are the example.

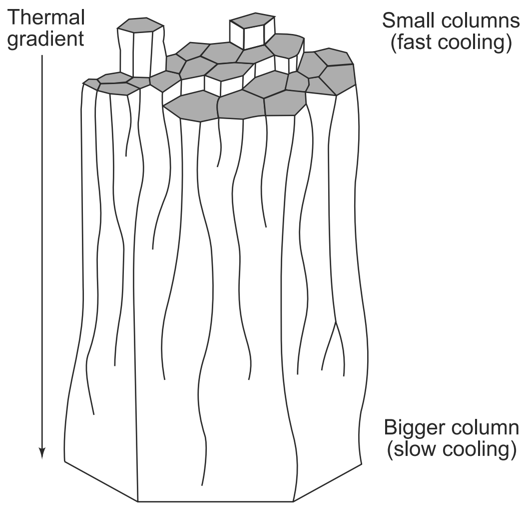


Fig. 8.20 *Columnar joint—a type of tensional joint*

- *Sheet Joints* The joints in rocks that develop parallel to the ground surface are known as sheet joints. These joints mostly occur in plutonic igneous rock (Fig. 8.21). Joints developed in granite are some of the examples.

■ **Secondary Joints** Joints which develop after the deposition of rocks and due to involvement of external forces are known as secondary joints. The compressional and shear joints are examples of the secondary joints.

- *Compressional Joints* The joints which are developed due to compressional forces are called compressional joints. These joints are characterized by crushing and a fragile nature with rough surfaces.

- *Shear Joints* The joints which are developed due to shear forces are called shear joints. These joints are characterized by crushing and generation of rock powders.

Fig. 8.21 *Sheet joints in granite*

8.4.3 Importance of Joints

Joints play an important role in assessing the strength of rocks as well as affecting the safety of civil structures. Furthermore, identification and classification of joints are required to ascertain the amount of grouting for civil structures like dams, bridges and tunnelling. The mapping of joints should be carried out carefully in case of civil engineering projects like tunnelling and dam construction. It is so because hair fractures which are not part of joints even or not properly sealed during grouting. The hair fractures weaken the rock mass and may destabilize the engineering structure.

8.5 UNCONFORMITY

Unconformity is characterized by time gap or break in continuous activity of deposition of rocks. In other words, it is a boundary between the layer of erosion and deposition of beds which are not chronologically continuous. The unconformity may be generated due to a break in sedimentation and start of erosion or by tectonic disturbances occurred from time to time. The features of unconformity are quite large. Partially, these features are related to the tectonic forces and other geological operations that take place through different geological agencies.

The origin of unconformity involves processes like discontined sedimentation in a basin, erosional activity and faulting and folding of existing rock formations. Under this process, two major categories of unconformity are: *genetic* or *in situ* and *deformational* unconformity.

■ ***In situ* Unconformity** The unconformity which is developed at the place where sedimentation is taking place in a basin is known as in situ unconformity. The hiatus (time gap) in sedimentary basins like Narmada basin where there is gap in regular deposition is an example.

■ **Deformational Unconformity** When the continuity of rock formations is broken due to folding and faulting, the unconformity is called deformational unconformity.

8.5.1 Classification

Unconformities have been classified on the basis of disposition of underlying and overlying strata or beds and their origin. The important types of unconformities are as follows.

■ **Disconformity** This is an unconformity in which the upper beds overlie on the horizontal beds which have not been deformed [Fig. 8.22(a)]. But the age of these two underlying and overlying formations are not sequential.

■ **Nonconformity** The unconformity which has necessarily igneous rocks at the bottom, unconformably overlain by the metamorphic or sedimentary rocks is known as nonconformity [Fig. 8.22(b)].

■ **Angular Unconformity** The unconformity which has inclined beds either of metamorphic or sedimentary rocks at the bottom and overlain by any type of rock with or without angularity is called angular unconformity [Fig. 8.22(c)].

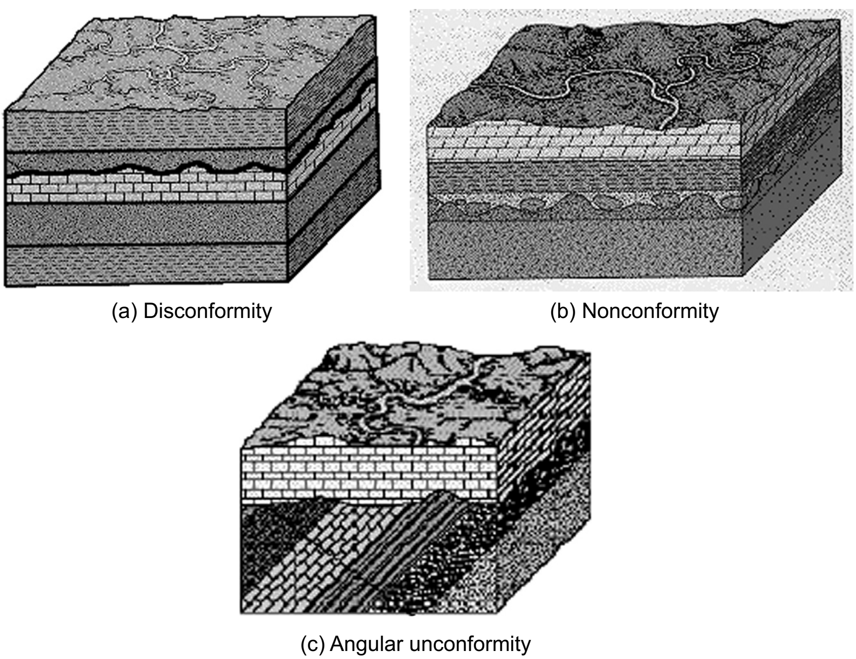


Fig. 8.22 *Different kinds of unconformities*

8.5.2 Field Identification of Unconformity and its Importance

Unconformity is characterized by the time gap of continuous deposition and erosional activity. In this process, topmost beds are eroded and again followed with deposition and other geological activities like volcanism and glaciation. There are several signatures which are left on the surface of the beds during erosion or intermittent deposition. The unconformities may be identified in field on the basis of following criteria.

1. **Presence of conglomerate on the surface of bed** When the erosion of existing rocks takes place, the coarser and heavier grains are rounded during transportation, hence the coarser grains mixed with fine sediments are deposited in the nearby area of the unconformity.
2. **Loss of sequential bed** There is a gap in sequential deposition of beds, therefore, the beds that are just underlain and overlain, are not followed chronologically.
3. **On the basis of flora and fauna** Fossils constitute both flora and fauna and have a definite age. The presence of particular flora and fauna in sedimentary beds determine the time gap for sequential deposition.

The importance of unconformity in geological domain is as follows.

1. It is an indicator of the geo-environment under which the rock formations have been deposited.
2. It is a suitable locale for getting fuel and mineral deposits.
3. The placer deposit of gold and diamonds are associated with unconformity.

Summary

In order to understand the secondary activities in different rocks which take place in nature over the period, an understanding of rock deformation as explained in this chapter would be beneficial to the students and planners. Different types of forces like compressional, tensional and shear have been described. These forces are responsible for the generation of different types of geological structures like folds, faults and joints. The origin and classification of different geological structures has also been highlighted. Field identification of folds, faults, joints and unconformities has been discussed. The importance of the know-how of the structural deformations in finalizing the location of civil structures has been explained.

Terminology

Active Faults Structures along which displacement is expected to occur frequently.

Dip An angle that describes the steepness of the fault surface. This angle is measured from the Earth's surface, or a plane parallel to the Earth's surface. The dip of a horizontal fault is zero (usually specified in degrees: 0°), and the dip of a vertical fault is 90°.

Fault Line	The surface trace of a fault, the line of intersection between the fault plane and the Earth's surface.
Fault Zone	Faults do not usually consist of a single, clean fracture. A fault zone consists of several smaller regions defined by the style and amount of deformation within them. Fault zone thus refers to the zone of complex deformation associated with the fault plane.
Fold Train	A collection of folds that are joined together such that the limbs of each fold are continuous with the limb of an adjacent fold.
Fracture	A fracture in the continuity of a rock formation caused by a shifting or dislodging of the Earth's crust, in which adjacent surfaces are displaced relative to one another and parallel to the plane of fracture. It is also called a shift.
Hanging Wall and Footwall	The two sides of a non-vertical fault are known as the hanging wall and footwall. The hanging wall occurs above the fault plane and the footwall occurs below the fault.
Heave	The horizontal component of net slip is known as a heave of fault.
Inactive Fault	Inactive faults are structures that can be identified, but which do not have earthquakes.
Reactivated Fault	Reactivated faults form when movement along the formerly inactive faults can help to alleviate strain within the crust or upper mantle.
Slip	Slip is the relative movement of geological features present on either side of a fault plane, and is a displacement vector. In measuring the horizontal or vertical separation along the net slip, the throw of the fault is the vertical component of the dip separation and the heave of the fault is the horizontal component. Further, it may be noted that the net slip has two components, a magnitude and a direction. The practice is to specify the magnitude and direction separately. The magnitude of slip, i.e. net slip, is simply how far the two sides of the fault moved relative to one another. The direction of slip is measured on the fault surface; it is specified as an angle. Specifically, the slip direction is the direction that the hanging wall moved relative to the footwall. If the hanging wall moves to the right, the slip direction is 0°; if it moves up, the slip angle is 90°, if it moves to the left, the slip angle is 180°, and if it moves down, the slip angle is 270° or –90°.
Strike	An angle used to specify the orientation of the fault and measured clockwise from north. For example, a strike of 0° or 180° indicates a fault that is oriented in a north-south direction, 90° or 270° indicates east-west oriented structure. It provides only direction.
Throw	The vertical component of net slip is known as the throw of a fault.

Exercises

1. (a) What is rock deformation?
   (b) Enumerate the various types of deformations and their effects.
   (c) Briefly explain the different types of forces responsible for rock deformation.
2. Differentiate between the following:
   (a) Anticline and syncline folds
   (b) Plunging and non-plunging folds
   (c) Domes and basins
   (d) Brittle and ductile rock deformation
3. (a) Describe the anatomy of folds with neat sketches.
   (b) What are folds? Explain how they are recognized in a field.
4. (a) Enumerate different types of forces for the genesis of faults.
   (b) Describe the classification of faults with illustrations.
5. Differentiate between the following:
   (a) Dip-slip and strike-slip faults
   (b) Normal and reverse faults
   (c) Thrust and overthrust faults
   (d) Primary and secondary joints
6. Write short notes on the following:
   (a) Columnar and sheet joints
   (b) Classification of faults
   (c) Drag fold and ptygmatic fold
7. (a) Explain the criteria for identification of folds and faults in field.
   (b) Give a brief account of classification of folds.
8. (a) Define unconformities. How are they formed?
   (b) Enumerate the conditions for the development of joints.
9. (a) Describe different types of unconformities and their properties.
   (b) Describe how unconformities are recognized in the field.

Multiple-Choice Questions

1. If the folds plunge, the strike of beds would be
   (a) parallel to the strike of the fold axis
   (b) diagonal to the strike of the fold axis
   (c) perpendicular to the strike of the fold axis
   (d) relationship is uncertain
2. A strike fault separating two lithospheric plates is generally known as
   (a) slip fault (b) transform fault
   (c) transverse fault (d) dip fault
3. Repetition of beds on a geological map may be due to
   (a) folding (b) faulting
   (c) unconformity (d) disconformity

4. Sheet joint is
(a) a secondary joint
(b) a primary joint
(c) an example of unconformity
(d) developed in basalt

5. Dip fault is a
(a) fault plane parallel to the dip of beds
(b) fault plane parallel to the strike of a bedding plane
(c) fault plane diagonal to the dip of a bedding plane
(d) fault plane has no relationship to the bedding plane

6. In strike-slip fault, the
(a) strike of a bed is parallel to the fault plane
(b) net slip is parallel to the strike of beds
(c) net slip is parallel to the dip of beds
(d) dip of a bed is parallel to the fault plane

7. Symmetrical fold is categorized on the basis of
(a) axial plane and limb
(b) axis of fold
(c) limb of fold only
(d) hinge of fold

8. Tight fold has interlimb angle
(a) between 70–120^{o}
(b) between 30–70^{o}
(c) between 30–10^{o}
(d) less than 10^{o}

9. Consider the following rocks.
1. Igneous rocks
2. Sedimentary rocks
3. Metamorphic rocks

A fold is generally developed in
(a) 1 and 2 only
(b) 2 and 3 only
(c) 1 and 3 only
(d) 1, 2 and 3

10. Consider the following with regards to unconformity.
1. The upper beds overlie on the horizontal beds which have not been deformed.
2. Igneous rocks at the bottom, unconformably overlain by the metamorphic or sedimentary rocks.
3. Inclined beds either of metamorphic or sedimentary rocks at the bottom and overlain by any type of rock with or without angularity.

The disconformity is described by
(a) 1 and 2 only
(b) 2 and 3 only
(c) 1 and 3 only
(d) 1 only

Answers to MCQs

1. (b) 2. (b) 3. (a) 4. (a) 5. (a) 6. (b) 7. (a) 8. (b)
9. (a) 10. (c)

chapter 9

Engineering Structures and Geological Investigations

9.1 INTRODUCTION

Different rocks occurring in nature have diverse physical properties and mineralogical compositions. The physical and optical properties like texture and structures of different igneous, sedimentary and metamorphic rocks have been described in chapters 5, 6 and 7 respectively. Besides the use of rocks as construction material, all the sites of civil engineering projects like dam, bridge, tunnel, etc., are founded on rocks. This requires the classification of rocks from their use and application point of view to achieve economy and ensure safety and sustainability of the project.

The composition, strength, durability and other properties of construction materials affect the life and economy of a structure. Consequently, it becomes essential to ascertain the engineering properties of rocks. It must be noted that rocks which are useful for one purpose may not be suitable for the other. Hence, a civil engineer must be well versed with the engineering properties of rocks so as to make the right choice of the material for the particular structure. Moreover, the foundations of structures of national importance such as dams, bridges, etc., and linear structures such as tunnels are directly concerned with the geology, rock types and the geological structures encountered. A civil engineer must understand the implications of locating these structures at wrong locations, and solve the engineering problems when encountered.

9.2 PROPERTIES OF ROCKS

The properties of rocks are explained below.

9.2.1 Physical Properties

❑ ***Density***

Density is a measure of mass per unit of volume. Density of rock material varies, and is often related to the porosity of the rock. It is sometimes defined by unit weight as well as specific gravity. Density is influenced by specific gravity of the minerals and their compaction in the rock. However, most rocks are well compacted and have specific gravity between 2.5 to 2.8.

Nonporous and compact rocks have higher density and toughness. Typically, rocks have three times the density of that of water. But few rocks with high porous volume have density less than water, like pumice rock. Most rocks have density between 2.5 and 2.8 g/cm^3. Density of some of the important rocks is basalt: 3 g/cm^3, granite: 2.7 g/cm^3 and sandstone: 2.3 g/cm^3.

High-density rocks like massive gabbro, basalt and quartzite are very hard and most suitable for foundation purposes. Density of the rock is used to estimate the overburden stress.

❑ *Porosity*

Porosity is defined as the ratio of total volume of pores to total volume of rock sample. Porosity therefore is a fraction that ranges between 0 and 1. Typically, porosity ranges from less than 0.01 for solid granite to up to 0.5 for porous sandstone. It may also be represented in per cent terms by multiplying the fraction by 100. Since low-porosity rocks are generally strong and durable, they are quite favourable for construction and foundation purposes. Some of the examples of low porous rocks are quartzite, massive granite, marble, etc.

Porosity is one of the governing factors for permeability. Porosity provides the voids for water to flow through in a rock material. High porosity, therefore, naturally leads to high permeability except clay.

❑ *Permeability*

Permeability is a measure of the ability of a material to transmit fluids. Most rocks generally have very low permeability. The permeability of rock material is governed by porosity. Porous rocks such as sandstones usually have high permeability while granites have very low permeability. High permeability will allow fluids and gases to move rapidly through rocks.

The permeability of rocks, to some extent, may be thought to be important for structures like dams, reservoirs, etc. Permeability of rock materials, except for porous rocks, however, has limited interest. It is so because flow in the rock mass is concentrated in fractures in the rock mass.

❑ *Hardness*

Hardness is the measure of resistance to abrasion. The property indicates resistance to permanent deformation. Hardness of rock materials depends on a number of factors including mineral composition, density and arrangement of grains. A typical measure of hardness is the *Schmidt rebound hardness number*. It is a measure of the hardness of the rock material by count of the rebound degree. At the same time, the hardness index can be used to estimate uniaxial compressive strength of the rock material. The correlation is also influenced by the density of the material.

The hardness of a stone is one of the properties that contribute to the identification of rock. Hardness is also an attribute which is important to be aware of, because it may be helpful in deciding the use of a particular variety of rock for a particular purpose (carving, facing, jewellery, handling, storage, etc.).

❑ *Abrasivity*

The resistance to abrasion is defined as the capacity to rub the material with minimum required force. For example, gabbro and quartzite are very good abrasive materials because they have much harder minerals. This property helps in deciding the rocks for building decorative, and flooring and paving purposes.

❑ *Swelling*

Some rocks swell when they are saturated with water. Swelling is governed by the amount of montmorillonite clay minerals in the rock. Rock swelling is measured in confined and unconfined conditions. While confined swelling index measures the swelling in one direction, the unconfined swelling is measured by the percentage increase of length in three perpendicular directions (X, Y and Z) when a rock specimen is placed in water.

9.2.2 Geomechanical Properties of Rocks

The properties which are determined in a geo-technical laboratory through different equipments are known as geomechanical properties. On the basis of these properties, rocks are classified and declared suitable for different purposes along with other geological properties. Few important geomechanical properties are compressive, tensile, shearing and abrasive strengths. Strength is the property of rock to resist the load on it. Strength of rock is dependent on hardness, density, texture and structures occurring in the rock. Triaxial cut method is used to obtain resulting strain and stress in rocks (Fig. 9.1).

❑ *Compressive Strength*

Compressive strength of a rock is the capacity of a material to withstand axially directed compressive forces. It is one of the most important mechanical properties of rock used in design, analysis and modelling and their classification. It is also known as *crushing strength* of the rock. This property is very important for the road metal, and foundation stones for structures.

Usually, the compressive strength of rock is defined by the ultimate stress. The most common measure of compressive strength is the uniaxial compressive strength or unconfined compressive strength. Compressive strength of some of the important rocks is given in Table 9.1. Based on the compressive strength, the classification of rocks is presented in Table 9.2.

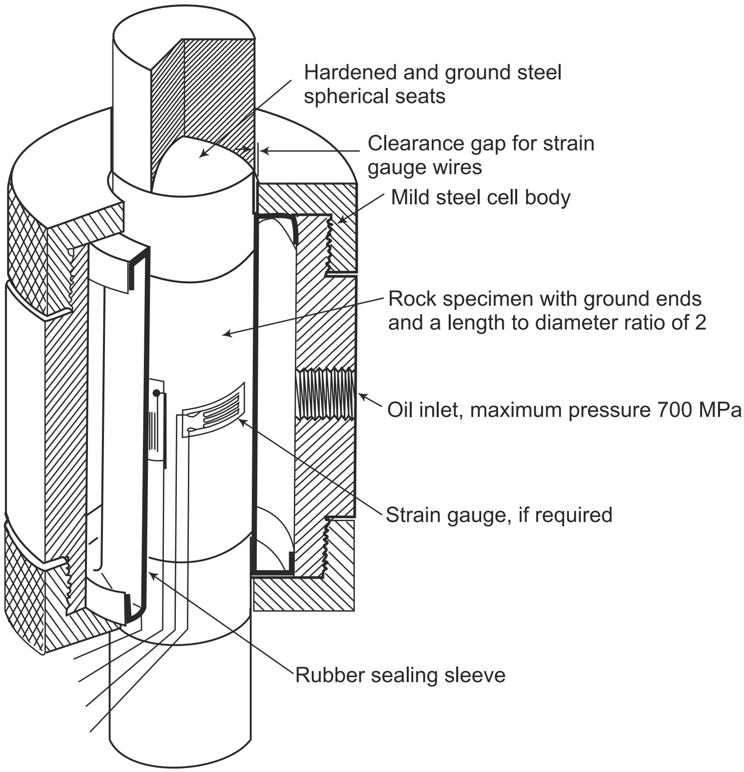


Fig. 9.1 *Triaxial cut cell for rock testing*

Table 9.1 *Compressive strength of various rocks*

S. No	*Name of Rocks*	*Compressive Strength (kN/m^2)*
1	Pink granite	101–164
2	Grey granite	101–156
3	Porphyritic granite	124–150
4	Diorite	91
5	Granite Gneiss	101–133
6	Dolerite	140–180
7	Basalt	101–138

Table 9.2 *Classification of rocks according to compressive strength*

Category	*Grade*	*Compressive Strength (kN/m^2)*
A	Very high, strong	109–209
B	High, strong	54–109
C	Medium	54–109
D	Low	27–54
E	Very low	> 27 and < 54

❑ *Tensile Strength*

Tensile strength of rock material is normally defined by the ultimate strength in tension, i.e., the maximum tensile stress that the rock material can withstand. Most rocks generally have low tensile strength. The low tensile strength is due to the existence of microcracks in the rock which are developed either during the formation of rocks or deformational process.

Tensile strength of rock can be obtained from several types of tensile tests: direct tensile test, Brazilian test and flexure test. *Direct test* is not commonly performed due to the difficulty in sample preparation. The most common tensile strength determination is by the *Brazilian test*. Typically, tensile strength of rock is about 1/10 to 1/8 of the compressive strength. In design, a rock should be subjected to minimum tensile stress. The tensile strength of different rocks is given in Table 9.3.

Table 9.3 *Tensile strength of various rocks (MPa)*

S. No	*Name of Rocks*	*Compressive Strength (MPa)*
1	Basalt	3–18
2	Gneiss	7–16
3	Granite	11–21
4	Limestone	3–5
5	Marble	7–12
6	Quartzite	4–23
7	Sandstone	5–11
8	Schist	5–12
9	Slate	2–17
10	Tuff	2–4

❑ *Shear Strength*

Shear strength is used to describe the resistance against deformation of the rock due to shear stress. Rock resists shear stress by two internal mechanisms, cohesion and internal friction. Cohesion is a measure of internal bonding of the rock material. Internal friction is caused by contact between particles, and is defined by the internal friction angle. Different rocks have different cohesions and different friction angles.

❑ *Young's Modulus*

Young's modulus is the modulus of elasticity which is a measure of the stiffness of a rock. For small strains, it is defined as the ratio of the rate of change of stress with strain. This can be experimentally determined from the slope of a stress-strain curve obtained during compressional or tensile tests conducted on a rock sample.

Strain at failure is the strain measured at ultimate stress. Rocks generally fail at a small strain, typically around 0.2 to 0.4% under uniaxial compression. Brittle rocks, typically crystalline rocks, have low strain at failure, while soft rocks, such as shale and mudstone, could have a relatively higher strain at failure. Strain at failure sometimes is used as a measure of brittleness of the rock. Strain at failure increases with increasing confining pressure under triaxial compression conditions. Rocks can have brittle or ductile behaviour after peak. Most rocks, including all crystalline igneous, metamorphic and sedimentary rocks, behave brittle under uniaxial compression. A few soft rocks, mainly of sedimentary origin, behave ductile.

9.3 RELATIONSHIPS BETWEEN PHYSICAL AND GEOMECHANICAL PROPERTIES

It is important to observe the relationship amongst physical and geomechanical properties because the inherent physical character of rocks governs the geomechanical properties. Table 9.4 presents the relationship between physical and geomechanical properties.

Table 9.4 *Correlation between physical and geomechanical properties of rocks*

S. No.	*Physical properties*	*Geomechanical properties*	*Interrelationship/ Correlation*
1	Hardness	Strength	Positive correlation
2	Permeability	Strength	Negative correlation
3	Seismic velocity	Elastic modulus	Positive correlation
4	Compactness	Compressive strength	Positive correlation
5	Brittleness	Tensile strength	Positive correlation
6	Discontinuities	Compressive strength, tensile strength and shear strength	Negative correlation

9.4 ROCK MASS RATING (RMR)

It is combination of a number of engineering and geomechanical properties which are very important for engineering projects like tunnels, bridges and dams. The rocks are classified on the basis of RMR. RMR is taken in the range from 0–100. Weightage of different engineering properties are assigned like joints pattern including spacing and condition of joint (Table 9.5), Rock Quality Designation (RQD) and groundwater condition. These parameters have been tabulated along with their weight assignments (Table 9.6).

Table 9.5 *Rock Mass Rating (RMR) on the basis of engineering and physical properties*

1	Strength of intact rock material (MPa)	Point-load strength index	> 10	10–4	4–2	2–1	Uniaxial compressive strength (MPa)		
		Uniaxial compressive strength	> 250	250–100	100–50	50–25	25–5	1–10	< 1
	Rating		15	12	7	4	2	1	0
2	RQD		90–100%	75–90%	50–75%	25–50%	< 25%		
	Rating		20	17	13	8	3		
3	Spacing of discontinuities		> 2 m	0.6–2 m	0.2–0.6 m	60–20 mm	< 60 mm		
	Rating		20	15	10	8	5		
4	Conditions of discontinuities		Very rough surfaces. Not continuous. No separation. Unweathered wall rock.	Slightly rough surfaces. Separation < 1 mm. Slightly weathered walls.	Slightly rough surfaces. Separation < 1 mm. Highly weathered walls.	Slickensided surfaces or Gouge < 5 mm thick or Separation 1 – 5 mm. Continuous.	Soft gouge > 5 mm thick. Separation > 5 mm. Continuous.		
	Rating		30	25	20	10	0		
5	Ground water	Inflow per 10 m tunnel length	None	< 10 litres/min	10–25 litres/min	25–125 litres/min	> 125 litres/min		
		(Joint water press)/(Major principal stress)	0	0.0–0.1	0.1–0.2	0.2–0.5	> 0.5		
		General conditions	Completely dry	Damp	Wet	Dripping	Flowing		

Table 9.6 *Rock mass classes on the basis of total ratings*

Rating	*100–81*	*80–61*	*60–41*	*40–21*	*< 20*
Class	I	II	III	IV	V
Description	Very good rock	Good rock	Fair rock	Poor rock	Very poor rock

❑ *Rock Quality Designation (RQD)*

It is a geomechanical property, which is estimated in the field. This estimation requires coring of the rocks. The ratio of broken length to total length of core is known as *rock quality designation*. It is represented always in percentage. On the basis of RQD, the rocks are classified as below:

Range of RQD	*Classification of Rocks*
90–100	Excellent
75–90	Very good
50–75	Good
25–50	Poor
< 25	Very poor

9.5 GEOLOGICAL INVESTIGATION FOR CIVIL ENGINEERING STRUCTURES

The physical and geomechanical properties of different rocks have been described in Section 9.2 and geological structures/rock deformation have been dealt in the previous chapter. It is of utmost importance to assess the lithological and structural behaviour of any rock or groups of the rock in outcrop. The effects of these parameters significantly govern the suitability for construction of the civil structures like dams, tunnels, bridges and highways. It must be remembered that the parameters of geological investigations are not uniform for different civil structures.

In this present scenario of urbanization and development taking place in real estates, the proper geological investigation for safe, stable and durable civil structures is of prime importance. The geological investigations particularly include the detailed study of rocks and different types of structures like folds, faults and joints. Besides these, aspects related to slope, topographic features and groundwater conditions are also investigated for site selection. In the light of the above, the geological investigations required for different civil structures are discussed as follows.

9.6 GEOLOGICAL INVESTIGATION FOR DAMS AND RESERVOIRS

Dam is a structure which arrests the water flow across the streams/nalas/khads. Reservoir is an integral part of any dam which refers to the basin type of structure impounding water in upstream side. Dams are the structures that are constructed to store water for irrigation, electricity generation, water supply for cities and to control floods. Before explaining the geological investigations needed to finalize the site for construction, the structure and components of a dam are introduced.

9.6.1 Components of a Dam

The different components of a dam are the axis of a dam, crest, wing wall, toe and heel, free board, spillways and sluice (Fig. 9.2). These are introduced as follows.

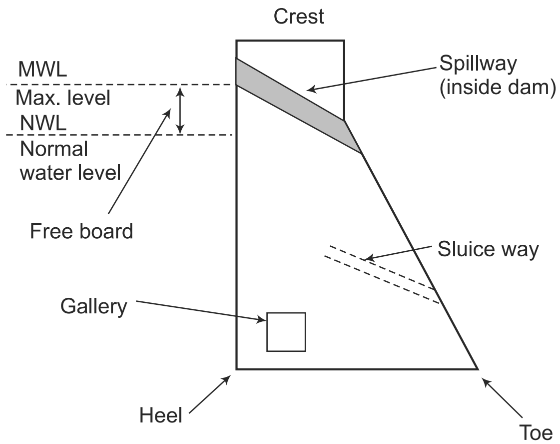


Fig. 9.2 *Components of a dam*

■ **Axis of a Dam** An imaginary line which runs perpendicular to the crest and along the length of the dam is known as *axis of dam*. The axis of a dam is used to classify dams.

■ **Crest** The transverse part of a dam which is constructed perpendicular to the flow of stream is known as *crest*. The width and length of the crest is governed by the momentum of water, slope and width of streams. The dimension of the crest determines the cost of the dam.

■ **Wing Wall** The wall which is longitudinal and parallel to the stream/ river is called *wing wall*. The wing wall protects the side erosion and scouring effects.

■ **Toe and Heel** The toe of the dam is a downstream edge of the dam-base, while the heel is an upstream edge of the dam-base.

■ **Abutment** These are the sloping sides of river valley upon which the sides of the dam are keyed.

■ **Spillway** The structural opening, made along the side of dam to drain off surplus water to downstream is known as *spillway*. They must be constructed on safe foundation.

■ **Sluice** The opening in the dam near ground level is called *sluice*. It is useful in clearing the silt of the reservoir.

■ **Free Board** It is the part of the dam structure between the top of the dam and highest storage level.

9.6.2 Types of Dams

Dams are commonly made up of earth or concrete, depending upon the geology of the area. Dams of different types may be constructed across river valleys and are described below.

■ **Gravity Dam** It is also known as *concrete dam*. In this type of dam, the axis is straight or slightly curved (Fig. 9.3). These dams resist the thrust of water by their weight; gravity dams are massive concrete structures. The foundation rock of the dam should be very strong so that the load of the dam may be borne by the rock. *Example*: Bhakra Dam.

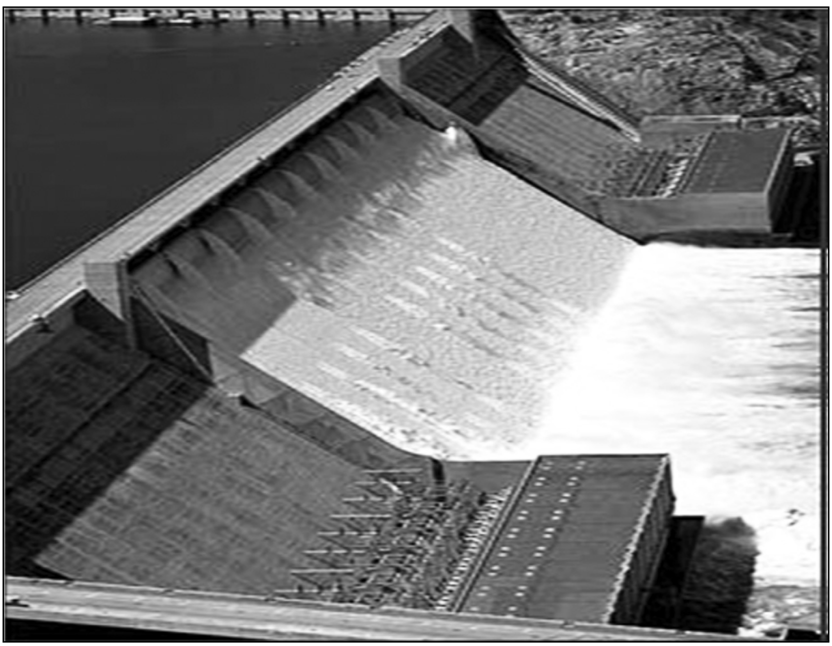


Fig. 9.3 *Gravity dam*

■ **Arch Dam** In this dam, the length of axis is curved and less than the height of the dam (Fig. 9.4). The arch-shaped structure is made of concrete, with its convex side facing upstream. The thrust of water in the reservoir is transmitted to the walls of river valley on either side of the dam. Arch dams are, therefore, constructed when valley walls are quite strong. The areas having a steeper slope in hilly region are locales for construction of such types of dam. *Example*: Idduki Dam (Kerala).

Fig. 9.4 *Arch dam*

■ **Buttress Dam** The dam which is characterized by a series of girders and concrete panels parallel to the axis of the dam is known as *buttress dam* (Fig. 9.5). The buttresses are constructed at the downstream side to support an upstream deck. The foundation rocks should be quite strong.

Fig. 9.5 *Buttress dam*

■ **Earth Dam** They are made with clay, silt and alluvial materials that are available in the river valleys and adjoining areas of the proposed site of construction (Fig. 9.6). These dams can be constructed on earth or poor rocks.

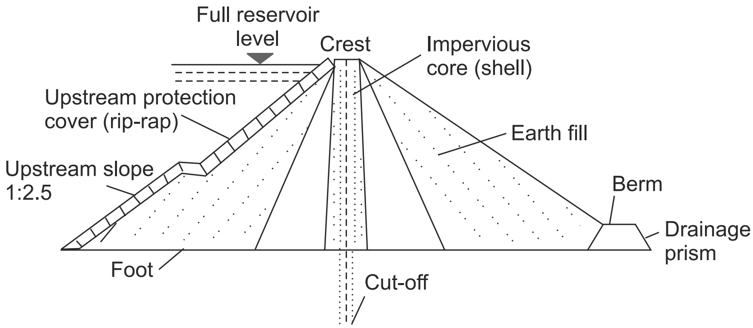


Fig. 9.6 *An earth dam with impervious core and gentle slope*

■ **Rock-Fill Dam** The dam has a trapezoidal shape and filled up with gravel, pebbles and boulders (Fig. 9.7). This type of dam is constructed in high seismic zones. *Example*: Salal Dam in J&K.

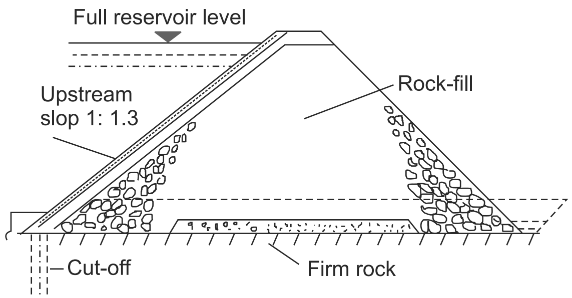


Fig. 9.7 *Rock-fill dam where upstream slope is made up with concrete*

■ **Masonry Dam** The dam which is constructed from bricks, boulders and stones, which are nonreactive and nonporous, is known as masonry dam. In this dam, the materials are used in such a way that permeability is totally negligible (Fig. 9.8). *Example*: Srisailam Dam in Andhra Pradesh.

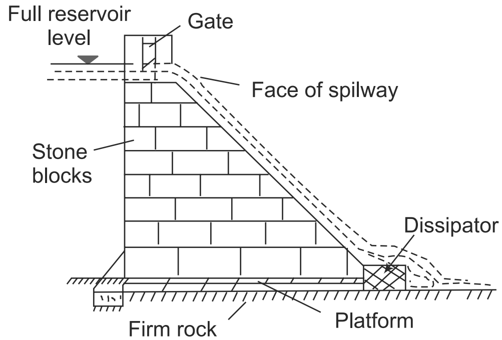


Fig. 9.8 *Masonry dam made up of stone blocks, acting as impervious layer*

9.6.3 Geological Factors Influencing Site Selection

Some of the important geological factors to be investigated before selection of site for a dam are compactness and bearing capacity of foundation rock, geological structures, attitude of beds, thickness of overburden, and width of the river valley. These are described as follows.

❑ *Compactness*

Any of the igneous, sedimentary or metamorphic rock may be present at the dam site. The compactness of a rock depends upon its mineral composition, hardness, homogeneity and massiveness. Shale is the most common sedimentary rock followed by sandstone. Shale may be compaction-shale or cementation-shale. The *cementation-shale* being stronger is preferable. Moreover, *compaction-shale* is soft and slakes when subjected to alternate wetting and drying, and has tendency to flow away under load, causing the structure to settle. The compactness of rocks like quartzite, granite and basalt is quite more than sandstone, shale and limestone, and therefore, the area characterized with massive quartzite is more suitable. Although limestones, dolomites and marbles are soluble rocks, they also are strong enough to support the weight of a dam if massive in nature. However, these rocks if have solution channels and caverns may need their grouting to check leakage.

❑ *Bearing Capacity*

Bearing capacity of a rock is the load that can be withheld by any rock without failure. It depends upon the cohesive forces among grains of the rock and its hardness. Quartzite has the largest bearing capacity amongst different rocks.

❑ *Geological Structures*

It is one of the most important parameter for site selection of dams. The rocks in the area of interest should be free from fault and joints. The study of drainage from toposheet, satellite images and field investigations are carried out to identify the location and magnitude of fault, fold and joints. The presence of such weak zones at major scales would certainly prohibit the site for the construction of a dam and a reservoir. The stability of dams in different folded and faulted conditions has been enumerated below.

■ **Folded Region** The limbs of fold may be treated as dipping beds or strata of the site selected for the construction of a dam. The upstream limb forms the most suitable place, followed by the crest of folded region. The downstream limb of a fold should not at all be selected for constructing a dam (Fig. 9.9).

■ **Faulted Region** The occurrence of a fault is a tectonic phenomena. The area with faults is never suitable for construction of a dam; the bearing capacity of foundation rock is reduced drastically. Also, the area is prone to earthquakes if faults are reactivated. Furthermore, faults accelerate the seepage of water and in turn dam becomes unsafe. However, if the situation demands to construct the dam, the area may be prioritized as follows:

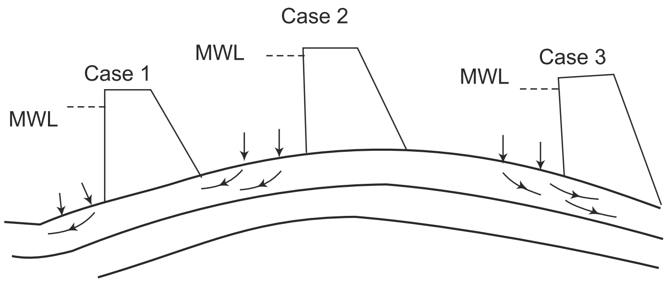


Fig. 9.9 *Suitability of dams at crest, downstream and upstream side*

- *Case 1* If a fault plane is in the upstream side, and beds have also an upward dip then the faulted plane should be sealed so that the dam is safe (Fig. 9.10).
- *Case 2* If a fault plane is in the upstream side, but beds have downward dip, the construction of dam must be avoided (Fig. 9.10).
- *Case 3* If fault occurs in the downstream side then there is no threat for the construction of dam (Fig. 9.10).

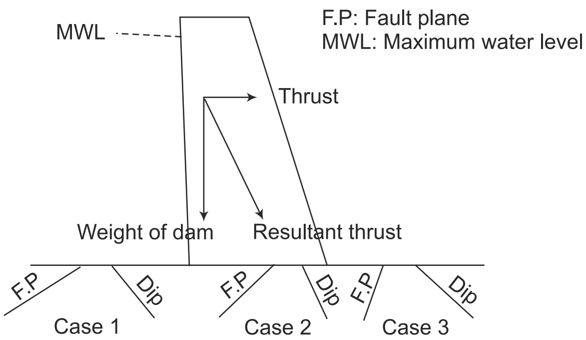


Fig. 9.10 *Suitable conditions in faulted region*

❑ *Attitude of Rock Formations/Beds*

The dip direction of existing formation/beds is important for the stability of dams. The dip direction of beds when follows the direction of upstream side, it is supposed to be the most suitable site. It is so because the resultant force will act opposite to the toe of the dam. Moreover, the beds may have different magnitude of dips affecting the stability of dam. Different conditions of dip direction along with magnitude and effects of overburden, fold and faults are discussed below.

■ **Condition 1** When the beds have dip amount of 10°–45° towards upstream side, the resultant force of water would be negated and the dam would be safe. When the beds have a dip amount greater than 45° towards upstream side, the resultant force of water would be negated but it would be a little dangerous as compared to a previous condition [Fig. 9.11(a)].

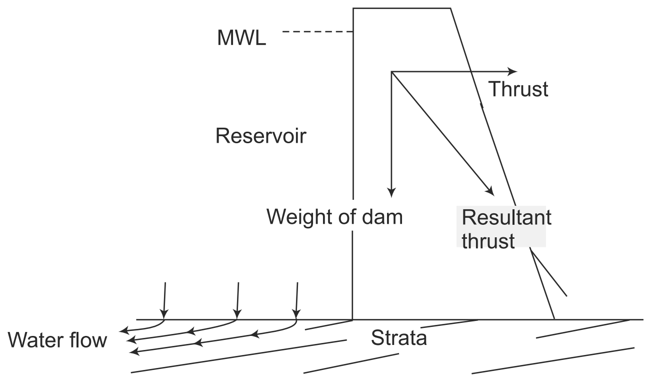


Fig. 9.11 (a) *When the dip of bed is towards upstream side*

- **Condition 2** When the beds have a dip amount of 10°–45° towards downstream side, the resultant force of water would be accelerated and the dam would be unsafe. When the beds have a dip amount greater than 45° towards downstream side, the resultant force of water would be more accelerated and it would be devastating [Fig. 9.11(b)].
- **Condition 3** When the beds have vertical disposition, which are rarely found, the foundation remains water-tight and the dam will not be subjected to uplift pressure created by the dam [Fig. 9.11(c)].

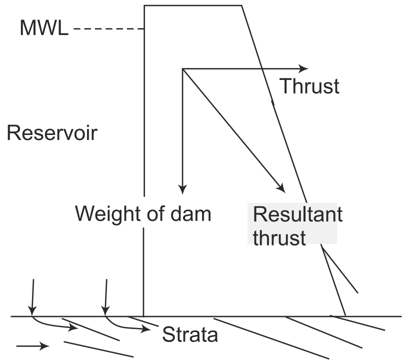


Fig. 9.11 (b) *When dip of beds is downwards*

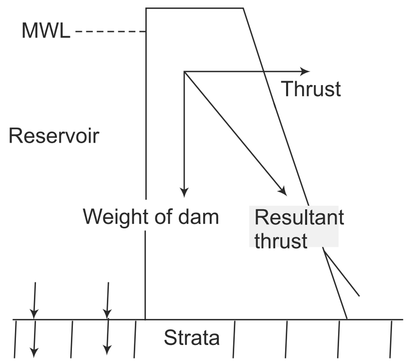


Fig. 9.11 (c) *When dip of beds is vertical*

❑ *Thickness of Overburden*

Thickness of loose sediments or debris, below which the hard or consolidated rock formation exists is known as *overburden*. Thickness of overburden can be estimated by electrical resistivity survey and borehole drilling. Since thickness of the overburden affects the cost as well as the stability of dam structures, it is essential to excavate and remove the overburden. Greater thickness of overburden is not suitable criteria for the construction of a dam.

❑ *Stream/River Condition*

A narrow river channel is the most suitable place for the construction of the proposed dam because it can be blocked with a relatively small dam. Apart from it, the slope of stream bed should be gentle and free from meandering of the river. The cost of the dam is proportional to the width of the stream.

9.6.4 Common Factors for Dam Disasters

Some of the common factors which damage the dam structure are scouring effect, piping, landslides, faulty design of spillway and a lack of proper drainage management. These are discussed as follows.

❑ *Scouring*

When a dam is allowed to release water from its reservoir, it results in enhanced stream velocity. Consequently, occurrence of small floods near the dam or reservoir takes place. This leads to scouring and armouring of the river bed. The higher energy of the sudden flood picks up and removes smaller sediments like silt, sand and gravel, as well as aquatic plants and animals, leafy debris and large woody debris. Furthermore, sand is removed downstream. The river, which has initially negligible sediment load, will have improved carrying capacity and will pick up sediment from the stream bed below the dam. The nature of rocks existing in the reservoir or near to the dam site, controls the intensity of scouring effect.

❑ *Piping*

Internal erosion of soil particles within a dam by water that seeps through it is one of the most common causes of failure of earth dams. Internal erosion is especially dangerous because there may be no external evidence, or only subtle evidence, that it is taking place. Internal erosion manifests by the migration of soil particles by suffusion or piping. Piping is induced by regressive erosion of particles from downstream and along the upstream line towards an outside environment until forming a continuous pipe.

❑ *Landslides*

It is one of the most devastating causes for failure of any dam. Occurrence of landslides either in the upstream side of a dam or inside the reservoir is hazardous due to instability of core of the structure. Moreover, it causes siltation of the dam. It is, therefore, necessary to have a catchment-area treatment in the upstream side of the dam in the landslide-prone areas. This would save the life of the dam and will protect it from damage.

❑ *Faulty Design of Spillway*

A spillway is a structure used to provide the controlled release of flows from a dam or levee into a downstream area. Spillways release floods so that the water does not overtop and damage or even destroy the dam. Except during flood periods, water does not normally flow over a spillway. It cannot be stressed too heavily and the site should be examined carefully before detailed planning for construction of dam. The design of spillway, if made along the loose sediments or fractured rocks, may create hazard.

❑ ***Lack of Proper Drainage Management***

The drainage is an important factor for the efficient functioning of any reservoir or dam. The slope modifications in upstream and downstream sides of the dam are necessary so that the velocity of water, which creates a thrust on the wall of a dam, is minimized. If the drainage modification and its slope magnitude are not managed, it would accelerate the siltation.

9.7 GEOLOGICAL INVESTIGATION FOR TUNNELLING

A tunnel is an underground or underwater passageway which facilitates transportation of traffic (pedestrian, road, rail, etc.) or fluid (canal). It is completely closed from all the sides, except for openings at both the ends (entering and leaving). Although the cost of tunnelling is greater than its surface alternative, these are constructed to facilitate transportation. The purposes of tunnelling are many, viz. unobstructed passage, water supply, mining, river diversion, wildlife passage and secret tunnels (military purpose). Before describing the geological investigations which are required for deciding the feasibility for tunnelling, the definitions involved in the methods for tunnelling and the hazards are introduced.

9.7.1 Anatomy of a Tunnel

Before describing the different methods of tunnelling, it is necessary to be conversant with the components of tunnels. The common parts of a tunnel are crown/roof, arch, wall and floor. These are defined as follows.

■ **Crown/Roof** The crest of a tunnel is known as the *crown* or *roof* of the tunnel (Fig. 9.12). This part of the tunnel requires timber or steel reinforcement in weaker or fractured rocks.

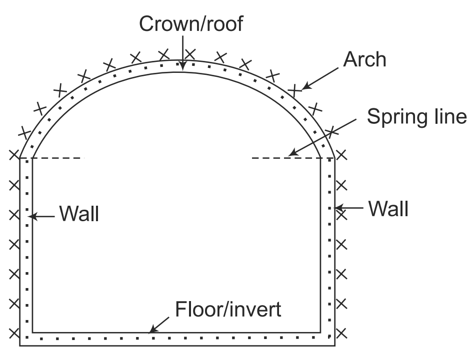


Fig. 9.12 *Different parts of a tunnel*

■ **Arch** The curved part on both sides of the tunnel is known as *arch* (Fig. 9.12). The tensile strength is maximum at the arch of the tunnel.

■ **Wall** Vertical segments of the tunnel which connect the floor and crown are known as the *walls* of tunnel.

■ **Floor** The base of the tunnel which is flat and on which traffic or fluid moves along with continuous contact is called the *floor* or *invert*. The strength of the floor is controlled by the nature of underlying rocks.

■ **Portal** The area near to the tunnel is called the *portal* of the tunnel. The tunnels never pass into the portal but the strength of a portal affects the life and strength of the tunnel.

9.7.2 Geological Parameters

Before site selection for tunnelling the geological conditions, i.e., lithology, structures, attitude of disposition of beds and groundwater conditions, play a vital role. The importance of these geological parameters for tunnelling is great as compared to other engineering structures. The geological conditions govern the feasibility, planning, costing, design and techniques of tunnels.

To understand the above-mentioned geological parameters, surface and subsurface geologic studies are carried out. These studies comprise of surface and subsurface investigations. Surface investigations include determination of dip and strike of rock beds through a Brunton compass, identification of geological structures and lithological characters, and study of drainage pattern. Subsurface investigations consist in borehole drilling to get depthwise characters, and resistivity survey to get subsurface information about the rocks and fractures. The Rock Quality Designation (RQD), which is related to core samples, may be found through borehole pits.

❑ *Nature of Rocks*

The natural disposition of different rocks is quite variable at different places; it is not homogeneous. Further, the construction of tunnels involves the excavation of different rock types which may have different degrees of abrasion or hardness. The rocks through which tunnels are proposed or excavated are known as *outcrops*. The rocks which have a high tensile strength and hardness without any fracture are most suitable for tunnelling. Granite, basalt, gabbro, dolerite and syenite are favourable rocks, although the expenditure for excavation is too high. Moreover, the rocks through which tunnels are driven should be massive with least permeability. Geo-chronologically, the older rocks are more massive and harder than younger rocks.

❑ *Attitude of Rock Beds*

As we know that the nature of rock changes along the strike direction, tunnelling is favourable along the dip direction of the beds [Figs. 9.13 (a) to (f)]. The gentle dip of beds provides better scope for tunnelling than steeper slope. Slope failure will take place where the beds dip at steeper angles. Tunnelling along strike direction creates an overbreak phenomena which is undesirable in any tunnel. Attitudes of involved beds in tunnel and their effects on suitability are explained casewise as follows.

■ **Case 1** *If the beds are parallel to horizontal or have approximately zero degree inclination* [Fig. 9.13(a)].This is the most favourable situation for tunnelling and provides maximum stability.

■ **Case 2** *If the beds are vertically dipping and the axis of the tunnel is perpendicular to the strike* [Fig. 9.13(b)]. This situation is also suitable for tunnelling and provides maximum stability. However, in nature, a vertical dip of rock formations is rare.

■ **Case 3** *If the strike of involved beds is parallel to the axis of the tunnel* [Fig. 9.13(c)]. This situation is not at all suitable for tunnelling due to an occurrence of the overbreak phenomena.

■ **Case 4** *If the dip of involved beds is parallel to the axis of the tunnel* [Fig. 9.13(d)]. This situation is most suitable for tunnelling because similar rock formations occur along the axis of the tunnel.

■ **Case 5** *If the strike of vertically dipping beds is parallel to the axis of the tunnel* [Fig. 9.13(e)]. This situation is suitable for tunnelling due to the occurrence of similar nature of rocks.

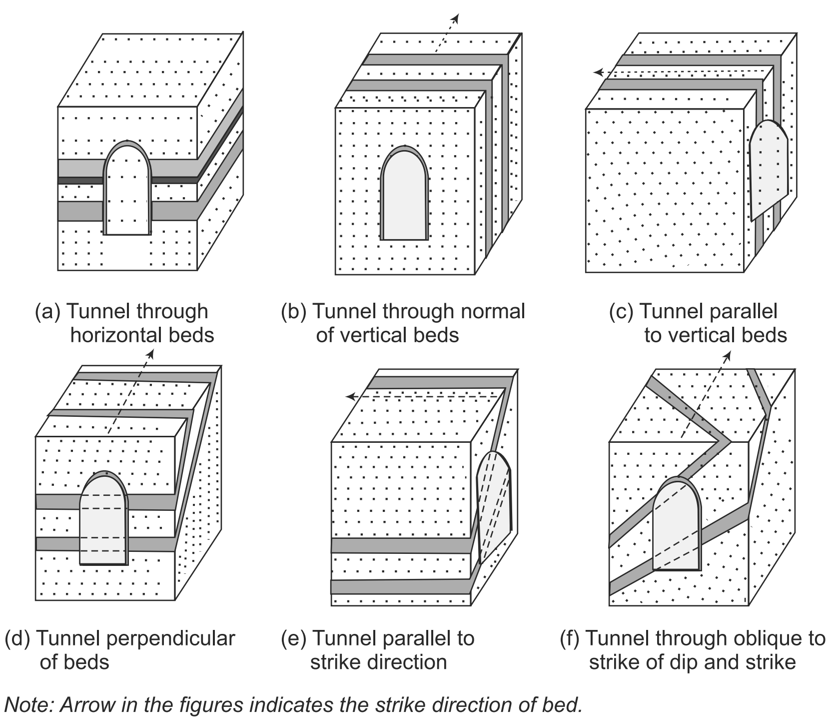


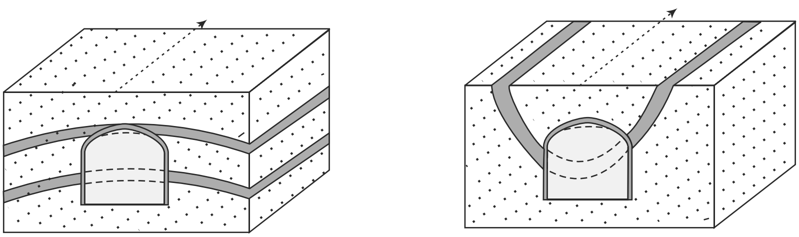
Fig. 9.13 *Tunnels and attitudes of beds*

■ **Case 6** *If the strike of involved beds is oblique to the axis of the tunnel* [Fig. 9.13(f)]. This situation is suitable for tunnelling because there will be pressure on the limbs of the tunnel and not on the crest.

❑ *Geological Structures*

The role of geological structures like folds, faults and joints are most significant in tunnelling. The impact of different geological structures on tunnelling is as follows.

■ **Fold** A fold results from deformation of existing rocks and there is significant lateral stress on the rocks. In case of *anticlinal fold*, the intense lateral pressure exists on a crest of the fold and in turn tensional stress is developed [Fig. 9.14(a)]. This produces joints on the crest in anticlinal fold which is harmful and, therefore, the digging of outcrop should be more to minimize the number of joints. In case of *synclinal fold*, the lateral pressure becomes more in the middle part, [Fig. 9.14(b)]. The tunnelling in a syncline will pose serious problems in case the rocks are permeable because the seepage of water takes place and requires dewatering. The construction of tunnels is more problematic in a complex folded situation like plunging, overturned and recumbent folds. Therefore, during site selection the location of fold, its type and extent should be investigated and mapped on micro scale.



(a) Anticline fold (b) Syncline fold

Fig. 9.14 *Tunnels passing through folds*

■ **Fault** The existence of faults, its type and extent in particular region where tunnelling is proposed, play an important role in the site selection for safe tunnelling. The impact and implications of few major types of faults on selection of sites for tunnelling are as follows.

1. The location of a tunnel should not lie on the hanging wall side of a reverse fault because there is a chance to dislocate the structure due to heavy load due to gravity in reverse fault [Fig. 9.15(a)].
2. The location of a tunnel should not lie on the foot-wall side of a normal fault also because the excavation of a tunnel along its axis will be very difficult and more costly in a normal fault. [Fig. 9.15(b)].
3. If the tunnelling is made perpendicular to the fault plane [Fig. 9.15(c)] the zone of intersection of a fault plane and axis of tunnel creates problems. However, it is in better condition than oblique faults crossing the tunnel.

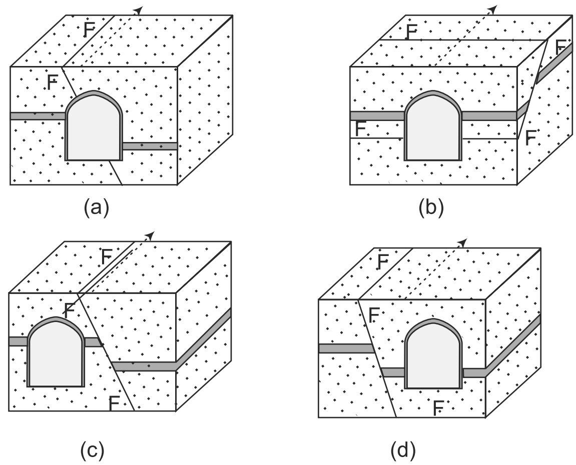


Fig. 9.15 *Relationship of faults with tunnels in different fault-plane conditions*

4. If the tunnelling is made oblique to the fault plane [Fig. 9.15(d)], the zone of crushed portion will be more which would require much more preventive measures like grouting and become unstable in future.
5. The construction of tunnels must be avoided in active fault zones because the fault may reactivate any time with a slight change in tensional stress condition. It becomes more vulnerable in low angle reverse fault, i.e., thrust fault because formation of gauge and crushing of rocks become more intensive.

❑ *Groundwater Conditions*

It is one of the important factors influencing the stability and feasibility in tunnelling. The groundwater conditions include consideration of its level, fluctuations and discharge of groundwater from underlying rock formations.

■ **Groundwater Level** The water level is encountered at different depths below the ground surface in different regions. A shallow groundwater level is not favourable because during excavation, seepage of groundwater creates construction problems. If the groundwater level cuts the surface of the ground then construction of a tunnel is very difficult due to the formation of spring line.

■ **Groundwater Fluctuations** The groundwater fluctuation refers to the difference of pre-monsoon to post-monsoon groundwater level in any area. The water-level fluctuation is higher in hard rock than soft-rock formations. The groundwater level fluctuation should be a minimum because it would reduce the reaction of rocks like dissolution activity of limestone taking place due to moisture content. Higher fluctuations weaken the rocks due to moisture content and ultimately damage the tunnel.

■ **Groundwater Discharge** The discharge from underlying rocks which form the aquifer should not have high discharge because it would exert pressure on the floor of the tunnel and may weaken the strength of the wall as well. Excess pressure of groundwater may also put obstacles during construction of tunnelling.

9.7.3 Methods of Tunnelling

Since the lithological and structural variations are common in nature, the excavation of ground surface and subsurface depends upon factors like geology of the area, groundwater table and depth of excavation. The basic types of tunnel construction are cut-and-cover, and boring. While cut-and-cover-type tunnels are constructed in shallow trenches and then covered up, the bored tunnels are constructed *in situ* without removing the ground above. Deep tunnels are excavated, often using a tunnelling shield. Some of the methods of tunnelling are described below.

❏ *Cut-and-Cover Method*

It is also known as a *conventional method* of tunnelling and is suitable for the construction of shallow tunnels. Most tunnelling projects are constructed by this method being more practical and economical. In this method, a trench is excavated and its roof is covered with an overhead support system strong enough to carry the load of what is to be built above the tunnel. Two basic forms of cut-and-cover tunnelling are bottom-up method and top-down method (Fig. 9.16). Metro tunnels in New Delhi are an example of cut-and-cover method of tunnelling.

Fig. 9.16 *Cut-and-cover method of tunnelling*

■ **Bottom-up Method** A trench is excavated from the surface downwards. Once the final depth is reached, the tunnel floor is built. Then the walls and roof are constructed. The tunnel may be of *in situ* concrete, precast concrete, precast arches, or corrugated steel arches; in the early days, brickwork was used. Finally, the trench is back-filled and the surface is restored.

■ **Top-down Method** Side-support walls and capping beams are first constructed from the ground level in this method. Then a shallow excavation allows making the tunnel roof. The surface is then restored except for access openings. This allows minimum disturbance of roadways, services and other surface features. Excavation then takes place under the permanent tunnel roof, and the base slab is constructed.

❏ *Tunnel Boring Machine (TBM)*

This machine is characterized by a circular cutter head with an array of suitable cutters. The rotational and translational movement of the cutter takes place with a speed between 1 to 3 rpm. Foam or slurry is used at the face of the machine so that it remains cool to work. Hydraulic arrangement is also an in-built feature in this machine. The stress created by TBM on soil or rock is significantly less than blasting. This method is very suitable for driving long tunnels in mountainous regions and where the geological profile remains constant. The overbreak does not take place in bigger diameter tunnels and hence, the earth loss is very less. *Example*: TBM is being used for the second phase of construction of Delhi Metro (Fig. 9.17).

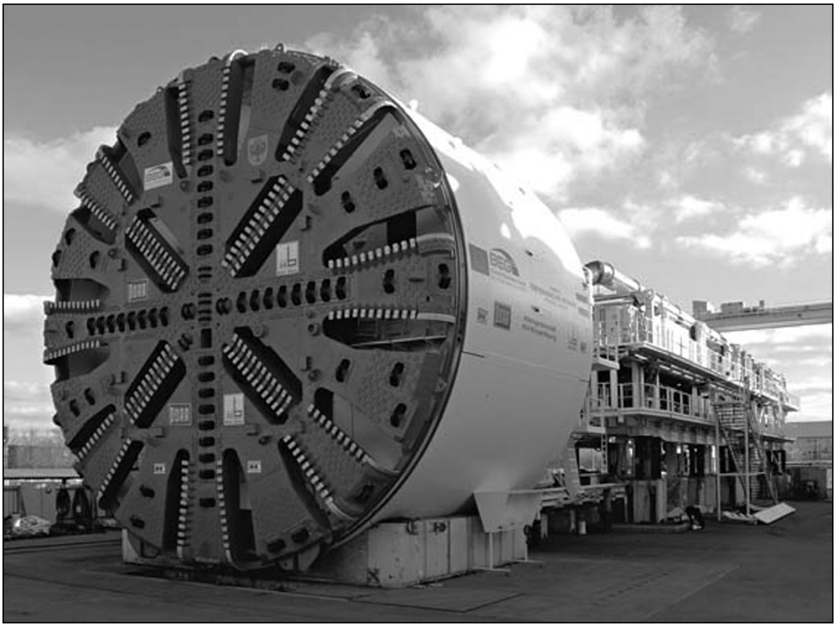


Fig. 9.17 *Tunnel boring machine (TBM)*

Note A temporary access *shaft* is sometimes necessary during the excavation of a tunnel. They are vertical holes dug to carry out the longitudinal drilling in the construction process of long tunnels. Shafts are not only helpful for excavation but also provide a conduit for ventilation. Once the access shafts are complete, TBMs are lowered to the bottom and excavation can start. Shafts are the main entrance in and out of the tunnel until the project is completed. If a tunnel is going to be long, multiple shafts at various locations may be bored so that entrance to the tunnel is closer to the unexcavated area. Once construction is complete, construction access shafts are often used as ventilation shafts, and may also be used as emergency exits.

❏ *Clay-kicking Method*

Clay-kicking is a specialized method developed for manually digging tunnels in strong, clay-based soil structures. The method is suitable for construction of small tunnels. It is a fast and less costly method. In this method of tunnelling, the clay-kicker lies on a plank at 45° away from the working face. The grafting tool consists of a flat base and arrowlike structure which penetrates the soft soil.

Tunnels are dug in types of materials varying from soft clay to hard rock. The method of tunnel construction depends on such factors as the ground conditions, the groundwater conditions, the length and diameter of the tunnel drive, the depth of the tunnel, and the logistics of supporting the tunnel excavation, and the final use.

9.7.4 Uses of a Tunnel

Some of the more specific uses of tunnels are passage way, mining, water supply, pipelines for transportation of oil and gas, and secret tunnels for defence purposes.

9.7.5 Geological Hazards in Tunnelling

Although geological criterion are considered before implementation for tunnelling, still the weakness in rocks and impact of geological structures cannot be ruled out. Some of the hazards which are interlinked with geology are as follows.

■ **Overbreak and Wall Collapse** During these hazards, the undesired portion of the portal gets excavated and the wall of a tunnel is also damaged. These hazards occur commonly in soft and heterogeneous rocks. The Himalayan region area having tectonic disturbances experiences such type of tunnelling hazards.

■ **Gas Flow** This hazard occurs in the area which is characterized by peat or swampy nature. When the line of tunnel passes through these formations and if ventilation is inadequate, the methane or marsh gas passes in the tunnel. Methane or marsh gas is inflammable and poisonous; it becomes torturous to people who work inside the tunnel.

■ **Seismic Effect** The area lying in seismic zones or active fault zones is quite vulnerable from the tunnelling point of view. Due to seismic effects, the ground motion may dislocate the tunnel. Since, it is observed that the ground motion is restricted up to 30 m depth only and the tunnel construction may be restricted up to this depth.

■ **Spalling** When the splitting of rock layers occur from the roof as well as wall, due to contact of water or moisture, it is known as *spalling*. This hazard is common where two different rocks of different compositions lie over each other. *Example*: Argilaceous sedimentary rock like shale is overlain by aranaceous rock (sandstone). During the construction of Dul Hasti tunnel in J&K, these hazards took place.

■ **Inundation** When the piezometric head becomes higher and groundwater gushes out, the loose fragments/sediments get transported in the tunnel and deposit at a certain corner inside the tunnel, it is called *inundation*. Due to seepage or flow of groundwater, the tunnel may be inundated which can stop the excavation work as well as shifting of the debris from the floor of the tunnel.

9.8 GEOLOGICAL INVESTIGATION FOR BRIDGES

Bridges are important civil engineering structures which form an integral part of roadways and railways under transportation system. These are constructed across a river, stream, valley or hills. The bridges also reduce the distance and in turn save time and money to move from one corner to another corner of the country. Bridges bear the traffic load (dynamic in nature) and self-weight (static in nature) of the bridge. Since both the static and dynamic loads act continuously on the bridge, the stability of any bridge depends upon many factors. Also, construction of a bridge requires detailed geological investigations of the area and dynamics of the river/stream. Before coming to the other aspects, the components of a bridge are introduced.

9.8.1 Anatomy of a Bridge

There are three main parts of any bridge: the *abutments, piers* and *beams*.

❑ *Abutment*

Abutment refers to the substructure at the end of a bridge span whereon the superstructure of the bridge rests (Fig. 9.18). Abutments should be strong enough to safely bear the load exerted by the pressure of rocks or soil. Stability of abutment depends upon geological factors like nature of a country rock and geological structures.

❑ *Piers*

These are pillarlike structures which are erected from the base of a river up to the span of the bridge (Fig. 9.19). Piers should be strong enough to support the bridge because in many cases the distribution of loads is the maximum on piers.

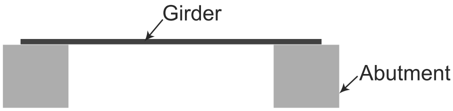


Fig. 9.18 *Single-span girder (beam) bridge*

❑ *Single-span Bridge*

A bridge which has a single pier is known as a *single-span bridge* (Fig. 9.18). Single-span bridges have abutments at each end which provide vertical and lateral support for the bridge. They also act as retaining walls to resist lateral movement of the earthen fill of the bridge approach. Single-span bridges are generally constructed in rural areas where the stream width is quite small.

❑ *Multiple-span Bridge*

Multi-span bridges require piers to support ends of spans unsupported by abutments (Fig. 9.19). Multiple span bridges are generally constructed in both rural and urban areas where the stream width is quite appreciable.

9.8.2 Types of Bridges

Different types of bridges are girder or beam bridge, cantilever bridge, arch bridge, truss bridge, suspension bridge and cable-stayed bridge. These are introduced as follows.

❑ *Girder (Beam) Bridge*

This is one of the simplest types of bridges. Beam bridges (Fig. 9.19) are horizontal beams supported at each end by substructure units (piers and abutments) and can be either *simply supported* when the beams only connect across a single span, or *continuous* when the beams are connected across two or more spans. The beam bridges can range from small wooden beams to large steel boxes. The vertical force on the bridge becomes a shear and flexural load on the beam which is transferred down its length to the substructures on either side. They are typically made of steel, concrete or wood.

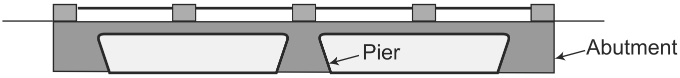


Fig. 9.19 *Multispan girder (beam) bridge*

❑ *Arch Bridge*

This type of bridge is characterized by arch-shaped beams; it may be single or multiple arch bridge (Fig. 9.20). The distribution of load is transferred from the arches to abutment and pier; the major portion of load is transferred to the pier. Arch bridges are constructed in hilly regions where span is relatively small and the location of piers and abutments is quite strong.

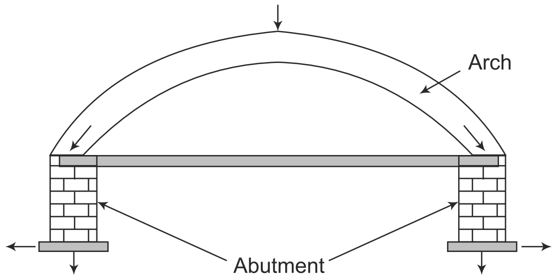


Fig. 9.20 *Single-span arch bridge*

❑ *Truss Bridge*

Truss bridges are one of the oldest types of bridges. A truss bridge is a bridge whose load-bearing superstructure is composed of a truss. The truss is a structure of connected elements forming triangular units (Fig. 9.21). The connected elements (of steel or wood) may be stressed in tension, compression, or sometimes both in response to dynamic loads. This type of bridge is most economical because it uses materials efficiently.

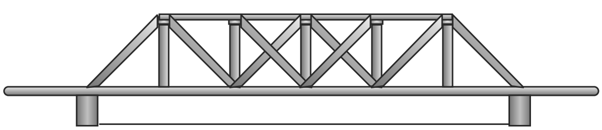


Fig. 9.21 *Truss bridge*

❑ *Cantilever Bridge*

This type of bridge is characterized by a narrow concave platform resting on the piers (Fig. 9.22). The bridge is built using cantilevers—horizontal beams supported on only one end. Most cantilever bridges use a pair of continuous spans that extend from opposite sides of the supporting piers to meet at the centre of the stream the bridge crosses. Cantilever bridges are constructed using much the same materials as beam bridges. In this bridge, all the loads are transferred on piers. Such bridges are constructed in the area where the basement within the width of the stream is stronger than that of the location of abutment area.

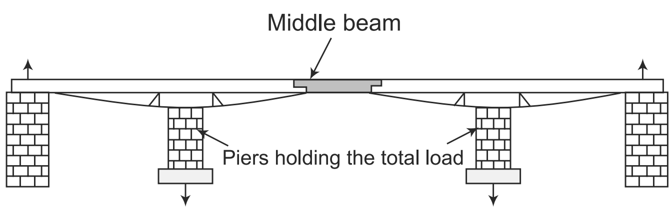


Fig. 9.22 *Cantilever bridge*

❑ *Suspension Bridge*

These are the bridges that are suspended from cables. The bridge is characterized by an inverted arch in shape formed by cables (Fig. 9.23). In the modern bridges, the cables hang from towers that are attached to caissons. The load is transferred from abutments to the towers through cables. Suspension bridges are constructed in areas where the banks of streams are weak which hold the abutments. Laxman Jhula at Rishikesh (Uttarakhand) is an example of suspension bridge.

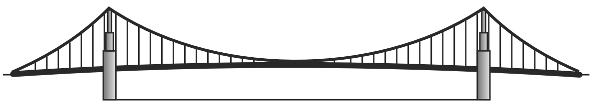


Fig. 9.23 *Suspension bridge*

❑ *Cable-Stayed Bridge*

Cable-stayed bridges, like suspension bridges, are held up by cables. However, in a cable-stayed bridge, less cable is required and the towers holding the cables are proportionately higher. The bridge has many cables and towers apart from abutments (Fig. 9.24). The load is transferred from deck towards piers through cables. These types of bridges are constructed in the area where the banks of streams have softer rock which holds the abutments. *Example*: new Yamuna Bridge, Allahabad (UP).

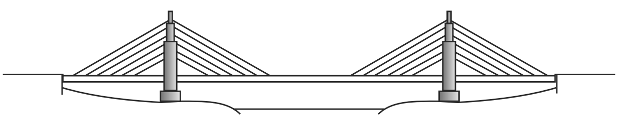


Fig. 9.24 *Cable-stayed bridge*

9.8.3 Geological Parameters

All the loads from the bridge are transmitted to the ground through the foundations of piers and abutments. Before design and construction of a bridge; therefore, several geological investigations are required to provide a stable and durable bridge. These geological investigations include the nature of rocks, attitude of rock beds, geological structures and nature of river/stream.

❑ *Nature of Rocks*

Various types of rocks are encountered in any region with different inherent properties. Compact or consolidated rocks like quartzite, massive granite, basalt, sandstone are more suitable if they occur in the locations of abutments. Rocks that have foliation and unconsolidated characters are not suitable for bridges because over the period, the disintegration of existing rocks would take place. Secondly, the out crop of homogeneous rock is more suitable than heterogeneous rock for the longer life of bridges.

❑ *Attitude of Rock Beds*

For abutments, the valley walls need a thorough investigation. The amount of dip of existing rock beds is an important controlling factor for the stability of a bridge. The steeper slope of the beds at abutment side does not provide the feasibility for the construction of the bridge. The valley walls with the strata dipping into the river result in unstable slopes and are, therefore, avoided; there is a tendency of the bridge to slide into the river. Therefore, attempts must be made to make the abutments at gentle sloping beds.

❑ *Geological Structures*

Rocks do not always have horizontal dips and are not always free from deformations. The site for the construction of a bridge should be so selected that rocks do not have fault and conjugate joints. Joints, if exist, must be grouted. Grouting helps in protecting the bridge against damage due to the presence of joints.

❑ *Nature of River/Stream*

The nature of river or stream must be analyzed critically because the piers and abutments are always in contact of the river water. The velocity of water and its erosive capacity governs the stability of piers and abutments. The proposed site for a bridge with the course of river meandering should outrightly be rejected.

9.9 MAJOR DAMS, TUNNELS AND BRIDGES IN INDIA

9.9.1 Dams

Dams are the lifeline for sustaining the Green Revolution and maintaining a healthy ecosystem. Hydropower generation is also one of the most important outputs of major dams in India. Siltation in upstream side of all the dams in our country has been a major concern. This is quite related to the geology of a catchment area of reservoirs and dams.

After independence, commendable progress has been made in the construction of dams and water reservoirs. Around 4300 large dams exist and many are under progress. A few important dams in India along with their salient features are described below.

❑ *Tehri Dam*

The Tehri dam is the highest dam in India, and the eighth tallest dam in the world [Plate14 (a)]. This dam is very popular and has received attraction from all over the country regarding its environmental viability. It is so because it significantly affects the discharge of river Ganga in the downstream side; it is located on the Bhagirathi river in Uttarakhand. The first phase of the dam was completed in 2006 and other two phases are under construction. The water of its reservoir is used for irrigation, municipal water supply and the generation of 1,000 MW of hydroelectricity. The salient features of the Tehri Dam are as follows.

- Height: 260 m
- Length: 575 m

- Type: Earth and rock-fill
- Reservoir capacity: 2,719,436,688 Cum
- River: Bhagirathi river
- Location: Uttarakhand
- Installed capacity (power generation): 1,000 MW

❑ *Bhakra Nangal Dam*

It is a gravity dam across the Sutlej River, Himachal Pradesh. The Bhakra Nangal dam is the second largest dam in India and in Asia as well. Its reservoir, known as the Gobind Sagar Lake, is the second largest reservoir in India [Plate14 (b)]. High siltation rate in Bhakra Nangal is of prime concern. It has reduced the capacity of the reservoir up to 30%. The salient features of Bhakra Nangal dam are given below.

- Height: 226 m
- Length: 520 m
- Type: Gravity dam (Concrete)
- Reservoir Capacity: 9,714,572,457 Cum
- River: Sutlej river
- Location: Punjab and Himachal Pradesh
- Installed capacity (power generation):1325 MW

❑ *Hirakud Dam*

It has been built across the Mahanadi river in the tribal state of Odisha. The Hirakud Dam is one of the longest dams as far as its crest length is concerned. The crest length of the dam is about 26 km which is the highest in the world [Plate14 (c)]. There are two observation towers on the dam, the Gandhi Minar and the Nehru Minar. The Hirakud Reservoir is 55 km long, used as a multipurpose scheme intended for flood control, irrigation and power generation. It was one of the major multipurpose river-valley projects after independence. The salient features of Hirakund Dam are described below.

- Height: 60.96 m
- Length: 25.8 km
- Type: Composite dam (concrete + masonary)
- Reservoir Capacity: 6,189,910, 566 Cum
- River: Mahanadi river
- Location: Odisha
- Installed capacity (power generation): 307.5 MW

❑ *Nagarjuna Sagar Dam*

It is the world's largest masonry dam built across the Krishna river in Andhra Pradesh [Plate 14(d)]. Nagarjuna Sagar Dam is certainly the pride of India. The unique feature of this dam is its length of 1.6 km and 26 opening gates. This proves the symbol of modern India's architectural and technological triumphs over nature. The salient features of this dam are as follows.

- Height: 124 m
- Length: 1,450 m
- Type: Masonry dam
- Reservoir capacity: 12,136,256,727 Cum
- River: Krishna river
- Location: Andhra Pradesh
- Installed capacity (power generation): 816 MW

❑ *Sardar Sarovar Dam*

This dam, also known as Narmada Dam, is the largest dam as proposed to be completed, with a height of 163 metres across the river Narmada in Gujarat [Plate 14(e)]. Drought-prone areas of Kutch and Saurashtra will get irrigated by this project. This is a kind of gravity dam and is the largest dam of the Narmada Valley project with power generation up to 200 MW. The dam is beneficial to the four major states of India—Gujarat, Madhya Pradesh, Maharashtra and Rajasthan. The salient features of the Sardar Sarovar Dam are as follows.

- Height: 163 m
- Length: 1,210 m
- Type: Gravity dam
- Reservoir capacity: 9,973,566,428 Cum
- River: Narmada river
- Location: Gujarat
- Installed capacity (power generation): 1,450 MW

9.9.2 Tunnels

Tunnels are constructed to connect two distant places which indirectly reduce the time and distances. The tunnels are useful for traffic, transportation of water and oil, etc. They also facilitate the hydropower generation. India is characterized by diverse topographic features which requires numbers of tunnels. A few important tunnels constructed in India are as follows.

❑ *Jawahar Tunnel*

It is also known as Banihalb Tunnel, and is named after the first Prime Minister, Pt. Jawaharlal Nehru, of India. It was constructed during 1954–1960. The Jawahar Tunnel is one of the longest tunnel-road in Asia; located in Jammu & Kashmir. The Jawahar Tunnel has been operational since 22 December, 1956. The length of the tunnel is 2.85 km, its elevation is 2,194 above msl and it is a one-lane road in either direction [Plate 15(a)]. It is situated between Banihal and Qazigund on NH 44. The tunnel facilitates round-the-year road connectivity from Srinagar to Jammu.

It was designed for 150 vehicles per day in each direction but the number of vehicles has increased to 7,000 in both directions. After renovations, the tunnel now has a two-way ventilation system, pollution and temperature sensors, lighting system and with emergency phones for any assistance.

❑ *Bhatan Tunnel*

It is situated on the Mumbai–Pune expressway. This tunnel is 1 km long with all the possible new technologies. The Mumbai–Pune expressway is the first six-lane concrete, high-speed, access controlled tolled expressway passing through Bhatan tunnel [Plate15(b)]. The expressway through this tunnel has reduced travel time between the cities of Mumbai and Pune to approximately two hours. There are a total of 5 tunnels in the Mumbai–Pune expressway. Bhatan Tunnel is one of the longest tunnels of these five tunnels.

❑ *Karbude Tunnel*

It is the longest rail tunnel in India located on the Konkan railway route near Ratnagiri in Maharashtra [Plate 15(c)]. The Karbude tunnel is 6.5 km long. Konkan Railway runs from Mangalore in Karnataka to Mumbai in Maharashtra through Goa, along the west coast of India and Western Ghats.

9.9.3 Bridges

Bridges are important civil structures which connect two parts of the same or distant places over rivers/streams. Due technological developments in the area of bridge engineering, different types of bridges have been constructed. Some of the more important bridges are described below.

❑ *Mahatma Gandhi Bridge*

It is a girder bridge over River Ganges connecting Patna in the south to Hajipur in the north of Bihar [Plate 15(d)]. It was the longest river bridge in India at the time of its construction and remains the longest river bridge in Asia. Its total length is 5,575 m with a width of 25 m. This bridge consists of 45 intermediate spans of 121.065 m each and a span of 65.530 m at each end. The deck provides for a 7.5 m wide two-lane roadway for IRC class 70 R loading with footpaths on either side. The cantilever segmental construction method was adopted to construct this mega bridge.

❑ *Jadukata Bridge*

This bridge is situated in Ranikor in the West Khasi Hills District of Meghalaya which is 130 km from its capital, Shillong. It is the longest cantilever bridge in India. The panoramic view of this bridge is also very unique [Plate 15(e)]. This bridge over the Jadukata River is close to the Indo-Bangladesh border.

❑ *New Yamuna Bridge*

This is the longest cable-stayed bridge of India, located in Allahabad. The bridge has been constructed over the river Yamuna [Plate 15(f)]. It connects different parts of UP to MP. It was constructed by the end of 2004 with the aim of minimizing the traffic over the Old Naini Bridge, which is quite old (118 years). The bridge runs North-South across the Yamuna River. It carries 6 lanes, and caters to pedestrians and bicycles as well. Its width is 83 m with a span of 260 m.

Summary

To understand the utility of different rocks for different purposes, the engineering properties of rocks are of utmost importance. Besides the geological and optical properties of the rocks that have already been described in previous chapters, engineering properties like, porosity, permeability, hardness, crushing strength, abrasion and RQD, etc., are also required and are described. Among these properties, few are studied on the field itself and others in the laboratory. After estimating the sets of engineering properties, the correlation is made between engineering and physical properties of rocks. On the basis of rock mass rating, different types of civil engineering project sites are decided in view of their longer life and stability.

Important engineering projects like dams, tunnels and bridges have been described for their site selection on the basis of geological parameters. It is important to know the geological parameters like types of rock and their physical properties like density, water absorption capacity, grain size, shape and the binding materials before finalizing a site for dam.

The attitude of beds and geological structures like fold, fault and joints which control the feasibility of dams and tunnels have also been discussed. Different types of dam and their suitability have also been described in the chapter. The anatomy of a tunnel and geological investigation for safe tunnelling are described. The role of different types of rocks along with different geological structures for tunnelling has been explained. The effect of groundwater during tunnelling has been elaborated.

Bridges, which are a lifeline for transportation of roads and railways have also been considered and presented at the end of the chapter. Different parts of a bridge, classification and transfer of loads have been described in the chapter. Geological investigations required for suitable site selection like nature of rocks, overburden, presence of discontinuities like fractures and joints are presented.

The chapter ends with classical examples of dams, tunnels and bridges with their salient features.

Terminology

Lining In weak, fractured and thin bedded rocks, while driving, tunnels need lining to support the roof load and check the seepage of water into the tunnel.

Meandering A *meander*, in general, is a bend in a sinuous watercourse or river. A meander is formed when the moving water in a stream erodes the outer banks and widens its valley and the inner part of the river has less energy and deposits the silt it carries. The stream, as it flows, may assume a *meandering* course, alternately eroding sediments from the banks on the outside of a bend and depositing them on banks that lie on the insides of a bend. The result is a *snaking* pattern as the stream meanders back and forth across its down-valley axis.

Overbreak When concrete lining outside the perimeter of the tunnel is desirable, the additional area of rocks is excavated to facilitate lining. This is known as *overbreak*.

Scouring Action The piers of a bridge when constructed in a river; obstruct the river flow. Consequently, the water velocity around the piers and abutments increases making them susceptible to local scour, termed as contraction scour. The removal of sediment such as sand and rocks from around bridge abutments or piers by the swiftly moving water is known as *scour*. Degradation scour occurs both upstream and downstream from a bridge over large areas. Over long periods of time, this can result in lowering of the stream bed.

Exercises

1. (a) What are the important physical and geomechanical properties of rocks? State their importance.
   (b) Describe the factors affecting the strength, hardness and toughness of rocks.

2. Write short notes on the following:
   (a) Rock quality designation
   (b) Uniaxial compressive strength
   (c) Abrasion
   (d) Hardness and its measurement

3. (a) What are dams? Enumerate the important parts of a dam.
   (b) Discuss the various types of dams with neat sketches.
   (c) Discuss the parameters considered for geological investigation at dam sites.

4. Critically analyze a proposed site for the construction of dams with regard to folds and faults.

5. (a) What are the important geological conditions of site investigation for tunnelling with regard to their safety and stability?
   (b) Explain different methods of tunnelling.

6. Comment on the problems and associated hazards of tunnelling in the following cases.
   (a) Normal and reverse faults
   (b) Strike direction of beds
   (c) Anticline and Syncline structures
   (d) Groundwater

7. (a) Discuss the geological conditions that contribute towards selection of a bridge site.
   (b) Describe briefly the different types of bridges with neat sketches.

8. Differentiate between the following:
   (a) Girder bridge and cantilever bridge
   (b) Cable-stayed bridge and suspension bridge
   (c) Pier and abutment
   (d) Rock-fill dam and gravity dam

9. Write short notes on the following:
   (a) Overbreak
   (b) Stability of bridges
   (c) Rock mass rating

Multiple-Choice Questions

1. The colour of a rock is its
   (a) physical property (b) mechanical property
   (c) optical property (d) engineering property
2. If any rock has RQD of 40%, it will be kept under which of the following class?
   (a) Excellent (b) Good
   (c) Very good (d) Poor
3. Abrasion test of rocks is conducted to know
   (a) air-absorption capacity (b) resistance to abrasion
   (c) water absorption capacity (d) hardness of rock
4. A dam has the following components:
   (a) Axis, toe and crest (b) Tower, piers and abutments
   (c) Axis, limb and crest (d) Limb, saddle and reef
5. Rock-fill dam is constructed in an
   (a) area characterized with hard rock (b) area characterized with soft rock
   (c) area characterized with folded rock (d) area with earthquake vulnerability
6. Nature of river at a bridge site should
   (a) be scouring and erosive
   (b) have high velocity of current
   (c) have high silt
   (d) be nonscouring and low velocity of current
7. A tunnel should not be constructed along
   (a) strike direction
   (b) dip direction
   (c) oblique to the bed attitude
   (d) both along dip and strike direction
8. A tunnel is more suitable at
   (a) hanging wall side (b) foot wall side
   (c) thrust fault (d) reverse fault
9. Consider the following components of a dam.
   1. limb of the upward side
   2. at crest of fold
   3. at limb of downward side

   For the safe and stable construction of a dam, the correct geologic condition(s) would be

   Codes:
   (a) both 1 and 2 (b) both 2 and 3
   (c) both 3 and 1 (d) 2 only

10. Consider the following with regard to strength of rocks.

1. Mineral composition
2. Discontinuities
3. Texture and structure

Strength of rocks depend(s) upon

Codes:

(a) both 1 and 2 (b) both 2 and 3

(c) 1, 2 and 3 (d) 2 only

Answers to MCQs

1. (a) 2. (b) 3. (c) 4. (a) 5. (d) 6. (d) 7. (a) 8. (b)
9. (a) 10. (c)

chapter 10

Natural Agencies and Landforms

10.1 INTRODUCTION

The Earth surface and its topography are an intersection of climatic, hydrologic, and biologic action with geologic processes. Local climate can modify the topography, for example orographic precipitation modifies the topography by changing the hydrologic regime in which it evolves. Biological process involves decomposition and deposition of dead and decayed materials on the Earth's surface through microbial and unicellular organisms. As a consequence, the original structure of the existing landforms get modified.

The natural agencies slowly and continually modify the surface of Earth and bring about changes in the landscape. The natural agencies comprise of wind, water and glacier, etc. These agents involve surface processes, for example their actions like erosion, transportation and deposition. Besides the surface processes there are subsurface processes as well, e.g., earthquake and volcanism. While the surface processes may get strongly modified by climate resulting in new landforms, the subsurface processes cause tectonic uplift and subsidence. The resulting landforms include the uplift of mountain ranges, the growth of volcanoes, isostatic changes in land surface elevation (sometimes in response to surface processes), and the formation of deep sedimentary basins. The study of landforms and the natural processes involved for their formation is known as *geomorphology*.

10.2 PHYSICAL WORK OF WIND

Wind is one of the major natural agents to cause changes on the Earth's surface. The changes are affected mainly due to the movement of the wind and may be of temporary or permanent nature. These changes manifest themselves in the form of surface features, their exact nature depending on the velocity of the wind, its volume, and nature of the surface and its duration of time for which it blows and the wind-blown material gets deposited. Strong winds blowing over loose surface, dry soil and over desert may create new temporary morphological features.

Wind acts as an agent of erosion, as a carrier of transporting the eroded particles and grains from one place and for deposition of the wind-blown material at some other places. The three principal modes of activities of the wind, therefore, are erosion, transportation, and deposition.

10.2.1 Erosion

Wind alone can do little to erode solid rock exposed at the Earth's surface. However, in conjunction with chemical and mechanical weathering, it acts as an effective agent of erosion to disintegrate solid rocks in to small loose fragments. Since wind is capable of transporting loose unconsolidated material very efficiently, the disintegrated loose fragments can be picked up and transported. For this process to take place, a dry climate is necessary. It is so because in a humid climate, vegetation usually covers the surface and holds loose particles together. Moreover, wet material is usually cohesive because water tends to hold loose fragments together. On a small scale, wind can also abrade and polish solid rock surface. Deflation, abrasion and attrition are the different ways in which erosion of preexisting rocks can take place.

■ **Deflation** The most significant type of wind erosion is deflation. In this process, loose sediments are lifted from the surface and blown away. Thus the process of removal of particles of sand and dust by strong wind is termed as *deflation*. It is the main process of wind erosion in desert regions. The lowering down of the land surface due to deflation may cause enough depression sometimes with its base touching water table to considerable depth. It is called *blowout* when it develops on a small scale and *oasis* when it intersects with the water table and gets partially filled with water. Deflation basins commonly develop where calcium carbonate in sandstone formations is dissolved by groundwater, leaving loose sand grains that are picked up and transported by the wind.

Note Large deflation basins, covering areas of several hundred square kilometres, are associated with the greatest desert areas of the world, particularly in north Africa near River Nile.

■ **Abrasion** Wind becomes a powerful agent for rubbing and abrading the rock surfaces with the load (sand and dust particles) it carries. The load is acquired by the strong winds quite easily when blowing over sand dunes and over dry ploughed field. This type of erosion involving rubbing, grinding, polishing and abrading a rock surfaces by wind, with the help of its load, while travelling over the rocks is termed as *abrasion*. Wind abrasion is responsible for numerous features of erosion of land surface.

■ **Attrition** The sand grains and other particles lifted by the winds from different places are carried away to considerable distances. During this journey, the particles do not move in straight lines for two reasons. First, all the particles are not of same weight, and second, the wind velocity varies from the base to the top of the current. The grains, therefore, move in zig-zag paths that often cross each other and suffer repeated mutual collision. The wear and tear of load sediments due to mutual impacts during the transporting process is termed as *attrition*. Attrition is responsible primarily for reduction in size of load particles.

❑ *Erosional Features*

There are several types of landforms which can develop during the erosional process of wind. Some of the more common landforms developed due to erosion by wind are as follows.

■ **Yardangs** These are streamlined hill carved from bedrock or any consolidated (harder material) or semiconsolidated (softer material) material by the dual action of wind abrasion, dust, sand, and deflation. The soft material is eroded and removed by the wind, and the harder material remains. Depending upon the winds and the composition of the weakly indurated deposits of silt and sand from which they are carved, yardangs may form very unusual shapes. Yardangs form in environments where water is scarce and the prevailing winds are strong and unidirectional which carry an abrasive sediment load. The wind cuts down low-lying areas into parallel ridges which gradually erode into separate hills that take on the unique shape of a yardang (Fig. 10.1). Yardangs are elongated features typically three times or even more long than their width. When viewed from top, an yardang resembles the hull of a boat.

Fig. 10.1 *Yardang produced by wind erosion*

They are more commonly created from softer rock types like siltstone, sandstone, shale and limestone, but have also been observed in crystalline rocks such as schist and gneiss.

■ **Pedestal Rock** Also called *rock pedestal*, it is a naturally occurring rock whose shape resembles a mushroom after erosion (Fig. 10.2). Usually, found in desert areas, these rocks are formed over thousands of years when wind erosion of an isolated rocky outcrop progresses at a different rate at its bottom to that at its top. Abrasion by wind-borne grains of sand is most prevalent within the first one meter of the ground, causing the bases of outcrops to erode more rapidly than their tops. Occasionally, the chemical composition of the rocks can be an important factor also, if the upper part of the rock is more resistant to erosion and weathering, it will erode more slowly than the base.

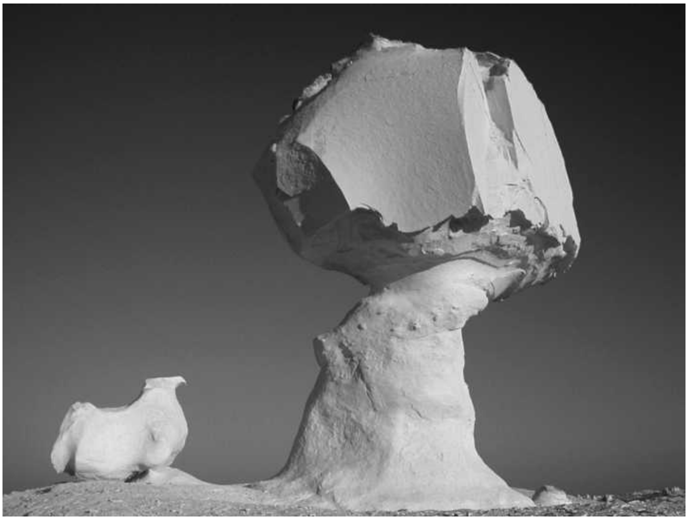


Fig. 10.2 *Pedestal rock*

■ **Ventifacts** These are the rocks that have been abraded, pitted, etched, grooved, or polished by wind-driven sand. These geomorphic features are most typically found in arid environments where there is little vegetation to interfere with aeolian particle transport, where there are frequently strong winds, and where there is a steady but not overwhelming supply of sand. In strong winds, sand grains cannot be continuously held in the air. Instead, the particles bounce along the ground, rarely reaching higher than a few feet above the Earth. Overtime, bouncing sand grains can erode the lower portions of a ventifact, while leaving a larger less eroded cap. Ventifacts can be abraded to eye-catching natural sculptures.

10.2.2 Transportation

Wind is an active agent of sediment transport in nature. Material of fine-grained size such as clay, silt and sand occurring on surface of the Earth are transported in huge volumes from one place to another. A great part of the wind load is contributed by dry incoherent regions like sand deserts and freshly ploughed fields. The transportation of loose fragments or sediment particles by wind can be explained by the processes of suspension and saltation.

❑ ***Suspension***

The light-density clay and silt particles may be lifted by the turbulent wind from the ground and carried high upward to upper layers of the wind where these particles move along the wind. This is called suspension because the particles once lifted are not allowed to rest on the ground again till the velocity of wind in those upper layers is checked.

❑ *Saltation*

The heavier and coarse sediments such as sand grains, pebbles and gravels, etc., are lifted periodically during high velocity and only for short distances and that too are for smaller heights from above the ground. The movement takes place close to the surface and the sediment may be dropped and picked up again and again during the transport process. On falling, the lifted particles transmit an impact to another stationary particle resting on the ground, thereby making the particle originally at rest to be available for transport. The height and distance to which, these sediments are transported in one cycle depends on the size and shape of the grains. Therefore, saltation process involves a series of jumps.

The transporting power of the wind depends on its velocity and on the size, shape and density of the particles it carries as sediment. The amount of sediment already present in the wind at a given point of time will also determine its capacity to take up any further load from an area that happens to lie in the course. Thus, at a point, the wind may be underloaded, fully loaded or overloaded.

10.2.3 Deposition

Sediment and particles once picked up by the wind from any source on the surface are carried forward for varying distances depending on the carrying capacity of the wind. Whenever and wherever the velocity of wind suffers a check for any reason, a part of or whole of sediment are deposited at that place. Obstructions such as hills, mountains, forest belts and precipitation (rainfall and snowfall) put a check on the velocity of wind. Load dropped by wind in a particular region may be very small or of considerable volume. These wind made deposits may ultimately take the shape of landforms that are commonly referred as *Aeolian deposits*.

❑ *Landforms by Deposition of Wind*

■ **Sand Dunes** A sand dune is a mound, hill or ridge of sand that lies behind the part of the beach affected by tides. Dunes are also observed commonly in desert areas of Rajasthan and Gujarat. They are formed over many years when windblown sand is trapped by beach grass or other stationary objects. Dune grasses anchor the dunes with their roots, holding them temporarily in place, while their leaves trap sand promoting dune expansion. Without vegetation, wind and waves regularly change the form and location of dunes. Dunes are, therefore, not permanent structures.

- o *Morphology of Sand Dunes* A sand dune is defined as a broadly conical shape of sand characterized with two slopes on either side of a medial ridge or crest. A dune is normally developed when sand-laden wind comes across some obstruction. When the process of deposition of sediments due to obstruction is continued for a long time, the accumulating sand takes shape of mound or a ridge. Since the development of sand dunes take place due to transportation and deposition of sand at a particular place, the direction of wind and its relationship with parts of dune is considered for anatomy of sand dunes. The convex shape of a sand dunes has a leeward and windward side. *Leeward side* is characterized by flipside of the dune while the side which faces the wind direction is known as *windward side*.

o *Types of Dunes*

Crescent Dunes The most common dune form on the Earth is the crescent. Crescent-shaped mounds generally are wider than their length. The slip face is on the dune's concave side. These dunes form under winds that blow from one direction only, and they are also known as *barchans*. Some types of crescent dunes move faster over desert surfaces than any other type of dune.

Note The largest crescent dunes on Earth, with mean crest-to-crest widths of more than 3 km, are in China's Taklimakan Desert.

Linear Dunes straight or slightly sinuous sand ridges, typically much longer than their width, are known as linear dunes. They may be more than 160 km in length. Linear dunes may occur as isolated ridges, but they generally form sets of parallel ridges separated by kilometres of sand, gravel, or rocky interdune corridors. Some linear dunes merge to form Y-shaped compound dunes. The long axes of these dunes extend in the resultant direction of sand movement.

Star Dunes Radially symmetrical, star dunes (Fig. 10.3) are pyramidal sand mounds with slip faces on three or more arms that radiate from the high centre of the mound. They tend to accumulate in areas with multidirectional wind regimes. Star dunes grow upward rather than laterally. They dominate in Rajasthan.

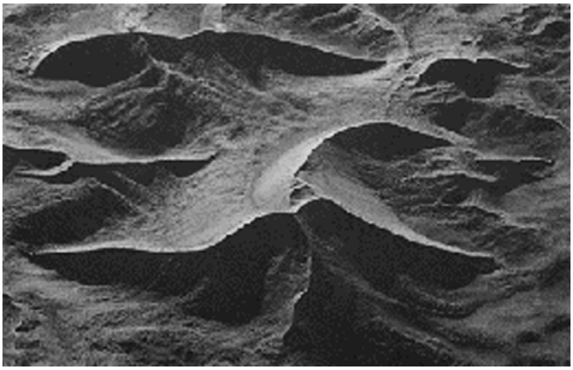


Fig. 10.3 *Star dune*

Barchans Sand dune characterized by crescent shape in which convex side faces the wind direction is known as barchan. Horn of dune is away from the wind direction as shown in Fig. 10.4(a).

Parabolic Dunes U-shaped mounds of sand with convex noses trailed by elongated arms are called parabolic dunes. Sometimes these dunes are called *U-shaped*, *blowout* or *hairpin dunes*. They are well known in coastal deserts. Unlike crescent dunes, their crests point upwind [Fig. 10.4(b)]. The elongated arms of parabolic dunes follow rather than lead because they have been fixed by vegetation, while the bulk of the sand in the dune migrates forward. The longest known parabolic dune has a 12 km long trailing arm.

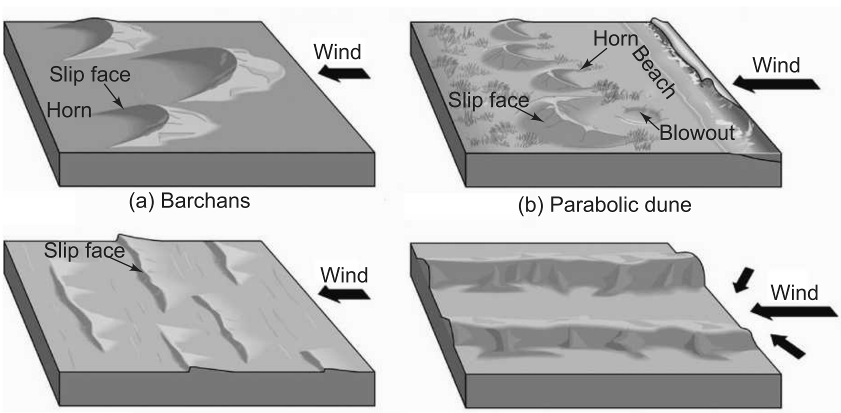


Fig. 10.4 *Different types of dunes*

Transverse Dune A transverse dune is characterized by its elongated shape when the wind direction is perpendicular to longer axis of the dune [Fig. 10.4 (c)].

Longitudinal Dune A longitudinal dune is characterized by its elongated shape when the wind direction is parallel to longer axis of the dune [Fig. 10.4(d)]

o *Importance of Sand Dunes* Sand dunes support an array of organisms by providing a nesting habitat for coastal bird species including migratory birds. Sand dunes are also a habitat for coastal plants. The Seabrook dunes are home to 141 species of plants, including 9 rare, threatened and endangered species. Sand dunes provide sand storage and supply for adjacent beaches. They also protect inland areas from storm surges, hurricanes, flood-water, and wind and wave action that can damage property.

o *Threats to Dunes and Protection* Construction of beachfront homes and hotels can encroach on sand-dune habitat. Increased tourism, foot traffic, and removal of plant species can cause severe erosion. Beach litter is aesthetically unpleasing, and can be harmful to shorebirds and other animals.

Methods commonly used to combat the advancement of sand dunes and thus protecting the built-up areas and agricultural lands from them include the following:

(a) Establishing frontal tracts or belts of vegetation that can resist the advancing sand by checking the velocity of the wind. Grasses, heather and some types of conifers have been tried with reasonable success in different areas of Rajasthan and Gujarat.
(b) Construction of wind breaks or wall around the area to be protected.
(c) Treating the sand locally with crude oil, reducing their susceptibility for transport by wind.

■ **Loess** The suspended clastic load (predominantly silt-sized sediment) transportated by wind when settles results in a blanket deposit of silt, known as loess. The silt deposited is typically in the 20–50 micrometer in size range. It is characterized by 20% of clay and remaining 80% by equal parts of sand and silt that are loosely cemented by calcium carbonate. Loess is usually homogeneous and highly porous and also traversed by vertical capillaries that permit the sediment to fracture and form vertical bluffs. Loess grains are angular with little polishing or rounding and composed of crystals of quartz, feldspar, mica and other minerals. Loess can be described as a rich, dustlike soil.

10.3 PHYSICAL WORK OF RIVERS

The water available on the Earth's surface is either due to rainfall or melting of snow, together called *precipitation*. This surface water divides itself into three parts—vaporization, underground water, and surface runoff—each following its own course and work physically in grading the Earth's surface. Of the total amount of precipitation, in any region, a portion evaporates and is known as *vaporization*. It moves within the atmosphere and finally returns to the surface mostly in the form of precipitation. While some part of the precipitation percolates through the pore-spaces in soil and rock and sink down gradually to form *subsurface water* also known as *underground water*, the remnant, which could neither evaporate nor sink down underground, flows down along the slope of the Earth's surface, forming *surface runoff*.

The water flowing upon the surface of the Earth tends to flow downwards, along the slope, within the topography. It ultimately gives rise to stream and river systems and is termed as *running water*. The exact amount of surface runoff, in any region, is controlled mainly by the prevailing climatic condition, gradient, porosity, permeability and solubility of the country rocks.

The water flowing in the river along its seaward course erodes the land over which it flows, brings about its channel decay, denudes the country rocks, transports the rock debris formed during erosion and weathering and finally, deposits the transported materials under favourable conditions. Figure 10.5 shows different physical works performed by rivers. The geological work of running water is considerable and can be broadly divided in processes like hydraulic action, abrasion, attrition, solution, transportation and deposition. While deposition, at suitable sites and under favourable conditions, causes aggradation, rest all the processes cause degradation. Erosion, weathering, transportation and deposition occur during an entire course of action of river in all of its stages; *the youth stage*—when it cuts its valley downward to establish graded condition with its base level, *the mature stage*—found in the plains lying adjacent to the mountain region, and *the old stage*—found near the mouth of the river. These processes and the developed landforms are described as follows.

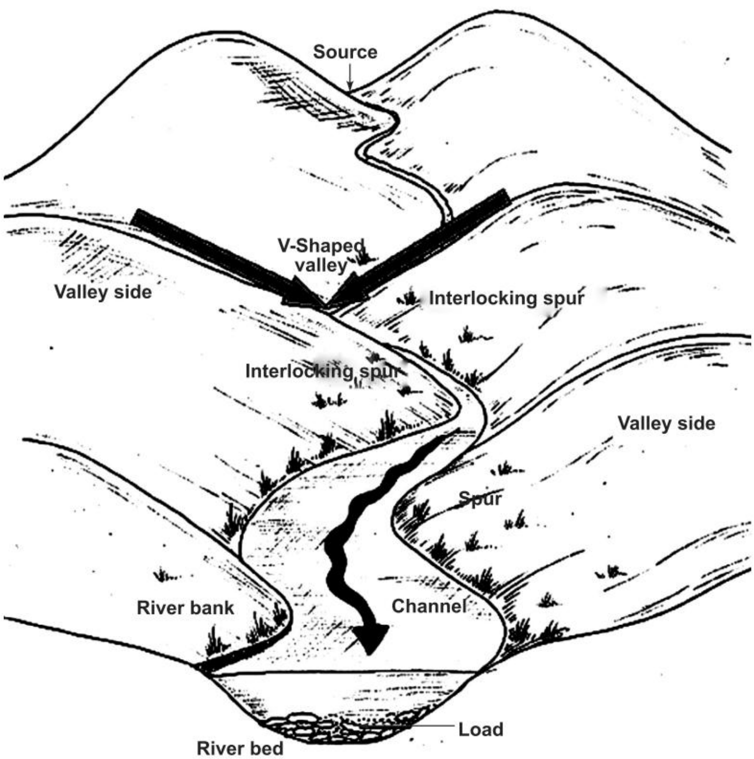


Fig. 10.5 *Schematic diagram showing physical work of a river*

10.3.1 Erosion

The surface runoff starts commonly in the form of a thin sheet of water in motion. This is known as *rain wash*. As soon as rainfall accumulates within valleys and begins its downward journey, it becomes a *stream*. All streams and rivers flow along *channels*, also called *course*, of their own. The amount of water passing through the channel per unit time is known as *discharge* of river (steam). The discharge of any stream is seldom constant. It increases to a maximum during monsoons, while in summer and winters, it dwindles down to a considerable extent. The channel of river adjusts itself periodically with regards to its shape and size depending upon the seasonal fluctuation in the discharge.

The discharge of river and the gradient of its valley-floor are responsible for the velocity of running water in its channel. The water flowing along a river valley has, therefore, the tendency to drag loose rock-fragments of variable dimensions due to kinetic energy associated with the flow. The continuous impact of running water with exposed rock-masses brings about, in the long run, breaking down of the latter. The broken rock-debris is driven further downstream with the river. Erosion due to running water includes hydraulic action, abrasion and attrition.

❑ *Hydraulic Action*

This is the dominating process of erosion along the upper part of the course of river, where the gradient is considerable. The wear and tear of country rocks due to a continuous impact of running water (i.e. its hydraulic action) produces lot of rock-fragment which is transported downstream along with discharge. The fragments produced by the hydraulic action vary in size from large boulders to fine silts and clay. These are subsequently transported along with the flow until they drop down and settle under suitable conditions. In rocks containing sets of cracks, also called *joints*, the inherent energy of flowing water often quarry out the individual blocks of rocks.

❑ *Abrasion*

The larger boulders and pebbles roll along the valley floor and move downstream while the smaller fragments travel in *saltation* or *suspension*. The rolling boulders and pebbles naturally rub themselves against the valley floor during their travel while the smaller fragments travelling in saltation or suspension impinge periodically upon the floor of the river valley. Such impacts bring about a mechanical wear and tear of the rock forming the base and banks of the channel. At the same time, the impinging rock-fragments themselves are worn out. This process of mechanical breaking down of the bedrocks is known as *abrasion*.

The effect of abrasion, along the course of river, is very well illustrated in the development of potholes ranging from a few centimetres to several metres. Potholes are formed upon the valley floor, made up of comparatively softer rocks when boulders and pebbles of harder rocks are caught up in eddies of water and allowed to have a swirling motion upon the floor of the channel.

> ***Note*** The effect of abrasion is more remarkable in case of running water than in case of wind. It is because the running water is definitely a more forceful and energetic agent than the blowing wind.

❑ *Attrition*

During flow of a river, there is collision among particles of sediments it carries. These particles in turn get reduced in size by friction and impact. Attrition can occur when the density of medium- to fine-grained particles are dominant with high energy condition of river. In this process, the grain shape and size are also modified.

10.3.2 Erosional Landforms

It is evident that the erosion takes place mostly during the young stage of the river when the energy condition is high. Several landforms as described below may develop during erosion by rivers.

❑ *Waterfall*

Falling of stream water from a height is called waterfall. Waterfalls are found in the upper course of a river during the initial process of erosion. They usually occur where a band of soft rock is ahead of hard rock. Waterfalls may often start as rapids. As the river passes over the hard rock, the soft rock ahead is eroded more quickly than the hard rock, thus leaving the hard rock elevated above the stream bed below. Consequently, a step in the river bed develops which grows further with the river flow over the hard rock step (cap rock), termed as *vertical drop*.

The drop gets steeper as the river erodes the soft rock beneath by processes such as abrasion and hydraulic action. A plunge pool forms at the base of the waterfall. This erosion gradually undercuts the hard rock and the plunge pool gets bigger due to further hydraulic action and abrasion. Eventually, the hard cap rock is unsupported and collapses. The rocks that fall into the plunge pool will continue to enlarge it by abrasion as they are swirled around. A steep-sided valley known as a *gorge* is left behind and as the process continues, the waterfall gradually retreats upstream.

❑ *Valley*

Valleys are one of the most common landforms on the Earth and are formed through erosion or the gradual wearing down of the land by water. In river valleys for example, the river acts as an erosional agent by grinding down the rock or soil and creates a valley. The shape of a valley varies and is mostly steep-sided canyons.

The most common valley landform developed by a river is a V-shape valley. The V-shaped valley, sometimes called a *river valley*, is a narrow valley with steeply sloped sides that appear similar to the letter *V* in cross section (Fig. 10.6). They are formed by strong streams, which over time have cut down into the rock through a process called *down cutting*. These valleys form in mountainous and/or highland areas with streams in their youth stage. At this stage, streams flow rapidly down steep slopes. An example of a V-shaped valley is between Darcha and Rohtang Pass, Himachal Pradesh, India.

❑ *Meander*

Symmetrical S-shaped loops in the course of a river are known as *meanders*. Meanders are formed due to change of velocity and energy condition at the same place during its progressive course of erosion. Water flows fastest on the outer bend of the river where the channel is deeper and there is less friction. This is due to water being moved towards the outer bend; as it flows around the meander this causes greater erosion which deepens the channel. Consequently, there is a reduction in friction and increase in energy for greater erosion. This lateral erosion results in undercutting of the river bank and the formation of a steep-sided river cliff. A meander is asymmetrical in cross section. It is deeper on the outer bend (due to greater erosion) and shallower on the inside bend (an area of deposition).

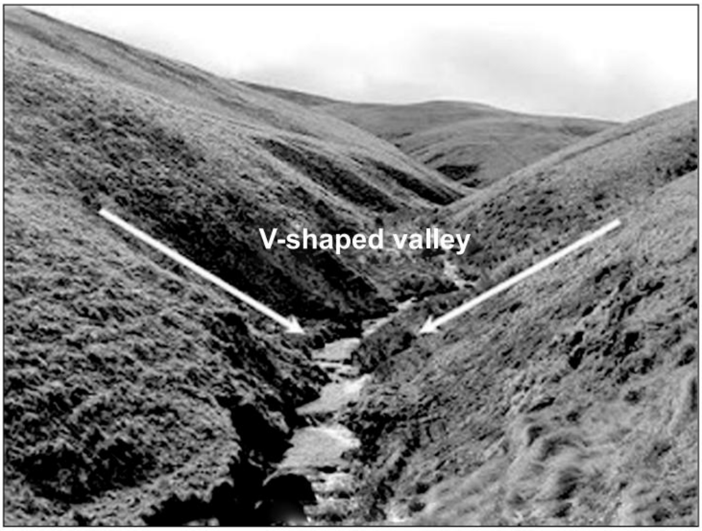


Fig. 10.6 *V-shape valley formed during erosional process*

In contrast, on the inner bend, water flows with slow velocity due to it being a low energy zone, deposition occurs resulting in a shallower channel. This increased friction further reduces the velocity, thus further reducing energy, encouraging further deposition. Over time, a small beach of material builds up on the inner bend. This is called a *slip-off slope* or *point bar*. The water in a meander flows in a corkscrew like movement as it moves from the inside of the bend towards the outside of the bend.

❑ *Braided Channel*

Braiding occurs when the river is forced to split into several channels separated by lands (Fig. 10.7). This feature develops when the river is supplied with large loads of sand and gravel. It is most likely to occur when a river has variable discharge and variable energy condition. The banks formed from sand and gravel are generally unstable and easily eroded. As a consequence, the channel becomes very wide in relation to its depth. The river may be choked with several sandbars and channels that are constantly changing their locations. Braiding also occurs in environments in which there are rapidly fluctuating discharges.

❑ *Ox-bow Lake*

As the outer banks of a meander continue to be eroded through processes such as hydraulic action, the neck of the meander becomes narrower. Eventually due to the narrowing of the neck, the two outer bends meet and the river cuts through the neck of the meander, usually during a flood event when the energy in the river is at its highest level. The water now takes its shortest route rather than flowing around the bend. Deposition gradually seals off the old meander bend forming a new straight course of river channel. Due to deposition, the old meander bend is left isolated from the main channel as an *ox-bow lake* (Fig. 10.8). Over time, this feature may fill up with sediment and may gradually dry up (except for periods of heavy rain). When the water dries up, the feature left behind is known as a meander scar.

Fig. 10.7 *Braided river*

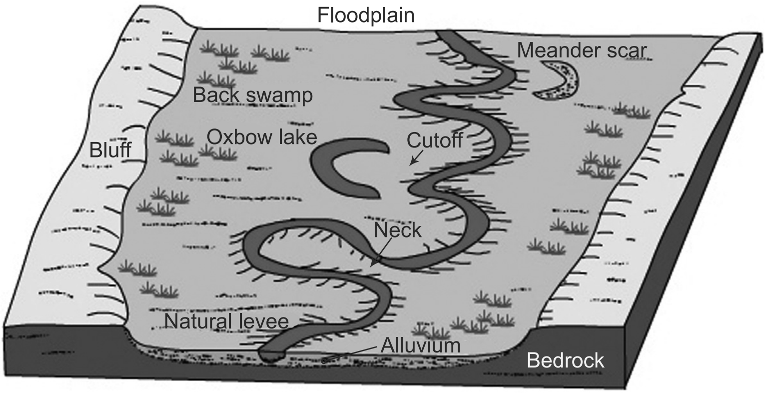


Fig. 10.8 *Formation of ox-bow lake*

■ **Transportation** The water running along a river channel is necessarily characterized with some amount of rock debris formed due to hydraulic action of river. The larger boulders and pebbles roll along the valley floor and move downstream while the smaller fragments travel in saltation (solution) and suspension. The rolling boulders and pebbles naturally rub themselves against the valley-floor during their travel while the smaller fragments, travelling in saltation, impinge periodically upon the floor of the river valley. Such impacts, therefore, bring about a mechanical wear and tear of the rocks forming the base and widening of the bank of river.

The energy condition of a river is high during transportation but slowly diminishes due to sediment particles and load carried by the river. However, during transportation, the action of abrasion and attrition takes place simultaneously apart from the dissolution activity.

10.3.3 Deposition

When the energy condition of a river diminishes and sediment load increases, the deposition of sediments occur. A basin is the most suitable locale for deposition of graded sediments having a calm and quite environment. A river is also under mature or in an old stage when deposition of transported material takes place. Different types of depositional landforms by the river are shown in Fig. 10.9. Depositional process is influenced by the depth of basin, sediment load and catchment area.

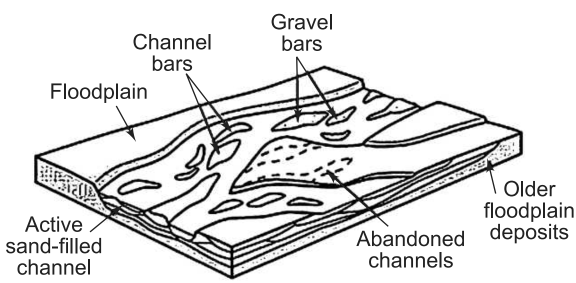


Fig. 10.9 *Different types of depositional landforms produced by river*

❑ *Depositional Landforms (Mature and Old Stage)*

■ **Levees** In its mature and old stages, river is at risk from flooding during the time of high discharge. If it floods, the velocity of the water falls, as it overflows the banks. This results in deposition of the sediment, because the sediment holding capacity of the river is suddenly reduced. It is usual for the coarsest material to be deposited first, forming small raised banks (levees) along the sides of the channel (Fig. 10.10). Subsequent floods increase the size of these banks and further deposition on the bed of the river also occurs. Therefore, the river with channel sediment builds up and flows at a higher level than the floodplain.

■ **Floodplain** Floodplains are created as a result of both erosion and deposition, although they are predominately depositional features. They are relatively flat areas of land on either side of the river, which form the valley floor in the mature and old stages of the river. During floods, the river overflows its banks, submerges the adjacent low lying areas, and deposition of alluvium-river silts and clays take place. Over time, a floodplain becomes wider and the depth of sediment accretions increases.

Fig. 10.10 *Natural levees produced by a river*

The width of the floodplain is determined by the amount of meander migration and lateral erosion that has taken place. The depth of the alluvial deposits depends partly on the amount of flooding in the past and rate of sedimentation. Over time, point bars and old meanders scars get incorporated into the floodplain, adding to the alluvial deposits. These become stabilized by vegetation as the meanders migrate and abandon their former courses.

■ **Alluvial Fans and Cones** When streams flow abruptly from steeper to gentler gradients, e.g., from top to the base of a mountain or ridge, its velocity is reduced and huge quantities of material carried by the river are dropped. This gives rise to a broad, low cone-shaped deposit called an *alluvial fan*. Thus, alluvial fans form where a stream leaves a confined valley and enters a flatter region.

The material constituting a fan includes coarse boulders and pebbles at its head to finer material down its slope. The term *alluvial fan* is commonly used when the slope of the deposit is below 10 degrees, and *alluvial cone* when the slope is from 10° to 50°. A series of adjacent fans may in time coalesce to form an extensive piedmont alluvial plain, also known as *bajada*.

■ **Delta** It is a feature of deposition located at the mouth of a river before it enters into a sea or lake. Deposition occurs as the velocity and sediment carrying capacity of the river decreases at the time it enters the lake or sea when bed load and suspended material are dumped. Flocculation occurs as fresh water mixes with seawater and clay particles coagulate due to chemical reaction and clay settles on the river bed. Deltas form only when the rate of deposition exceeds the rate of sediment removal.

Deltas can be described according to their shape (Fig. 10.11). The most commonly recognized is the characteristic *arcuate delta* which has a curving shoreline and a dendritic pattern of drainage. Many distributaries break away from the main channel as deposition within the channel itself occurs, causing the river to braid. Long shore drift keeps the seaward edge of the delta relatively smooth in shape. Fingers of deposition build out into the sea along the distributaries' channels, giving the appearance, from the air, of a bird's claw is known as *bird's foot delta*. A *cuspate delta* is pointed like a cup or tooth and is shaped by gentle, regular, but opposing, sea currents or along shore.

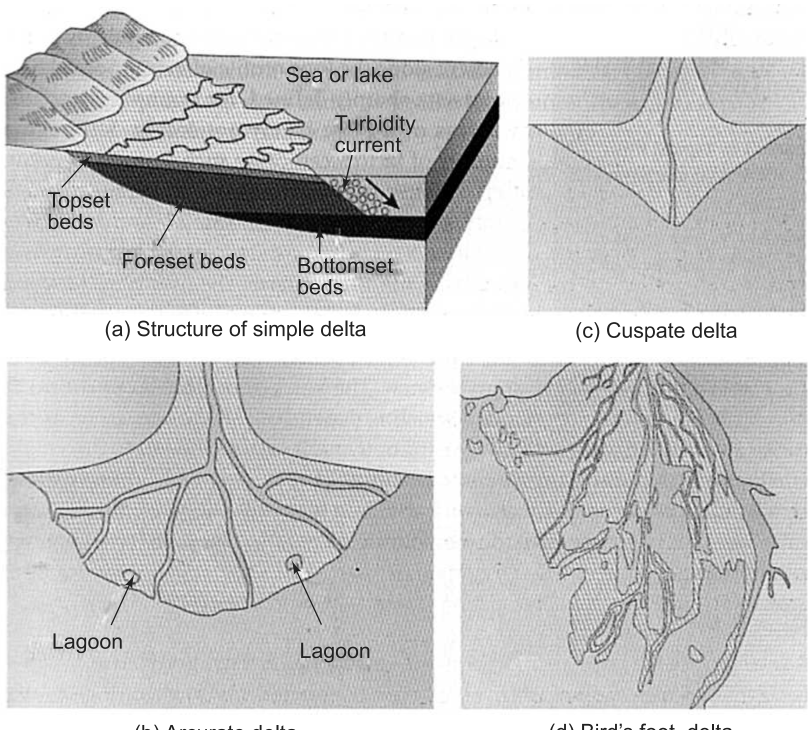


Fig. 10.11 *Different types of deltas produced by a river*

In order to form a delta the conditions required are abundant supply of sediments, absence of powerful waves or shore currents, stable body of water and shallow water offshore.

The step-by-step process for the formation of delta is as follows:

1. The sediment load of the river is very large, e.g., Hooghli Delta (West Bengal).
2. The coastal area into which the river pours its load has a small tidal range and weak currents. This means that there is limited wave action and, therefore, little transportation of sediment after deposition has taken place.

3. The larger and heavier particles are the first to be deposited as the river loses its energy. These form the topmost beds.
4. Medium-graded particles travel a little further before they are deposited as steep-angled wedges of sediment, forming the foreset beds.

10.4 PHYSICAL WORK OF GLACIERS

Glaciers are thick masses of ice which move over the ground surface under gravity. Glaciers may be looked upon as rivers of ice. They originate from compaction and recrystallization of snow. When the ground surface is level, snow fields slowly gain in thickness and do not, ordinarily, cause the ice to move. Along slopes of hill, on the other hand, the increasing weight of the ice flow or creep downwards. Such bodies of slowly moving ice are known as *glaciers*. They smoothly descend down along the hill slopes and continue to exist as such, even much below the *snow line*. Sometimes, however, a portion of the creeping mass of ice may break off and slide down under gravity, forming an *avalanche*.

Glacial erosion takes place due to abrasion, quarrying and frost wedging (plucking) and these together with transportation and deposition complete the cycle of physical work undertaken by the glaciers. This process of glacier erosion, transportation and deposition together are described by the term *glaciation*.

Glaciers are of common occurrence within the Himalayan region. Some of the more important Himalayan glaciers are Zemu, Kanchanjangha, Gangotri, Biafo, Siachen, Hispar and Batura, etc. The glaciers of the Himalayas are commonly found to be associated with rock debris, which have covered the masses of ice either partially or completely.

10.4.1 Morphology of Glaciers

The shape and size of a glacier together constitute its morphology. Different shapes of glaciers are derived, only due to its melting. This process brings about a conversion of loose snow flakes into small granules of ice. Such granular masses of ice, lying underneath the snow flakes in snow fields, are known as *neve* or *firn.* With further addition of snow to the field, *neve* is gradually transformed into a compact block of ice. In any snow field, therefore, loose flakes of snow are likely to be underlain successively by *neve* and compact ice.

They range in sizes between wide limits. While most of the Himalayan glaciers are about two to three kilometres in length, there are a few like the Fedchenko and the Siachen which are about fifty kilometres long. The Hispar, Batura, Biafo and the Baltoro range in length between forty and forty-five kilometres.

10.4.2 Erosion

The erosion by glaciers takes place by processes like abrasion, plucking and frost wedging as shown in Fig. 10.12. Large amounts of coarse gravel and boulders carried along underneath the glacier provide the abrasive power to cut trough like glacial grooves. Finer sediments in the base of the moving glacier further scour and polish the bedrock surface, forming a glacial pavement. Ice itself is not a hard enough material to change the shape of a rock but because the ice has rock embedded in the basal surface, it can effectively abrade the bedrock.

Plucking, also referred sometime as *quarrying*, is a phenomenon responsible for the erosion and transportation of bedrock, especially large jointed blocks. As a glacier moves down a valley, friction causes the basal ice of the glacier to melt and infiltrate into joints. Plucking is largely dependent on the amount of stress exerted on a clast overlain by glacial ice.

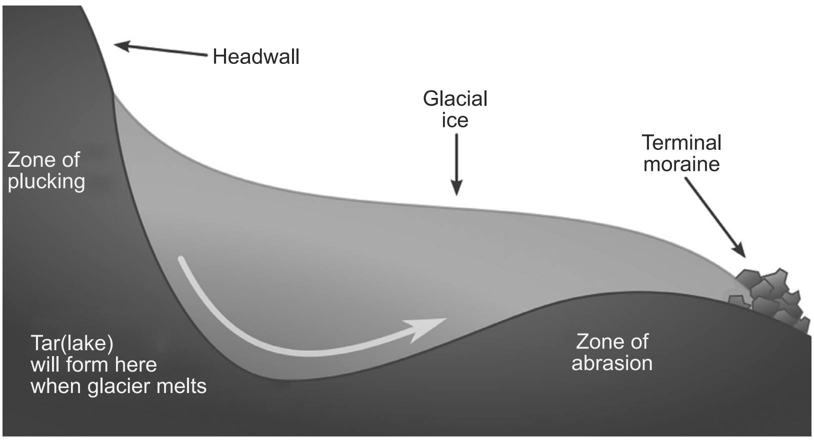


Fig.10.12 *Process of glacier erosion and deposition*

Frost wedging is the process by which water that has trickled into cracks in rocks (ranging from microscopic to large cracks) because of alternate freezing and thawing. Frozen water (ice) occupies 10% greater volume than does its liquid equivalent. Water that freezes thus pushes outward on the sides of a fracture with tremendous force. This eventually breaks rocks apart and triggers the erosion and transportation.

Glacial striations are scratches or gouges cut into bedrock by glacial abrasion. These scratches and gouges are signatures of erosive process by moving glacier. Glacial striations are usually multiple, straight and parallel, representing the movement of the glacier using rock fragments and sand grains, embedded in the base of the glacier, as cutting tools.

10.4.3 Erosional Landforms

Large numbers of landforms are developed due to erosion of existing rocks by glaciers. Few important landforms (Fig. 10.13) are described below.

❑ *Cirques*

Frost wedging followed by quarrying of the shattered rocks render the heads of a glaciated valley to produce blunt and steep slope. Such landforms are described as *cirques*. They are characterized by bowl-shaped hollows present at the glacier valley heads in the mountains. Cirque glaciers have rotational sliding that abrades the floor of the basin more than walls and that causes the bowl shape to form. As cirques are formed by glaciation in an alpine environment, the headwall and ridges between parallel glaciers called *arete* become more steep and defined. This occurs due to freeze/thaw and mass wasting beneath the ice surface. It is widely held that a common cause for headwall steepening and its extension headwards is the crevasses known as *bergschrund* that occur between the moving ice and the headwall. Plucking and shattering can be seen in cirques by exploring the crevasses. A cirque is exposed when the glacier that created it recedes.

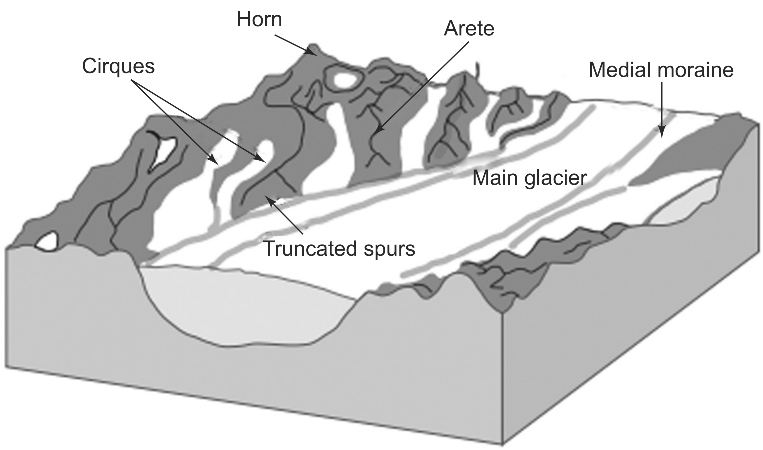


Fig. 10.13 *Different types of erosional landforms developed by glacier activity*

❑ *Arete*

A sharp sawtooth or serrated ridge that divides two cirque basins is known as *arete*. It is developed when the top of cirques becomes narrower and narrower.

❑ *Col Saddle*

It is a narrow depression formed by two headward eroding cirques that reduce an *arete*.

❑ *Horn*

A pyramidal sharp-pointed peak that results when several cirques and glacier gorges form individual mountain summit from all the sides is called *horn*.

❑ *U-Shaped Valley*

A valley carved by glaciers is normally U-shaped. The valley becomes visible upon the recession of the glacier that forms it. When the ice recedes or thaws, the valley remains, often littered with small boulders that were transported within the ice. Floor gradient does not affect the valley's shape, it is the glacier's size that does. Continuously flowing glaciers, especially in the Ice Age and large-sized glaciers carve wide, deep incised valleys.

❑ *Hanging Valley*

Valleys carved by tributary glaciers that are left standing high above the primary valley floor are known as a hanging valley. It is associated with an already existing U-shaped valley.

Examples of U-shaped valleys are found in every mountainous region that has experienced glaciation, usually during the Pleistocene Ice Ages. Most present U-shaped valleys started as V-shaped before glaciation. The glaciers carved it out wider and deeper, simultaneously changing the shape. This proceeds through the glacial erosion processes of glaciation and abrasion, which results in large rocky material (glacial till) being carried in the glacier.

10.4.4 Transportation

The huge amount of rock debris acquired by the glacier due to plucking, abrasion and frost wedging is transported as superglacial load—the load of debris or fragments on the surface of the glacier, englacial load—the load of debris or fragments within the ice sheet of glacier, and subglacial load—the load of debris or fragments beneath the ice sheet of glacier.

The amount of rock debris in the basal surface is important factor for abrasion during transportation. Higher quantity of rock in the basal surface of the ice influences the motion of the glacier affecting abrasion rates. As the bedrock is being worn away, the abrading fragments within the glacier are also being worn similar to sandpaper being worn away with use.

A continued supply of abrading fragments is required to uphold a similar level of abrasion. The fragments must be harder than the bedrock. Quartz fragments will abrade shale but shale fragments will not abrade quartz rich bedrock. A constant flow of melt water between the basal surface and the bedrock accelerates abrasion. The melt water constantly rinses away the rock floor allowing the coarser fragments to abrade bedrock.

Transportation of glaciers depends on the following conditions:

❑ *Nature of Flow*

The flow may be *plastic flow* (creep) which occurs within the ice under pressure, ice behaves as a plastic material; or *basal slip* in which the entire ice mass slips along the ground, most glaciers are thought to move by this process.

❑ *Speed of the Glacier*

The faster the glacier moves, the faster the bedrock will be eroded.

❑ *Thickness of the Ice*

Since thicker ice is heavy, it causes more downward force and increased pressure between the abrading fragments and the bedrock. There is a limit to how much ice will enhance abrasion. If the friction force between fragments and bedrock is too great, the ice will flow around the fragments. If the melt water is under sufficiently high pressure, it will cause ice to effectively buoy up and decrease the normal force of the ice on the bedrock. Moreover, the velocity of the glacier is increased, i.e., shape of the fragments. Larger, more angular fragments will scratch and scour more effectively than small and round fragments.

10.4.5 Deposition

The depositional activity by glaciers takes place when the velocity of the glacier retards and sediment loads increase. The rock waste, dropped down by a glacier enroute, or at its terminus, forms characteristic deposit of glacial origin, which is unsorted heaps of glacial deposits made up of debris and rock fragments. The glacial deposits are of two types. The ones which are deposited directly by the glacier, called *till* and the other which are deposited by the glacial melt-water called *tillite*. The types of landforms (Fig. 10.14) formed during depositional stage of glaciations are as follows.

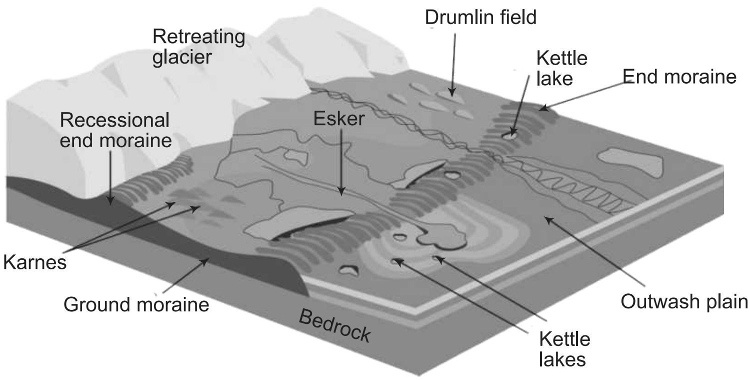


Fig. 10.14 *Different types of depositional landforms developed by glacier activity*

❑ *Depositional Landforms*

■ **Drumlins** It is an elongated, smooth, elliptical hill in the shape of an inverted spoon or half-buried egg formed by glacial ice acting on underlying unconsolidated till or ground moraine (Fig. 10.15). Drumlin is composed primarily of glacial till that lie parallel to the direction of ice movement.

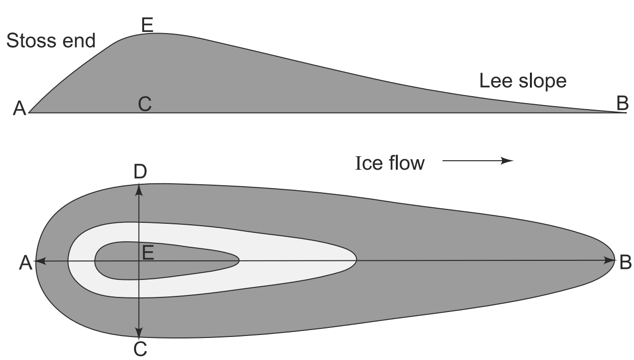


Fig. 10.15 *Drumlin and its cross section*

Drumlins are formed a short distance within the receding glacier ice and record the final direction of ice movement. They occur in symmetric, spindle, parabolic, and transverse asymmetrical forms. Drumlins are commonly found with other major glacially formed features and are related on a regional scale. They generally have a consistent ratio of 2:3.5 of width: length dimensions.

■ **Moraines** Moraine is an elongated ridge of unconsolidated drift deposited along the margins of a glacier. They are classed as end, terminal, recessional, lateral, and medial moraines. An *end moraine* is the general term describing a moraine deposited at the toe of the glacier during times of glacial stability (when the glacier stays in one place long enough for a significant amount of drift to accumulate). A *terminal moraine* is an end moraine that marks the greatest advance of the glacier before its retreat (i.e. it is farthest from the cirque). A *recessional moraine* is an end moraine deposited during periods of stability while the glacier is retreating. A *lateral moraine* is deposited along the margins of a glacier (often found on the walls of U-shaped valleys). A *medial moraine* is formed when two glaciers advance beyond their valleys and merge, at which point their lateral moraines combine to form a medial moraine between the two glaciers (Fig. 10.16).

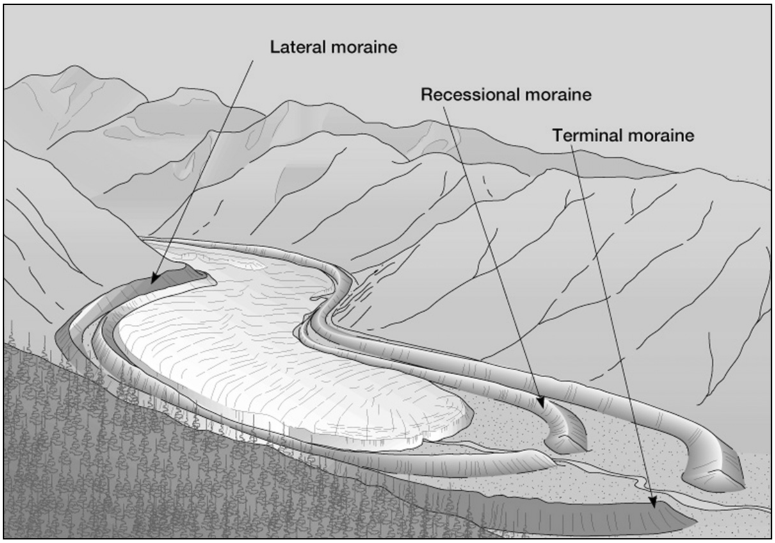


Fig. 10.16 *Different types of moraine*

Note Lateral and medial moraines only form in mountain glaciers, while the other moraines form in both mountain and continental glaciers.

■ **Eskers** The name *esker* is characterized by a ridge or elevation, especially one separating two plains or depressed surfaces. The term was used particularly to describe long sinuous ridges (Fig. 10.14). Eskers may be broad-crested or sharp-crested with steep sides. They can reach hundreds of kilometers in length and are generally 20–30 m in height.

Most eskers are argued to have formed within ice-walled tunnels by streams which flowed within and under glaciers. They tended to form around the time of the glaciation when the glacier was slow and sluggish. Eskers may also form by accumulation of sediment in supraglacial channels in crevasses, in linear zones between stagnant blocks, or in narrow embankment at glacier margins. Eskers form near the terminal zone of glaciers, where the ice is not moving as fast and is relatively thin.

The path of an esker is governed by its water pressure in relation to the overlying ice. Generally, the pressure of the ice was at such a point that it would allow eskers to run in the direction of glacial flow, but force them into the lowest possible points such as valleys or river beds, which may deviate from the direct path of the glacier. This process is what produces the wide eskers upon which roads and highways can be built. Less pressure, occurring in areas closer to the glacial maximum, can cause ice to melt over the stream flow and create steep-walled, sharply-arched tunnels.

■ **Buried Valley** It is an ancient river valley or stream valley that has been filled up with glacial or unconsolidated sediment. This sediment is made up of gravel, sand, silt and clay. These types of sediments can often store and transmit large amounts of groundwater and act as a local aquifer. Buried valleys may have been created by glacial lake runoff prior to the last major advance and retreat of continental glaciation. These valleys often have no surface expression. Recently, research has been focused on understanding the sedimentology of buried valleys in an effort to determine the safety of the continued use of the aquifers which are often found in them.

■ **Kames** It is a landform developed by a glacier which is an irregularly shaped hill or mound composed of sand, gravel and till that accumulates in a depression on a retreating glacier, and is then deposited on the land surface with further melting of the glacier. Kames are often associated with kettles, and this is referred to as kame and kettle topography. With the melting of the glacier, streams carry sediment to glacial lakes, building kame deltas on top of the ice. However, with the continuous melting of the glacier, the kame delta eventually collapses on to the land surface, furthering the kame and kettle topography.

Summary

The surface of the Earth is being continuously modified by the natural agents like river, wind and glacier, etc. These agencies cause the disintegration of the exposed rocks. The chapter discusses the role of wind, rivers and glaciers in erosion, transportation and deposition of the sediments eroded from one place and deposited at other places. The resulting landforms from these processes have also been discussed.

The erosional processes, due to wind, e.g., deflation, attrition and also abrasion are described. Wind action is more conspicuous in desert and semi-desert regions. Different types of topography created by the action of wind, known as aeolian topography, and depositional features like sand dunes, etc., known as aeolian deposits, are described. The direction of wind and its relationship with the morphology of dunes is presented. Different components of river erosion like abrasion, attrition and dissolution responsible for major changes of existing ground surface and the resulting landforms have been described. Glaciers are another important modifiers of the Earth's surface. Different types of glacial processes and landforms developed by them have been described.

Terminology

Alpine Environment The environment in which most of the time ice fall occur and area is covered with ice.

Aeolian Processes It is also spelled eolian or aeolian which pertains to wind activity in the study of geology and weather, and specifically to the winds ability to shape the surface of the Earth.

Bajada Sedimentary rocks made up of silt, sand and gravel.

Basal Surface The bottommost surface on which the glacier moves is called basal surface.

Beach Litter The waste material like excreta of living beings lying on the beach is called beach litter. This is a cause for the damage of dunes.

Canyon It is also known as a gorge characterized by a deep ravine between pairs of escarpments or cliffs and is most often carved from the landscape by the erosive activity of a river

Cap Rock The rock which covers the underlying layers or beds of different rocks is called cap rock.

Cliff (river cliff) Cliff is any steep slope that has been formed by natural processes. Cliffs formed by rivers are called river cliffs. They are on the outside of the curving section (meander) or a river and may be from a few meters to hundreds of meters high. Cliffs are formed when rivers cut swiftly into the land.

Crevasses A crevasse is a deep crack in an ice sheet or glacier. Crevasses form as a result of the movement and resulting stress associated with the shear stress generated when two semi-rigid pieces above a plastic substrate have different rates of movement.

Col A saddlelike narrow depression formed by two headward eroding cirques that reduce an arete.

Deep-incised Valley The valley is characterized by deep erosion of its base as well as lateral erosion.

Downward Erosion Also called vertical erosion, is a geological process that deepens the channel of a stream or valley by removing material from the stream's bed or the valley's floor.

Drumlin It is an elongated hill in the shape of an inverted spoon or a half-buried egg formed by glacial ice acting on underlying unconsolidated till or ground moraine.

Firn The granular masses of ice, lying underneath the snowflakes in snow fields, are also known as *neve*.

Fjord A drowned glaciated valley or glacial trough along a seacoast.

Floodplain The floodplain is the flat land of the river valley close to the river banks. The floodplain is usually found in the lower course of a river. It is a fertile area of land, used for agriculture.

Glacial Till Unsorted heap of glacial deposit made up of an assemblage of rock fragments and particles of different dimensions.

Ice Age It implies the presence of extensive ice sheets in the northern and southern hemispheres. It has intermittent glacial and interglacial periods.

Lateral Erosion It refers to the widening of a stream channel or valley. When a stream is high above its base level, down cutting will take place faster than lateral erosion, but as the level of the stream approaches its base level, the rate of lateral erosion increases.

Piedmont When the deposition of sediments take place adjacent to the place of denudation in hilly areas, the place of deposition is known as piedmont.

Striation It is characterized by a series of ridges, furrows or linear marks developed by glacial activity.

Supraglacial Channel It is formed when the rate of incision of surface-melt water exceeds the rate of glacier surface ablation.

Till Glacial sediment deposited directly by glacial ice (i.e. not melt water). Till is characteristically, unsorted and unstratified, consisting of sand, silt, pebbles, cobbles, boulders, and other debris.

Exercises

1. Define the surface geological process. Briefly describe the different natural agencies responsible for this process.

2. (a) Briefly explain the components of processes involved during wind erosion.
(b) What are the various depositional landforms made by wind?

3. (a) Describe the different types of sand dunes with neat sketches and factors responsible for their origin.
(b) Enumerate the importance of sand dunes and threats to their existence.

4. (a) How do rivers cause erosion? What are the important landforms developed thereof?
(b) Describe different stages of rivers and landforms associated with it.

5. (a) With neat sketches, describe different types of delta and their process of formation.

(b) What are the various stages of river in the development of a valley?

6. (a) Define glaciers and explain the erosional process made by a glacier.
(b) Describe the different landforms developed during glacier erosion.

7. In a valley glacier, does all of the ice move at the same time? Explain.

8. Write short notes on the following:
(a) Meanders (b) Waterfalls
(c) Cirques (d) Ox-bow lake
(e) Moraines (f) Valley sand bars
(g) Eskers (h) Hanging valley

9. Differentiate between the following.
(a) Yardangs and pedestal rock
(b) Barchan and parabolic dune
(c) Transverse dune and longitudinal dune
(d) Abrasion and attrition
(e) Ventifacts and pedestal rock
(f) Loess and dune
(g) Alluvial fan and delta
(h) U-shaped valleys and hanging valleys
(i) Eolin and alluvial deposits
(j) Erosion and weathering
(k) Abrasion and attrition
(l) Suspension and saltation

Multiple-Choice Questions

1. Abrasion by the river is related to which of the following process?
(a) Transportation (b) Erosion
(c) Deposition (d) Disintegration

2. Yardangs are landforms developed by
(a) river (b) glacier
(c) wind (d) groundwater

3. Ox-bow lake is produced by
(a) glacier (b) wind
(c) river (d) glacier and river

4. Saltation process is involved during
(a) wind erosion (b) river erosion
(c) glacier erosion (d) wind deposition

5. The wind direction to cause transverse dunes
(a) should be parallel to the dune
(b) should be perpendicular to the dune
(c) should be oblique to the dune
(d) has no relation with a dune

6. A U-shaped valley is generated due to the physical action of a
(a) river (b) glacier
(c) wind (d) sea

7. Hanging valley is formed by
(a) depositional action of river
(b) erosional action of river
(c) depositional action of glacier
(d) erosional action of wind

8. A river divides into several channels to deposit mainly silt and mud at the
(a) youth stage (b) mature stage
(c) old stage (d) depositional stage

9. A river in its old stage deposits its sediment mass in the
(a) ocean (b) pond
(c) desert (d) glaciated region

10. Cirques are the landforms formed due to
(a) erosion by glacier (b) deposition by glacier
(c) deposition by stream (d) erosion by river

Answers to MCQs

1. (b) 2. (c) 3. (a) 4. (c) 5. (b) 6. (b) 7. (b) 8. (b)
9. (a) 10. (a)

chapter 11

Earthquake

11.1 INTRODUCTION

Of the entire natural calamities, earthquakes are the most devastating hazards. It causes considerable destruction and the toll of human lives and properties is unimaginable. A thorough understanding of the causes of earthquakes to ascertain the factors leading to strong ground motions, prediction of future earthquakes, and to design earthquake-resistant structures are expected from civil engineers. An earthquake may be defined as a wavelike motion generated by forces in constant turmoil under the surface layer of earth travelling through the Earth's crust. In simple words, an earthquake may be defined as vibrations or tremors of the Earth.

The occurrence of earthquake is due to the sudden release of energy in the Earth's crust that creates a series of waves, known as *seismic waves*. The seismicity of a region is, in general, defined as earthquakes over a period of time and refers to the frequency, type and size of an earthquake for that particular region. The size of an earthquake is defined by its intensity and magnitude. For recoding the occurrence of an earthquake and vibrations, a *seismograph* (seismometer) is used. The record of measurement is known as *seismogram*. The *magnitude* of an earthquake is measured using observations from seismometers. They are defined in terms logarithmic to the base 10 of its amplitude. The most recent earthquake of magnitude 11.0 (or even larger) took place in Japan in 2011 (*as of* October 2012), and is the largest recorded earthquake. On the other hand, *intensity* of shaking is measured on the modified Mercalli intensity scale. The shallower an earthquake, the more damage it causes to structures.

Earthquakes are caused mostly by ruptures taking place in form of geological faults, but also by other events such as volcanic activity, landslides, mine blasts, and nuclear tests. Landslides are a common phenomenon during earthquakes. The resulting flow of pyroclastic debris mixed with water destroys structures in their ways causing huge destruction. The place of origin of earthquake, i.e. the point of initial rupture is called its *focus* or *hypocentre* or *focal area*. The *epicentre* of an earthquake is the point on the Earth's surface directly above the *focus*, the point of origin of earthquake. It may be taken note of that for an earthquake to trigger; it is not merely a point but a considerable area of variable extent that is involved in elastic rebound of rocks. However, this is idealized to be a point, *the focus*. Accordingly, the epicentre is also a tract and not an isolated point.

An earthquake causes shaking of the ground or in other words, it causes displacement of the ground. Since a strong ground motion is of concern, a civil engineer has to pay due attention to the regions susceptible to strong ground motions while selecting a site for a particular project. Therefore, mapping of the hazard zones is of paramount importance to ensure safe construction of the civil engineering structures. Earthquakes can also trigger landslides, and occasionally volcanic activity. When the epicentre of a large earthquake is located offshore, the seabed may get displaced sufficiently to cause a tsunami.

11.2 GROUND MOTION

Before discussing motion of the ground, it is essential to have a knowhow about the interior of the Earth. The Earth is formed of four concentric layers the *inner core*—having temperatures up to 5,500°C and is a solid mass of iron and nickel; the *outer core*—is a liquid layer of iron and nickel, extremely hot, this layer has temperatures similar to the inner core (the inner and outer cores together constitute *barysphere*); the *mantle*—characterized by medium density and semi-solid material, is the widest section of the Earth, approximately 2,685 km thick. The upper parts of the mantle are hard rock but its lower part is softer and begins to melt; and the *crust*—which is part of *lithosphere* (comprised of the crust and upper mantle), is a solid rock layer which is about 35 km in thickness in plains and 100 km in thickness in Himalayan regions. It is the outer layer of the planet.

The crust and the upper mantle form a cold, strong layer floating on the lower liquidous mantle. The lithosphere is fragmented into a dozen of huge, irregularly shaped pieces, called *tectonic plates*. There are 7 large and several small moving plates. The plates have a depth of about 100 kilometers and on average they move only a few centimeters (5 to 10 cm), a year relative to one another. These plates are in constant motion and slide over, under and past each other on top of the partly molten inner layer. The reason attributed to the movement of plates in different directions is the convection currents in the mantle.

As the hotter mantle rises upwards, the cooler material sinks; the material rises and spreads out while the crust splits and diverges; the plates converge and subduct as the material sinks. Subduction occurs when plates collide and one is drawn beneath another. This process can take thousands of years. The collision of plates creates mountains as rock layers are forced upward. As the plates diverge, lava pushes through the mantle, cools and forms a new section of crust.

From the foregoing, it is evident that the moving plates may collide, sink, or pull apart as the plates scrape boundaries, creating stress which results in strain setting energy free. Plates moving slowly alongside of each other create friction and intense heat as they slide. It must be noted that stress is exerted on the plates as they move and in those around them. Sometimes, the plates are locked together and are unable to release the energy accumulated which builds up in the rock. When this energy elevates to the elastic limit of the rocks, they break free causing the ground to shake. This usually occurs when two plates either ride over, or slide against each other, and the material at the edge of the tectonic plates deforms and ruptures at its weakest point. The accumulated strain energy stored within the plate is released in the form of vibrations. Thus, an earthquake can occur if the plate slips, sliding away or towards each other or side by side.

As discussed above, it is obvious that an earthquake is caused due to the sudden motion of the ground. The ground motion at a particular instant of time can be completely defined by three orthogonal components of translation; the three components of rotation being quite small are neglected. Vibration of the Earth's surface is a net consequence of horizontal and vertical motions, caused by seismic waves that are generated by release of energy due to rupture at the fault. When there is a sudden localized disturbance in rocks, waves similar to those caused by a stone, thrown into a pool spread out through the Earth; an earthquake generates a similar disturbance. Since the Earth vibrates continuously at periods ranging from milliseconds to days and amplitudes varying from nanometres to metres, the response of civil engineering structures to strong ground motions is of great concern. However, weak ground motions are hardly felt and are therefore not important at all for civil engineers. But, however, they are important for seismologists. Further, the ground motion can be described in terms of displacement, velocity, or acceleration. However, for structural engineering purposes, acceleration gives the best measure of earthquake intensity, and forms a basis for dynamic analyses of structures. In the section to follow, a brief description of seismic waves is presented.

11.3 SEISMIC WAVES

Seismic waves are formed due to an earthquake, explosion, or a volcano that imparts low-frequency acoustic energy waves that travel through the Earth's layers. These are recorded by mean of instruments known as seismometer, hydrophone (in water), or accelerometer. The propagation velocity of the waves depends on density and elasticity of the medium through which they travel. Velocity tends to increase with depth, and ranges approximately 2 to 8 km/s in the Earth's crust and up to 13 km/s in the deep mantle. Earthquakes create various types of waves with different velocities; when reaching seismic observatories, their different travel times help scientists locate the source of the earthquake, the hypocentre. The two main types of waves are *body waves* and *surface waves*. Earthquakes radiate seismic energy as both body and surface waves.

11.3.1 Body Waves

Body waves travel through the interior of the Earth. The examples are P- and S-waves. They travel deep into the body of the Earth before emerging on the Earth's surface. These waves create ray paths refracted by the varying density and modulus (stiffness) of the Earth's interior. The density and modulus, in turn, vary according to temperature, composition, and phase. This effect is similar to the refraction of light waves.

❑ *Primary Waves (P-waves)*

P-waves are compressional waves that are longitudinal in nature (the particles vibrate in the direction of propagation), and accordingly they are also known as *compression waves* or *longitudinal waves*. P-waves are pressure waves that travel faster than other waves through the Earth to arrive at seismograph stations first, and hence are called *primary waves*. Sometimes these waves are also called *push and pull waves* since oscillations occur to and fro in the path of the wave as shown in Fig. 11.1. They can travel through any type of material, including fluids. In air, they take the form of sound waves; hence they travel at the speed of sound. Typical speeds are 330 m/s in air, 1450 m/s in water and about 5000 m/s in granite; they travel fastest in the rigid rocks. However, P-waves are not as destructive as the other waves, since they have smaller amplitude and the force that their customary vertical motion creates, rarely exceeds the force of gravity.

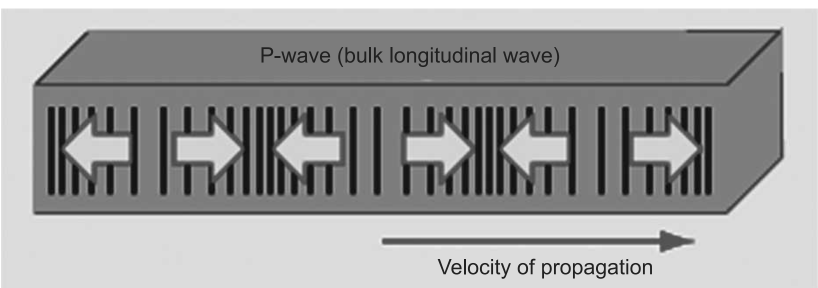


Fig. 11.1 *Primary wave*

❑ *Secondary Waves (S-waves)*

S-waves are shear waves which are transverse in nature. They are also called *transverse waves* or *distortional waves*. Being transverse in nature, they displace the ground perpendicular to the direction of propagation; the particles vibrate at right angles to the direction of propagation as shown in Fig. 11.2. S-waves may develop violent tangential vibrations strong enough to cause great destructions. Depending on the propagation direction, the wave can take on different surface characteristics; for example, in the case of horizontally polarized S-waves, the ground moves alternately to one side and then the other. However, shear waves can travel only through solids, since fluids (liquids and gases) do not support shear stresses. S-waves are slower than P-waves, and speeds are typically around 60% of that of P-waves in any given material. S-waves usually have larger amplitude than the P-waves. These waves arrive at seismograph stations after the P-waves during an earthquake. Shear waves are more devastating than primary waves.

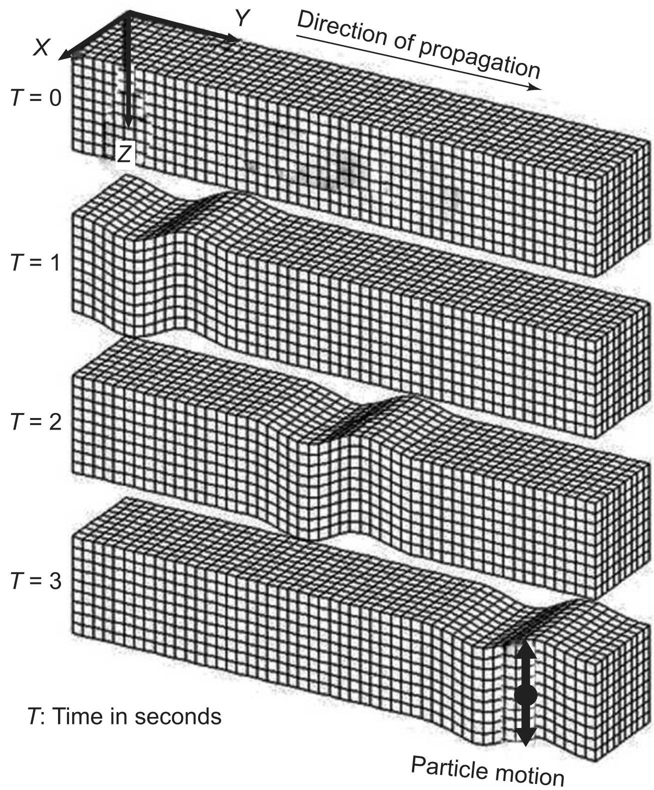


Fig. 11.2 *Secondary waves*

11.3.2 Surface Waves

Surface waves are analogous to water waves and travel along the Earth's surface. The examples of surface waves are Love waves and Rayleigh waves. They travel slower than body waves. Because of their low frequency, long duration, and large amplitude, they can be the most destructive type of seismic wave. They are called surface waves because they diminish as they get further from the surface.

❑ *Love Waves (L-waves)*

L-waves are horizontally polarized shear waves (SH waves), existing only in the presence of a semi-infinite medium overlain by an upper layer of finite thickness. The displacement of particles in L-waves is horizontal, in the direction of propagation as shown in Fig. 11.3. They are named after AEH Love, a British mathematician, who created a mathematical model of the waves in 1911. They usually travel slightly faster than Rayleigh waves and have the largest amplitude.

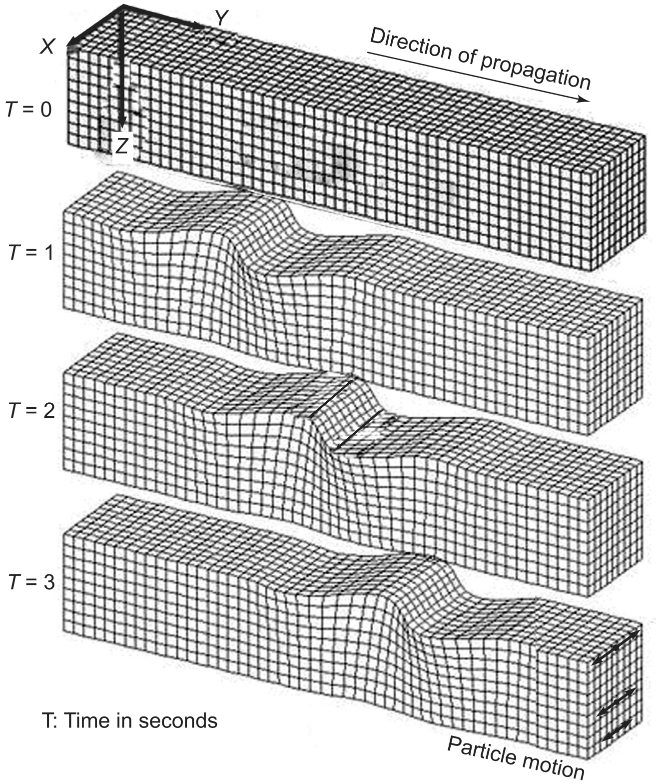


Fig. 11.3 *Love waves*

❑ *Rayleigh Waves*

Rayleigh waves (Fig. 11.4), also called *ground roll,* travel as ripples with motions that are similar to those of waves on the surface of water (note, however, that the associated particle motion at shallow depths is retrograde, and that the restoring force in Rayleigh and in other seismic waves is elastic, not gravitational as for water waves). The existence of these waves was predicted by John William Strutt, Lord Rayleigh, in 1885. They are slower than body waves, about 90% of the velocity of S-waves for typical homogeneous elastic media.

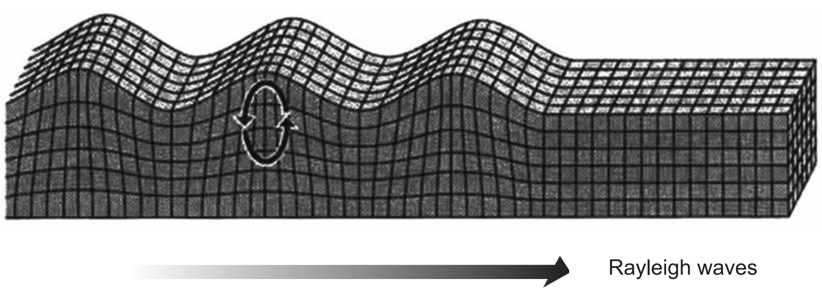


Fig. 11.4 *Rayleigh wave*

11.4 CLASSIFICATION OF EARTHQUAKES

Earthquakes may be classified as follows.

❑ *On the Basis of Depth of Focus*

Earthquakes are classified as *shallow-focus earthquakes*—when depth of focus is up to 70 km below the Earth's surface; *intermediate-focus earthquakes*—originate between 70 to 300 km below the Earth's surface and; *deep-focus earthquakes*—also called plutonic, originate between 300 to 700 km. The deep focus earthquakes are associated with the Benioff zone.

❑ *On the Basis of Mode of Origin*

Earthquakes are classed as *tectonic earthquakes*—caused due to faulting or relative movement of crustal plates and; *non-tectonic earthquakes*—caused due to volcanic eruptions, atomic explosions, landslides, reservoir induced seismicity (Koyana earthquake, Maharashtra), etc.

❑ *On the Basis of Magnitude*

Representation of earthquakes by its magnitude may also be considered its class.

11.5 CAUSES OF EARTHQUAKES

Earthquakes are vibrations of the ground surface caused by a transient disturbance of the elastic or gravitational equilibrium of the rocks at or beneath the Earth's surface. The Earth's crust is being slowly displaced at the margins of plates, presumably by convection currents, in the upper mantle. Differential displacements give rise to elastic strains which eventually exceed the strength of rocks involved and a fault is developed. The gradual build-up of shearing stress results in fracturing of rocks when their yield point is exceeded. In the process, the strain may be partly or wholly dissipated. Initially, movement may occur over a small area of the fault plane, which is followed by a much larger surface. The initial movement results into *foreshocks* followed by an earthquake. The displacement of rock masses involved in faulting relieves the stress, however develops new set of stresses in the adjacent areas. This consequently leads to readjustments along the fault plane, resulting in *aftershocks*. Tectonic earthquakes are the most common and can be explained on the basis of elastic rebound theory and plate tectonic theory.

11.5.1 Elastic Rebound Theory

Tectonic earthquakes occur anywhere in the Earth where there is sufficiently stored elastic strain energy to drive fracture propagation along a fault plane. The probability of occurrence of an earthquake is likely along the fault. The sides of a fault move past each other smoothly and seismically only if there are no irregularities or along the fault surface that increase the frictional resistance. Most fault surfaces do have such irregularities and this leads to a form of stick-slip behavior. Once the fault has locked, continued relative motion between the plates leads to increasing stress and, therefore, stored strain energy in the volume around the fault surface. This continues until the stress has risen sufficiently to break through the asperity, suddenly allowing sliding over the locked portion of the fault, releasing the stored energy. This energy is released as a combination of radiated elastic strain seismic waves, frictional heating of the fault surface and cracking of the rock, and an earthquake is caused.

This process of gradual build-up of strain and stress punctuated by occasional sudden earthquake is referred to as the elastic-rebound theory. It is estimated that only 10 per cent or less of an earthquake's total energy is radiated as seismic energy. Most of the earthquake's energy is used to enhance the earthquake fracture growth or is converted into heat generated by friction. Therefore, earthquakes lower the Earth's available elastic potential energy and raise its temperature, though these changes are negligible compared to the conductive and convective flow of heat out from the Earth's deep interior.

11.5.2 Plate Tectonic Theory

The theory of plate tectonics has been outlined in Section 11.2. The Earth's crust consists of a number of crustal plates (seven major plates), which are in constant motion over the viscous mantle. These plates override, plunge beneath one another, collide with each other, or brush past each other. In the process, the plate boundaries are stressed and are either diverging or converging or subducting. The plate movements are in fact very slow and the stresses build up gradually. A state is reached when faulting occurs and rebounding of displaced edges takes place with release of the stored elastic energy as seismic waves. Shallow-focus earthquakes occur on the ridge; while intermediate and deep-focus earthquakes occur on the down going plate as it collides with another plate. The continental drifts, volcanic eruptions, and ridges on ocean floors have given way to the theory of plate tectonics.

11.5.3 Causes of Non-Tectonic Earthquakes

The tremors that are originated due to other than tectonic activities such as volcanisms, landslides, mining, reservoirs, etc., are categorized as non-tectonic earthquakes. The examples of the non-tectonic earthquakes are Koyana earthquake (magnitude: 6.1) and Bhasti (magnitude: 4.8). The indirect consequence of these earthquakes is reactivation of existing faults.

11.6 EFFECTS OF EARTHQUAKES

The hazards imposed by earthquakes are unique and catastrophic. The magnitude and destructive consequences of earthquakes have serious implications and the damage, therefore, needs to be minimized so far as possible. The effects of earthquakes may be direct or indirect. While the direct effects include ground motion and faulting, the indirect (consequential) effects cause damages as a result of the processes set in motion by an earthquake.

❑ *Direct Effects*

As discussed above, the seismic waves result in ground motion that can damage or cause complete collapse of the structures. Further, in hilly areas, the induced vibrations may cause landslides leading to damage and loss of life. The soil vibrations may affect the foundation of the structure as well. Liquefaction of the soil may take place and large masses of soils can be displaced laterally, which may lead to serious consequences. The ground may crack, rifting and buckling may take place disrupting the foundations, structures and breaking of service pipelines. Groundwater and its circulation may be greatly disturbed. Old lakes may get drained off through cracks, and new one's form in depressions.

■ **Damage to Structures** Earthquakes cause great damage to structures such as buildings, roads, rails, factories, dams, bridges, etc., and thus cause heavy damage to human property. One of the reasons for the loss of human life in highly populated areas is due to collapse of buildings.

■ **Landslides** The shocks produced by earthquakes, particularly in hilly areas and mountains which are tectonically sensitive cause landslides. The debris fall on human settlements and transport system on the lower slope segments, inflicting damage to them.

■ **Deformation of Ground Surface** Severe tremors and resultant vibrations caused by earthquakes result in the deformation of ground surface. This is due to the rise and subsidence of ground surface and faulting activity (formation of faults).

■ **Liquefaction** Under earthquake loading, some soils may get compacted; increasing the pore water pressure and causing a loss of shear strength, and behave like liquid mud. This is known as liquefaction. Consequently, this may lead to settlement of buildings.

❑ *Indirect Effects*

Some of the more prominent indirect effects are as follows.

■ **Fires** The strong vibrations caused by severe earthquakes shake the buildings and may cause severe fires in houses, industries and mines because of the damaging of gas lines, contact of live electric wires, and displacement of other fire related and electric appliances.

■ **Flash Floods** The sloshing of enclosed water in reservoirs, lakes and harbours may cause severe flash floods, termed as *sieches*. Severe floods are also caused because of blocking of water flow of rivers due to rock blocks and debris produced by severe tremors in the hill slopes facing the river valleys; the rivers may even change their main course.

■ **Tsunamis** The seismic waves caused by violent movement of sea floor (measuring more than 7 on the Richter scale) travelling through sea water generate high sea waves and cause great loss of life and property. These waves, known as *tsunamis*, are of extremely long time periods and usually take place in subduction zones.

11.7 MEASUREMENT OF EARTHQUAKES

The measurement of earthquakes is important because it dictates about the future planning and implementation of civil engineering projects in various parts of the country. A civil engineer is concerned with the effect of earthquake ground motions on structures and the damage affected. The damage caused depends on the size of the earthquake. Measurement of earthquakes also help in earthquake zonation so as to facilitate design of structures with adequate safety using the appropriate zone factors. The two popular ways to assess the severity of earthquakes are quantifying its magnitude and evaluating the intensity and are described as follows.

11.7.1 Magnitude

Magnitude of an earthquake is a measure of the energy released by the earthquake, which defines its size. Earthquakes are rated on the basis of amplitude of seismic waves recorded as seismograms. Contrary to the intensity, the magnitude does not vary from place to place. Because earthquakes vary a lot in size, earthquake magnitude scales are logarithmic. Richter in 1935 devised a logarithmic scale for comparing the magnitudes of California earthquakes. It was the first earthquake magnitude scale. The scale is a base-10 logarithmic scale. The Richter scale was developed to assign a single number to quantify the energy released during an earthquake. However, this scale is found not to be very accurate for measuring the size of earthquakes above about magnitude of 6.5. This led to the development of other refined magnitude scales, such as local or moment magnitude (although news readers still often talk about the Richter scale). The new magnitude scales are set up so that the numbers used are similar to the Richter scale for easy comparison.

The magnitude M of an earthquake is given by Eq. (11.1), when a standard seismometer shows maximum amplitude of A μm at a point 100 km from the epicentre.

$$M = \log_{10} A \tag{11.1}$$

When a standard seismometer is not placed at a point 100 km from the epicentre, which is most usual, then Ritcher magnitude scale M (also referred to as local magnitude M_L) given by (11.2) may be used.

$$M = \log_{10} A - \log_{10} A_0 \tag{11.2}$$

where A = maximum recorded trace amplitude for a given earthquake at a distance, and

A_0 = maximum amplitude for a particular earthquake selected as a standard.

There are many different methods for measuring magnitude from seismograms and with different types of seismometers; each method only works over a limited range of magnitudes. The methods are either based on body waves (which travel deep within the structure of the Earth), or on surface waves (which primarily travel along the uppermost layers of the Earth), or on completely different methodologies. However, all of the methods are designed to agree well over the range of magnitudes where they are reliable. The different ways of representing earthquake magnitudes are summarized in Table 11.1.

Table 11.1 *Different types of earthquake magnitudes and ranges of their applicability*

Magnitude Type	*Applicable Magnitude Range*	*Distance Range*	*Comments*
Duration (M_d)	<4	0–400 km	Based on the duration of shaking as measured by the time decay of the amplitude of the seismogram. Often used to compute magnitude from seismograms with “clipped” waveforms due to limited dynamic recording range of analog instrumentation, which makes it impossible to measure peak amplitudes.
Local (M_L)	2–6	0–400 km	The original magnitude relationship defined by Richter and Gutenberg for local earthquakes in 1935. It is based on the maximum amplitude of a seismogram recorded on a Wood–Anderson torsion seismograph. Although these instruments are no longer widely in use, M_L values are calculated using modern instrumentation with appropriate adjustments.
Surface (M_s)	5–8	20–180 degrees	A magnitude for distant earthquakes based on the amplitude of Rayleigh surface waves measured at a period near 20 seconds.
Moment (M_w)	>3.5	All	Based on the moment of the earthquake, which is equal to the rigidity of the Earth times the average amount of slip on the fault times the amount of fault area that slipped.
Energy (M_e)	>3.5	All	Based on the amount of recorded seismic energy radiated by the earthquake.
Moment (M_i)	5–8	All	Based on the integral of the first few seconds of P–wave on broadband instruments.
Body (M_b)	4–7	16–100 degrees (only deep earthquakes)	Based on the amplitude of P–waves. This scale is most appropriate for deep–focus earthquakes.

Note The magnitude is basically defined as the logarithm of the ratio of the amplitude of waves measured by a seismograph to arbitrary small amplitude. In simple terms, this means that at the same distance from the place of earthquake, the tremour will be 10 times as large during an earthquake of magnitude 5.0 as during an earthquake of magnitude 4.0. The total amount of energy released by the earthquake, however, goes up by a factor of 31.6. For example, an earthquake of magnitude 5.0 is about 32 times bigger than an earthquake of magnitude 4.0; and an earthquake of magnitude 6.0 is about 1000 times bigger than an earthquake of magnitude 4.0.

11.7.2 Intensity

Earthquake intensity describes how much ground shaking occurred, or in other words how strong an earthquake was, at a particular location. Lines joining locations of equal intensity are known as *isoseismals*. Earthquake waves weaken as they travel away from the earthquake source, so in general, it is felt less strongly with the distance from its source. Moreover, since intensity is expressed on the degree of destruction caused and hence varies from place to place. The perception of an earthquake, therefore, depends on the location of the observer and his sensibility. The intensity of earthquake shaking at a particular location depends on the magnitude of the earthquake (how much energy was released), and how deep and how far away it was. Local topography, geology and soils also influence the amount of earthquake shaking significantly.

Several earthquake intensity scales have been proposed from time to time. However, the most common and widely accepted scale is the Mercalli scale which was modified later by Richter (1956). The Mercalli scale quantifies the effects of an earthquake on the Earth's surface, humans, objects of nature, and human-made structures on a scale from I (not felt) to XII (total destruction). Values depend upon the distance to the earthquake, with the highest intensities being around the epicentral area. Data gathered from people who have experienced the quake are used to determine an intensity value for their location. The intensity of an earthquake is determined from this scale, and intensity values are assigned to different locations of the region on a map.

The Modified Mercalli scale (MM), also known as Modified Mercalli Intensity scale (MMI), is shown in Table 11.2. The lower degrees of the MMI scale generally deal with the manner in which the earthquake is felt by people. The higher numbers of the scale are based on observed structural damage.

11.8 SEISMIC MEASUREMENT INSTRUMENTS

These instruments are based on the basic that some part of the instrument should remain stationary while the other part is shaken by the Earth tremor. This is achieved by suspending a mass heavy enough to remain motionless while the ground vibrates.

Table 11.2 *Modified Mercalli intensity scale*

Scale	Intensity	Characteristic Effects
I.	Instrumental	Generally not felt by people unless in favourable conditions.
II.	Weak	Felt only by a couple of people that are sensitive, especially on the upper floors of buildings. Delicately suspended objects (including chandeliers) may swing slightly.
III.	Slight	Felt quite noticeably by people indoors, especially on the upper floors of buildings. Many do not recognize it as an earthquake. Standing automobiles may rock slightly. Vibration similar to the passing of a truck. Indoor objects (including chandeliers) may shake.
IV.	Moderate	Felt indoors by many to all people, and outdoors by few people. Dishes, windows, and doors disturbed, and walls make cracking sounds. Chandeliers and indoor objects shake noticeably. The sensation is more like a heavy truck striking building. Standing automobiles rock noticeably. Dishes and windows rattle alarmingly. Damage none.
V.	Rather strong	Felt inside by most or all, and outside. Dishes and windows may break and bells will ring. Vibrations are more like a large train passing close to a house. Possible slight damage to buildings. Liquids may spill out of glasses or open containers. None to a few people are frightened and run outdoors.
VI.	Strong	Felt by everyone, outside or inside; many frightened and run outdoors, walk unsteadily. Windows, dishes, glassware broken; books fall off shelves; some heavy furniture moved or overturned; a few instances of fallen plaster. Damage slight to moderate to poorly designed buildings.
VII.	Very strong	Difficult to stand. Furniture broken. Damage light in building of good design and construction; slight to moderate in ordinarily built structures; considerable damage in poorly built or badly designed structures; some chimneys broken or heavily damaged. Noticed by people driving automobiles.
VIII.	Destructive	Damage slight in structures of good design, considerable in normal buildings with a possible partial collapse. Damage great in poorly built structures. Brick buildings easily receive moderate to extremely heavy damage. Possible fall of chimneys, factory stacks, columns, monuments, walls, etc. Heavy furniture moved.
IX.	Violent	General panic. Damage slight to moderate (possibly heavy) in well-designed structures. Well-designed structures thrown out of plumb. Damage moderate to great in substantial buildings, with a possible partial collapse. Some buildings may be displaced off foundations. Walls can fall down or collapse.
X.	Intense	Many well-built structures destroyed, collapsed, or moderately to severely damaged. Most other structures destroyed, possibly displaced off foundation. Large landslides.
XI.	Extreme	Few structures remain standing. Numerous landslides, cracks and deformation of the ground.
XII.	Catastrophic	Total destruction Objects thrown into the air. The ground moves in waves or ripples. Large amounts of rock move position. Landscape altered. Even the routes of rivers can change.

11.8.1 Seismograph and Seismometer

The primitive or the base versions of instrument for measuring earthquakes are known as *seismographs*. They are used to measure relatively weak ground motions. However, with the digital sophistication of the basic form, these are known as *seismometer*. Seismographs are used to determine *magnitude*—the size of an earthquake, *depth*—how deep the earthquake was, and its *location*—the point from where it triggered.

A seismograph is an instrument that provides a record of seismic waves known as *seismogram*. The seismometer is held in rigid position, either on the bedrock or on a concrete base. A seismometer consists of a frame and a mass that can move relative to the frame. With the ground shaking, the frame vibrates but the mass tends to remain stationary due to its inertia. The difference in movement between the frame and the mass is amplified and recorded electronically. A seismometer can measure Earth tremors in one direction only. Therefore, a network of seismometers is used to calculate the magnitude and source of an earthquake in three dimensions. To accomplish this, two seismometers are placed orthogonally in horizontal plane while a third is placed vertically. The records obtained from seismographs can be directly read as displacement, velocity, or acceleration of the ground. Acceleration seismograph, known as *accelerograph,* is the most useful as it can measure strong ground motions as well and is described as follows.

❑ *Accelerograph*

An accelerograph is also sometimes referred as an *accelerometer*. In an accelerograph, the period of pendulum is set short enough relative to that of ground motion, and thus the ground acceleration can also be recorded. They are usually constructed as a self-contained box. Within the accelerograph, there is an arrangement of 3 accelerometer sensing heads, which are usually micro-machined (MEMS) chips that are sensitive to measurements in one direction. Thus, the accelerometer can measure full motion of the device in three dimensions. Moreover, the recent versions are capable of being connected directly to the internet. Accelerographs are most useful in case of strong ground motions when the sensitive seismometers may go off-scale. The type of information such as rupture velocity, etc., may not be possible with the standard seismometers.

Accelerographs are used to monitor structures for earthquake response. Sometimes, with the gathered data, a response spectrum can be computed. The analysis of the data gathered is used to design structures for earthquake resistance and also help to decide the locations of important structures in safer areas.

11.9 PREDICTION OF EARTHQUAKES

It consists in the estimation of time, location, and magnitude of a future earthquake within stated limits, and in particular the next strong earthquake to occur in a region. This can be distinguished from *earthquake forecasting*, which is the probabilistic assessment of general earthquake hazard, including the frequency and magnitude of damaging earthquakes, in a given area over a period of years or decades. There are a number of possible earthquake precursors, but none have been found to be reliable.

Earthquake prediction is an immature science in the sense that it cannot predict from its first principles the location, date and magnitude of an earthquake. Therefore, the methods used as of today empirically derive a reliable basis for predictions in either distinct precursors, or some kind of trend or pattern.

❑ *From Animal Behaviour*

There are many accounts of unusual phenomena prior to an earthquake, especially reports of anomalous animal behaviour. The mice, snakes, centipedes and beetles, and every other creature of that kind leave the region. The animals may climb up the hills.

❑ *From Changes in V_p/V_s*

Small-scale laboratory experiments have shown that the ratio of the two velocities V_p/V_s changes when a rock is near the point of fracturing, where V_p is the velocity of the P-wave and V_s is the velocity of the S-wave. In the 1970s, it was considered a significant success and a likely breakthrough when Russian seismologists reported observing such changes in the region of a subsequent earthquake. This effect has been attributed to dilatancy, where a rock stressed to near its breaking point expands (dilates) slightly.

❑ *From Radon Emissions*

Most rock contains small amount of gases that can be isotopically distinguished from the normal atmospheric gases. There are reports of spikes in the concentrations of such gases prior to a major earthquake; this has been attributed to release due to pre-seismic stress or fracturing of the rock. One of these gases is radon, produced by radioactive decay of the trace amounts of uranium present in most rock.

❑ *From Electromagnetic Variations*

Various attempts have been made to identify possible pre-seismic variations in various electrical, electric-resistive, or magnetic phenomena.

❑ *From Change in Water Level*

Prior to the effects of tremors and at the inception of tremors, the ground water level first declines and then is followed by fluctuations.

❑ *From Change in Ground Elevation*

Change in elevation of ground points under GPS monitoring system indicates about the occurrence of earthquakes.

❑ *From Trends*

Instead of watching for anomalous phenomenas that might be precursory signs of an impending earthquake, other approaches to predict earthquakes look for trends or patterns that lead to an earthquake. As these trends may be complex and involve many variables, advanced statistical techniques are often used to understand them, therefore these are sometimes called statistical methods. These approaches also tend to be more probabilistic.

11.10 LOCATION OF EPICENTRE

The epicentre can be located by the principle of intersection of three circles, in a point, and is as follows.

1. In any recording station, P-waves arrive first followed by S-waves. From the seismogram, the exact time of arrival of these waves can be ascertained.
2. The time interval between the arrivals of the two waves is directly proportional to the distance of recording station from the focus of the earthquake. If the velocities of the two waves are known, the distance of the focus of the earthquake from the recording station can be determined by Eq. (11.3).

$$D\left(\frac{1}{V_S}-\frac{1}{V_P}\right)=t \tag{11.3}$$

V_p, V_s = velocities of P- and S-waves.

3. The amplitude of the strongest wave is measured. The amplitude is the height (on the particular earthquake record) of the strongest wave.
4. To locate the epicentre, the distances of the point of origin of an earthquake are calculated from at least three recording stations.
5. Circles with radii equal to the calculated distances of the focus from the recording stations are drawn.
6. All of the circles should overlap (intersect). The point where all of the circles overlap is the approximate epicentre of the earthquake (Fig. 11.5).

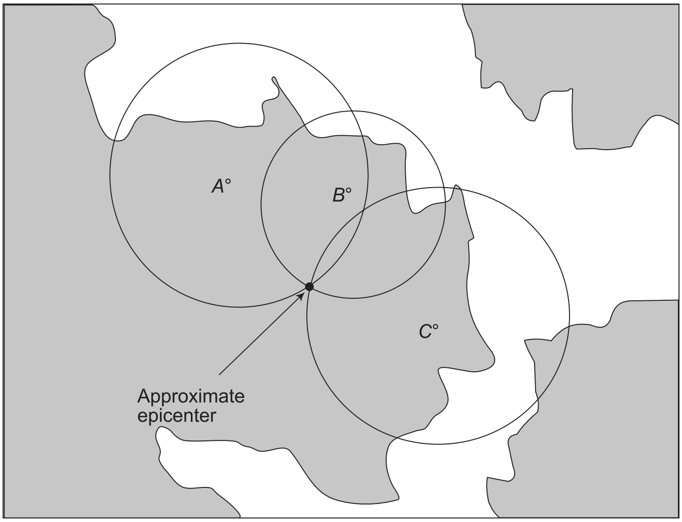


Fig. 11.5 *The point where the three circles intersect is the epicentre of the earthquake*

7. In case, the three circles do not intersect in a point, the area enclosed by their overlap is considered to be the epicentral tract.
8. To determine the magnitude of the earthquake, a ruler (or straight edge) is placed on the chart between the points for the distance to the epicentre and the amplitude. The point where the ruler crosses the middle line (denoting magnitude) on the chart (Fig. 11.6) marks the magnitude of the earthquake. Figure 11.6 shows the scale proposed by Richter and its use to determine magnitude of the earthquake from a typical earthquake record.

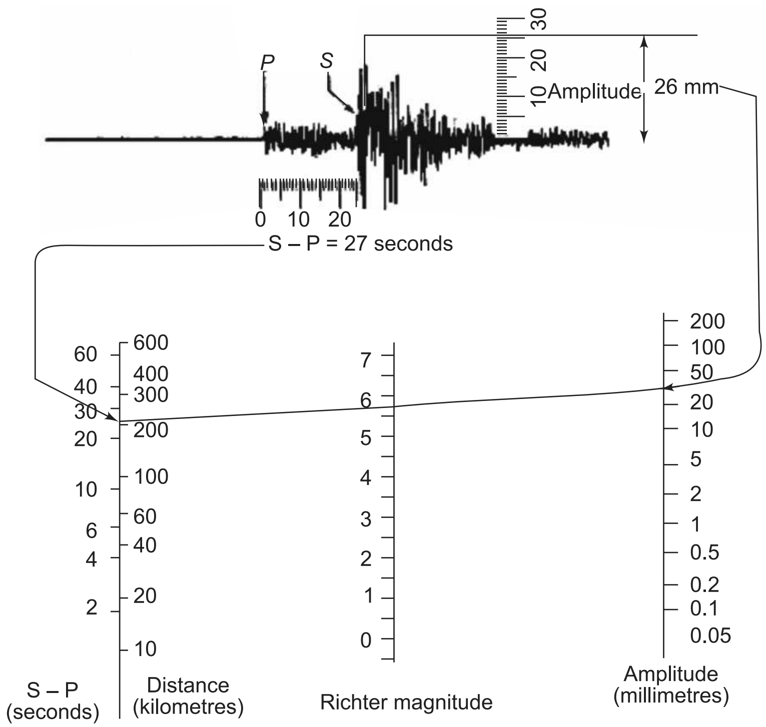


Fig. 11.6 *Determination of earthquake magnitude from an earthquake record*

11.11 SEISMIC ZONATION OF INDIA

The Indian subcontinent has a history of devastating earthquakes. The major reason for the high frequency and intensity of the earthquakes is that the Indian plate is driving into Eurasian plate at a rate of approximately 47 mm/year. Geographical statistics of India show that almost 54% of the land is vulnerable to earthquakes. A World Bank and United Nations report estimates that around 200 million city dwellers in India will be exposed to storms and earthquakes by 2050.

As already discussed in Section 11.9, prediction of earthquake is based on precursors and research in the area is in its infancy and not precise enough to be of much help. However, since protection against damage and loss of life is the foremost consideration, the concept of seismic zoning has been developed.

Based on the seismic evidences and historical records, maps can be prepared, indicating the epicentral areas of earthquakes and zoned according to activity. A seismic zoning map, therefore, shows the zones of different seismic danger in a particular area. The zoning map is reviewed and revised periodically based on additional data from the research in the field. By the use of seismic zoning and zone factor, it is expected that the level of risk involved and collapse of the structures will be minimized.

The first zoning map of India was prepared in 1962 on the basis of historical data available regarding occurrence of earthquakes and their severity. The latest version of seismic zoning map of India (Fig. 11.7) given in the earthquake resistant design code [IS 1893 (Part 1) 2002] assigns four levels of seismicity for India in terms of zone factors. In other words, the earthquake zoning map of India divides the country into 4 seismic zones (Zone II, III, IV and V), unlike its previous version which consisted of five zones. According to the present zoning map, Zone V expects the highest level of seismicity whereas Zone II is associated with the lowest level of seismicity.

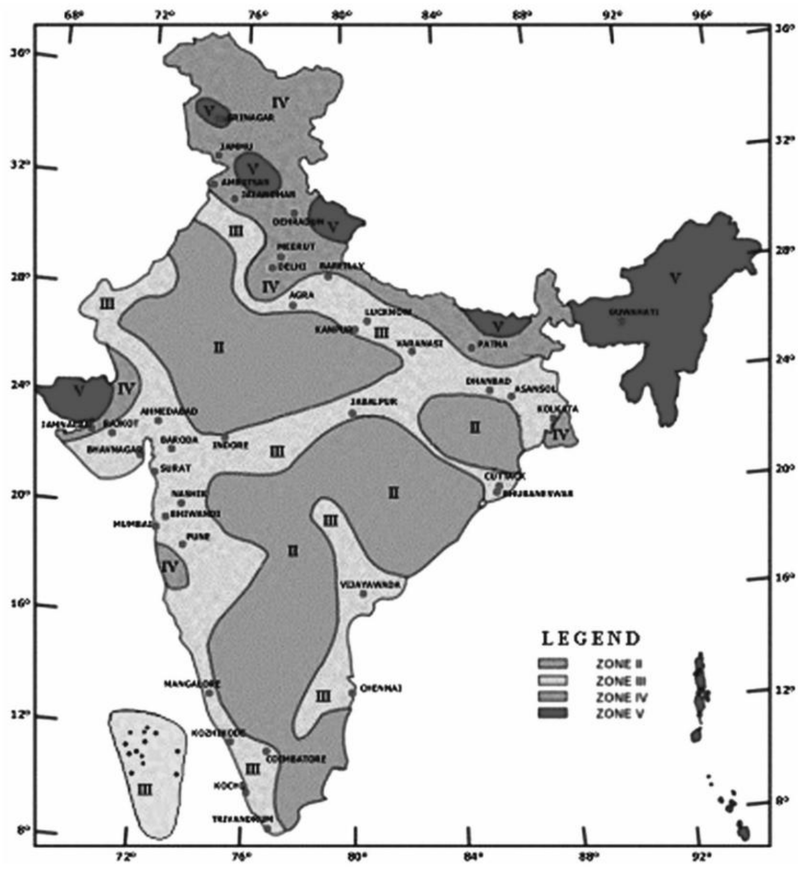


Fig. 11.7 *Seismic zone map of India: 2002*

❑ *Zone V*

This zone covers areas with the highest level of risk that is expected of earthquakes of intensity MSK IX or greater. It is referred to as the *very high-damage risk zone*. IS code assigns zone factor of 0.36 to the areas situated in this zone. The zone factor of 0.36 is indicative of effective (zero period) peak horizontal ground accelerations of 0.36 g (36% of gravity) that may be generated during maximum consideration earthquake (MCE) in this zone. Designers use this value for earthquake resistant design of structures in Zone V. The state of Kashmir, the western and central Himalayas, the North-East Indian region and the Rann of Kutch fall in this zone. Generally, the areas having trap or basaltic rock are prone to earthquakes.

❑ *Zone IV*

This zone is referred to the as *high-damage risk zone* and covers areas liable to earthquake intensity levels of MSK VIII. The IS code assigns zone factor of 0.24 for this zone. The Indo-Gangetic basin, the capital of the country (Delhi), and some parts of Jammu and Kashmir fall in Zone IV. In Maharashtra, Patan area (Koyananager) also lies in Zone IV.

❑ *Zone III*

This zone is classified as *moderate-damage risk zone* which is liable to earthquake intensity level of MSK VII, and of magnitude 7.8. IS code assigns zone factor of 0.16 for Zone III. Andaman and Nicobar Islands, some parts of Kashmir, and Western Himalayas fall under this zone.

❑ *Zone II*

This zone is classified as the *low damage risk zone* which is liable to earthquake intensity level of MSK VI or less. IS code assigns zone factor of 0.10 (maximum horizontal acceleration that can be experienced is 10% of gravitational acceleration by a structure in this zone) for Zone II. Parts of U.P, Bihar and West Bengal fall under this category.

11.12 EARTHQUAKE CATALOGUE OF INDIA

Earthquake catalogue implies a list of earthquakes and their properties, e.g., origin, time, hypocentre, magnitude, etc.). Table 11.3 enlists some major earthquakes that occurred in India.

Table 11.3 *Some significant earthquakes in India*

Date	*Epicentre*		*Location*	*Magnitude*
	Lat. (Deg N)	*Long. (Deg E)*		
1819 June 16	23.6	68.6	Kutch, Gujarat	8.0
1869 Jan. 10	25	93	Near Cachar, Assam	7.5
1885 May 30	34.1	74.6	Sopor, J&K	7.0
1897 June 12	26	91	Shillong Plateau	8.7

(*Contd.*)

Date	Epicentre		Location	Magnitude
	Lat. (Deg N)	Long. (Deg E)		
1905 April 04	32.3	76.3	Kangra, HP	8.0
1918 July 08	24.5	91.0	Srimangal, Assam	7.6
1930 July 02	25.8	90.2	Dhubri, Assam	7.1
1934 Jan. 15	26.6	86.8	Bihar–Nepal Border	8.3
1941 June 26	12.4	92.5	Andaman Islands	8.1
1943 Oct. 23	26.8	94.0	Assam	7.2
1950 Aug. 15	28.5	96.7	Arunachal Pradesh–China Border	8.5
1956 July 21	23.3	7.0	Anjar, Gujarat	7.0
1967 Dec. 10	17.37	73.75	Koyna, Maharashtra	6.5
1975 Jan. 19	32.38	78.49	Kinnaur, HP	6.2
1988 Aug. 06	25.13	95.15	Manipur–Myanmar Border	6.6
1988 Aug. 21	26.72	86.63	Bihar–Nepal Border	6.4
1991 Oct. 20	30.75	78.86	Uttarkashi, UP Hills	6.6
1993 Sep. 30	18.07	76.62	Latur–Osmanabad, Maharashtra	6.3
1997 May 22	23.08	80.06	Jabalpur, MP	6.0
1999 March 29	30.41	711.42	Champoli, UP	6.8
2001 Jan. 26	23.40	70.28	Bhuj, Gujarat	6.9

http://www.imd.gov.in/section/seismo/static/signif.htm

11.13 DAMS AND EARTHQUAKES

Because of the construction of major civil engineering projects, the in-situ stress state along the existing fault in the area is altered. This may lead to the movements along the fault and an earthquake may trigger. For example, when large dams are constructed they may induce seismicity in the region by means of certain mechanism as follows.

The column of water in a dam alters *in-situ* stress state along an existing fault or fracture. In these very large and deep reservoirs, the load of the water column can significantly change the stress state on the fault or fracture by increasing the total stress through direct loading, or decreasing the effective stress through the increased pore water pressure. This significant change in stress state can lead to movement along the fault or fracture resulting in an earthquake.

Reservoir-induced seismic events can be relatively large, compared to other forms of induced seismicity. Though understanding of reservoir induced seismic activity is very limited, it has been noted that seismicity appears to occur on dams with heights larger than 100 m. The extra water pressure created by vast reservoirs is the most accepted explanation for the seismic activity. Induced seismicity is usually overlooked due to cost cutting during the geological surveys of the locations for proposed dams. Once the reservoirs are filled, induced seismicity could occur immediately or with a small time lag.

Koynanagar (1967) earthquake of magnitude 6.3 occurred in Maharashtra, with its epicentre, foreshocks and aftershocks all located near or under the Koyna Dam reservoir. The number of people who died were 180 and 1,500 were seriously injured. The effects of the earthquake were felt even 230 km away in Bombay with tremors and power outages.

Summary

The chapter discusses the causes, nature, effect and consequences of an earthquake. This is one of the most devastating natural calamities, which is associated with the movement of lithospheric plates. The tectonics of plates that create a rupture in rocks inside the Earth is responsible for the shaking of the ground. The resulting ground motion and different seismic waves, like body and surface waves, have been described. Elastic rebound theory, plate tectonic theory and reservoir-induced seismicity reflect light on different modes of origin of earthquakes. The method to locate an epicentre is also described. Major effects of an earthquake like flooding, volcanism, damage to infrastructure are also outlined. Available measures of earthquake, the intensity and the magnitude, are then presented in detail.

Classification of earthquakes based on different parameters like focal depth, intensity and origin (tectonic and non-tectonic) has been presented. To access the severity of this natural hazard, the concept of zoning is described. Earthquake zonation and different seismic zones of India are elaborated. This helps planners and technocrats understand the vulnerability to which a structure may be subjected.

Although it is not possible to forecast an earthquake's exact time and place but certain parameters considered for prediction of an earthquake are briefly explained. The brief history of Indian earthquakes along with magnitude and locations has been presented. The chapter ends with highlighting the induced seismicity because of constructing a dam.

Terminology

Aftershocks These occur when rocks adjust to the new uniform stress field after an earthquake.

Aseismic Fault on which no earthquake has been observed, i.e., a region free from earthquake. The design of buildings to withstand earthquakes is known as aseismic design.

Continental Drift It is the movement of the Earth's continents gradually over the surface of the planet on a substratum of magma and comprises of formation or reformation of continents.

Epicentre The projection on the surface of the Earth directly above the focus (hypocentre).

Fault	It is a crack in the Earth's crust, resulting from the displacement of one side of the rock with respect to the other. It may result from the sliding of one tectonic plate under the other, resulting in tension and faulting in the Earth's crust.
Focus	Location of earthquake just below the epicentre.
Foreshocks	These occur due to stress release in the weaker zones across the fault prior to an earthquake.
Hypocentre	Location of initial radiation of seismic wave (first location of dynamic rupture). It is also known as focus.
Precursor	An earthquake precursor could be any anomalous phenomena that can give effective warning of the imminence or severity of an impending earthquake in a given area.
Tectonic	Related to, causing, or resulting from structural deformation of the Earth's crust.
Tsunami	A series of water waves caused by the displacement of large volume of body of water, generally on an ocean due to submarine earthquakes.
Tremor	A relatively minor seismic shaking.

Exercises

1. (a) Define an earthquake. At what depth do earthquakes occur?
   (b) What are the causes of an earthquake?

2. Can we cause an earthquake? How do human activities influence earthquakes?

3. (a) Discuss the theories that explain the causes of earthquakes?
   (b) How are the earthquakes classified?

4. What are surface waves? Explain Rayleigh and Love waves.

5. Describe the various effects of an earthquake. How do we locate the epicentre of an earthquake?

6. What are the different measures of earthquakes? Discuss the various earthquake magnitudes specifying the conditions governing their reliability.

7. In what senses are magnitude and intensity of earthquake different. Discuss briefly the MMI scale.

8. What is meant by seismic zoning? In how many seismic zones has India been divided? Specify the associated zone factors.

9. Write short notes on the following:
   (a) Seismograph
   (b) Modified Mercalli scale
   (c) Ground motion
   (d) Characteristics of seismic waves
   (e) Plate tectonics
   (f) Interior of the Earth
   (g) Seismic waves
   (h) Tsumani
   (i) Isoseismals

10. Distinguish between the following:
(a) Focus and epicentre
(b) P-waves and S-waves
(c) Lithosphere and asthenosphere
(d) Foreshocks and aftershocks
(e) Focus and epicentre
(f) Seismograph and seismogram
(g) Magnitude and intensity of earthquake
(h) Tsumani and seiches

Multiple-Choice Questions

1. Which of the following describes the build-up and release of stress during an earthquake?
(a) Modified Mercalli Scale
(b) Elastic rebound theory
(c) Principle of superposition
(d) Travel time difference

2. The amount of ground displacement in an earthquake is known as
(a) epicentre (b) dip
(c) slip (d) focus

3. The place where movement occurs in a crustal plate that triggers an earthquake is called
(a) epicentre (b) dip
(c) focus (d) strike

4. Which of the following sequence of seismic waves correctly lists the different arrivals from first to last?
(a) P-waves, S-waves , Surface waves
(b) Surface waves, P-waves, S-waves
(c) P-waves, Surface waves, S-waves
(d) S-waves, P-waves, Surface waves

5. How do rock particles move during the passage of a P-wave through the rock?
(a) Back and forth parallel to the direction of wave travel
(b) Back and forth perpendicular to the direction of wave travel
(c) In a rolling circular motion
(d) The particles do not move

6. How many seismograph stations are needed to locate the epicentre of an earthquake?
(a) 1 (b) 2
(c) 3 (d) 4

7. Supposing that only density increases with increasing depth within the Earth, the velocity of a P-wave should
(a) stay the same (b) increase
(c) decrease (d) not vary

8. If an S-wave were to pass from a solid to a liquid stratum, what would happen to its velocity?
(a) Stay the same (b) Increase
(c) Decrease to zero (d) Can not be ascertained

9. Body waves consist of the
(a) P-waves only (b) S-waves only
(c) P- and S-waves (d) Surface waves

10. With increasing travel time, the difference in arrival times between the P- and the S-waves
(a) increases (b) decreases
(c) stays constant (d) cannot be ascertained

11. Earthquake A has a Richter magnitude of 7.0 and that of earthquake B is 6.0.
(a) A is 10 times more intense than B.
(b) A is 1000 times more intense than B.
(c) Richter magnitude does not measure intensity.
(d) B is 0.01 times as intense than A.

12. In general, the most destructive earthquake waves are
(a) P-waves (b) S-waves
(c) Surface waves (d) L-waves

13. Where does the focus lie with respect to the epicentre?
(a) Directly below the epicentre (b) Directly above the epicentre
(c) In the P-wave shadow zone (d) In the S-wave shadow zone

14. Which of the following measure of an earthquake's intensity is based on the observed effects on people and structures?
(a) Ritchter scale (b) Modified Mercalli scale
(c) Centigrade scale (d) Moment magnitude scale

15. How do rock particles move during the passage of P-wave through the rock?
(a) Back and forth, parallel to the direction of wave travel
(b) Perpendicular to the direction of wave travel
(c) In a rolling elliptical motion
(d) In a rolling circular motion

Answers to MCQs

1. (b) 2. (c) 3. (c) 4. (a) 5. (a) 6. (c) 7. (b) 8. (c)
9. (c) 10. (a) 11. (a) 12. (b) 13. (a) 14. (b) 15. (a)

chapter 12

Landslides

12.1 INTRODUCTION

Landslides are one of the most devastating natural hazards. They may occur in any part of a country in general and in particular in the hilly regions. Landslide may be defined as geological phenomena in which there is gradual or sudden movement of soil and rock mass under gravity. They may occur when the driving forces tending to pull soil and rock downhill equal or exceed the resisting forces holding it in place.

The driving forces for landslides may be that part of the weight of the soil and rock acting either parallel to the slope, or that part of the weight that tries to rotate the material out of the slope, or seismic shaking. These forces increase with slope steepness and rock density, and, in the case of rotational failures, with increasing slope height. The resisting forces to prevent landslides are the strength of the slope materials, strength added by roots of trees and vegetation, and buttressing of the lower part of the slope by stronger materials that have to be pushed or rotated out of the way before the upper part of the slope can move. Human activities affect both of these. Obviously, landslides may occur either due to an increase in driving force or/and a reduction in the resisting force.

Landslides occur in a wide variety of settings, including subduction complexes, volcanic arcs, transform faults, and intraplate settings like the Himalayan region. Landslides are particularly common along stream banks, reservoir shorelines, large lakes and seacoasts. They also are common anywhere on the Earth's surface where steep topographic slopes exist or where water saturated material lies on slopes even ranging from a fraction to few degrees of inclination. Under such conditions, the downslope movement of material is commonly referred to as mass wasting or landslides. The velocity of landslides varies from imperceptible to over 22 kmph. Some volcanic induced landslides have been known to travel between 30 to 90 kmph. Landslides can move long distances, sometimes as much as several kilometres.

The geological processes, their causes, classification, affects, landslide zonation and preventive measures have been discussed in this chapter. In the section to follow, some of the important components of landslides that are needed to develop familiarity are described.

12.2 MORPHOLOGY OF LANDSLIDES

Landslides are characterized by their different shapes and sizes in different terrains. The components of landslides have been shown in Fig. 12.1.

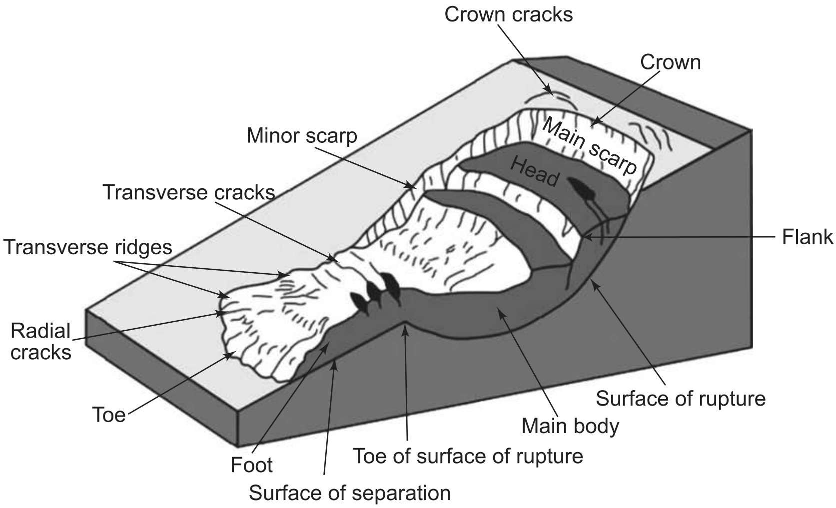


Fig. 12.1 *Morphology of landslides*

- **Crown** It is the uppermost part of any soil or rock surface which is not involved in a landslide but is nearest to the part of landslide. It is characterized by deposition of coarse material.

- **Accumulation** The volume of the displaced material which lies above the original ground surface is termed accumulation.

- **Main Scarp** A steep surface on the undisturbed ground at the upper edge of the landslide is known as main scarp. It is the visible part of the surface of rupture. It is caused by movement of the displaced material away from the undisturbed ground.

- **Minor Scarp** A steep surface on the displaced material of the landslide produced by differential movements within the displaced material is known as minor Scarp.

- **Main Body** The part of the displaced material of the landslide that overlies the surface of rupture between the main scarp and the toe of the surface of rupture is called main body.

- **Flank** The undisplaced material adjacent to the sides of the rupture surface is termed flank. It can be viewed very clearly from the crown. The flank is denoted as left and right flanks.

- **Foot** The portion of the landslide that has moved beyond the toe is called its foot.

12.3 CAUSES OF LANDSLIDES

Since landslide is a sudden or gradual movement along gravity, it is triggered by a number of factors like precipitation, lithology, geological structures and human intervention. The conditions and possible causes of landslides are morphological, geological, physical (intense or prolonged rainfall, rapid snowmelt or sharp fluctuations in groundwater levels) and human activities. All soil types can be affected by natural landslide-triggering conditions. These are briefly described below:

12.3.1 Morphological Causes

The morphological causes constitute slope angle and erosion of the existing soils and rocks. The slope of the ground surface subjected to landslides or prone to landslides is the controlling factor to accelerate or decelerate the velocity of landslides. Moreover, the steeper slopes can be at an increased risk for landslides and trigger the rate of erosion as well. Further, the volume of detached mass and its accumulation also increases if the erosion of soil or rock mass results in an increased landslide hazard. When the angle is more than 45°, an intensive landslide can take place. Topography of a slope its shape, size, degree of slope and drainage in the area contribute significantly to landslides. Concave-shaped slopes with larger drainage areas appear to be more susceptible to landslides than other landforms. The nature of rock mass also controls the rate of erosion. Hard and compact rocks are less affected with landslides than the soft rocks.

12.3.2 Geological Causes

Geological causes comprise of earthquakes, volcanism and change in groundwater. Seismic tremors can trigger landslides on slopes historically known to have landslide movement. Earthquakes can also cause additional failure (lateral spreading) that can occur on gentle slopes above steep stream and river banks.

Due to the movement of plates and faulted blocks, the rock mass is weakened resulting in triggering the movement of ground mass of soil and rocks. Further, shocks or vibrations caused by earthquakes (M 3-4 or greater) or construction activity can loosen granular soils even when they are dry. In conditions where the soil is saturated, granular or otherwise, even light vibrations can trigger a rearrangement of the soil particles resulting in a temporary increase of pore pressure and a reduction of the frictional forces in the material, destabilizing the slope.

Volcanism is responsible as one of the geological causes and it dislocates the existing rock mass and accelerates soil and rocks erosion. Volcanic activities produce younger and unconsolidated rocks which are more susceptible for erosion and disintegration. Volcanic eruptions that produce loose ash deposits and debris flows weaken the rocks. Erosion by rivers, glaciers, or ocean waves that create over-steepened slopes is also responsible for landslides.

12.3.3 Groundwater

Water flowing below the ground is often the factor that finally triggers many landslides. Groundwater acts as a lubricant to the landslide. Groundwater occurs in the form of seepage, shallow groundwater and deeper groundwater levels in different rocks and regions. Seepage which cuts the ground surface, also known as spring, is quite vulnerable for landslides. While the shallow water level accelerates the rate of landslides, the deeper water level does not. Any activity that increases the amount of water flowing into landslide-prone slopes can increase landslide hazards. The groundwater level monitoring and its long-term data is collected to prepare landslide zonation maps.

12.3.4 Physical Causes

Physical causes encompass rainfall and snowmelt. The rate of precipitation is one of the most significant causes for landslides. Of the natural processes the rainfall and the earthquake, rainfall-initiated landslides tend to be smaller, while earthquake-induced landslides may be very large, but less frequent. It is well known that most of the landslides occur during rainy season only. Rainfall/snowmelt triggers the disintegration of rock mass and results in its transportation from the original place. Heavy rainfall/snowfall is more dangerous for landslides than normal rainfall in the area. In case of cloud burst, the amount of rainfall exceeds the limit of infiltration and saturation of rock mass; the rate of landslides increases.

The two principal reasons attributed to the triggering of landslides by rainfall are rise in pore pressure in the soil, and an increase of the slope weight. In case of clay soils, prolonged rainfall will be the main triggering factor. This is because clay soils often need days of rainfall to cause their saturation. Intense rainfall over a short period of time will, however, not be sufficient to cause their saturation and triggering of a landslide. This is not the case for residual and granular soils because the soil structure facilitates relatively rapid drainage; prolonged (not intense) rainfall does not saturate these soils. Intense rainfall will cause their saturation and the consequent reduction of frictional forces in the material (due to the increase in pore pressure, there is a reduction in effective stress and consequently shear strength is reduced drastically), resulting in a potential landslide. For these types of soils, landslides will either occur during a downpour or shortly thereafter. Hourly rainfall of more than 40 mm is enough to trigger a landslide. With hourly rainfall over 70 mm, the landslide hazard becomes severe.

12.3.5 Human Causes

Landslides may result directly or indirectly from the activities of people. Slope failures can be triggered by construction activity that undercuts or overloads dangerous slopes, or that redirects the flow of surface or groundwater. There are several manmade reasons for creating landslides and their movement. These include excavation, loading, deforestation and mining and are described as follows.

■ **Excavation** The digging of land surface and excavation of massive rocks certainly weakens the massiveness or strength of rocks. Since the strength of rocks is affected, the landslides are triggered, and that too at enhanced rate.

■ **Loading** Rocks or soil has its own bearing capacity. Different types of overburden accelerate the landslides. The weight of excavated material and some of the other types of loads, e.g., construction of buildings on the outcrop of landslide prone areas fall in this category. Excess weight from accumulation of rain or snow, from stockpiling of rock or ore, from waste piles, or from human-made structures, may cause weak slopes susceptible to failure. This is so because the loading on upper slopes results in an additional load to be carried by the slope which could result in its failure.

■ **Deforestation** It is one of the most important causes under human activity resulting in landslides. Plants or trees hold the soil firmly and prevent the soil erosion reducing the intensity of landslides. Therefore, deforestation results in an increased probability of landslide and its intensity. As an example, in the Himalayan region, deforestation has intensified the frequency and area coverage of landslides (Fig. 12.2).

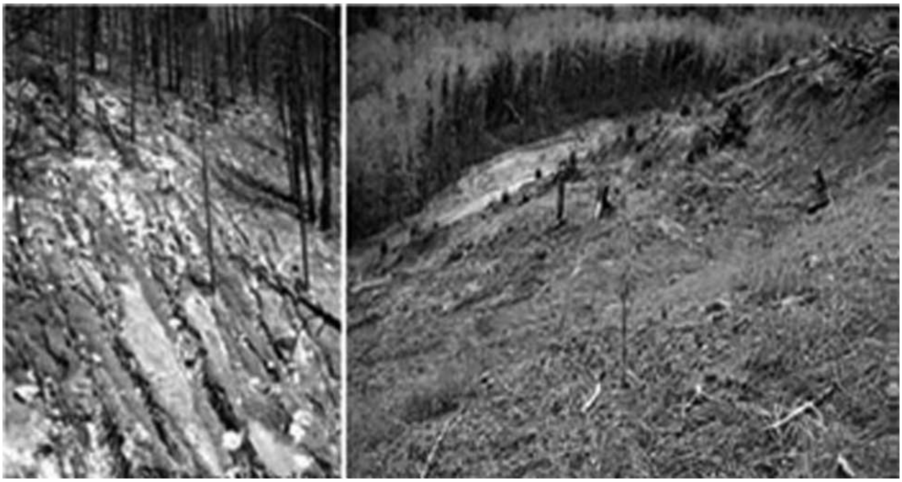


Fig. 12.2 *Deforestation of a slope and landslide hazard*

■ **Vegetation Loss** Removing vegetation from very steep slopes can increase landslide hazards. Areas that have experienced wildfire and land clearing for development can be expected to have longer periods of increased landslide hazards than after timber harvesting because forest recovery may take a very long time, or may never occur.

12.4 TYPES OF LANDSLIDES

Although landslides are primarily associated with mountainous regions, they can also occur in areas of generally low relief. In low-relief areas, landslides occur as cut-and-fill failures (roadway and building excavations), river bluff failures, lateral spreading landslides, collapse of mine-waste piles (especially coal), and a wide variety of slope failures associated with quarries and open-pit mines. The most common types of landslides described as follows are illustrated in Fig. 12.3.

12.4.1 Slides

Mass movements for landslides are used in the general term. However, there is a distinct zone of weakness that separates the material from more stable underlying material that is termed as slide. The two major types of slides are rotational slides and translational slides. The slide is characterized by slow to rapid speed (> 5 m/s) and with a slope of rapture 45–90°.

- **Rotational Slide** This is a type of slide in which the surface of rupture is curved concavely upwards and the slide movement is roughly rotational about an axis that is parallel to the ground surface and transverse across the slide [Fig. 12.3(a)].

- **Translational Slide** When the landslide mass moves along a roughly planar surface with little rotation or backward tilting [Fig. 12.3(b)], it is characterized as translational slide. A block slide is a typical type of translational slide in which the moving mass consists of a single unit or a few closely related units that move down-slope as a relatively coherent mass [Fig. 12.3(c)].

12.4.2 Falls

It is an abrupt movement of masses of geologic materials such as rocks and boulders that are detached from steep slopes or cliffs [Fig. 12.3(d)]. It is characterized by extremely rapid speed and with slope of 45–90° with the surface of rupture.

Separation occurs along discontinuities such as fractures, joints, and bedding planes and movement occurs by free-fall, bouncing and rolling. Falls are strongly influenced by gravity, differential weathering, and by the presence of interstitial water.

12.4.3 Topples

Toppling is characterized by the forward rotation of a unit or units about some pivotal point and has intermittent contact with the surface of detachment. It is characterized by slow to high speed and without contact of slope. These phenomena take place under the actions of gravity and other forces exerted by adjacent units or by fluids in cracks [Fig. 12.3(e)].

12.4.4 Flows

Flows of fine-grained materials are characterized by slow movement and low angle of contact surface with dominant constituents. It is characterized by slow speed (< 5 m/s) and with a slope of 45–90° with the surface of rupture. Types of flows are related to the nature of materials and agencies involved for the development of landslides. There are five basic categories of flows that differ from one another in fundamental ways. These different flows are explained below:

■ **Debris Flow** A debris flow is characterized by slow movement in which a combination of loose soil, rock, organic matter, air, and water mobilizes as slurry that flows down-slope [Fig. 12.3 (f)]. Debris flow consist of fine-grained particles less than fifty per cent. Debris flows are commonly caused by intense surface-water flow due to heavy precipitation or rapid snowmelt that erodes and mobilizes loose soil or rock on steep slopes. Debris flows may also mobilize from other types of landslides that occur on steep slopes, are nearly saturated, and consist of a large proportion of silt and sand-sized material. Source areas of debris flow are often associated with steep gullies, and debris-flow deposits are usually indicated by the presence of debris fans at the mouths of gullies. Fires that denude slopes of vegetation intensify the susceptibility of slopes to debris flows.

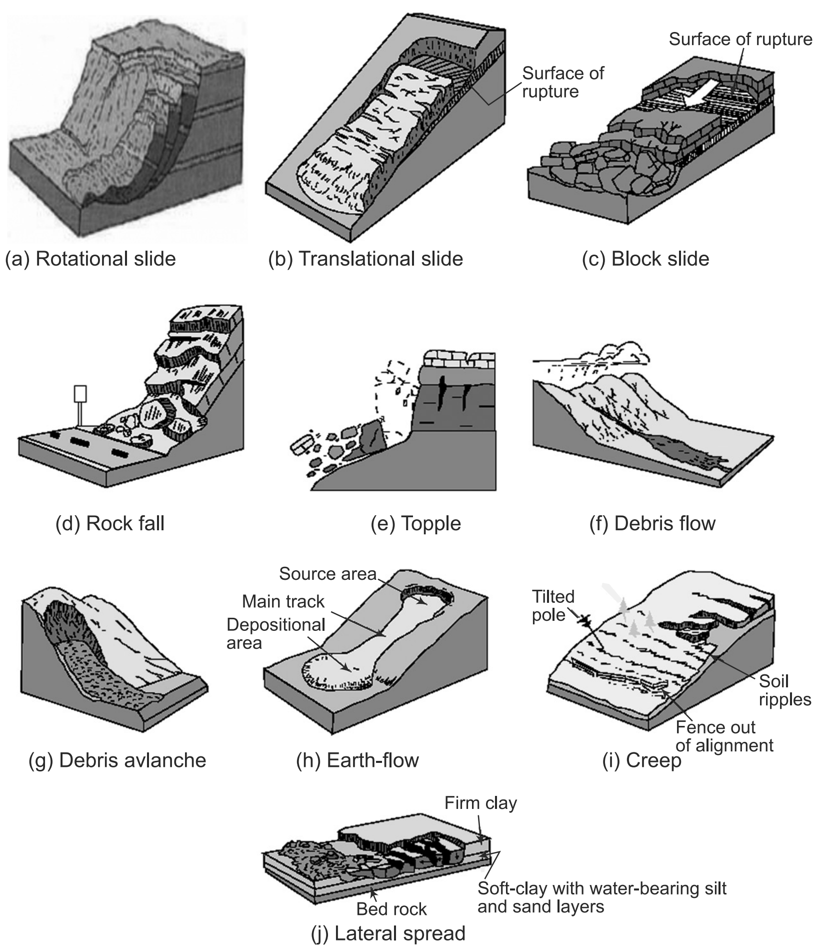


Fig. 12.3 *Different types of landslides*

■ **Debris Avalanche** This is a variety of very rapid to extremely rapid debris flow generated by glaciers [Fig. 12.3(g)].

■ **Earthflow** Earthflows have a characteristic bowl-shape [Fig. 12.3(h)]. The slope material liquefies and runs out, forming a bowl or depression at the head. The flow itself is elongated and usually occurs in fine-grained materials or clay-bearing rocks on moderate slopes and under saturated conditions. However, dry flows of granular material are also possible.

■ **Mudflow** A mudflow is an earthflow consisting of material that is wet enough to flow rapidly and that contains at least fifty per cent sand-, silt- and clay-sized particles. In some instances, e.g., in many newspaper reports, mudflows and debris flows are commonly referred to as mudslides.

■ **Creep** The imperceptibly slow, steady, downward movement of soil or rock is called creep. The movement is caused by shear stresses producing permanent deformation, but too small to produce shear failure [Fig. 12.3(i)]. There are three types of creep the *seasonal creep*—where movement is within the depth of soil affected by seasonal changes in soil moisture and soil temperature; the *continuous* creep—where shear stress continuously exceeds the strength of the material and the *progressive creep*—where slope is related to the point of failure, which shifts slowly forward as in the case of other types of mass movements. The effect of creep is indicated by curved tree trunks, bent fences or retaining walls, tilted poles or fences, and small soil ripples or ridges.

■ **Lateral Spread** Lateral spreads are distinctive because they usually occur on very gentle slopes or flat terrains [Fig. 12.3(j)]. The dominant mode of movement is lateral extension accompanied by shear or tensile fractures. The failure is caused by liquefaction; the process whereby saturated, loose and cohesionless sediments (usually sands and silts) are transformed from a solid into a liquefied state. Failure is usually triggered by rapid ground motion, such as that experienced during an earthquake, but can also be artificially induced. When coherent material, either bedrock or soil, rests on materials that liquefy, the upper units may undergo fracturing and extension and then subside, translate, rotate, disintegrate, or liquefy and flow. Lateral spreading in fine-grained materials on gentle slopes is usually progressive. The failure starts suddenly in a small area and spreads rapidly. Often the initial failure is a slump, but in some materials, movement occurs for no apparent reason.

Note Involvement of two or more of the above classes fall, slide, flow, or spread may be considered as a complex landslide. For example, in its lower parts, a rotational slide commonly transforms into an earthflow. Hence, such a landslide would be classified as a *complex rotational slide-earthflow*.

12.5 CLASSIFICATION OF LANDSLIDES

The causes of landslides as described in Section 12.3 form the basis for classification of landslides. There are many classification systems used to describe landslides. Landslides are generally classified on the basis of the type of material that existed prior to the landslide—rock, soil, earth, mud, and debris, and the type of movement that dominates during the landslide. The four general classes of movement during any given landslide are fall, slide, spread, and flow. Hence, to classify a landslide, it is required to first determine the type of material that existed prior to the landslide and then attach to that name the class of movement. For example, a rock-fall is a landslide that involved intact, hard, and firm material that fell down slope while an earthflow is a landslide that involved the flowage of earth material down slope.

One of the most commonly adopted classifications (Table 12.1) is that developed by Varnes taking the parameters like type of movement and the type of material or rock mass involved. Later on, the classification was slightly modified by Cruden and Varnes in 1996 by considering grain size as well. Some of the other classification systems that incorporate additional variables, such as the rate of movement and the water, air, or ice content of the landslide material also exist.

Table 12.1 *Tabular classification of landslides (after Varnes, 1978)*

Type of Movement		*Type of Material*		
		Bed rock	Soil	
			Coarse grained	Fine grained
Falls		Rock fall	Debris fall	Earth fall
Topples		Rock topple	Debris fall	Earth topple
Slides	Rotational	Rock slide	Debris slide	Earth slide
	Translational			
Lateral Spreads		Rock spread	Debris spread	Earth spread
Flows		Rock flow	Debris flow (deep creep)	Earth flow (soil creep)
Complexes		Combination of two or more types of movement		

12.6 IDENTIFICATION OF LANDSLIDES

The general approach in field investigation of landslide is concerned with the preparation of a contour map and plotting of geological features including rock structures covering the area affected by the landslide. It also includes comprehensive field work to elaborate dip and strike of beds, delineation of different rocks, zone of sliding and structural control like fold, fault and joints. The causes of landslides are evaluated and treatment of the slide affected area for reconstruction is proposed or remedial measures to minimize the possibility of future slides are suggested to the engineers.

The scope of investigation of a landslide area will depend on the importance of the slide. There are factors to be ascertained in the investigation of any slide in order to assess its importance which include its location, effect on traffic, size, material, water, weather, evidence of movement, and history of slope.

Each investigative factor is discussed with methods of investigation. The field data comprises the observable and measurable facts in and adjacent to the site. A photographic record of slide is most important in properly documenting the successive stages in development of the slide. The minimum requirement of the data includes a base map showing the structure and distribution of materials in and adjacent to the slide. The data base required for identification of slide are as follows:

1. Cross section showing the relation of the materials in the slide to those in adjacent stable ground and the location of the water surface.
2. The charts expressing the precipitation and temperature records during and preceding the motion, and a chronological record of the events connected with motion.
3. The mathematical examination of conditions, where applicable, should provide an indication of the magnitude of forces involved in the failure.

The nature and signs of instability can often vary depending on the type and scale of the failure. However, ground movement or low intensity landslides can be recognized by other features also which may not be immediately associated with slope instability. These features are as follows:

1. Ancillary structures such as decks tilting and/or moving relative to the main house
2. Sunken or down-dropped road beds
3. Tilting or cracking of concrete floors and foundations
4. Soil moving away from foundations
5. Broken waterlines and other underground utilities
6. Leaning telephone poles, trees, retaining walls, or fences
7. Offset fence lines or retaining walls
8. Springs, seeps, or saturated ground in areas that have not typically been wet
9. Cracks and creeps in hilly and valley areas (Fig. 12.4)

Fig. 12.4 *Cracks on the ground surface indicating initial process of creeping*

10. Rapid increase in creek water levels, possibly accompanied by increased turbidity (soil content)
11. Sticking doors and windows, and visible open spaces indicating jambs and frames out of plumb
12. Sudden decrease in creek water levels, though rain is still falling or just recently stopped.

12.7 MEASUREMENT OF LANDSLIDES

Landslides are the recurring and volatile natural phenomena that take place in different parts of the country. Their identification and measurement in time and space is therefore necessary. Instrumentation can be used to characterize the location of shallow and deep failure planes as well as measure the direction of landslide movement. Subsurface movements or ground deformations can be characterized in a variety of ways using different sensor technologies and data acquisition methods. The two most commonly used instruments for measurement of landslides from minor scale to major scale areas are *inclinometer* and *borehole extensometer.* Study of satellite data is also helpful for measurement of landslides in 2D and 3D. These are discussed as follows:

12.7.1 Inclinometer

Inclinometers are used to monitor lateral earth movements in areas and embankments prone to landslides. Inclinometer can acquire subsurface movements automatically at frequent time intervals and provide a useful tool for geologists and engineers to enhance subsurface characterization, improve geotechnical design, and monitor construction activities in real time. Principally, inclinometers are used for site investigation, verification of design assumptions, determination of the need for corrective measures, monitoring of long-term performance and safety monitoring.

Inclinometers have been developed to accurately measure the movement of pre-existing landslides and to detect signs of pre-failure creep in intact (un-failed) coastal slopes. They are very useful to monitor settlement in foundations and embankments and monitor the deflection of retaining walls and piles under load. Measurement of sub-surface movement can be determined with the help of inclinometer systems and slip indicators, using a variety of methods. Slope inclinometers/indicators are used to determine the magnitude, rate, direction, depth, and type of landslide movement. This information is usually vitally important for understanding the cause, behaviour, and remediation of a landslide. However, many inclinometer measurements fail to achieve these intended aims because of lack of appreciation of the many factors that need to be correctly implemented during installation, monitoring, and data reduction to yield useful data.

The basic principle of operation is that a torpedo probe is lowered down the entire length of a vertical access tube installed in a borehole. The inclination of the access tube from the vertical, in two mutually perpendicular planes, is measured at pre-determined depths. If the location of one end of the access tube is known or fixed to a datum, it is possible to obtain a complete profile of the tube by taking a succession of readings. Depending upon site conditions, the datum used can be either the bottom of the access tube, keyed into stable ground, or the top, whose position is fixed by ground survey methods. By comparing these profiles, the rate and magnitude of horizontal displacement of the tube may be determined over a period of time. If the inclinometer access tube crosses an active shear surface, it will tend to develop a convexo-concave slope in section, with the point of inflexion of the curve approximately at the level of the shear surface. Eventually, the magnitude of such displacements will become too large for the inclinometer instrument to pass through the access tube.

12.7.2 Borehole Extensometers

A continuous recording of landslide displacements is often required in order to better understand the complex relationship between the triggering factors and the dynamics of the movement.

Borehole extensometers are used to monitor settlement, heave, convergence and lateral deformation in soil and rock. Typical applications include monitoring settlement or heave in excavations, foundations and embankments, monitoring settlement or heave above tunnels and other underground openings. Borehole wire extensometer equipment is cheap and simple. It enables very frequent readings that may be stored in a data logger. Superficial landslide displacements may differ significantly from those measured with the wire. This is because the total displacement of the wire depends on several factors such as the diameter of the borehole, the type of landslide mechanism, and both the thickness and the dip angle of the surface of rupture. The readings made with the potentiometer allow an accuracy of 0.1 mm in the measurements.

The wire extensometer is a simple and low-cost device that allows the measurement of the relative displacement between two points, one in the landslide mass that is in motion and the other in stable ground. The device that will be described here requires a borehole drilled through the landslide mass, up to the stable ground. It can be installed together with an inclinometer. It consists of a protected steel wire anchored to a fixed point inside the borehole below the slip surface of the landslide. The opposite end of the wire is attached to a frame outside the borehole. The frame is anchored to the landslide surface and holds a pulley. The wire is placed around the pulley and is kept in tension by means of a counterweight (Fig. 12.5).

In order to protect the wire against corrosion, it is inserted into a plastic sheath and sealed with silicone. The movement of the landslide displaces the wire either inside or outside the borehole with the consequent rotation of the pulley. The amount of wire displacement is measured by means of a potentiometer mounted on the axle of the pulley, which provides an electrical signal proportional to the angle of rotation. Readings of the potentiometer may be carried out at defined time steps and the signal transmitted to a data logger. Long-life batteries allow data storage for 2 or 3 months, and the device may last working for several metres of displacement, provided that enough wire has been left outside the borehole.

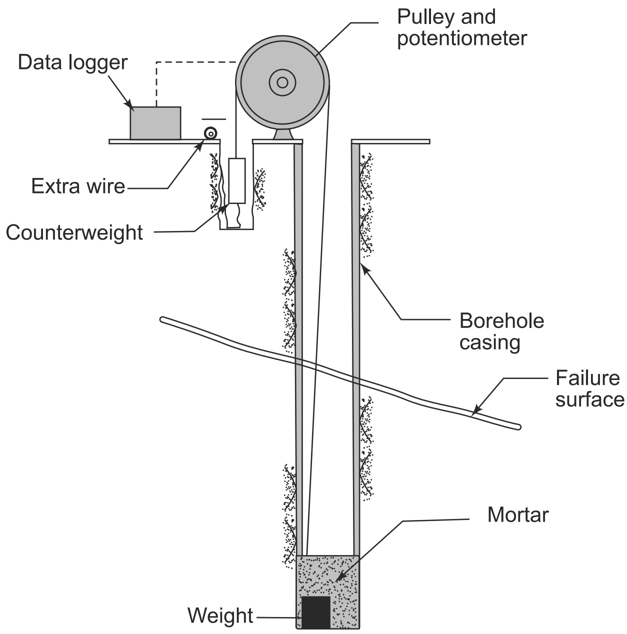


Fig. 12.5 *Borehole extensometer*

The rates of displacement obtained with the wire may be easily related to rainfall records and groundwater fluctuations. When combined with piezometers, the extensometric wire has a great capability to reproduce the response to the rainfall and groundwater fluctuations with a high degree of accuracy. It also allows temporal trends of the displacement to be observed during critical rainy events.

The combined use of the wire extensometers with devices such as probe inclinometers is highly recommended. They complement each other very well. Inclinometers have a short life when the landslide is very active, but they produce high-quality information on landslide displacement profiles, velocities and the position of the shear surface, immediately after its installation. Instead, at the early stages of deformation, the wire extensometer may only record negative displacements that are not directly related to the superficial ones. Once the inclinometer is lost, it allows a continuous recording, and it is operational for very large displacements. The relationship found between the wire and superficial displacements enables continuous recording of both horizontal and vertical displacements of the landslide to be achieved.

12.7.3 Aerial Photographs and Remotely Sensed Data

Aerial photographs and remotely sensed data may be used to their advantage for mapping landslides affected zones. The preference of methods depends mainly on the type of hazard parameters to be studied and the extent of mapping. All previously identified landslides from geologic maps, previous landslide studies, and other local sources are compiled for further study.

When the aerial photographs are available, the mapper should use at least one set of historical stereo-pair aerial photographs to locate landslides in the area being studied. Non-spatial data should also be collected at the time of the mapping so that a comprehensive database can be formed. Non-spatial data should generally include confidence of interpretation, movement class, direction of movement, etc. A comprehensive check of spatial (map) and non-spatial data should be developed and implemented including technical review of mapped landslides and field checks where possible. A step-by step procedure for landslide investigation by air photos is as follows:

1. The layout locations of road or other planned structure on photos is marked.
2. A quick survey of all cliffs or banks adjacent to river bend, and all steep slopes in the photo area is made.
3. Areas along the right-of-way that show consistent characteristics of topography, drainage, and other natural elements within the same unit are marked.
4. A detailed study of all cliffs or banks that are adjacent to river bends and all steep slopes above and below the centre line of the road is made.
5. Ground check for some of the landslides that are recognized in air photos is done.
6. Ground check of all suspected spots, using method and criteria described previously is done.

The advantages of using air photos in the investigation of landslides are as follows:

1. Air photos present an overall perspective of a large area.
2. Boundaries of existing slides can be readily delineated on air photos.
3. Surface and near-surface drainage channels can be traced.
4. Important relationships in drainage, topography, and other natural and human-made elements that seldom are correlated properly on the ground become obvious in air photos.
5. Moderate vegetative cover seldom blankets details to the photo interpreter as it does to the ground observer.
6. Soil and rock formations can be seen and evaluated in their undisturbed state.
7. Continuity or repetition of features is emphasized.
8. Recent photographs can be compared with old ones to examine the progressive development of slides.

9. Air photos can be studied at any time, in any place, and by any person.
10. Through air photos, information about slides can be transmitted to others with a minimum of ambiguous description.

Since early 1970's, satellite remote sensing techniques have become a popular approach for detecting and analyzing the temporal changes and dynamic phenomena on the Earth's surface. The technique has great potential in mapping the individual landslide and quantifies the damage at the desirable scale. Remote sensing technology, in managing the natural hazard, has two significant functions, like real time monitoring and mapping the changes or the dynamics of the process. Lidar data should be used to identify landslides and accurately locate the extents of previously mapped landslides. An orthophoto of similar age to the Lidar data should be used to minimize the mis-identification of human-made cuts and fills as landslides.

A most important method used in the recognition and classification of landslides is air photo interpretation. When properly interpreted, they reveal not only the topography, but also considerable information about other geomorphological features.

12.8 LANDSLIDE HAZARD ZONATION MAPPING

The identification of landslide-prone locations is done by knowing the geologic and geographic factors of their environment, and through mapping and inventories. The occurrence of landslides is not uniform in both extent and intensity. This therefore necessitates demarcation of hazards of landslides, which is known as Landslides Hazards Zonation (LHZ). The mapping of landslides affected area and prone to landslides are carried out for its different applications. These maps help in planning for mitigation against the post-disaster effects of landslides and in taking decisions towards development work in the unstable areas.

Several methods are available for preparation of LHZ maps based on different parameters. The guidelines given by the Bureau of Indian Standard (BIS) is being generally observed. The codes of BIS published in 1998 and 2004 are generally followed nowadays. The factors which are considered for LHZ by BIS are lithology, geological structures, slope morphology, relief, land use and land cover, and hydrology. LHZ maps are also prepared on different scales like 1:50000, 1:25000, 1:10000 and 1:5000.

Landslide Hazard Evaluation Factors (LHEF) considered by BIS code for preparation of LHZ maps are listed in Table 12.2. Different factors have different weights to decipher the magnitude of landslides' vulnerability.

After analyzing and adding the hazard evaluation factors, the different causative factors as gathered under modified BIS code, the landslide hazard zonation is carried out. The different landslides zones have been categorized and are given in Table 12.3.

Table 12.2 *Causative factors and landslide hazard evaluation factor*

Causative Factors	*Landslide Hazard Evaluation Factor*
Lithology	2
Geological structures	2
Slope	2
Relief	1
Land use	1
Land cover	1
Hydrological condition	1
Rainfall	1
Landslide incidences	2
Slope erosion	1
Total	15

Table 12.3 *Landslide zones on the basis of LHEF*

Total Estimated Hazards Factors	*Zones of Landslides Hazards*
< 4.9	Very low hazard
4.91–7.0	Low hazard
7.1–8.4	Moderate hazard
8.41–10.50	High hazard
> 10.50	Very high hazard

12.9 MAJOR LANDSLIDES AND AFFECTED AREAS IN INDIA

Hilly and mountainous regions of India are fragile and vulnerable from landslides point of view. Occurrence of landslides, the affected area and the reported casualties are listed in Table 12.4.

Table 12.4 *Major landslides in India*

S. No.	*Name of Landslides*	*Area Affected*	*Year*	*Total Casualties (Approx. No.)*
1	Darjeeling	Parts of Sikkim and West Bengal	1968	1000
2	Assam	Assam, Meghalaya and Tripura	2006	1500
3	Western Ghat	Nilgiri, and Konkan valley	1978	90
4	Amboori	Parts of Kerala	2001	23
5	Alakananda	Parts of Uttarakhand	1970	124
6	Malpa	Parts of Uttarakhand	2005	220
7	Leh	Laddakh of J&K	2012	300
8	Kedarnath	Uttarakhand	2013	1056

12.10 LANDSLIDE HAZARD MITIGATION

Landslides are one of the most devastating hazards that occur each rainy season and catapulted in hilly and geologically fragile regions of the country. Therefore, mitigation of landslide hazards is required on priority to reduce the annual loss of property and life. Several attempts are being made by the government, in general, and National Disasters Management Centre, in particular, to delineate the landslide zones on the micro scale and their remedial measures. Few important preventive measures are described as follows.

12.10.1 Geometry Modification

One of the ways to increase the slope stability is by placing retaining structures for increasing the resistance to movement of landslides. This includes gravity retaining walls, crib-block walls, gabion walls, passive piles, piers and caissons, cast-in situ reinforced concrete walls, and reinforced earth-retaining structures with strip/sheet-polymer/metallic reinforcement elements, etc. Generally, the following minimum information is required to determine the type and size of a restraining structure:

(a) the boundaries and depth of the unstable area, its moisture content and its relative stability;
(b) the type of landslide that is likely to develop or has occurred; and
(c) the foundation conditions, since restraining structures require a satisfactory anchorage.

■ **Slope Modification** Slope of the ground surface on which detached blocks of rock or soil moves has to be characterized by gentle slope. The angle must be minimized as much as possible, but at least it should be kept less than 45° so as to reduce the intensity of landslides (Fig. 12.6).

Fig. 12.6 *Slope modification and stone pitching*

Potentially unstable slopes can be monitored so as warn the probable affected residents and, if necessary, evacuated. When the acceleration imposed on the slope exceeds its critical acceleration, displacement or failure is resulted. If a slope is most possibly to be brought to failure by rainfall, a monitoring system can be installed, and landslide warning based on real-time monitoring data may be issued.

■ **Drainage Management** It is a known fact that water lubricates the rock and soil which triggers the landslides and intensifies the landslides as well. The path of existing drainage in landslide prone area can be modified so as to divert the drainage towards non-landslide areas. Consequently, this reduces the concentration of water in the landslide prone area. Moreover, it would reduce the frequency and intensity of landslides.

Drainage is the most widely used method for slope stabilization. Underground drainage systems and pumping wells remove groundwater and decrease pore water pressure, thus increasing the shear strength of soil. Surface water is drained from the unstable areas by surface ditches so as to reduce surface water infiltration into the potential slide mass. In the design of underground drainage systems, to stabilize slopes, the capacity of each drain or outlet pipe should be accounted for. The underground drainage system should have the capacity to decrease pore water pressure at the failure surface in order to stabilize the landslide as much as possible.

■ **Grouting** It is one of the important methods to prevent landslides in highly jointed or fractured rock mass area. The landslide movement is accelerated due to the presence of joints since lubrication of rock mass takes place due to entrapment of water in fractures or joints. Grouting of joints is carried by injection of slurry, made up of cement and sand. It seals the joints and makes the rock mass stable and strong.

■ **Retaining Wall** Retaining walls are structures built for the purpose of neutralizing the effects of unstable slopes holding back rock or soil from buildings, roads or structures. Retaining walls reduce the erosion and down-slope movement providing support for near-vertical or vertical grade changes. Retaining walls can be made of wood, natural stone, reinforced cinder block, concrete block systems, or reinforced cement concrete (Fig. 12.7).

■ **Afforestation** Plantation is one of the important measures to control the intensity of landslides since it arrests the soil erosion. Afforestation is implemented in the area which is prone to landslides.

■ **Gabions** These are wire mesh boxes filled with rough cut-stone or a combination of stone and topsoil to promote vegetative growth for reducing the erosion. These preventive measures are adopted in the areas of low intensity landslides (Fig. 12.8). The structure is low cost and can be maintained by local people.

Fig. 12.7 *Retaining wall*

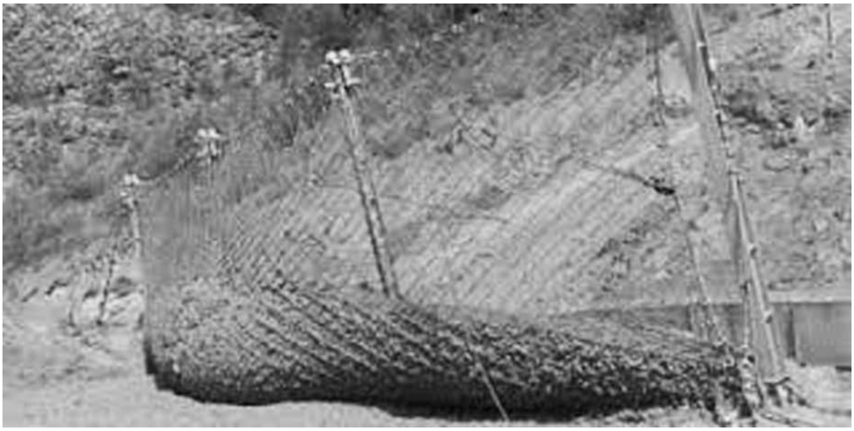


Fig. 12.8 *Gabion structure*

■ **Development of Real-Time Warning System** Landslide warnings in areas prone to landslides during major storms has proved to be very effective measure. Real time warning system includes the following factors, (a) empirical and theoretical relations between rainfall characteristics and landslide initiation, (b) geological determination of areas prone to landslides, (c) real-time monitoring of a regional network of telemetering rain gauges, and (d) precipitation forecasts made by the weather service authorities.

12.11 KEDARNATH MAJOR LANDSLIDE (2013, UTTARAKHAND)—A CASE STUDY

Kedarnath is one of the ancient and famous pilgrims place situated in Uttarakhand, India. It is located in the snow cover area of Himalayan region at the height of approx. 3,583 m above mean sea level in the Mandakini valley of Rudraprayag district, Uttarakhand. The fragile nature of oldest crystalline basement of the Himalaya is very sensitive in case of landslides or any other disaster. Basically, the frequency and magnitude of landslides depend on the underlying structures, physiographic setting, type and condition of vegetation and anthropogenic pressure of the location.

Kedarnath has gained importance because of the Kedarnath Temple (latitude: 30°73′ and longitude: 79°06′). This region is seismically and ecologically very sensitive. Even minute changes, anthropogenic or natural, can lead to disaster. Due to decisive weather condition, it is not possible to visit this holy place round the year, and is safe to visit from May to October only.

The race between tourism industries, population growth, several hydroelectric projects are in fast track in Uttarakhand. After the constitution of Uttarakhand as a state, there is an increment of approximately 141 % in population. Nowadays, lots of residents and villagers have started to live near the temple and commercialize this holy region in the valley by building hotels, shops and markets. It is clear that there is tremendous growth in infrastructure during last few decades and proportionally, the number of pilgrimages has increased to a greater extent. Currently there are 558 hydroelectric power projects in pipe line and will affect rivers Bhagirathi (80%) and Alaknanda (65%), as per the statement of Sunita Narayan, Director, Centre for Science and Environment. Due to development of roads and a dam in between mountains, the incidents of landslides have increased.

The Rudraprayag district, where Kedarnath is located, has already faced natural disasters eight times in the past 34 years. During 1953–1980, 0.76 million people suffered due to flood and natural disaster. The problems become more provoked during monsoon period (mid-June to mid-September). Uttarkashi town, Chamoli to Badrinath road sector, Narainbada, Mandakini Valleys, etc., are the critical areas in terms of landslides.

In 2012, the Okhimath area of Rudraprayag witnessed unprecedented damage to the life and property, infrastructure and landscape during September 13 to 16 due to torrential rainfall and a cloud burst incident. Kedarnath is situated on a glacial outwash plain bordered by impenetrable green forest, with a waterfall nearby, the tiny village of Rambara. Rambara is the most popular resting place for devotees while trekking to Kedarnath from Gaurikund. As per the different news agencies it was reported that nothing is left there. The entire area, which housed around 100–150 shops and five hotels, to serve the needs of the ever increasing number of pilgrims, was completely washed away leaving no trace of the once lively rural community situated at an altitude of 2591 m, halfway on the 14 km long track to Kedarnath.

Major landslides took place in Kedarnath valley due to torrential rainfall during 16 and 17 June, 2013. After viewing this disaster due to torrential rainfall, an attempt was made to utilize the high resolution satellite data of prior to and after the incident of the devastation in Kedarnath of Rudraprayag district, Uttarakhand. The study area of Kedarnath landslides lies in between 30°39′ to 30°48′ latitudes and 79°02′ to 79°10′ longitudes from Gaurikund to Kedarnath in the Mandakani Catchment of Rudraprayag district. The upper part of this area is flipside by two glaciers i.e. Chaurabari and Companion. The Chorabari glacier covers around 4.23 sq km area and length of this glacier is about 7 km. The Companion glacier covers around 3.59 sq km area and length of this glacier is around 5.97 km. The study area is basically situated at an altitude (2000 m at Gaurikund to 6500 m at upper reaches) and most of this area is covered by snow-glaciers.

The level of loss at the Kedarnath Temple in the debris flow was unimaginable. In fact, it is not clear as to what actually happened at Kedarnath and how did this enormous debris flow generated. It is well known that the event was triggered by prolonged heavy rainfall interspersed with at least one cloud-burst-type event. Moreover, the debris came from above the town in the formerly-glaciated valleys, and there was enough of sediment in those valleys. Some of the possible explanations as outlined in the report of Prof. Dave Petley, Durham University, UK are as follows.

- **The Collapse of a Moraine-Dammed Lake** This is the simplest and most obvious explanation. In this scenario, there is a lake upstream of the town, with meltwater from the glacier impounded by glacial debris. In the extreme rainfall, the barrier failed, releasing a huge flood that struck the town.

- **A Catastrophic Landslide Onto, and then Down the Glacier** This scenario is entirely possible in such a landscape. Here, a collapse event on the valley walls above the glacier transitioned into a flow that swept down the ice. This then picked up debris and water below the glacier, and turned into a debris flow. This is entirely possible, and might account for the morphology of the right hand glacier in the ISRO image. However, the morphology of the area upstream of the town doesn't really suggest that this is what happened.

- **A Landslide below the Glacier Created a Dam, which then Ruptured, Releasing the Flood** There seems to be quite a lot of change is this area, which could indicate a blocking event in this region, perhaps from a failure on the lower part of the valley wall. However, this area is more likely to have been scoured from some other event.

- **A Landslide event in a Higher Valley that became a Channelized Debris Flow** It is entirely possible that a landslide elsewhere in the catchment became a debris flow that struck the town, as shown by a possible scar marked 2 (PLATE 16) in the annotated image above, although this could just be an area of erosion, or something similar. There are other areas with similar features.

- **A Simple Case of Too Much Rain on a Large Catchment and a Misplaced Town** The final scenario is that there was simply too much rain across the large catchment, resulting in flows across all of the channels, which exceeded their limits. As a result, large volumes of water reached the town simultaneously, having picked up huge amounts of loose sediment enroute. The location of the town at the confluence of these channels meant that the disaster was inevitable.

Summary

Landslide is a geological process that brings about immense loss of property and life apart from environmental damage. Landslides damaging the wealth of the country as well human resource are major obstacles for development of the areas affected by these phenomena. They have been occurring since historical time but have received serious attention during the twentieth century. Although it is a natural phenomena, but is triggered by number of geological, atmospheric causes and human activities. In India, landslide hazards take place every year in many regions in different states, and have posed challenges to the scientists, engineers and planners.

Landslides as described in this chapter provide a holistic approach to address the problems apart from geological and geomorphological considerations. Morphology of landslides has been described which reflects the light on its different parts. Causes of landslides have been explained in detail emphasising the geological controls. Natural conditions and human activities can both play a role in causing landslides. Certain geologic formations are more susceptible to landslides than others. Locations with steep slopes are most susceptible to landslides. The landslides occurring on steep slopes tend to move rapidly and are therefore more dangerous than other landslides. Although landslides are a natural geologic process, the incidence of landslides and their impacts on people and property can be accelerated by human activities. Developers who are uninformed about geological materials and processes may create conditions that trigger landslide activity or increase probability of landslide hazards.

Classification of landslides, considering the nature of material involved and its movement has been described and tabulated. The different process involved under landslides has also been discussed. Landslides measurement methods have been outlined which would help in monitoring the landslides. Landslides hazard zonation maps and landslide vulnerability has been explained. The grading of landslides and zones under different landslides hazards has been categorized. Major landslides those occurred in India have been tabulated. It is pertinent to mention that preventive measures for landslides have also been explained briefly. The chapter ends with the case study of Kedarnath landslides that is considered to be the most devastating catastrophe in the recent past.

Terminology

Accumulation The volume of displaced material that lies above the original ground surface is known as accumulation.

Creek Water Level Water level that is encountered in fractures developed by landslides.

Crown The practically displaced material still in place and adjacent to the highest parts of the main scarp is called crown.

Depleted Mass	The volume of the displaced material which overlies the rupture surface but underlies the original ground surface is termed depleted mass.
Displaced Material	The material displaced from its original position on the slope by movement in the landslide is known as displaced material. It forms both the depleted mass and the accumulation.
Head	The upper parts of the landslide along the contact between the displaced material and the main scarp are known as head.
Lidar	Also known as Light Detection And Ranging, it is a remote sensing technology that measures distance by illuminating a target with a lazer and analyzing the reflected light. It is popularly used to make high resolution maps.
Original Ground Surface	This is the surface of the slope that existed before the landslide took place.
Orthophoto	Also known as orthophotograph or orthoimage, it is an aerial photograph geometrically corrected such that the scale of photograph is uniform.
Spatial (Map)	It is the data or information that identifies the geographic location of features and boundaries on the Earth. It may be natural or constructed features, oceans, etc. Spatial data is usually stored as coordinates and topology which can be mapped. Spatial data is often accessed, manipulated or analyzed through Geographic Information Systems (GIS).
Non-spatial Data	The information which is independent with all geometric consideration. It is also called as attribute or characteristics like text or image. It is linked with spatial data under GIS for proper construction of maps and their interpretation.
Surface of Separation	This is the part of the original ground surface overlain by the foot of the landslide.
Tip	The point of the toe farthest from the top of the landslide is known as tip.
Toe	The lower, usually curved margin of the displaced material of a landslide, is called toe. It is the most distant edge from the main scarp.
Toe of Surface of Rupture	The intersection (usually buried) between the lower part of the surface of rupture of a landslide and the original ground surface.
Zone of Accumulation	The area of the landslide within which the displaced material lies above the original ground surface is known as zone of accumulation.
Zone of Depletion	The area of the landslide within which the displaced material lies below the original ground surface.

Exercises

1. (a) What are landslides? Describe the causes and methods to prevent them.
   (b) How are landslides measured?
2. Discuss about classification of landslides and the criteria on which they are based.
3. (a) Which areas of India are prone to major landslides? Specify causes of landslides.
   (b) Explain in detail the preventive measures of landslides.
4. (a) Describe the landslide zonation map and its significance.
   (b) Give a brief account of landslide hazard mitigation.
5. (a) Discuss the role of groundwater in causing landslides.
   (b) Describe various types of landslides with the help of neat sketches.
   (c) Discuss briefly the various methods to increase the slope stability.
6. Give a brief account of the catastrophe that took place in 2013 in Kedarnath, Uttarakhand.
7. Write short notes on the following:
   (a) Crown of landslides
   (b) Rotational and translational slides
   (c) Landslides hazard zonation
   (d) Earthflow
8. Differentiate between the following:
   (a) Soil creep and lateral spread
   (b) Rock fall and topple
   (c) Rock flow and debris flow
   (d) Transverse and radial cracks
   (e) Afforestation and deforestation
   (f) Earthflow and mudflow
   (g) Physical and human causes of landslides
   (h) Debris avalanches and lateral spreads

Multiple-Choice Questions

1. Which of the following factor is not responsible for triggering of landslides?
   (a) Precipitation (b) Structural discontinuities
   (c) Mining activity (d) Plantation
2. Rock fall is a type of landslide when the
   (a) rock slowly moves down
   (b) soil debris moves down with rapid velocity
   (c) earth mass is detached and flow takes place
   (d) rock is detached and falls directly on the ground surface

3. Which of the following measure is not included in landslides mitigation techniques?
(a) Modification of slope geometry
(b) Drainage modification
(c) Construction of retaining walls
(d) Mining operations

4. Landslides mostly occur during
(a) pre-monsoon (b) post-monsoon
(c) monsoon (d) summer

5. Creep is characterised by
(a) slow and steady movement (b) fast and steady movement
(c) slow and random movement (d) fast and random movement

6. A slope can be stabilized by which of the following measure?
(a) Dumping of overburden
(b) Trenching
(c) Construction of walls
(d) Modification of slope geometry

7. Landslides hazards zonation mapping is based on
(a) lithology (b) rainfall
(c) topography (d) all the above

8. The reason of landslides being more common on steep slopes is
(a) slope angle determines the relative magnitude of driving forces
(b) water flows much faster on steep slopes
(c) the steeper the slope, the less vegetation plays a role in anchoring the slope
(d) steeper slopes typically are underlain by weaker earth materials

9. Vegetation influences landslides by
(a) anchoring the slope materials
(b) influencing the local climate
(c) aerating the soil
(d) promoting deeper weathering of underlying rock

10. What aspect of hillside development has contributed to the frequency of landslides in the Himalayan regions of Uttarakhand?
(a) Drainage of naturally occurring subsurface water
(b) Grading of hill slopes to create pads for construction of buildings
(c) Logging of hillside vegetation
(d) All of the above

Answers to MCQs

1. (d) 2. (d) 3. (d) 4. (c) 5. (a) 6. (d) 7. (d) 8. (a)
9. (d) 10. (d)

chapter 13

Groundwater

13.1 INTRODUCTION

The most common sources of surface waters are streams, lakes and rivers. Besides these depleting surface sources, groundwater has emerged as an important source of water supply to cater the need. All the water beneath the ground surface is termed as *groundwater or subsurface water*. It is relatively free from pollution and requires little treatment. Considering all of Earth's water, only about 0.3 per cent occurs underground. However, this small percentage is a vast quantity itself, when only sources of freshwater are considered. The largest volume of freshwater occurs as glacial ice. Then to follow is groundwater, with slightly more than 14% of the total fresh water. However, when ice is excluded and just liquid water is considered, more than 94% per cent of all freshwater is groundwater. Although, the chief source of groundwater is *meteoric water* (the downward percolated rain water) but some groundwater is also available as *juvenile water* (magmatic water) and *connate water* (entrapped water in sedimentary rocks during their deposition).

The occurrence, distribution, storage and movement of water below the surface is referred to as *groundwater hydrogeology*. When rain falls to the ground, the water starts moving and is known as *run-off*. Some of the rainfall flows along the surface as run-off in streams or lakes, some evaporates and returns to the atmosphere, some of it is used by plants, and some goes into the ground. The percolating water into the ground gets stored wherever formations are porous. Groundwater is stored in and moves slowly through layers of permeable soil and rocks. These permeable formations containing water are called *aquifers*.

Water in aquifers is brought to the surface naturally through a spring or can be discharged into lakes and streams. This water can also be extracted through a well drilled into the aquifer. Some wells, called *artesian wells*, do not need pumping because of natural pressures that force the water up and out of the well. The availability of the groundwater depends upon porosity and permeability of the rocks, the rate at which water infiltration takes place and the rate at which water is lost by evaporation, transpiration, seepage through surface courses and withdrawal by man. Groundwater is one of the components of *hydrologic cycle* in nature that explains the recharge, storage and movement of groundwater.

Note More than 97 per cent of the Earth's water occurs as saline water in the oceans. Of the world's freshwater is less than 3 per cent, out of that almost 75 per cent is in polar ice caps and glaciers, which leaves a very small amount of freshwater readily available for use. Groundwater accounts for nearly all of the remaining freshwater. All of the freshwater stored in the rivers and lakes accounts for less than 1 per cent of the freshwater.

13.2 HYDROLOGICAL CYCLE

The hydrological cycle, also sometimes called *water cycle*, describes the continuous movement of water above, on, and below the surface of the Earth (Fig. 13.1). The water on the Earth's surface called the *surface water* occurs as streams, lakes, rivers and oceans. The surface water also includes the solid forms of water, snow and ice. The water below the surface of the Earth primarily is groundwater, but includes soil water as well. Following is the description of the movement of water in hydrological cycle.

1. The water molecules from lakes, rivers, streams, reservoirs, and the sea get heated up by the sun and turn into vapour that rises into the air. This process is called evaporation.
2. These water molecules then form into clouds because of a process called condensation.
3. When the air and the water cool, they form drops of water which then fall to the Earth as rain. If they are frozen, they become snow or sleet.
4. Once the water reaches the ground, it can flow across the land until it reaches rivers, lakes, streams, or the sea.
5. It can also percolate into the ground and flow because of gravity through pores and fractures in rock, gravel and sand. Because of this, it reaches water bodies.
6. The cycle described above keeps on repeating continuously.

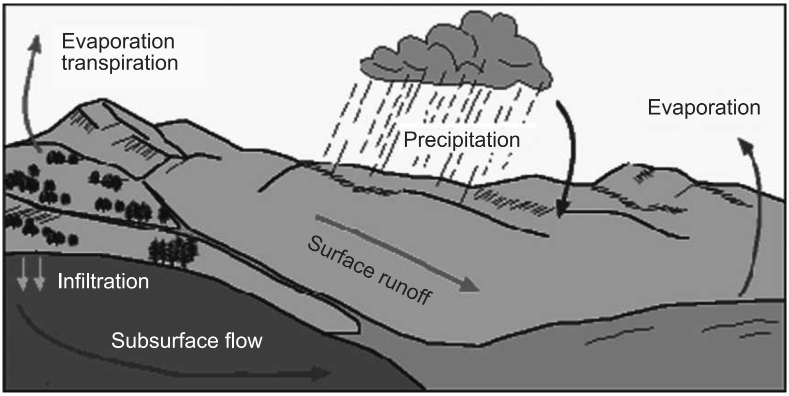


Fig. 13.1 *Hydrological cycle*

13.3 ORIGIN OF GROUNDWATER

Groundwater is a part of the hydrological cycle. As described above, the rain and snowmelt either becomes run-off in channels or infiltrates into the subsurface. Some of the infiltrated water transpires by plants and returns to the atmosphere, while some clings to particles surrounding the pore spaces in the subsurface, remaining in the unsaturated zone. The rest of the infiltrated water moves gradually under the influence of gravity into the saturated zone of the subsurface, becoming groundwater. Water flow from recharge areas to discharge areas describes the groundwater contribution in the hydrological cycle.

At greater depths below the Earth's surface, due to the pressure of the overlying rocks, the extent of openings permitting percolation of water are believed to be practically nil. The depth of the extent of groundwater is therefore considered to be limited within a shallow zone below Earth's surface. The groundwater thus accumulates here with the openings completely saturated. With any further percolation of water, the process of saturation of the openings starts upward. This constitutes the upper limit defined as *water table*. The water below the water table and within the zone of saturation is known as *groundwater* (Fig. 13.2).

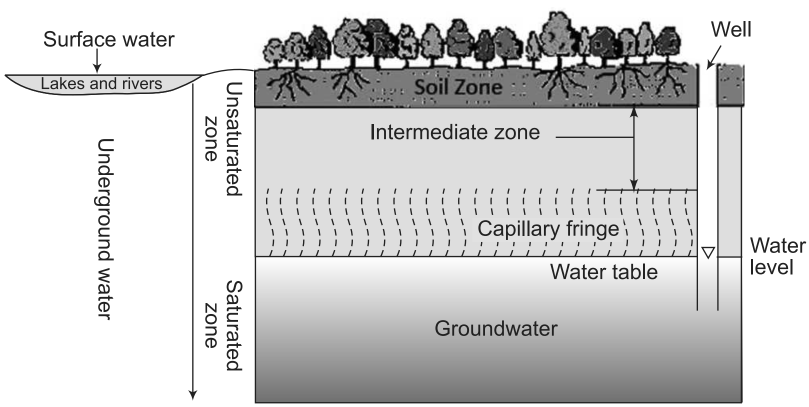


Fig. 13.2 *Origin and distribution of groundwater*

13.4 WATER-BEARING FORMATIONS

Understanding the nature of the bedrock geology is important to determine the quantity of groundwater that can be pumped from a well at a given place. For example, the bedrock may consist of sedimentary layers that have abundant pore spaces between individual grains. These layers can form laterally extensive aquifers, or conduits for groundwater movement (Fig. 13.3). Groundwater in these areas is a potential source of public water supply needs. Hardrock areas comprising massive igneous and metamorphic rocks are not potential to yield groundwater as in case of sedimentary rocks. The water-bearing geological formations can be classified on the basis of their hydraulic properties.

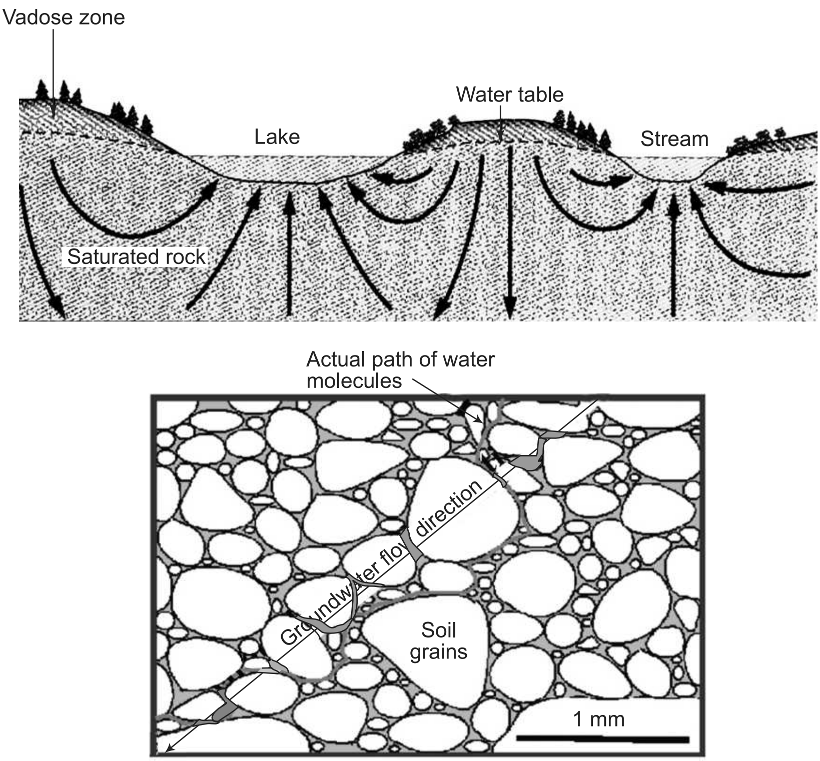


Fig. 13.3 *Movement of groundwater*

■ **Aquifer** An aquifer is defined as a saturated geological formation that is permeable enough to yield significant quantities of water to wells and springs under gravity. Thus, a porous and permeable water bearing formation is called an *aquifer*. The terms *water-bearing formation/stratum* and *groundwater reservoir* are synonyms for the aquifer. The granular, unconsolidated sedimentary formations, such as gravel and sand, form potential aquifers. Aquifers may be of unconfined, confined and semi-confined types.

■ **Aquifuge** It is the geological formation, which is neither porous nor permeable and hence neither contains nor yields groundwater. Massive quartzite rock is an example of aquifuge.

■ **Aquiclude** It is a saturated formation through which virtually no water is transmitted. Aquicludes may have high porosity but relatively have very low permeability and hence do not yield appreciable quantities of water to wells. In other words, a highly porous and an impermeable (that does not transmit water at all) geological formation is called an *aquiclude* e.g. clay and shale.

■ **Aquitard** A saturated formation that has low permeability and yields water slowly in comparison to the adjoining aquifers is known as *aquitard*. It is a body of rock or sediment that is typically capable of storing groundwater but does not yield in significant quantities. Fine-grained sediments with low hydraulic conductivity, such as silts, often function as aquitards. Sandy clay is an example of aquitard. Most aquitards do yield some water but usually not enough to meet even the modest demand.

13.5 TYPES OF AQUIFERS

A classification of aquifers in an area can be made on the basis of their location in the groundwater basin and the position of their associated water levels. Aquifers are of three types: Unconfined, confined and semiconfined (Fig. 13.4).

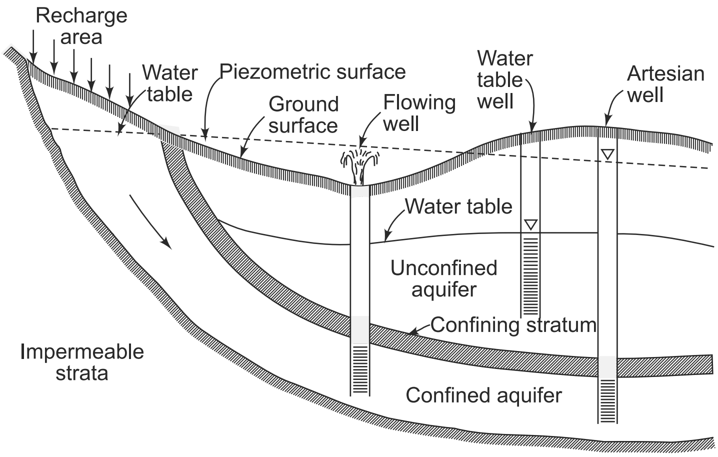


Fig. 13.4 *Confined and unconfined aquifers*

13.5.1 Unconfined Aquifers

In most depositional environments, coarse-grained deposits are interbedded with fine-grained deposits creating a series of aquifers and aquiclude. When the topmost water bearing stratum has no confined impermeable overburden (i.e. aquiclude) lying over, it is called unconfined aquifer.

The upper surface of an unconfined aquifer is defined by the water table and it is in direct contact with the atmosphere. Water in an unconfined aquifer is under atmospheric pressure and therefore does not rise above the water table. The water table in unconfined aquifers is free to rise and fall. Rise and fall in the unconfined aquifer correspond to changes in the volume of water in storage within aquifer. It is also referred to as *water table* or *phreatic aquifer*. The water table in unconfined aquifers is often termed as *phreatic water level*. Movement of the groundwater is in direct response to gravity in unconfined aquifer.

The gravity wells of 2 to 5 m diameter are constructed to trap water from the top most bearing strata. Such wells are, therefore known as gravity wells or water table wells or open wells or dug wells.

13.5.2 Confined Aquifers

A confined aquifer is bounded above and below by an aquiclude, which is impermeable to water flow. Water in the confined aquifer occurs under pressure, which is usually more than the atmospheric pressure, so that if a well taps the aquifer, the water level will rise above the top of the aquifer, i.e. above the base of the overlying confining bed. It will rise up to an elevation at which it is in balance with the atmospheric pressure. If this elevation is greater than that of the land surface at the well, the water will flow from the well and such wells are termed *artesian* or *flowing wells* (Fig. 13.4). The confined aquifers have only an indirect or distant connection with the atmosphere. The imaginary surface, conforming to the elevations to which water will rise in wells penetrating confined aquifers is known as the *piezometric surface* or *potentiometric surface.* It coincides with the hydrostatic pressure levels of the water in the aquifer.

A well excavated through such an aquifer, yields water that flows out automatically under the hydrostatic pressure, even rise or gush out of surface for a reasonable height. However, if the ground profile is high, the water may remain well below the ground level.

Rise and fall of water in wells penetrating confined aquifers result primarily from changes in pressure rather than changes in storage volumes. Hence, confined aquifers display only small changes in storage and primarily serve as conduits for conveying water from recharge to discharge areas.

❑ *Perched (Unconfined) Aquifer*

It is a type of an unconfined aquifer (Fig. 13.5). Sometimes, an impermeable bed of clay or silt may be present in some areas above the regional water table within the zone of aeration. This impermeable barrier intercepts downward movement of water and causes some of it to accumulate in the interstices of the rocks and soil present above the water table. Thus, a zone of saturation of limited areal extent is locally formed with in the zone of aeration, i.e. a small water-bearing zone sometimes exists between the main water table and the ground surface. This

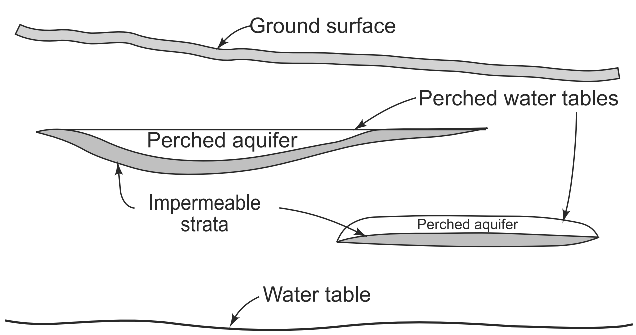


Fig. 13.5 *Perched (unconfined) aquifer*

zone is called the *perched groundwater zone* and the aquifer is called a *perched aquifer*. The upper surface of the groundwater in this case is called a *perched water table*. The perched aquifer has limited thickness and areal extent, not widely distributed, and are not used for water supply. Depending on the climatic conditions, a perched water table may be permanent or seasonal.

13.5.3 Semiconfined Aquifers

Semiconfined aquifer, also known as *leaky aquifer,* is the one whose upper and lower boundaries are bounded by aquitards. As the aquitards are semipermeable, it may slowly transmit appreciable water to or from adjacent aquifers. For example, a water bearing formation may be overlain by an aquitard, which permits water to move slowly upward out of the aquifer or vertically downward into the aquifer, depending upon the hydrostatic head in the aquifer.

Where the aquitard is under the aquifer, water may be lost to or gained from the rocks below. Confined aquifers that lose or gain waters from the surrounding formations are called *leaky confined aquifers*.

13.6 HYDRAULIC PROPERTIES OF ROCKS

To have an understanding of occurrence and movement of groundwater, knowledge of hydraulic properties of rocks such as porosity and permeability are required. These are described as follows.

13.6.1 Porosity

Porosity of soil, which is the major geological criteria for occurrence of groundwater, is a quantitative measurement of the interstices or voids present in the soil. These voids or openings are often called *pore spaces*. A rock is said to be saturated when all its interstices are filled with water. Porosity is generally defined as the percentage of the voids present in a given volume of soil. Porosity is usually of two types, the primary porosity and the secondary porosity. Mathematically, porosity can be expressed as

$$\text{Porosity } (\eta)\% = \frac{V_v}{V} \times 100$$

where, V_v = Total volume of voids in the soil, i.e. the volume of water required to saturate the dry sample

V = Total volume of the soil

For example, if 1 m^3 of sand contains 0.3 m^3 of open spaces (or) pores, its porosity is 30%.

The porosity of rocks and unconsolidated materials may vary considerably. It may range from negligible to even 90%. But generally, it does not exceed forty per cent, except in very poorly compacted materials. Table 13.1 gives the range of porosity for different rocks. The later value is reflective of recently deposited sediments whereas the former value is for dense crystalline rocks or highly compacted soft rock such as shales.

Table 13.1 *Porosity of different rocks*

Rock	*Porosity (%)*
Sedimentary Material	
Gravel, coarse	24–36
Gravel, fine	25–38
Sand, coarse	31–46
Sand, fine	26–53
Silt	34–61
Clay	34–60
Sedimentary Rocks	
Sandstone	5–30
Siltstone	21–41
Limestone, Dolomite	0–20
Karst limestone	5–50
Shale	0–10
Crystalline Rocks (Igneous and metamorphic)	
Fractured crystalline rocks	0–10
Dense crystalline rocks	0–5
Basalt	3–35
Weathered granite	34–57
Weathered gabbro	42–45

Notes

1. In general, a porosity greater than 20% is considered to be large and below 5% as small, and between 5 to 20% as medium. Generally, granite, quartzite, slate and shale have small porosity; limestone and sandstone have medium porosity and sand, gravel and clay have large porosity.
2. Individual pores in a fine-grained material like clay are extremely small but the total pore space is usually large. While clay formation has large water holding capacity, water cannot readily move through the tiny pores and hence is not aquifer, even though it may be saturated with water.

■ **Effective Porosity** The pores in the rocks may be connected or disconnected. The term *effective porosity* refers to the amount of interconnected pore spaces available for fluid flow and it is expressed as the ratio of volume of interconnected voids to total volume of rocks.

$$\eta_e = \frac{\text{Volume of interconnected voids}}{\text{Total volume}}$$

Note

The two porosities are not identical. For example, many crystalline rocks have a high total porosity, most of pores may be unconnected. Effective porosity implies to some connectivity through the solid medium, and is more closely related to permeability than its total porosity. Typical values of effective porosity are shown in Table 13.2.

Table 13.2 *Range of total porosity and effective porosity of different rocks*

Rock	*Total Porosity (%)*	*Effective Porosity (%)*
Anhydrite	0.5–5	0.05–0.5
Chalk	5–20	0.05–0.5
Limestone, dolomite	5–15	0.1–5
Sandstone	5–15	0.5–10
Shale	1–10	0.5–5
Granite	0.1	0.0005
Fractured crystalline rocks	–	0.00005–0.01

13.6.2 Controlling Factors for Porosity

In semiconsolidated (sedimentary) and unconsolidated (loose sediments) formations, the porosity of formation is controlled by the size, shape, sorting, packing of particles and degree of cementation. In consolidated formations (hard rocks), the porosity is dependent on the size of the individual fractures, joints and other openings; the extent, spacing and the pattern of fracturing or on the nature of solution channels. In hard rocks, fracturing and jointing results in higher values of secondary porosity. Some formations like hard shales and clays, may also acquire high secondary porosity and permeability due to joints and fractures (Fig. 13.6).

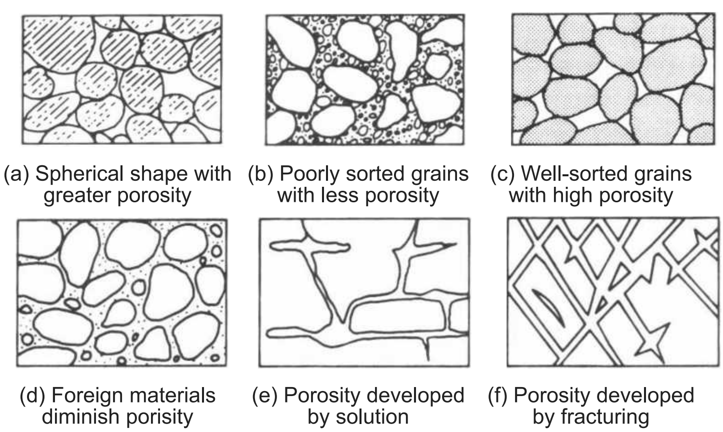


Fig. 13.6 *Controlling factors of porosity*

■ **Size** Grain size of sediments is important to control the porosity. Generally, coarser grains form high porosity while finer grains form low porosity. An exception to this is clay being fine grained sediment and has high porosity.

■ **Shape** Regarding the shape of grains, it is seen that angularity tends to increase porosity.

■ **Sorting** Where sediments are poorly sorted, the porosity is reduced because the finer particles tend to fill the openings among the larger grains. Most igneous and metamorphic rocks, as well as some sedimentary rocks, are composed of tightly interlocking crystals, therefore the voids between the grains may be negligible.

■ **Packing** The geometrical arrangement of grains or the types of packing also affects porosity. In cubic packing, the porosity is as high as 48%, while in rhombic packing it is as low as 26% (Fig. 13.7).

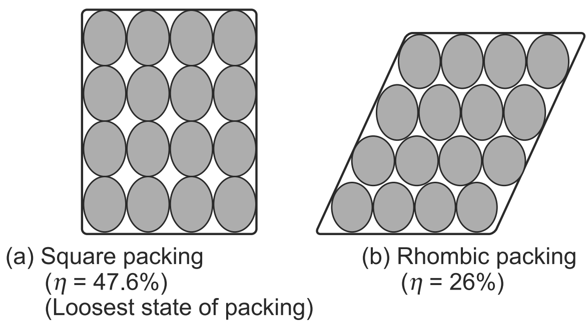


Fig. 13.7 *Arrangement of grains in cubic and rhombic packings*

Degree of cementation and compaction reduces porosity. In unconsolidated alluvial formations, the porosity at deeper levels is less due to greater compaction. In volcanic rocks, the porosity decreases with the deposition of secondary minerals in vesicles in the form of amygdule.

While porosity measures the total amount of water that may be contained in void spaces, there are two related properties that are important to consider: specific yield and specific retention. *Specific yield* is the fractional amount of water that would drain freely from rocks or sediments due to gravity and describes the portion of the groundwater that could actually be available for extraction. The portion of groundwater that is retained in small pore spaces is called *specific retention*. Specific yield and specific retention of the aquifer material together corresponds to the porosity. Specific retention increases with decreasing grain size.

13.6.3 Permeability

Porosity alone cannot measure a material's capacity to yield groundwater. Rock or sediment may be very porous yet still not allow water to move through it. The pores must be inter-connected to allow water flow. The porosity itself does not ensure the storage of groundwater because water can enter into a rock only if the rock permits the flow of water through it. The permeability of a material—its ability to transmit a fluid—is also very important (Table 13.3). The small pore spaces slow down the movement of water. The permeability is defined as the ability of rock or unconsolidated sediment to transmit water through itself. The permeability is measured in terms of coefficient of permeability. Various methods including constant head permeameter and various head permeameters are used to assess permeability.

Table 13.3 *Range of permeability in different rocks*

Rock Type	*Range of Permeability (m/day)*
UNCONSOLIDATED ROCKS	
Gravel	100–500
Coarse sand	50–200
Medium to coarse sand	20–70
Fine to medium sand	5–30
Fine sand	10^{-1}–10
Silt	10^{-3}–10^{-1}
Sandy clay	10^{-3}–1
Loose clay	10^{-7}–10^{-3}
Compact clay	10^{-10}–10^{-5}
CONSOLIDATED ROCKS	
Vesicular basalt	10^{-3}–10^{3}
Karstic limestone	10^{-1}–10^{3}
Fractured sandstone	10^{-3}–1
Limestone, non-karstic	10^{-6}–10^{-1}
Shale	10^{-8}–10^{-4}
Fractured intrusive/Metamorphic rocks	10^{-3}–10
Unfractured intrusive/Metamorphic rocks	10^{-9}–10^{-5}

Note Porosity is not always a reliable guide to the amount of groundwater that can be produced, but however permeability is significant in determining the rate of groundwater movement and the quantity of water that might be pumped from a well.

13.7 DISTRIBUTION AND OCCURRENCE OF GROUNDWATER

Precipitation (rainfall), which is the source of virtually all freshwater, falls nearly everywhere, but its distribution, is highly variable. When rain falls, a part of it flows over the Earth's surface, called run-off; some part returns to the atmosphere by evaporation and transpiration and the remainder percolates into the ground. The amount of water that takes each of these paths is influenced by the steepness of a slope, nature of surface material, intensity of rainfall, and type and amount of vegetation.

Heavy rains that falls on steep slopes; underlain by impervious materials, result in a high run-off. However, if rain falls steadily and gently upon more gradual slopes composed of materials that are easily penetrated by the water, a much larger percentage of water will percolate into the ground. Some of the water is held by intergranular spaces in soil particles. This near-surface zone is called the *zone of soil moisture*. It is crisscrossed by roots, voids left by decayed roots and animal and worm burrows that enhance the infiltration of rainwater into the soil. Soil water is used by plants in life functions and transpiration. Some water also evaporates directly back into the atmosphere.

❑ *Zone of Saturation*

Water that is not held as soil moisture percolates downward until it reaches a zone where all of the open spaces in sediment and rock are completely filled with water. This is known as *zone of saturation*. Water within this zone is called groundwater. The upper limit of saturated zone is known as the water table.

❑ *Zone of Unsaturation*

This zone is characterized by the groundwater that is held by surface tension in tiny passages between grains of soil or sediment. The area above the water table that includes the capillary fringe and the zone of soil moisture is called the *unsaturated zone* or *zone of aeration* or *vadose zone*. The pore spaces and openings are partially filled with water in this zone. Although a considerable amount of water can be present in the unsaturated zone, this water cannot be pumped by wells because it clings too tightly to rock and soil particles and percolates slowly through the openings. This water is called *vadose water*. By contrast, below the water table the water pressure is great enough to allow water to enter wells, thus permitting groundwater to be withdrawn for use.

Bedrock geology determines the density and distribution of underground water-bearing fractures. Different rocks contain more or less fractures that may or may not be interconnected with each other. The degree of interconnection among fractures, and their overall ability to move water, has a great deal to do with how productive a water well will be. Different rocks also make different soils when they weather, and the type of soil impacts its ability to absorb rainwater that falls at the surface, and transmit the water to bedrock fractures beneath.

13.8 THE WATER TABLE

The upper limit of the zone of saturation is called *water table*. It represents the level to which a dug well would fill with water. The depth to the water table, therefore, can be determined by installing wells that penetrate the top of the saturated zone just to monitor the groundwater level. The depth of the water table is highly variable and can range from zero, when it is at the surface, to hundreds of meters in some places (desert area of Rajasthan).

The water table in an area varies seasonally as well as yearly. The principal cause for the uneven water table is variations in rainfall and permeability of soil from place to place. This is due to the addition of water depending upon the quantity, distribution, and timing of precipitation. Any imbalance, e.g. fluctuations of rainfall raises or lowers the water table. If rainfall ceases completely, the water table gradually approach the level of the valleys. Water at any given point below the water table beneath a hill is under greater pressure than water at the same elevation below the lower water table in a valley.

13.9 MOVEMENT OF GROUNDWATER

The nature of subsurface materials strongly influences the rate of groundwater movement and storage. The principal factors controlling the movement of groundwater are porosity, permeability (hydraulic conductivity) and transmissivity. Determination of these properties for a given aquifer may be based on lithologic or geophysical observations, laboratory testing, or aquifer tests with varying degrees of accuracy. Overall ability of aquifer to yield significant groundwater also depends upon climatic conditions and topography of the area.

The movement of groundwater can be described based on the energy concept. Water possesses three forms of energy—the potential energy attributable to its height, the pressure energy owing to its pressure, and the kinetic energy due to its velocity. Energy in water usually is expressed in terms of head. Water moves in response to the difference in hydraulic head from the point of highest energy toward the lowest. On a regional scale, this results in flow of groundwater from recharge areas to discharge areas (Fig. 13.8).

The head possessed by groundwater in soils or rocks is manifested by the height to which it will rise in a standpipe above a given datum. This height usually is referred to as the *piezometric level* and provides a measure of the total energy of the water. If at two different points within a continuous area of groundwater, there are different amounts of energy, then there will be a flow towards the point of lesser energy and the difference in head is expended in maintaining that flow. Other things being equal, the velocity of flow between two points is directly proportional to the difference in head between them (Fig. 13.6). This loss of energy by the groundwater is due to the friction resistance of the ground material, and this is greater in fine- than coarse-grained soils. The movement of groundwater can be explained on the basis of Darcy's law.

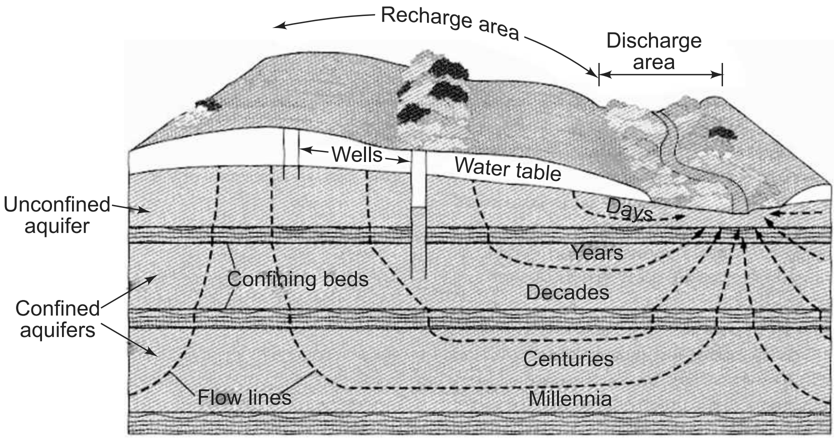


Fig. 13.8 *Recharge and discharge area*

In the mathematical treatment of groundwater flow, certain simplifying assumptions are made, namely, that the material is isotropic and homogeneous, that there is no capillary action and that a steady state of flow exists. Since rocks and soils are anisotropic and heterogeneous, as they may be subject to capillary action and flow through them is characteristically unsteady, any mathematical assessment of flow must be treated with caution.

In the mid-19th century, Henry Darcy found through his experiments on sand filters that the amount of flow through a porous medium is directly proportional to the difference between hydraulic head values and inversely proportional to the horizontal distance between them and flow through aquifer materials. The basic law concerned with flow is that enunciated by Darcy (1856), which states that the rate of flow, v, per unit area is proportional to the gradient of the potential head, i, measured in the direction of flow, k being the coefficient of permeability:

$$k = 2.3 \log_{10}(r_2/r_1)\frac{Q}{\pi(Z_1^2 - Z_2^2)} \tag{13.2}$$

$$v = \frac{Q}{A} = ki$$

Q = Rate of flow
i = Hydraulic gradient
k = Darcy's coefficient of permeability
A = Total cross-sectional area of soil mass perpendicular to the direction of flow
v = Flow velocity

Darcy's law is valid as long as a laminar flow exists because of very small pore dimensions in fine grained soils a laminar flow should exist, but for coarse-grained soils, turbulent flow may be expected under certain conditions. It has been observed experimentally that the limits in the validity of Darcy's law may be fixed with respect to particle size, velocity of flow and hydraulic gradient. Fancher, Lewis and Barnes demonstrated that flow through sands remains laminar and Darcy's law is valid so long as the Reynold's number, expressed in the form below is equal to or less than unity

$$\frac{\rho v d}{\mu} \leq 1 \tag{13.3}$$

where, ρ = Mass density
v = Velocity of flow
d = Diameter or particle size
μ = Dynamic viscosity

Notes

1. For the groundwater flow occurring in nature, the law is generally within its validity limits. But unconfined aquifers with the steep hydraulic gradients this law does not hold.
2. Darcy's law probably does not accurately represent the flow of water through a porous medium of extremely low permeability because of the influence of surface and ionic phenomena, and the presence of gases.

13.10 PROPERTIES OF AQUIFERS

Besides porosity and permeability, there are several parameters that are related to the flow of water through the aquifers and confining layers. The important parameters are transmissivity and storage coefficient which are known as aquifer parameters.

13.10.1 Transmissivity

Transmissivity is defined as the rate of flow of water in unit square meter per day, through a vertical strip of the aquifer of one meter wide (unit width) and extending through the entire saturated thickness of the aquifer under a unit hydraulic gradient. Transmissivity T has the dimensions of m^2/day. Values of T range fro < 12.4 to 12,400 m^2/day. Earlier, the term co-efficient of transmissibility was in usage. The concept of transmissivity holds good in confined aquifer but in unconfined aquifer, as the saturated thickness of the aquifer changes with time, the transmissivity also changes accordingly.

Transmissivity is expressed as a measure of the aquifer's ability to transmit groundwater through its entire saturated thickness and relates closely to the potential yield of wells. Transmissivity is defined as the product of the hydraulic conductivity and the saturated thickness of the aquifer. It is an important property to understand because a given area could have a high value of hydraulic conductivity but a small saturated thickness, resulting in limited yield of groundwater (Fig. 13.9).

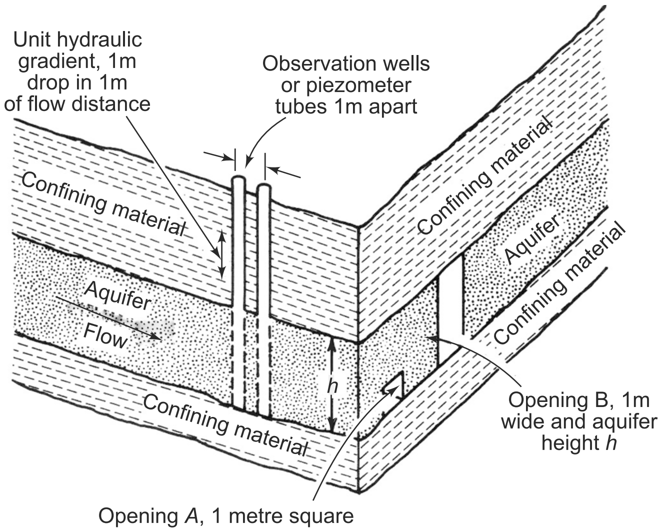


Fig. 13.9 *Transmissivity in confined acquifer*

$$T = Kb \tag{13.4}$$

where, T = Transmissivity in m^2/day
K = Hydraulic conductivity in m
b = Thickness of the aquifer

13.10.2 Coefficient of Storage/Storativity (*S*)

The capacity of an aquifer to store water is expressed as a coefficient designated as S. The head in the aquifer changes when the water is either stored or released indicating a change in the storage volume within the aquifer. Storativity is defined as the volume of water that an aquifer releases or takes in to storage per unit surface area of the aquifer per unit change in component of the head normal to that surface. Thus, storativity is equal to the amount of water removed from each vertical column of aquifer of height h and unit basal area when the head declines by one unit (Fig. 13.10).

Storativity S = Volume of water / (unit area) (unit head change)
$= m^3 / (m^2)$ (m)

Storatitivity is a non-dimensional parameter. In confined aquifers, storatitivity is a result of compression of the aquifer and expansion of the contained water, a result of reduced pressure due to pumping. The value of S ranges from 0.00001 (10^{-5}) to 0.001 (10^{-3}) for confined aquifers.

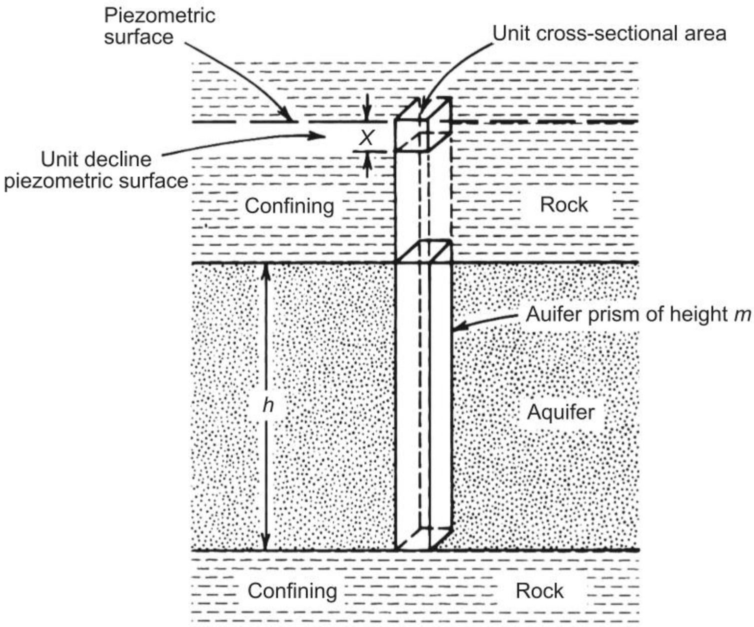


Fig. 13.10 *Storage coefficient of confined aquifer*

13.10.3 Specific Yield (S_y)

When water is drained from a saturated material by gravity force, only part of the total volume stored in its pores is released. In an aquifer, some water is held there by molecular attraction and can not be drained out freely under gravity. This held water is designated as *specific retention*. However, the water that can be drained under the force of gravity is termed *specific yield*. Specific yield may be defined as the ratio of the volume of water that a rock will yield by gravity to its own volume (Fig. 13.11).

$$\text{Specific yield} = \frac{\text{Volume of water drained by gravity}}{\text{Total volume of aquifer}} \tag{13.4}$$

$$\text{Specific retention} = \frac{\text{Volume of water retained}}{\text{Total volume of aquifer}} \tag{13.5}$$

$$\text{Specific yield} + \text{Specific retention} = \text{Porosity} \tag{13.6}$$

Note Both the specific yield and specific retention are expressed as decimal fractions or percentages, e.g. if 0.10 m^3 of water is drained from one cubic metre of saturated sand, the specific yield of sand is 0.10 or 10%.

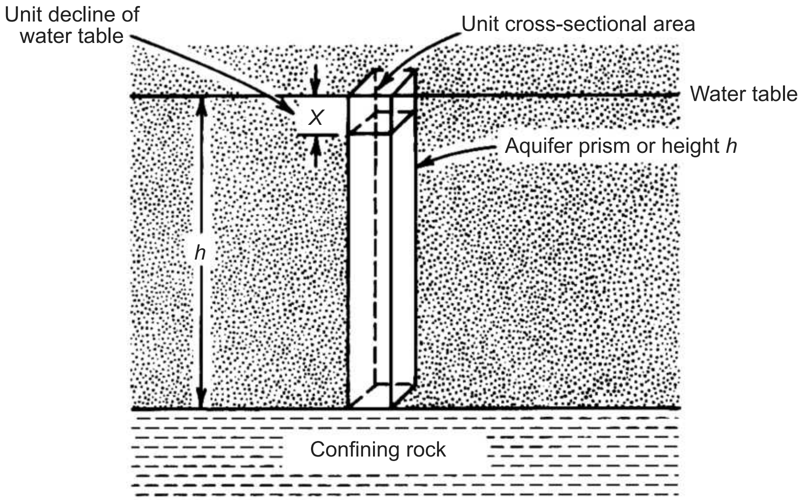


Fig. 13.11 *Specific yield of unconfined aquifer*

13.11 INTERACTION BETWEEN GROUNDWATER AND STREAMS

Groundwater contributes to streams in most geologic and climatic settings. Groundwater discharges into the channels of effluent streams and contributes to their base flow. On the other hand, groundwater in the zone of saturation may be recharged by water leaking from a surface stream into the underground. This is the general case for an influent stream.

The interaction between the groundwater system and streams can take place in one of three ways. Streams may gain water from the inflow of groundwater through the streambed. Such streams are called *gaining streams*. This requires the elevation of the water table to be higher than the level of the surface of the stream. When the elevation of the water table is lower than the surface of the stream, the streams may lose water to the groundwater system by outflow through the streambed. Such streams are called *losing streams*. The interaction may be a combination of the two cases—a stream gains in some sections and loses in others.

In some settings, a stream might always be a gaining stream or always be a losing stream. However, in many situations, flow direction can vary along a stream; some sections receive groundwater and other sections lose water to the groundwater system. Moreover, the direction of flow can change over a short time span as the result of storms adding water near the stream bank or when temporary flood peaks move down the channel.

13.12 GROUNDWATER ABSTRACTION STRUCTURES

Groundwater may be withdrawn through different types of abstraction structures, existing naturally or made artificially. Due to advancements in technology, the types and numbers of artificial (man made) groundwater abstraction structures have increased many folds. The examples of natural abstraction structures are springs and artesian wells, and that of man made are open wells, hand pumps and tube wells. These are described as follows.

13.12.1 Springs

The natural outflow of groundwater at the Earth's surface is said to form a spring. Springs occur whenever the water table intersects the land surface and a natural flow of groundwater results (Fig. 13.12). Springs are generally capable of supplying very small amounts of waters and are therefore not considered as sources of water supplies. However, developed springs may sometimes be used as a source of water supply for small towns, especially in hilly areas.

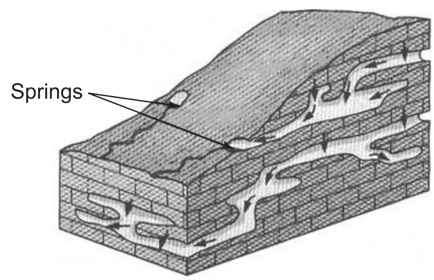


Fig. 13.12 *Springs*

When an aquifer is trapped between two aquicludes, the spring formed is called *artesian spring*. The aquifer is filled at the recharge area, which generally occurs at the highest elevation where permeable and impermeable layers are exposed. Another reason for the formation of artesian spring is due to a fault which has caused the top impermeable layer to slide down and partially block the impermeable layer. This causes the water to run along the impermeable layer to the surface. If the spring is located below the potential water table (an imaginary horizontal line that originates at the recharge area), then it is known as surface spring. If the spring is above the potential water table, it becomes an artesian spring.

13.12.2 Artesian Wells

In most wells, water cannot rise on its own. If water is first encountered at particular depth, it remains at that level, fluctuating perhaps a meter or two with seasonal wet and dry periods. However, in some wells, water rises, sometimes overflowing at the surface. The term *artesian* may be applied to any well drilled to great depths. Artesian wells are those in which groundwater flows on ground surface with certain heads above groundwater (Fig. 13.13).

For an artesian system to exist, two conditions usually are met. First, water is confined to an aquifer that is inclined so that one end can receive water; and second aquitards, which should be above and below the aquifer, must be present to prevent the water from escaping. When such a layer is tapped, the pressure created by the weight of the water above will force the water to rise. If there were no friction, the water in the well would rise to the level of the water at the top of the aquifer. However, friction reduces the height of the pressure surface. The greater the distance from the recharge area (where water enters the inclined aquifer), the greater is the friction and the less the rise of water.

Note It must be taken note that all artesian systems are not wells. *Artesian springs* also exist. Here, groundwater may reach the surface by rising along a natural fracture such as a fault rather than through an artificially produced hole.

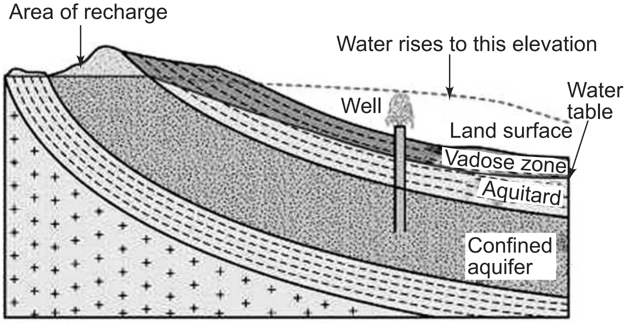


Fig. 13.13 *Artesian well*

13.12.3 Open Well

An open well is also known as *dug well*. In soft ground, since the water table is shallow, dug wells are very successful. Historically, dug wells were excavated by hand shovels below the water table until incoming water exceeded the digger's bailing rate. It is generally open masonry well having comparatively bigger diameters, and is suitable for low discharges. The diameters of the open wells generally vary from 2 to 9 m and they are generally less than 30 m in depth. The walls of an open well may be built by brick or stone masonry or precast concrete rings (Fig. 13.14). The yield of open wells is limited because such wells can be excavated only to a limited depth, where the groundwater storage is also limited.

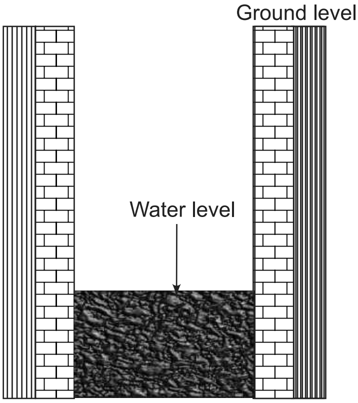


Fig. 13.14 *Open well*

The open wells may be classified as shallow and deep wells. While a shallow well is the one which is constructed at shallow depth encountering the pervious strata and accumulation of groundwater from the surrounding materials, a deep well taps deeper aquifers. These aquifers occur between two impervious layers and draw its supply from the pervious layer.

The nomenclature of the shallow and deep wells is purely technical and not related with the depth of the wells. Shallow wells sometimes may have more depth than deep wells. Since a shallow well draws water from the topmost water bearing stratum, its water is liable to be contaminated by the rain water, the water in deep well is not liable to get such contaminant. Moreover, the pervious formations below the impervious layer generally contain great quantity of groundwater, yielding higher specific yields. The larger supplies can be obtained from deep wells as compared with shallow wells.

13.12.4 Yield of an Open Well

The yield of an open well can be determined theoretically using Eq. (13.1) or by carrying out field tests and then calculating the yield from the observations gathered.

❑ *Theoretical Methods*

If a well is penetrated through an aquifer, water will rush into it with velocity v. If A is the surface area of the aquifer opening into the well, then the discharge,

$$Q = v \cdot A_s$$

where, $v = \eta v_a$

v_a = Actual flow velocity of the groundwater

v = Velocity with which water rushes into the well

η = Porosity

A_s = Area of the aquifer

$$Q = \eta v_a. A_s \tag{13.7}$$

In the above equation, the velocity of groundwater v_a can be found by using Slichter's or Hazen's formula, or by conducting actual measurements by chemical or electrical methods.

Opening into the well can be found by knowing the diameter of the well d and the depth H of the porous strata as $\pi\ d\ H$. η the porosity, can be found by studying the sample of the soil in the laboratory. Knowing η, v_a and A_s the discharge can be calculated.

❑ *Tube Well*

A tube well is a kind of abstraction structure which involves drilling by machines and lowering of pipes. In a tube well, the groundwater is tapped through a combination of blind and screen pipes [Fig. 13.15 (a) and (b)]. Tube wells are fast and easy to install, making them particularly popular in developing nations where the infrastructure for larger and more involved well designs is not in place. There are some potential drawbacks of tube wells, including the risks of water contamination, if the well is not sunk in an appropriate location apart from optimal discharge. Tube wells are fitted with a hand pump or a power-driven pump for domestic water supply or irrigation.

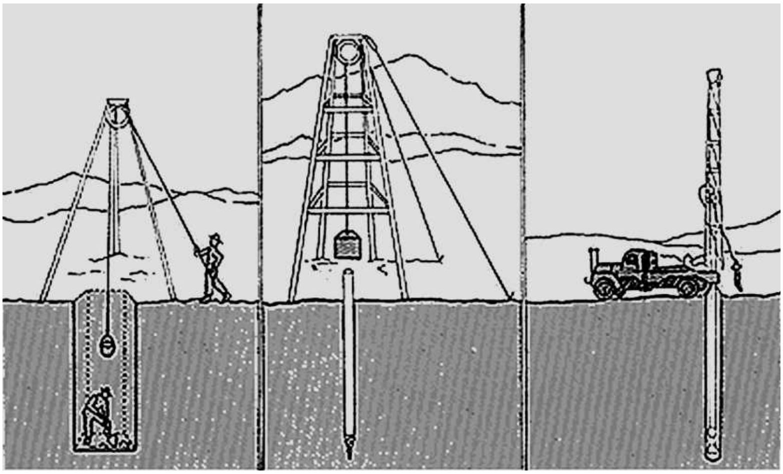


Fig 13.15(a) *Diagrammatic representation of construction of tube well*

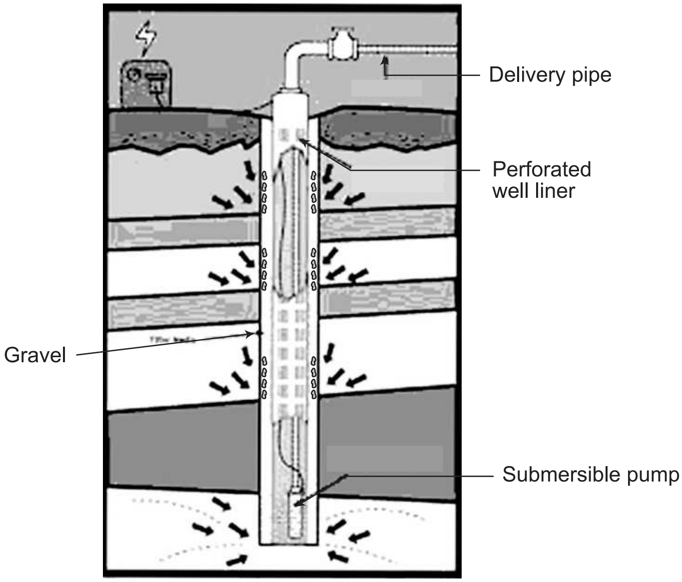


Fig. 13.15(b) *Working of tube well*

Similarly, the hand pump is a truly simple device that uses power, supplied manually by the user for its operation. The hand is pushed down and the power of suction is used to draw water up from an underground well. The hand pump is usually a cheap device, which can be operated with very little experience. It is constructed up to shallow depth (= 50 m below ground level) tapping phreatic aquifer. The only thing that may take a little skill is the priming of a water pump. Hand pumps are able to provide discharge up to 50–60 lpm.

13.13 NATURAL HAZARDS OF GROUNDWATER

Groundwater is one of the most important natural resources, and may sometime create natural hazards. These hazards occur in different pockets depending upon the local topographic condition, precipitation and groundwater withdrawal. Few natural hazards like waterlogging, soil salinity and triggering of landslides produced by groundwater are explained briefly.

13.13.1 Waterlogging

It is a situation of groundwater when the groundwater level becomes shallow and reaches up to 2 m below ground level. The area characterized by this water level is known as water logged area. When groundwater level rests between 2–5 m below ground level, the area is likely to be proned to waterlogging. The waterlogging conditions in a particular area may develop due to the following reasons.

- ***Shallow Groundwater Level and Poor Groundwater Withdrawal***

The groundwater level is under dynamic process and depends upon recharge and discharge of aquifer system. The groundwater level becomes shallow when recharge is either more or restricted to the shallow zone. Furthermore, the water level will also rise if withdrawal is restricted.

■ **Canal Command Area and Unlined Major Canals** The area which is situated near to canal and irrigated mostly with canal water is known as canal command area. When the canal is unlined, the seepage of surface water takes place and recharges the aquifer existing at shallow depth. The continuous recharge over longer period makes the groundwater level shallow.

■ **Availability of Granular Zones at Shallow Depth** This is a situation when subsurface lithology is characterized by granular zones at shallow depth and underlained by clay or impervious layer. Such lithological configuration does not allow the proper fluxing of groundwater and generation of a waterlogging situation is developed.

13.13.2 Soil Salinity

The soil salinity may produce hazardous groundwater. There are two types of salinity, the inland salinity and the coastal salinity. In both the conditions, the soil and aquifer becomes saline and enriched with sodium chloride.

■ **Inland Salinity** This is caused due to an increase in sodium chloride content of the soil due to poor fluxing of groundwater. In case of shallow groundwater level, the evaporation loss is intensified and concentration of sodium chloride in groundwater increases. This process produces the kankar pan which prevents percolation of surface water into groundwater and consequently the soil salinity increases. It degrades the soil and formation of *reh* takes place. This is exemplified in many parts of UP such as in Jaunpur and Pratapgarh districts.

■ **Coastal Salinity** The coastal salinity is developed in groundwater due to an ingress of sea water, which is saline, into aquifers. Coastal salinity is observed in areas near to the coast of Kerala, Tamil Nadu and Andhra Pradesh, etc. When the groundwater level becomes deeper due to over-withdrawal of groundwater from shallow aquifer and if shallow water level of sea exists, then the sea water tries to intrude into freshwater. This entire process develops coastal salinity.

13.13.3 Landslides and Tunnelling

Groundwater may act as a triggering agent for landslides under condition of change in groundwater regime. Relationship of water level with the elevation of ground surface is important because water level should never cut the ground surface. In hilly regions, when groundwater level cuts the ground surface, the seepage takes place which is quite harmful and may cause landslides.

Shallow groundwater level is harmful in the area prone to landslides because it lubricates the broken fragments and also enhances the velocity. Shallow groundwater level is also harmful for tunnelling because it may cut the axis of tunnel. When groundwater is below the axis of a tunnel or even below ground surface of tunnel, it is most suitable for tunnelling. In case when groundwater level either cuts the axis of tunnel or even above the basal surface of the tunnel, it damages the strength of tunnel.

13.13.4 Land Subsidence

It is a phenomena in which the topmost layer of the land is moved down gradually or all of sudden. The subsurface soil containing water in their pore spaces creates certain amount of pressure which holds the soil particles intact with underlain or overlain soil. When, due to over-pumping, the water is withdrawn from subsurface soil at higher rate, the pressure exerted by pumping becomes more than the existing pressure of soil due to which groundwater is withdrawn. In such situation, the land collapses and occurrence of land cracks and land subsidence occurs. Several land cracks and subsidence have occurred in recent past in districts of Hamirpur, Banda and Sant Ravidas Nagar of UP.

13.14 IMPACT AND CONSEQUENCES OF GROUNDWATER OVER-WITHDRAWAL

Groundwater resource is exhaustible as well as renewable for limited time and replenished over the periods, particularly during monsoon season. The south-west monsoon is the main contributor for recharging the groundwater in India.

Due to rapid growth in agriculture and industrial sectors, the consumption of groundwater has increased many folds in the recent past. The domestic need has also increased many times due to urbanization and population growth. Due to erratic pattern of rainfall and varied geographical as well as geological conditions, the accumulation of groundwater in an aquifer system is quite variable.

Through the technological interventions and mechanization, the groundwater has been extracted at quite higher rate than the replenishment. This situation is known as *over-withdrawal* of groundwater.

Technically, the over-withdrawal, sometimes called *overdraft*, is dependent upon quantum of water extracted, recharge and magnitude of water-level decline. On the basis of these parameters, the groundwater units like blocks or watersheds are divided into four categories, viz. safe, critical, semicritical and overexploited. Over-exploited blocks are more vulnerable for groundwater withdrawal. Therefore, restriction has been imposed to withdraw the groundwater in overexploited blocks by the Government of India.

Following are some of the impacts of over-withdrawal of groundwater.

1. Continuous lowering of groundwater level during pre and post monsoon.
2. Reduction of well yields, and creation of well interference.
3. Drying up of phreatic aquifer and extraction of groundwater from deeper aquifer.
4. Emission of silt and sand particles from wells.

The consequences of over-withdrawal of groundwater are as follows:

1. Lowering of pump sets at deeper level causing low efficiency and higher cost of operation.
2. Drying up of soil moisture and in turn damage to vegetative covers.
3. Increase in cost of groundwater extraction due to higher consumption of energy to lift the groundwater from deeper depth.
4. Risk of ground subsidence due to inter-relationship between withdrawal and downward trend in water levels due to overdraft of groundwater.

To overcome the natural and man-made groundwater hazards it becomes essential to manage groundwater through suitable techniques. Appendix VIII describes the groundwater management and techniques in practice in India.

Terminology

Bhabhar Zone This is the region just below the Shiwalik Hills in Uttarakhand characterized by boulders mixed with sand and silt.

Capillary Fringe The subsurface layer in which groundwater seeps up from a water table by capillary action to fill pores is known as *capillary fringe*. Pores at the base of the capillary fringe are filled with water due to tension. This saturated portion of the capillary fringe is less than total capillary rise because of the presence of a mix in pore size. If pore size is small and relatively uniform, it is possible that soils can be completely saturated with water for several meters above the water table.

CGWB Central Ground Water Board

Drawdown It is the difference between the static water level and the pumping water level. Drawdown affects the yield of the well.

Drylands	These are defined by their scarcity of water. They are zones where precipitation is counterbalanced by evaporation from surfaces and transpiration by plants. The drylands can be further classified into four subtypes: dry subhumid lands, semi-arid lands, arid lands, and hyper-arid lands. Some authorities consider hyper-arid lands as deserts, although a number of the world's deserts include both hyper-arid and arid climate zones.
Hydraulic Conductivity	Hydraulic conductivity is a measure of a rock or sediment's ability to transmit water and is often used interchangeably with the term permeability. The factors that affect the hydraulic conductivity are size, shape, and interconnectedness of pore spaces effect. It is usually expressed in units of length/time: feet/day, metres/day, or gallons/ day/ square-foot.
Hydric Soil	This is soil which is permanently or seasonally saturated by water, resulting in anaerobic conditions, as found in wetlands.
Kankar Pan	This is characterized by a solid layer of sodium chloride which is imperious in nature.
Primary Porosity	This is the inherent character of a rock which is developed during the formation of the rock itself. In semi-consolidated (sedimentary) rocks and unconsolidated (alluvial) formations, porosity is of primary nature and is due to the inter-granular space. In volcanic rocks, the primary porosity is due to the presence of gas cavities (vesicles) and also lava tubes and lava tunnels. Vesicular and scoriaceous lavas have high primary porosity.
Pumping Water Level (PWL)	This is the level at which water stands in a well when pumping is in progress. This level is variable and changes with the quantity of water being pumped. The pumping water level is also called the dynamic water level.
Saltwater Intrusion	In coastal regions, springs of outflowing groundwater may lie under the ocean. As long as a high water table maintains a sufficient head of pressure in the aquifer, there is a flow of freshwater into the ocean. Thus, wells near the ocean yield freshwater. However, a lowering of the water table or a rapid rate of groundwater removal may reduce the pressure in the aquifer permitting salt water to flow back into the aquifer and hence into wells.
Secondary Porosity	It is the induced character and is developed subsequent to the formation of rocks. It is characteristic of consolidated and semi-consolidated formations and it is introduced by weathering, fracturing and jointing in hard rocks and dissolution of minerals in carbonate rocks (limestones and dolomites). Joints and fracture may induce secondary porosity in sandstones already possessing primary porosity.

Static Water Level (SWL) The level at which the water level stands in a well before pumping is called *static water level*. It is generally expressed as the distance from the ground surface to the water level in a well. For example, when the SWL is 15 m, it means that the water stands 15 metres below the ground surface or measuring point when there is no pumping.

Swamp It is a wetland that is forested. Many swamps occur along large rivers where they are critically dependent upon natural water level fluctuations. Other swamps occur on the shores of large lakes. Some swamps have hammocks, or dry-land protrusions, covered by aquatic vegetation or vegetation.

Talus Screep The material derived from the disintegration at the foothill of Himalayan region and composed of fragments of rocks.

Wetland The wetlands are areas where water is the primary factor controlling the environment and the associated plant and animal life. They occur where the water table is at or near the surface of the land, or where the land is covered by water. The water found in wetlands can be saltwater, freshwater, or brackish. The major types of wetland are *marine*: coastal wetlands including coastal lagoons, rocky shores, and coral reefs; *estuarine*: including deltas, tidal marshes, and mangrove swamps; *lacustrine*: wetlands associated with lakes; *riverine*: wetlands along rivers and streams; and *palustrine*: marshes, swamps and bogs.

Exercises

1. (a) What is groundwater? How is it originated? What percentage of freshwater is groundwater?
(b) Compare and contrast the zones of aeration and saturation. Which of these zones contains groundwater?

2. (a) What is the importance of porosity and permeability with reference to groundwater?
(b) Under what circumstances can a material have a high porosity but not be a good aquifer?
(c) What are the controlling factors for porosity?

3. Briefly describe the important contribution to our understanding of groundwater movement made by Henri Darcy.

4. (a) What is meant by the term artesian?
(b) In order for artesian wells to exist, two conditions must be present. List these conditions.

5. (a) Give a brief account of groundwater as a natural hazard.
(b) Describe briefly impact and consequences of groundwater over-withdrawal.

6. (a) Discuss mode of occurrence of groundwater.
(b) Give a brief account of hydrological cycle.

7. Write short notes on the following:
(a) Groundwater abstraction structures

(b) Interaction of groundwater and streams
(c) Hydraulic properties of rocks
(d) Water bearing formations
(e) Leaking aquifers
(f) Perched aquifers
(g) Zones of underground water
(h) Pumping of wells
(i) Water table
(j) Darcy's law
(k) Specific yield

9. Distinguish between the following:
(a) Confined and unconfined aquifers
(b) Free groundwater and artesian water
(c) Open well and bore well
(d) Transmissivity and storativity
(e) Porosity and permeability
(f) Gaining stream and losing stream
(g) Aquitard and aquifer
(h) Specific yield and specific retention

Multiple-Choice Questions

1. Which of the following reservoir contains the most pure water?
(a) Rivers (b) Biosphere
(c) Groundwater (d) Lakes

2. Permeability is defined as the
(a) ability of a solid to allow fluids to pass through
(b) process by which plants release water vapour to the atmosphere
(c) amount of water vapour in the air relative to the maximum amount of water vapour the air can hold
(d) percentage of pore space in the rock

3. The best groundwater reservoirs would have
(a) low permeability and low porosity
(b) low permeability and high porosity
(c) high permeability and low porosity
(d) high permeability and high porosity

4. A local water table positioned above the regional water table is known as
(a) stranded (b) perched
(c) displaced (d) depressed

5. Which of the following statement about the water table is not correct?
(a) The water table changes when discharge is not balanced by recharge.
(b) The water table is generally flat.
(c) The water table is above the land surface in lakes.
(d) The water table is depressed near high volume pumping wells.

6. What is the term for a relatively impermeable geologic unit?
(a) Artesian (b) Aquiclude
(c) Aquifer (d) Aquitard

7. Which of the following is the difference between the saturated and the unsaturated zones of groundwater?
(a) The saturated zone has a higher porosity than the unsaturated zone.
(b) The saturated zone has a lower porosity than the unsaturated zone.
(c) The pore spaces in the saturated zone are completely full of water; while the pore spaces in the unsaturated zone are not completely full of water.
(d) The pore spaces in the saturated zone are not completely full of water; while the pore spaces in the unsaturated zone are completely full of water.

8. The saturated zone is
(a) the aquifer
(b) the water table
(c) the near-surface zone where all pores are filled with water
(d) the same as the vadose zone

9. The top of the water saturated zone is known as
(a) the water table (b) the hydraulic head
(c) the aquifer (d) the aquitard

10. An artesian well is one
(a) that is developed in an aquitard
(b) that flows to the surface without pumping
(c) that is developed in an aquifuge
(d) where a cone of depression develops around the well when pumped

Answers to MCQs

1. (c) 2. (a) 3. (d) 4. (b) 5. (b) 6. (d) 7. (c) 8. (c)
9. (a) 10. (b)

chapter 14

Geophysical Investigations

14.1 INTRODUCTION

To finalize a site for a particular civil engineering project, it is essential to know about the details of the surface and subsurface conditions. This ultimately helps to a great extent to ascertain the pros and cons, and most importantly feasibility of the project. Therefore, detailed site investigations become the foremost step in planning and for execution of any construction activity. If proper evaluation of the site and the correct interpretations are not carried out in advance, the stability of the proposed structure may be questionable. This will affect the overall cost of the project as well to account for and in taking corrective measures to mitigate the hazards encountered during execution of the project.

The investigations for surface and subsurface features comprise of geological and geophysical investigations, respectively. The geological investigations consist of preparing detailed geological maps depicting spatial distribution of all the formations, lithological details—types of formation with compositional variations and, structural details—joints, shear zones, faults, weathered zones, etc. To accomplish the task, it requires carrying out field mapping of formations (Chapter 16) supplemented with airborne data (Chapter 15). The geophysical methods on the other hand deal with the measurement of physical parameters of the Earth's subsurface and then interpreting the variations in terms of geological realities. While the geological investigations make use of maps, airborne tools (remote sensing) and GIS, the geophysical methods basically encompass surface and subsurface methods for the investigations. These techniques are based upon sound principles of physics, geochemistry, electrical and electronics.

The surface geophysical methods provide a rapid, and therefore a cost-effective, means of preliminary evaluation. Continuous data acquisition can be had at speeds even up to several kilometres per hour. The subsurface geophysical techniques provide non-destructive, in situ measurements of physical, electrical, or geochemical properties of the natural or contaminated soil, rock, and contained fluids. Because of the greater sample density, anomalous conditions can be detected. Consequently, a more accurate characterization of subsurface conditions can be established. However, appropriate resolution and depth limitations are the main constraints on the use of geophysical methods in most of the applications.

Since each of the geophysical method has its advantages and limitations, a judicially chosen combination of two or more techniques may result in a reduction of the degree of ambiguity. The methods and their combinations thereof should, therefore, be carefully selected depending upon specific site conditions and project requirements. Besides this, site visits are planned to have a comprehensive knowledge of the local geology and site conditions. The information gained from a surface geophysical survey can be used to choose optimal locations for the placement of boreholes, monitor wells or test pits, as well as to correlate geology between wells/boreholes. Geophysical investigations are most effective when used in conjunction with a drilling or boring program. In addition to the site visit, subsidiary data is gathered from examination of aerial photographs, geologic maps and well data.

The information obtained from a geophysical investigation can be used to determine the subsurface conditions at and in the vicinity of a site. Various geophysical techniques reveal physical properties of the subsurface which can be used to determine hydro-stratigraphic framework, depth to bedrock, extent of concentrated groundwater contaminant plumes, the location of voids, faults or fractures, and the presence of buried materials. Furthermore, geophysical methods can also be used to identify the hazardous waste and groundwater pollution sites.

This chapter provides an introduction of the various geophysical methods and their specific techniques. All geophysical methods have some or the other limitations that affect their applicability at specific site. Further, this chapter provides the reader with a basic understanding of when to consider using geophysical methods and which techniques are best applicable for specific conditions.

14.2 CLASSIFICATION OF GEOPHYSICAL METHODS

Geophysical methods consist in exploring the Earth's subsurface. The techniques employed provide information about the physical properties of the Earth's subsurface. The objective is to explore the ore deposits, oil reserves, aquifers, and to determine the structural planes and lithology up to a desired depth. These geophysical methods may be broadly classified as follows.

❑ *Surface Method and Subsurface Method*

Surface geophysical methods are generally non-intrusive and can be employed quickly to collect subsurface data. Subsurface method, also referred to as *borehole method,* requires drilling of wells or borings. Geophysical tools are lowered through the boreholes into the subsurface, and the measurement of in situ conditions of the subsurface are made.

❑ *Active Method and Passive Method*

Active methods are those which measure the subsurface response due to perturbations created by an impact, the examples being the nuclear radiations or seismic energy. Passive methods, on the other hand, measure the local variations in the Earth's natural force fields, e.g., the Earth's ambient magnetic, electrical, and gravitational fields. Information provided by these tools can be used to locate buried objects, determine geologic and hydrogeologic conditions, and, occasionally, to locate residual or floating products.

14.3 SURFACE GEOPHYSICAL METHODS

Some of the surface geophysical methods which are very effective and commonly used are: ground-penetrating radar method, electromagnetic method, resistivity method, seismic method, magnetic method and gravity method. Site investigations for civil engineering projects are concerned with foundations of structures and groundwater. Since the information required is of limited depths, the seismic refraction and electrical techniques are generally used to their advantages. A brief description of each of these surface geophysical techniques is presented below.

14.3.1 Ground-Penetrating Radar (GPR) Method

The ground-penetrating radar method can be used for a variety of civil engineering, groundwater evaluation and hazardous waste site applications. It is one of the most highly used and successful technique as of today. When integrated with other geophysical and geologic data, the most comprehensive site assessment is made. The subsurface information ranging in depth from a fraction of a metre to hundreds of metres can be obtained by using this method.

The GPR technique uses a transmitter that emits pulses of high-frequency electromagnetic waves (100 to 1000 MHz) into the subsurface, to acquire subsurface information. The electromagnetic energy is radiated downward into the ground from a transmitter and is reflected back to a receiving antenna and is recorded as a function of time. The technique employs the principle that the reflections of the radar wave occur whenever there is a change in dielectric constant or electrical conductivity between two materials as shown in Fig. 14.1. Changes in conductivity and in dielectric properties are associated with natural hydrogeologic conditions such as bedding, cementation, and water content of the subsurface lithology, clay content, bulk density, voids and fractures. Therefore, an interface between two soil or rock layers that have a sufficient contrast in electric properties will be reflected in the radar profile.

GPR data is best used to clarify the existence and location of suspected features within a specific area, and for assessing shallow, localized subsurface conditions. Under optimal conditions, the geologic features that can be detected or resolved with GPR include: fractures, and faults; depth and thickness of shallow sediments and bedrock; and occasionally, depth to groundwater. GPR can be used to estimate the depth and thickness of soil and rock layers to within about 30 m.

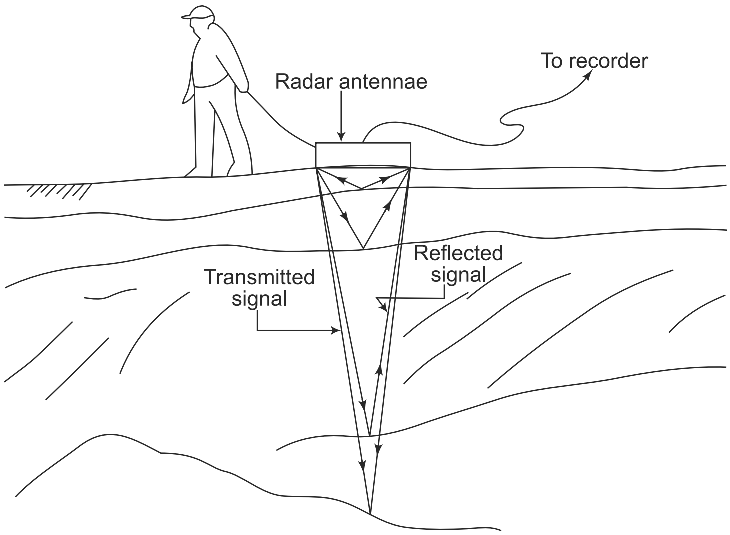


Fig. 14.1 *Ground-penetrating radar method*

❑ *Advantages*

GPR is the most powerful geophysical technique. It offers a number of advantages over some of the other geophysical methods, and are as follows:

1. Continuous profiling permits data to be gathered much more rapidly, providing a large amount of data. A continuous display of data along a traverse is produced, which can often be interpreted qualitatively in the field.
2. GPR is capable of providing high-resolution data under favourable site conditions. Vertical resolution of radar data can range from less than a centimetre to several metres, depending upon the depth and the frequency used.
3. A variety of antennas can be selected to cover frequencies from less than 100 to 1000 MHz. Lower frequencies provide greater depths of penetration with lower resolution, and higher frequencies provide less penetration with higher resolution.
4. GPR allows preparation of 2D slices (maps) of underground objects at various depths under the surface without their excavation. Furthermore, it is the only geophysical method which allows the preparation of 3D reconstructions of the precise shapes and depths of underground objects.
5. Precise determination of depths of the underground objects can be made.

❑ *Limitations*

Although GPR is supposed to be the most powerful geophysical method, but the interpretation of GPR data is very complicated and requires very complex data computing. Some of the limitations of GPR method are as follows:

1. GPR is the site-specific nature of the technique.
2. Most GPR units are towed across the ground surface. Ideally, the ground surface should be flat, dry, and clear of any bushes or debris. This requires site preparation prior to performing the survey.
3. The quality of the data can be degraded by a variety of factors such as an uneven ground surface or various cultural noise sources (such as strong electromagnetic fields).
4. Depth penetration of GPR is severely limited by attenuation and/or absorption of the transmitted electromagnetic (radar) waves into the ground. Generally, penetration of radar waves is reduced by a shallow water table, high clay content of the subsurface, and in areas where the electrical resistivity of the subsurface is less than 30 ohm-metres.
5. Overhead reflections may appear on the record when not using shielded antennas (generally a problem with lower frequency unshielded antennas), and system noise can sometimes clutter up the record.
6. The equipments are very costly.
7. The penetration depth, which depends on the soil humidity, is limited and usually varies from 1 m in wet soil to 30 m in general.

14.3.2 Electrical Methods

Electrical methods comprise a number of techniques employing different instruments and procedures, and have variable exploration depth and lateral resolution. Some of the methods make use of fields within the Earth, e.g. self-potential method, while the others require the introduction of artificially generated currents into the ground, e.g. the electromagnetic and resistivity methods. However, all these techniques are based on the fundamental fact that different materials of the Earth's crust possess widely different electrical properties. The most common electrical techniques are electromagnetic and direct current resistivity.

The Electromagnetic (EM) and resistivity methods are similar in the sense that they both measure the same parameter. Electrical conductivity values (ohm/meter) are the reciprocal of resistivity values (ohm/meter). Electrical conductivity/resistivity is a function of the type of soil and rock, its porosity, and the conductivity of the fluids that fill the pore spaces. The conductivity of the pore fluids often dominates the measurement. Both the methods are applicable for the assessment of natural hydrogeologic conditions and for mapping of contaminant plumes. However, the two techniques are different in the way the electrical currents are forced to flow in the subsurface. In the electromagnetic method, currents are induced in the subsurface by the application of time-varying magnetic fields, whereas in the electrical resistivity method, current is injected into the ground through surface electrodes.

❑ *Electromagnetic Method*

The method is also known as *electromagnetic induction* method. The method is based on the physical principles of inducing and detecting electrical current flow within geological strata. In this method, the bulk conductivity (the inverse of resistivity) of subsurface material is measured. The method is also known as *induced polarization* method. It makes use of capacitive action of the subsurface to locate zones where conductive materials are disseminated within their host rock.

There are two basic types of electromagnetic techniques—the Frequency Domain (FD) and the Time Domain (TD). Frequency domain electromagnetic technique measures the electrical response of the subsurface at several frequencies to obtain information about variations of conductivity (or its reciprocal, resistivity) with depth. The time domain electromagnetic technique achieves the same results by measuring the electrical response of the subsurface to a pulsed wave at several time intervals after transmission; longer time intervals measure greater depths. The FD-system is more common than the TD-system. While in FD-system the transmitter radiates energy at all times, and measures changes in magnitude of the currents induced within the ground; in the time-domain system, the transmitter is cycled on and off, and measures changes in the induced currents within the ground as a function of time.

In both the frequency domain and time domain systems, current is induced into the ground by EM induction. A transmitter coil is used to radiate an electromagnetic field which induces eddy currents in the subsurface. The eddy currents, in turn, induce a secondary electromagnetic field. The secondary field is then intercepted by a receiver coil. The voltage measured in the receiver coil is related to the subsurface conductivity. These conductivity readings can then be related to subsurface conditions. Figure 14.2 presents a schematic drawing of EM operating principles.

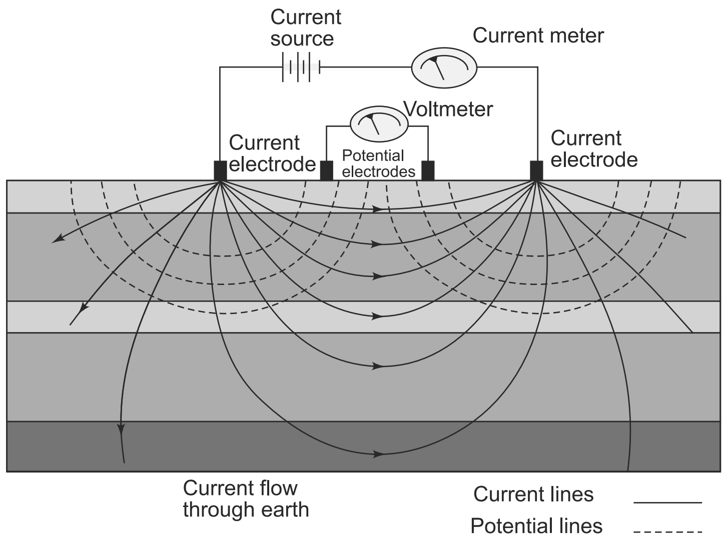


Fig. 14.2 *Schematic drawing of electromagnetic (EM) method*

It may be noted that the EM instruments do not require electrical contact with the ground. Lateral variations in conductivity can be detected and mapped by profiling. The conductivity of geologic materials is highly dependent upon the water content and the concentration of dissolved electrolytes. Clays and silts typically exhibit higher conductivity values because they contain a relatively large number of ions. Sands and gravels typically have fewer free ions in a saturated environment and, therefore, have lower conductivities. Metal objects, such as steel, display very high conductivity measurements which provide an indication of their presence.

EM methods are very useful for both shallow and deep geological and hydrogeological investigations, especially low-grade ore deposits such as disseminated sulphides, and groundwater pollution investigations. The frequency-domain fixed-coil separation EM method is the most practical approach for the shallow subsurface (less than 4 m) mineral deposits. For collecting data from deeper than 4 m, there are time-domain and frequency-domain equipments that can reach depths below 35 m. The electromagnetic method is commonly used to locate pipes, utility lines, cables, buried steel drums, trenches, buried waste, and concentrated contaminant plumes. The method can also be used to map shallow geologic features such as lithologic changes, clay layers, and fault zones.

❑ *Advantages*

The advantages of electromagnetic method are as follows:

1. EM methods are well suited for the reconnaissance of large open areas because data collection is rapid with a minimum number of field personnel, and a large variety of subsurface anomalies can be located, whether metal or non-metal.
2. EM methods can be useful for assessing both the shallow subsurface and deep geologic features and occasionally depth to groundwater.
3. Most electromagnetic equipment is lightweight and easily portable.
4. Most electromagnetic instrumentation has the capability to electronically store data. This capability provides for a greater degree of accuracy and allows for faster data collection.

❑ *Limitations*

The limitations of EM methods are primarily a result of the interferences, typically caused when this method is applied within 2 to 7 metres of power lines, buried metal objects (including rebar), radio transmitters, fences, vehicles, or buildings.

1. The main limitations of the electromagnetic method when used for hydrogeologic purposes (mapping contaminant plumes, clay layers, and geologic contacts) are cultural noise. Sources of cultural noise can include large metal objects, buried cables, pipes, buildings, and metal fences. However, this limitation is an advantage, in the sense that electromagnetics can successfully be used to map buried steel drums, tanks, pipelines and so

on. However, the presence of these objects will effectively mask the more subtle response of most geological features.
2. Lateral variability in the geology can cause conductivity anomalies or lineations. These features can easily be misinterpreted as a contaminant plume.

❑ *Resistivity Methods*

Electrical resistivity method, also referred to as *galvanic electrical method*, measures Earth resistivity (the inverse of conductivity). The electrical resistivity is a function of porosity, permeability, water saturation and the concentration of dissolved solids in pore fluids within the subsurface. The technique uses a direct or low frequency alternating current source. By measuring the electrical resistance, the method can be used to locate fracture zones, faults, buried valleys, location of aquifers and other preferred groundwater/contaminant pathways; clay lenses and sand channels; perched water zones and depth to groundwater; and occasionally to locate large quantities of residual and floating product. The measurements can also help resolve: sediment depth and thickness; depth to bedrock; and depth to groundwater.

In the resistivity method, artificially generated electrical currents are introduced through the ground using a pair of surface electrodes. The resulting voltage is measured at the surface between a second pair of electrodes; greater the spacing between electrodes the greater is the depth of measurement. Usually, the depth of investigation is less than the spacing between electrodes. Deviations from the pattern of potential differences expected from homogeneous ground furnish information on the form of electrical properties of subsurface inhomogeneities. The resistivity of the soil and rock is calculated based on the electrode separation, the geometry of the electrode array, the applied current, and the measured voltage.

The resistivity technique may be used for *profiling* or *sounding*, similar to EM measurements. Profiling provides a means of mapping lateral changes in subsurface electrical properties to a given depth and is well suited to the delineation of hydrogeologic anomalies and mapping inorganic contaminant plumes. Sounding measurements provide a means of determining the vertical changes in subsurface electrical properties. Interpretation of sounding data provides the depth, thickness, and resistivity of subsurface layers.

Rocks are electrically conductive as consequences of ionic migration in pore space water and more rarely, electronic conduction through metallic lustre minerals. Because the metallic lustre minerals typically do not provide long continuous circuit paths for conduction in the host rock. Bulk-rock resistivity are almost always controlled by water content and dissolved ions. High porosity causes low resistivity in water-saturated rocks.

❑ *Advantages*

The principal advantages of electrical resistivity method are as follows:

1. Quantitative modeling is possible using either computer software or published master curves.
2. The resulting models can provide accurate estimates of depth, thickness and electrical resistivity of subsurface layers.
3. The layered electrical resistivities can be used to estimate the electrical resistivity of the saturating fluid, which is related to the total concentration of dissolved solids in the fluid.
4. The method is useful for groundwater exploration and determination of overburden thickness.

❑ *Limitations*

Electrical resistivity technique has a number of limitations.

1. Electrodes must be in direct contact with soil; if concrete or asphalt is present, holes must be drilled for inserting the electrodes and then refilled when the survey is complete.
2. For deep investigations, electrode arrays can be quite long. The distance between outside electrodes must be 2 to 3 times the depth of investigation.
3. Measurements may be limited by highly conductive or highly resistive surface soils. If shallow clays and extremely shallow groundwater are present, most of the current may concentrate at the surface.
4. Electrical resistivity surveys require a fairly large area, far away from power lines and grounded metallic structures such as metal fences, pipelines and railroad tracks.
5. The fieldwork is labour intensive as a minimum of three crew members are required for the fieldwork.

14.3.3 Seismic Methods

Seismic methods provide information about the Earth's strata by measuring the modes of acoustic waves which travel through the subsurface. Seismic waves are transmitted into the subsurface by a source, which may be a simple sledge hammer or other mechanical sources with which to strike the ground. Explosives may be utilized for deeper applications that require greater energy. In addition to the seismic source, geophones, and a seismograph are required to make the measurements. Geophones implanted into the ground surface translate the ground vibrations of seismic energy into an electrical signal. The electrical signal is displayed on the seismograph, permitting measurement of the arrival time of the seismic wave and displaying the waveforms from a number of geophones as shown in Fig. 14.3. Geophone spacing can be varied from a few metres to a few hundred metres depending upon the depth of interest and the resolution needed.

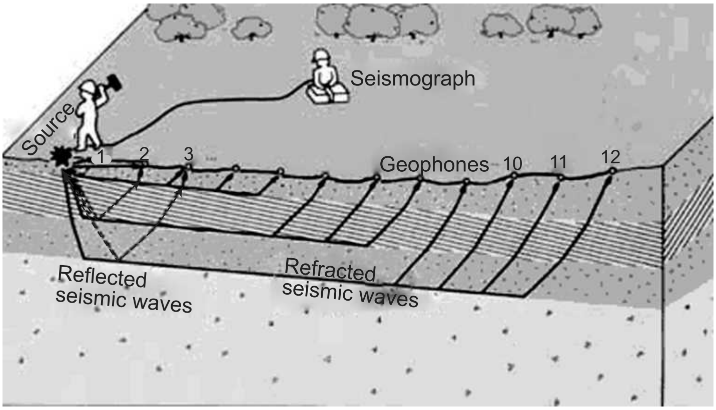


Fig. 14.3 *Seismic methods*

■ **Principle** Shocks or explosion within the Earth's crust are always accompanied by the generation of elastic waves which travel in all directions from the point or place of shock, the focus. Velocity of these shock waves is related to the nature of the medium through which they travel. In nature, these waves are produced during earthquakes. Of all the types of generated waves, the P-waves (longitudinal waves) are the fastest and strongest. Their velocity, V_p is related broadly to the medium (rocks) through the following equation:

$$V_p = \left[E \cdot \frac{(1-v)}{e(1+v)(1-2v)} \right]^{\frac{1}{2}} \tag{14.1}$$

where E is the Modulus of elasticity, e is density and v is the Poisson's ratio of the medium. The main controlling factor is the modulus of elasticity which itself is dependent upon the nature of the rock, its chemical and mineralogical composition, degree of freedom from structural discontinuities and degree of saturation with water and other fluids.

The subsurface velocity information, which is dependent upon the acoustic properties of the subsurface material, results in the seismic data. The velocities of the waves can categorize various geologic materials. Depth to geologic interfaces can be calculated using the velocities obtained from a seismic investigation. The interpretation of seismic data can indicate changes in lithology or stratigraphy, geologic structure, or water saturation (water table).

■ **Applications** The seismic techniques are used to determine the top of bedrock, depth and thickness of geologic strata, to assess the continuity of geologic strata, and to locate fractures, faults, and buried bedrock channels, depth to the groundwater and to estimate soil and rock composition. Moreover, these methods may also be used to characterize the type of rock, degree of weathering, and rippability, based upon the seismic velocity of the rock. The seismic velocity in rock is related to the rock's material properties such as density and hardness. By measuring both compressive (P) waves and shear (S) waves and knowing the density of a soil or rock, one can calculate the modulus properties of the materials through which the waves travel.

The seismic waves are refracted and reflected when they pass from a soil or rock type with one seismic velocity into another with a different seismic velocity. Consequently, there are two types of seismic method applications—refraction and reflection. Both the techniques use the travel times of the waves propagating through the subsurface and the geometry of the source-to-geophone. In the refraction method, the travel-time of waves refracted along an acoustic interface is measured. Seismic reflection, on the other hand, measures the travel time of acoustic waves in the subsurface as they reflect off from these interfaces.

❑ *Seismic Refraction*

Seismic refraction is the most applicable seismic technique for assessing subsurface conditions such as to find out sediment depth and thickness; fractures, and faults; depth to bedrock; and occasionally, depth to groundwater.

■ **Principle** In this method, it is the velocity of refracted waves that is determined. The seismic refraction technique utilizes an energy source, such as a sledge hammer or small explosives, to create acoustic waves in the subsurface. When there is a change in the seismic velocity of the waves travelling from one layer to the next, refracted waves are created. These waves are recorded by geophone sensors (i.e., seismic wave receivers) arranged in a direct line from the energy source. The time it takes the waves to refract is dependent on the composition, cementation, density, and degree of weathering and fracturing of the subsurface materials. Figure 14.4 presents a schematic drawing of seismic refraction operating principles. This seismic method is generally applied to shallow investigations only up to about maximum hundred metres deep. Up to three and sometimes four layers of soil and rock can normally be determined; if a sufficient velocity difference or contrast exists between adjacent layers.

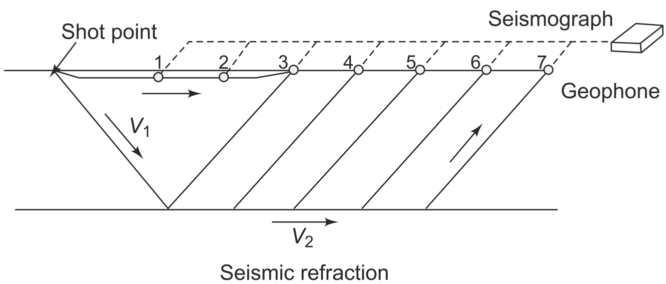


Fig. 14.4 *Schematic representation of seismic refraction method*

■ **Refraction Approach** The simplest approach consists in creating two separate seismic impulses, one at each end of the geophone array. The measurement provides twice the depth and thus the dip of rock under the array of geophone. The refraction survey may require a maximum source-to-geophone distance four to five times the depth of investigation. From seismic refraction survey, semi-continuous data is obtained which, in combination with borings and other sampling techniques can be extrapolated to resolve localized geologic features over the entire area of investigation.

■ **Advantages** The advantage of seismic refraction is that it can resolve three to four layers of stratigraphy and provide good depth estimates. Furthermore, it is fairly easy to implement, and the energy source can simply be a sledge hammer.

1. Seismic refraction surveys can be useful to obtain depth information at locations between boreholes or wells. Subsurface information can be obtained between boreholes at a fraction of the cost of drilling.
2. Refraction data can be used to determine the depth to the water table or bedrock.
3. The technique is very useful in buried valley areas to map the depth to bedrock or thickness of overburden.
4. The velocity information obtained from a refraction survey can be related to various physical properties of the bedrock.

■ **Limitations** Two inherent limits to the refraction method are its inability to detect a lower velocity layer beneath a higher velocity layer and its inability to detect thin layers. Some of the other limitations of seismic refraction are as follows.

1. Geophone spreads may be as much as five times as long as the desired depth of investigation, therefore, limiting its use in congested locations. Although seismic refraction can be used for depths below 100 m, it is usually used for depths less than 30 m because of the very long geophone spreads required and the energy sources necessary to reach these depths.
2. If numerous buried utilities are in the vicinity of the seismic profiles, they may interfere with the collection of usable data by creating a false layer near the surface.
3. Data collection is labour intensive.
4. Seismic velocities of geologic layers must increase with depth. Although this situation is typical, conditions such as frozen soil or buried pavement will prevent detection of underlying formations.
5. For success, the apparent dip of the units or layers should be less than ten to fifteen degrees.
6. Seismic methods are sensitive to acoustic noise and vibrations.

Note In order to be successful, the velocity of the refracted waves saturated zone must be significantly greater than the overlying formation. Because consolidated formations typically have very fast seismic velocities that are not significantly affected by groundwater, if the water table is located in a consolidated formation, it will not likely be discernable. Furthermore, seismic velocities will typically increase significantly in unconsolidated formation; however, if the boundary is sharp (e.g., as in coarse sands), a refraction survey will not be capable of determining, if the layer is groundwater or another formation.

❑ *Seismic Reflection*

The seismic reflection technique is capable of much deeper investigations with less energy than the refraction technique. The reflection technique can be used effectively to depths of a few thousand metres and can provide relatively detailed geologic sections. While reflections have been obtained from depths as shallow as 3 m, the shallow reflection method is more commonly applied to depths of 15 to 30 m or more. This technique finds its application in oil exploration, lithological investigation of the area, and for locating structural features.

■ **Principle** The technique is based on the fact that in an artificial explosion, some of the energy reaching the interface of two layers is reflected back and can be recorded at the surface. In the seismic reflection method, a sound wave travels down to a geologic interface and reflects back to the surface, as shown in Fig. 14.5. The waves are reflected at an interface where there is a change in the acoustic properties of the subsurface material. The waves are recorded by a series of geophones near to the source point. After treatment, the different records result in a combined high resolution image of reflector shapes in time.

■ **Reflection Approaches** There are two approaches currently used to obtain shallow seismic reflection data—the common offset method and the common depth point (CDP) method. The common offset technique uses low-cost equipment and software but has some site-specific limitations that are not inherent in the CDP technique. The CDP technique has fewer site-specific limitations, but is more dependent upon sophisticated hardware and software capabilities. The shallow high-resolution reflection techniques attempt to utilize the highest frequencies possible (150 to 600 Hz), to improve vertical resolution and relatively closely spaced geophones (0.3 to 6 m apart) to provide good lateral resolution.

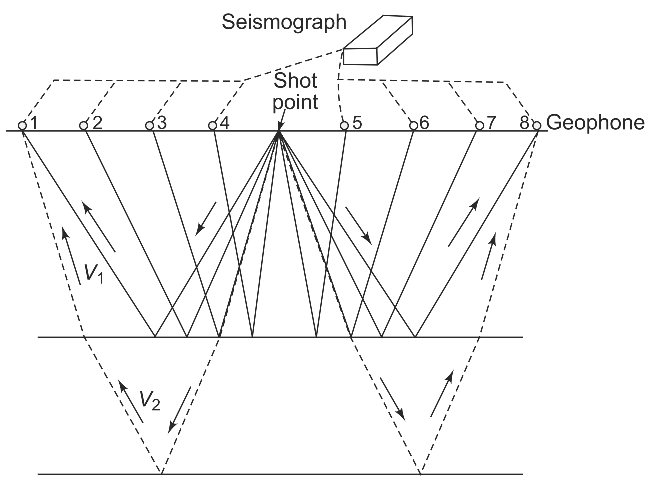


Fig. 14.5 *Schematic representation of seismic reflection method*

■ Advantages

1. The seismic reflection method yields information that allows the interpreter to discern between fairly discrete layers.
2. The reflection method can be used to map stratigraphy. Reflection data is usually presented in profile form, and depths to interfaces are represented as a function of time. Depth information can be obtained by converting time sections into depth from velocities obtained from seismic refraction data, sonic logs, or velocity logs.
3. The reflection technique requires much less space than refraction surveys.

■ Limitations

1. The major disadvantage in using reflection data is that a precise depth determination cannot be made. Velocities obtained from most reflection data are at least 10% and can be 20% of the true velocities.
2. The reflection method is limited by its ability to transmit energy, particularly high frequency energy, into the soil and rock. Loose soil near the surface limits the ability of the soil system to transmit high frequency energy into and out of the rock, limiting the resolution that can be obtained.
3. The most common limitation, however, is that of acoustic noise caused by natural or cultural sources.

14.3.4 Gravity Method

This method involves measuring the acceleration due to the Earth's gravitational field; the measurements normally being made on the Earth's surface. The unit of gravity is *gal*, which is 1 cm/s/s. A gravimeter is used to measure variations in the Earth's true gravitational field at a given location. Gravimeters respond to changes in the Earth's gravitational field caused by changes in the density of the soil and rock. Because density variations are very small and uniform, the instruments used are very sensitive. By measuring the spatial changes in the gravitational field, variations in subsurface geologic conditions can be determined. The method is very useful in delineating buried valleys, bedrock topography, geologic structure, ore deposits, and identification of lithologies and voids.

There are two basic types of gravity surveys: a *regional gravity survey* and a *local microgravity survey*. Regional gravity survey employs widely spaced (a few thousand metres to a few kilometres) stations and is carried out with a standard gravimeter. Such surveys are used to assess major geologic conditions over many hundreds of square kilometres, and to detect and map shallow localized geologic anomalies such as bedrock channels, fractures, and cavities. The lines passing through points of same gravity anomaly are called *isogams*. Gravity data may be presented as a profile or as a contour map, depending upon need of the project.

Note Gravity and magnetic (discussed below) methods detect only lateral contrasts in density or magnetization, respectively. Whereas, electrical and seismic methods can detect vertical, as well as lateral, contrasts of resistivity and velocity or reflectivity.

❑ *Advantages*

The main advantage of using gravity method for site assessment is that gravity measurements are not as susceptible to cultural noise and, hence, data can be acquired in heavily populated areas.

■ Limitations

1. Each station has to be precisely surveyed for elevation and latitude control, which is costly and time consuming.
2. The accuracy of vertical and horizontal positioning is directly related to the resolution capabilities of the gravity method.
3. Many computations are involved in the reduction and interpretation of gravity data. The use of personal computers or programmable calculators is a practical necessity when dealing with many readings. Also, there are two unknowns that must be determined for the interpretation: 1) the density contrasts between the underlying material, and 2) the depths of the contacts between areas of density contrasts.
4. Gravity metres are extremely sensitive mechanical balances in which a mass is supported by a spring. Small changes in gravity move the weight against the restoring force of the spring.
5. The main source of interference or noise is vibrations, which may be caused by vehicular traffic, heavy equipment, low flying aircraft and wind.

14.3.5 Magnetic Method

The method is based on the fact that the Earth is a gigantic magnet with a definite magnetic field. However, since the Earth is not ideally homogeneous, the theoretical values of magnetic intensities vary from the observed values at point of observations. Local variations, or anomalies, in the Earth's magnetic field are the result of disturbances caused mostly by variations in concentrations of ferromagnetic material in the vicinity of the magnetometer's sensor. A magnetometer is an instrument which measures the intensity of the Earth's magnetic field.

The primary application of magnetic measurements is in detecting buried ferrous metals. A magnetometer will only respond to ferrous metals (iron and steel) and will not detect nonferrous metals. Buried ferrous materials distort the magnetic field, creating a magnetic anomaly and cause a local variation in the strength of the Earth's magnetic field, thus permitting the detection and mapping of buried ferrous metal. The method may also be used at a site to map various geologic features, such as igneous intrusions, faults, and some geologic contacts that may play an important role in the hydrogeology of a groundwater pollution site. In certain geologic environments, the technique can also be used to map depth to bedrock, channels and fractures.

There are two methods for measuring these anomalies—*the total field method* and the *gradient method*. Any changes caused by a target, natural magnetic variations, and cultural magnetic noise (ferrous pipe, fences, buildings, and vehicles) leads to noise. A base station magnetometer can be used to reduce the effects of natural noise by subtracting the base station values from those of the search magnetometer. This can minimize any errors due to natural long-period changes of the Earth's magnetic field. The total field method utilizes one magnetic sensing device to record the value of the magnetic field at a specific location. The gradient method uses two sensors, one above the other. The difference in readings between the two sensors provides gradient information which helps to minimize lateral interferences. Total field magnetic methods are often used at sites with few cultural features. Figure 14.6 presents a typical schematic drawing of magnetometry operating principles.

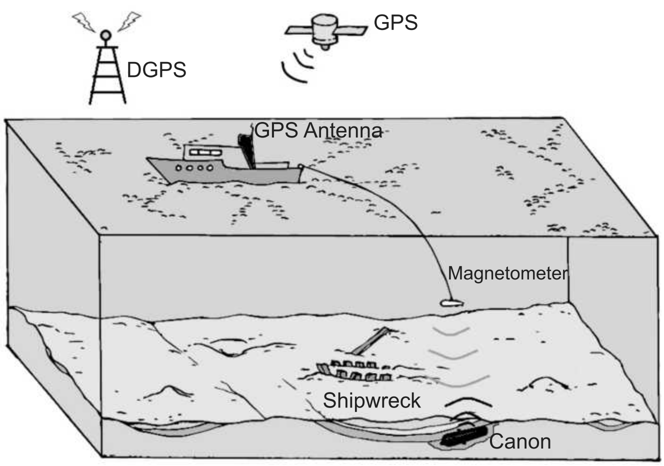


Fig. 14.6 *Schematic representation of magnetometry*

❑ *Advantages*

1. Magnetic methods are very useful for the initial assessment of hazardous waste sites.
2. The method is relatively less expensive and the work can be completed in a short amount of time.
3. Surveying requirements are not as stringent as for other methods, and may be completed with a transit and non-metallic measuring tape.
4. Magnetic exploration may directly detect some iron ore deposits (magnetite or banded iron formation).
5. Magnetic methods often are useful for deducing subsurface lithology and structure that may indirectly aid identification of mineralized rock.

❑ *Limitations*

Following are the limitations of the magnetic method.

1. The method suffers from the problem of cultural noise. Human-made structures that are constructed using ferrous materials, such as steel, etc. have a detrimental effect on the quality of the data. Therefore, features such as steel structures, power lines, metal fences, reinforced concrete, surface metal, pipelines and underground utilities should be avoided.

2. Magnetic methods detect only lateral contrasts in magnetization.

Table 14.1 depicts the various geophysical surface methods and their operative properties.

Table 14.1 *Geophysical surface methods*

Method	*Measured Parameter*	*Operative Physical Property*
Seismic	Travel times of reflected/refracted seismic waves	Density and elastic modulii, which determine the propagation velocity of seismic waves
Gravity	Spatial variations in the strength of the gravitational field of the Earth	Density
Magnetic	Spatial variations in the strength of the geomagnetic field	Magnetic susceptibility
Electrical resistivity	Earth resistance	Electrical conductivity
Self-potential	Electrical potentials	Electrical conductivity
Electromagnetic	Response to electromagnetic radiation	Electrical conductivity and inductance
Radar	Travel time of reflected radar pulses	Dielectric constant

14.4 SUBSURFACE GEOPHYSICAL METHODS

The most widely used technique for getting the detailed information on subsurface lithology is known as *boring*. The method finds its application in geotechnical investigations, environmental site assessment and mineral exploration. The process consists in drilling of holes into the ground, sampling at discrete points, and *in situ* or laboratory testing. The probes that measure different properties are lowered into the borehole to collect continuous or point data which is then displayed graphically as a geophysical log. The practice of making a detailed record of the geological formations penetrated by a borehole is known as *borehole logging* or *well logging*; the record is known as *well log*. The log may either be based on visual inspection of the samples brought to the surface or on physical measurements made by instruments lowered into the borehole. Most borehole methods are based on the same principles as surface geophysical methods.

The geophysical logging system consists of probes, cables, power and processing modules, and data recording units as shown in Fig. 14.7. State-of-the-art logging systems are controlled by a computer and can collect multiple logs with one pass of the probe. Each technique has specific requirements and limitations that must be considered.

Site investigations for geotechnical engineering consists in taking samples of soil and rock at discrete intervals by boring subsurface. The technique provides information on the formation variations along the depth. However, sand lenses, fractures, or other subtle changes in geology cannot be undetected by this technique. Thus, by using subsurface techniques, it is possible to obtain geologic information. Further, it is also possible to obtain the well construction details as well. In addition, logging may be used to determine whether a problem exists with well construction and the type of remedial work, if any, is necessary to correct it. The examples of commonly used borehole techniques in the water well industry are natural gamma ray and resistivity logs.

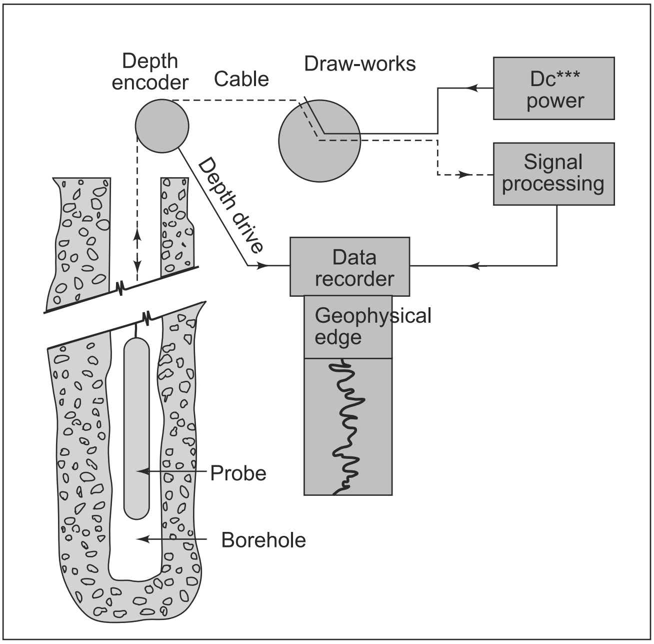


Fig. 14.7 *Schematic representation of subsurface geophysical method*

The advantages of bore-hole techniques lie in the fact that they supply an abundance of subsurface information. Information on the stratigraphy, hydrogeology and contamination of groundwater at a site can often be derived from the bore-hole logs. In addition to the initial assessment of the subsurface conditions at a site, borehole information can sometimes be used to monitor the remediation of a site. The limitations of bore-hole techniques include the huge expenses and that the information from borehole logs only comes from a limited radius around the well (< 1 m).

Further, a number of subsurface logging techniques have been developed for determining the characteristics of soil, rock, or fluid along the length of a borehole or a monitoring well. Some of the most widely used logging techniques are as follows. The techniques have been grouped as nuclear logs and non-nuclear logs.

14.5 NUCLEAR LOGS

By running nuclear logs in existing holes with steel or PVC casing, geologic strata outside the casing can be characterized. A subsurface television camera can be used within cased wells to assess monitoring well conditions or it can be used within an uncased borehole to assess the existence of fractures. The various nuclear log techniques are as to follow.

14.5.1 Natural Gamma Log

A natural gamma log records the amount of natural gamma radiation that is emitted by rocks and unconsolidated materials. The chief use of natural gamma logs is the identification of lithology and stratigraphic correlation in open or cased holes above and below the water table.

The gamma-emitting radioisotopes normally found in all rocks and unconsolidated materials are potassium-40 and daughter products of the uranium and thorium decay series. Because clays and shales concentrate these heavy radioactive elements through the processes of ion exchange and adsorption, the natural gamma activity of shale and clay-bearing sediments is much higher than that of quartz sands and carbonates. Therefore, the gamma log, which indicates an increase in clay or shale content by an increase in counts per second, is used to evaluate the presence, variability, and integrity of clays and shales. The radius of investigation for the natural gamma log is from about 15 to 30 cm.

Note All rocks emit natural gamma radiation originating from unstable isotopes (potassium, uranium, and thorium). Clayey formations (shale, clay) emit more rays than gravels and sands. Natural gamma logging can be used to differentiate between sand, clay and gravel.

14.5.2 Gamma–Gamma (Density) Log

A gamma–gamma log is used to determine the relative bulk density of the soil or rock and to identify lithology. The log can be used in open or cased holes above and below the water table. The gamma–gamma log is an active probe containing both a radiation source and a detector. This log provides a response, in counts per second, that is averaged over the distance between the source and the detector. The radius of investigation for the gamma–gamma log is relatively small (only about 15 cm). Therefore, boreholes diameter variations and well construction factors can affect this log more than other logs.

Gamma rays from a source in the probe (cobalt-60 or cesium-137) are scattered and diffused through formation. Part of the scattered rays re-enter the hole and are re-measured. The higher the bulk density of formation, the smaller the number of gamma–gamma rays that reach the detector. Primary applications include identification of lithology and, measurement of bulk density and porosity of rocks.

14.5.3 Neutron–Neutron (Porosity) Log

A neutron–neutron log provides a measure of the relative moisture content above the water table and porosity below the water table. It can be run in open or cased holes above and below the water table. The neutron–neutron log is an active probe with both a radiation source and a detector. It provides a response, in counts per second, that is averaged over the distance between the source and the detector.

The radius of investigation for the neutron–neutron probe is approximately 30 cm. Boreholes diameter variations and well construction factors can affect this log, but not as severely as the density log.

Neutron logging is used in determining the porosity of formation. A fast neutron source is used to bombard the rock. When any individual neutron collides with a hydrogen ion (of a water molecule) some of the neutron's energy is lost and it slows down. A large quantity of slow neutrons, as recorded by a slow neutron counter, indicates a large quantity of fluid (i.e. high porosity). Results are influenced by the size of the hole. Therefore, in large uncased holes, information on diameter of the hole is required for proper interpretation.

14.6 NON-NUCLEAR LOGS

Non-nuclear logs are helpful to conduct the geophysical investigations in uncased boreholes. It is therefore necessary that the pilot boreholes should be logged by non-nuclear log. There are several types of non-nuclear logs as follows:

14.6.1 Induction Log

The induction log is an EM induction method for measuring the electrical conductivity of soil or rock in open or PVC-cased boreholes above or below the water table. The induction log can be successfully used for identification of lithology and stratigraphic correlation.

Electrical conductivity is a function of soil and rock type, porosity, permeability, and the fluids filling the pore spaces. Because the response of the log (milli-ohm/meter) will be a function of the specific conductance of the pore fluids, it is an excellent indicator of the presence of inorganic contamination. Variations in conductivity with depth may also indicate changes in clay content, permeability of a formation, or fractures. An induction log provides data similar to that provided by a resistivity log (because conductivity is the reciprocal of resistivity). The advantage of the induction log is that it can be run without electrical contact with the formation. The radius of investigation for the induction log is approximately 75 cm from the center of the well. Because this log has a much larger radius of investigation than other logs, it is almost totally insensitive to boreholes and construction effects and as such is a good indicator of the overall soil and rock conditions surrounding the boreholes.

14.6.2 Resistivity Log

The resistivity log measures the apparent resistivity (measured in ohm-feet or ohm-meters) of rock and soil within a boreholes. Since resistivity is the reciprocal of conductivity, the property measured by the resistivity log responds to and measures the same properties and features as the induction log. However, because of the need for electrical contact with the boreholes wall, the resistivity log can only be run in an uncased hole filled with water or drilling fluid. Multi-electrode method is most commonly employed (minimizes the effects of drilling fluid and well diameter).

Uses of resistivity logs include interpretation and identification of rock types, identification of the position of the water table, determination of bed contacts and bed thickness, and determination of aquifer parameters.

14.6.3 Resistance Log

A resistance log (sometimes referred to as single-point resistance) measures the resistance (in ohms) of the Earth materials lying between a subsurface electrode and a surface electrode. It can only be run in uncased holes in the saturated zone. The primary uses of resistance logs are geologic correlation and the identification of fractures or washout zones in resistive rocks. The resistance log should not be confused with the resistivity log, which provides a quantitative measure of the material resistivity. The radius of investigation of the resistance log is quite small. It is in many cases as strongly affected by conductivity of the borehole fluid as it is affected by the resistance of the surrounding volume of rock.

14.6.4 Spontaneous-Potential Log

The Spontaneous-Potential (SP) log measures the natural potential (in milli-volts) developed between the borehole fluid and the surrounding rock materials. It can only be run in uncased holes within the saturated zone. The SP voltage consists of two components. The first component results from electrochemical potential caused by dissimilar minerals. The second component is the streaming potential caused by water moving through a permeable medium. SP measurements are subject to considerable noise from the electrodes, hydrogeologic conditions, and borehole fluids.

14.6.5 Temperature Log

A temperature log is a continuous record of the temperature of the borehole fluid immediately surrounding the sensor as it is lowered within an open borehole. The temperature log often indicates a zone of ground-water flow within the uncased portion of a borehole. Flow is indicated when an increase or decrease in water temperature occurs. Changes in temperature can also be used to monitor leaks in casing where damage or corrosion has occurred. A temperature log may have a sensitivity of 0.58°C or better.

The applications of temperature logging include identification of aquifers contributing water to a well, providing data on the source of water, identifying rock types, calculation of fluid viscosity and specific conductivity from fluid resistivity logs and distinguishing moving and stagnant water.

14.7 SURFACE VS SUBSURFACE METHODS

Surface geophysical methods can be used as initial reconnaissance tools to cover an area in a quick search for anomalous conditions. These methods can then be employed for a detailed assessment of site conditions. After potential problem areas have been identified, the drilling locations for boreholes can be selected with a higher degree of confidence to provide representative samples. Subsurface geophysical methods can therefore be applied to define details of conditions with depth. This approach delivers greater confidence in the final data interpretation with fewer borings and wells and an overall cost savings. Furthermore, the drilling operations are nowadays use specific quantitative tools and not for hit-or-miss reconnaissance. Analyses of soil and water samples from properly located borings or monitoring wells provide the necessary quantitative measurements of subsurface parameters.

The subsurface geophysical methods provide detailed high resolution data at depth around a borehole or well in which they are deployed. In the surface geophysical methods, the resolution decreases with depth, whereas the logging method is independent of depth.

In addition, most subsurface methods provide continuous data along the depth of the hole. However, the volume sampled by subsurface methods is usually limited to the area immediately around the boring. The cost per unit area of coverage for the subsurface methods is therefore much higher than for surface methods; all subsurface techniques require a borehole or monitoring well.

Through the use of appropriate combinations of geophysical measurements and borehole data, an accurate 3D picture of subsurface conditions can be generated. The resulting understanding of subsurface conditions can then be used to develop an accurate conceptual site model, which incorporates the big picture through the local details.

Summary

The ultimate aim of geophysical investigations for a civil engineer is to determine subsurface properties of the soils and rocks underlying the proposed site to ensure the feasibility for construction. For a geologist, the aim is to identify the location of minerals. The different geophysical methods are outlined and described. Each of the different geophysical methods depends on particular physical property of the strata and each has its own feasibility and limitations which must be clearly understood.

Surface and subsurface techniques together form a complete comprehensive plan for geophysical investigation for a civil engineering project. The surface methods provide an average response over a large volume of subsurface conditions; providing a means of detecting subsurface conditions such as buried channel or lithological characters like weak zones, density and salanity of formations. Once an overall characterization of a site has been made using geophysical methods and anomalous zones have been identified, a drilling and sampling plan may be designed by:

1. Locating soil borings and monitoring wells to provide samples that are representative of site conditions.
2. Minimizing the number of samples, borings, or monitoring wells required to accurately characterize a site.
3. Reducing field investigation time and cost.
4. Significantly improving the accuracy of the overall investigation.

The underlying principles of the methods discussed in the chapter are based on the classic laws of physics and geochemistry. The success depends entirely on the interpretation of the results into correct geological meaning. The methods are based on the differences existing between the density, magnetic susceptibility, elasticity and electric conductivity of the different strata. The gravimetric method reliably locates hidden structures, but does not give exact depth determinations.

The site conditions that may preclude the successful use of most or all geophysical techniques have been discussed. These conditions include the presence of factors that degrade the ability of the geophysical instruments to measure various physical parameters. For instance, the presence of strong electromagnetic fields at site may preclude the use of some geophysical techniques. Under such instances, the use of geophysical methods may not be recommended. The need for use of different geophysical methods in combinations for precise assessment of a site is stressed. The main advantage of geophysical methods is the possibility to produce 3D images of subsurface structures and physical properties. The necessity for considering each site as a unique is the key for the success of geophysical investigation programme.

Terminology

Acoustic Waves A type of longitudinal waves that propagate by means of adiabatic compression and decompression. Acoustic waves travel with the speed of sound which depends on the medium they are passing through.

Anomaly A localized change in the geophysical data characteristic of a discrete source, such as a conductive or magnetic body.

Noise Any unwanted signal, can be from the instrument, uncontrollable conditions, operator; noise can mask the contrast or manifest as an uncertainty in the inversion process.

Refraction Bending of electromagnetic rays as they pass from one medium into another when each medium has a different index of refraction.

Transmissivity The property of a material which determines the amount of energy that can pass through the material.

Exercises

1. What are the objects of geophysical investigations? Enumerate the various geophysical methods of subsurface investigations. Discuss the usefulness of various surface techniques.
2. Give an account of classification of geophysical methods. Explain briefly the subsurface geophysical techniques of investigation.
3. Comment: Subsurface methods and surface methods of geophysical techniques are complementary to each other.
4. Describe in detail the ground-penetration radar technique for geophysical exploration. Give the advantages and limitations of the technique as compared to other surface techniques.

5. Give a brief account of geophysical and hydrological investigations made in groundwater exploration.
6. Write short notes on the following:
   (a) Geophysical anomaly
   (b) Well logging
   (c) Nuclear logging
7. Explain the following geophysical methods with suitable sketches. Also discuss their importance.
   (a) Gravity method
   (b) Seismic refraction method
   (b) Seismic reflection method
   (d) Magnetometry
8. Discuss the following geophysical techniques, briefly highlighting their importance.
   (a) Electrical resistivity method
   (b) Seismic refraction method
   (b) GPR method
   (d) Electromagnetic method
9. Differentiate between the following with regards to geophysical exploration.
   (a) Nuclear and non-nuclear logs
   (b) Reflection and refraction seismic methods
   (c) Electrical resistivity technique and electromagnetics
   (d) Natural gamma log and induction log
10. What is a geophysical anomaly? With the help of a sketch, explain this with reference to lithology, geological structure and ores.
11. What are seismic methods of prospecting? Explain the principle behind them with neat sketches. What are their fields of applications and limitations?
12. How do you carry out geophysical physical investigation in groundwater prospecting? Add a note on interpretation.

Multiple-Choice Questions

1. Match the following items of Group I with those of Group II.

Group I	Group II
A) Electrical Method	1) Density
B) Magnetic Method	2) Velocity
C) Gravity Method	3) Resistivity
D) Seismic Method	4) Susceptibility
	5) Dielectric Permittivity

   (a) A–3 ; B –2 ; C–5 ; D–1 (b) A–3 ; B–4 ; C–1 ; D–2
   (c) A–3 ; B –4 ; C–2 ; D–1 (d) A–5 ; B–4 ; C–3 ; D–2
2. Which of the following logging technique is best suited to estimate the shale content of hydrocarbon reservoirs?
   (a) Resistivity (b) Sonic
   (c) Induction (d) Gamma ray

3. Which of the following methods is best suited to estimate the resistivity variations in the upper mantle of the Earth?
(a) Deep electrical resistivity
(b) Ground-penetrating radar
(c) Controlled source electromagnetics
(d) Magnetotellurics

4. Match the items of Group I with those of Group II.

Group I	Group II
A) Caliper log	1) Permeability
B) NMR log	2) Resistivity
C) Neutron log	3) Diameter
D) SP log	4) Velocity
	5) Porosity

(a) A–3, B–4, C–2, D–5 (b) A–3, B–1, C–5, D–2
(c) A–4, B–2, C–4, D–3 (d) A –1, B–3, C–2, D–4

5. A successful combination of geophysical methods for exploration of kimberlite pipe is
(a) gravity and radiometric (b) magnetic and electromagnetic
(c) radiometric and magnetic (d) radiometric and seismic

6. Which of the following logging technique is most suited to distinguish flowing and stagnant waters?
(a) Temperature log (b) Resistivity log
(c) SP-log (d) Resistance log

7. Magnetic survey is useful for
(a) metallic deposit (b) non-metallic deposit
(c) oil and gas (d) iron ore deposit

8. Oil and gas can be explored by:
(a) magnetic method (b) ground penetrating radar
(c) seismic method (d) resistivity method

9. Ground-penetrating radar is most useful for the exploration of
(a) coal (b) ore body
(c) groundwater and ore body at shallow depth
(d) groundwater and ore body at deeper depth

10. Subsurface geophysical method is
(a) resistivity method (b) electromagnetic method
(c) siesmic method (d) borehole logging

Answers to MCQs

1. (b) 2. (d) 3. (d) 4. (b) 5. (b) 6. (a) 7. (d) 8. (c)
9. (a) 10. (d)

chapter 15

Remote Sensing, Global Positioning System, and Geographic Information System

15.1 INTRODUCTION

Remote sensing, global positioning system (GPS) and geographic information system (GIS) are gaining popularity in exploring the surface and subsurface of the Earth since the last two decades. *Remote sensing* is the art of obtaining information about properties of an object without coming into physical contact with that object. The task is accomplished with the help of highly sophisticated sensors, usually mounted on satellites. A large area of the Earth can be captured instantaneously and can be processed to generate map-like products. *Global positioning system*, on the other hand, uses the satellite triangulation programme to collect the required data of interest. It quickly, accurately and inexpensively provides the position of the object anywhere on the globe at any time. In the case of geological mapping with GPS, there is no need of the measurement of horizontal distance as well as the measurement of horizontal direction; the location of the observation point is obtained directly in terms of longitude and latitude. Moreover, the altitude of the observation point can also be noted down directly from the GPS reading. *Geographic Information System* may be defined as a system of hardware, software, data, and people organizing, collecting storing, analyzing and disseminating information about the areas of the Earth. It can handle raster data as well as vector data. This chapter basically presents the application part of the three techniques in the field of engineering geology. For details of the processes involved and surveying techniques, the book on *Surveying* Volume 2 by the same author can be referred.

15.2 REMOTE SENSING

Remote sensing consists of collecting, processing, and interpreting information by measuring the electromagnetic radiation that is reflected, emitted and absorbed by objects in various spectral regions, ranging from gamma-rays to radio waves. The process of remote sensing is shown schematically in Fig. 15.1. To measure this radiation, both active and passive remote sensors are used.

Passive systems generally consist of an array of sensors which record the amount of electromagnetic radiation emitted by the surface being studied. *Active systems* transmit a pulse of energy to the object being studied and measure the radiation that is reflected or backscattered from that object. Passive radiometric methods of remote sensing technology include: imaging radiometer, spectrometer and spectro-radiometer. The examples of active remote sensor technologies are radar, scatterometer, lidar and laser altimeter.

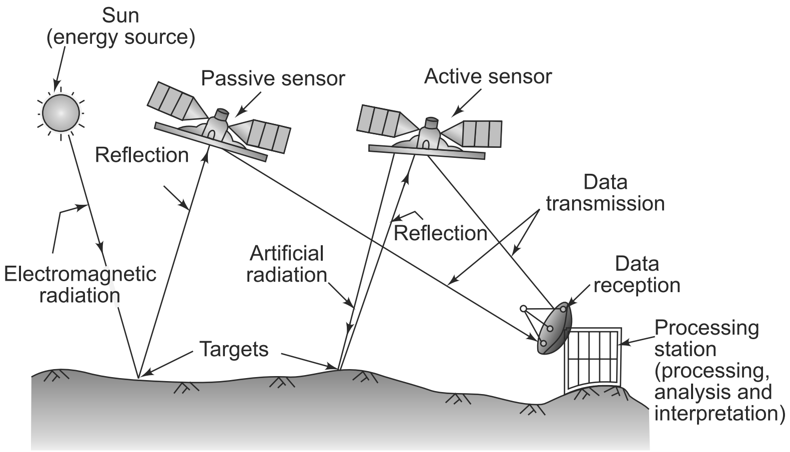


Fig. 15.1 *Electromagnetic remote sensing process*

The greatest advantage of remote sensing is the synoptic view that it provides. It gives a regional and integrated perspective of inter-relations between various land features. The availability of multi-spectral and high resolution data as well as the advanced capabilities of digital image processing techniques in generating enhanced and interpretable image, further enlarges the potential of remote sensing in delineating the lithological contacts and geological structure in great details and with better accuracy. The existing multispectral satellite systems are designed to investigate natural resources with special focus on vegetation coverage, lithology and mineral exploration. Remote sensing techniques have opened a new era in geological and natural resource mapping.

15.3 APPLICATIONS OF REMOTE SENSING

Remote sensing affords a practical means for accurate and continuous monitoring of the Earth's natural and other resources, and of determining the impact of human activities on air, water and land. This is the most effective and widely established analytical method for gathering the information related to geology and ground surface characteristics on a large scale, particularly in inaccessible areas.

Geology involves the study of landforms, structures, and the subsurface, to understand physical processes creating and modifying the Earth's crust. It involves the exploration and exploitation of mineral and hydrocarbon resources, generally to improve the conditions and standard of living in society. Engineering geological applications of remote sensing include the following.

15.3.1 Mineral Exploration

Remote sensing techniques have great promises both for reconnaissance and detailed exploration of non-renewable resource like minerals and fossil fuels. Remote sensing has been proved to be indispensable in this field and has been used in the following:

1. Mapping of regional lineaments having mineralization
2. Mapping local fracture patterns that may control individual ore deposits
3. Detecting hydrothermally altered rocks associated with ore deposits
4. For collecting geological data in difficult terrains

15.3.2 Geological Mapping

In the past, geological maps were prepared from conventional ground surveys based on field observations. They were made along traverse lines at regular intervals. The point (discrete) information thus collected along the traverse lines on the topographic base was plotted by extrapolating the details. The maps so prepared were bound to have certain errors and lead to inaccuracies in maps. With the development of remote sensing technology, the mapping procedures have undergone phenomenal change. Further, mapping of lithology and alteration zones in inaccessible mountainous and forest terrain was always challenging. Since vast areas to be surveyed and its inaccessibility forbids physical investigation of every outcrop, the potential of remote sensing is tremendous. The best part of the technique is that it provides access to inaccessible sites.

A civil engineering project either influences, or is influenced by, the site of construction and the adjoining areas. The distribution of materials and discontinuities in the total area involved may be shown on geological maps. Most investigations include the study and/or construction of a geological map of the area of interest. These maps display the geological information of the concerned area as an aid to design and construction of the project and the complexities involved as well. These specifically designed maps for engineering purposes include the following features:

1. The lithology of the strata and geological structures like folds, faults and joints,
2. The thickness of the layers and their depth below surface,
3. The depth to the water table,
4. The location of significant geomorphological features, such as the presence of karst features in limestone, landslides, active faults, etc.,
5. Hazards such as abandoned mines, old quarries, areas of toxic fills, etc., and
6. Locations of construction materials.

Notes

1. The most useful form of remote sensing for engineering geology applications is aerial photography (which is the primitive form of remote sensing) because of its high resolution, high information content, and low cost. Applications of other forms of remote sensing to engineering geology depend on the nature of the problem to be solved and the characteristics of the site geology.
2. Appropriate remote sensing data are often not available for the area of interest, and the data may have to be acquired specifically for the project.

15.3.3 Structural Mapping

Structural mapping is the identification and characterization of structural expression. Structures include faults, folds, and lineaments. Structures can indicate potential locations of oil and gas reserves by characterizing both the underlying subsurface geometry of rock units and the amount of crustal deformation and stress experienced in a certain locale.

Radar is well suited to these requirements with its side-looking configuration. Imaging with shallow incidence angles enhances superficial relief and structure. Shadows can be used to help define the structure height and shape, thus increasing the shadow effect, while shallow incidence angles may benefit structural analysis. Aerial photos can be used in temperate areas where large-scale imagery is required, particularly to map relief which is quite often determined by structure.

Certain remote sensing devices offer unique information regarding structures, such as in the relief expression offered by radar sensors. Comparing surface expression to other geological information may also allow patterns of association to be recognized. For instance, a rock unit may be characterized by a particular radar texture, which may also correlate with a high magnetic intensity or geological anomaly. In areas where the vegetation cover is dense, it is very difficult to detect structural features. Radar, however, is sensitive enough to topographic variation such that it is able to discern the structural expression reflected or mirrored as in case of the tree top canopy, and therefore the structure may be clearly defined on the radar imagery.

15.3.4 Lithological Mapping

Mapping geologic units consists primarily of identifying physiographic units and determining the rock lithology or coarse stratigraphy of exposed units. These units or formations are generally described by their age, lithology and thickness.

Remote sensing can be used to describe lithology by the colour, weathering and erosion characteristics, drainage patterns, and thickness of bedding. Unit mapping is useful in oil and mineral exploration, since these resources are often associated with specific lithologies. Structures below the ground, which may be conducive to trapping oil or hosting specific minerals, often manifest themselves on the Earth's surface. By delineating the structures and identifying the associated lithologies, geologists can identify locations that would most likely contain these resources, and target them for exploration.

15.3.5 Hydrology

Remote sensing offers a synoptic view of the spatial distribution and dynamics of hydrological phenomena, often unattainable by traditional ground surveys. *Hydrology* is the study of water on the Earth's surface, whether flowing above ground, frozen in ice or snow, or retained by soil. It is inherently related to many other applications of remote sensing, particularly forestry, agriculture and land cover, since water is a vital component in each of these disciplines. Examples of hydrological applications include

1. Wetlands mapping and monitoring
2. Soil moisture estimation
3. Snow peak monitoring (delineation and extent)
4. Measuring snow thickness
5. Determining snow-water equivalent
6. River and lake ice monitoring
7. Flood mapping and monitoring
8. Change in position of river/delta
9. Drainage basin mapping and watershed modelling
10. Irrigation canal leakage detection
11. Irrigation scheduling

Note Radar has brought a new dimension to hydrological studies with its active sensing capabilities, allowing the time window of image acquisition to include inclement weather conditions or seasonal or diurnal darkness.

15.3.6 Land Cover and Land Use

Land cover refers to the surface cover on the ground, whether vegetation, urban infrastructure, water, rocks, bare soil or other. Identifying, delineating and mapping land cover is important for global monitoring studies, resource management, and planning activities. Identification of land cover establishes the baseline from which monitoring activities (change detection) can be performed, and provides the ground cover information for baseline thematic maps. *Land use* describes how a parcel of land is used (such as for agriculture, residences, or industry). Land use applications involve both baseline mapping and subsequent monitoring, since timely information is required to know what current quantity of land is in what type of use and to identify the land use changes from year to year.

The properties measured with remote sensing techniques relate to land cover, from which land use can be inferred, particularly with ancillary data or a priori knowledge. The Government agencies have an operational need for land cover inventory and land use monitoring, as it is within their mandate to manage the natural resources of their respective regions. In addition to facilitating sustainable management of the land, land cover and land use information may be used for planning, monitoring, and evaluation of development, industrial activity, or reclamation. Detection of long term changes in land cover may reveal a response to a shift in local or regional climatic conditions, the basis of terrestrial global monitoring.

Remote sensing methods are becoming increasingly important for mapping land use and land cover for the following reasons:

1. Images of large areas can be acquired rapidly.
2. Images can be acquired with a special resolution that matches the degree of details required for survey.
3. Remote sensing images eliminate the problems of surface access that often hamper ground surveys.
4. Images provide a perspective that is lacking for ground surveys.
5. Image interpretation is faster and less expensive than conducting ground surveys.
6. Images provide an unbiased, permanent data set that may be interpreted for a wide range of specific land use/land cover, such as forestry, agriculture and urban growth.

There are some disadvantages of remote sensing surveys:

1. Different types of land use may not be distinguishable on images.
2. Most images lack the horizontal perspective that is valuable for identifying many categories of land use.
3. For surveys of small areas, the cost of mobilizing a remote sensing mission may be uneconomical.

Note Remote sensing interpretation should be supplemented by ground checks of areas that represent various categories of land cover.

15.3.7 Application in GIS

Remote sensing consists of data acquisition and data analysis. The most important uses of the remotely sensed data are for the analysis of geographical data acquired by digital images and detecting temporal changes. The acquired remotely sensed images, digital data as well as the information extracted from such data is primary data sources of modern Geographic Information System (GIS). The GIS environment permits the synthesis, analysis, and communication of virtually unlimited sources and type of data. The raw data can be incorporated directly as layers in the raster based GIS. The integration of the remotely sensed data with both spatial and non-spatial data stemming from a range of source provides a real-time spatial analysis. The user may then use the analysis made to their decision making process. However, it may be noted that interaction between remote sensing and GIS is two way in nature; the GIS information may be used to aid the interpretation of the remotely acquired imageries.

15.4 GLOBAL POSITIONING SYSTEM (GPS)

GPS system uses the satellite signals, accurate time, and sophisticated algorithms to generate distances in order to triangulate positions anywhere on the Earth. It comprises of 24 satellite constellations that provide the ranging signals and data messages to the user receiving equipment. The ground control network tracks and maintains the satellites in space. A schematic representation of GPS receiver is shown in Fig. 15.2. The GPS system can be of great help in finding a location anywhere on or above the Earth to within about 5 m. Even greater accuracy, usually within less than 1 m can be obtained with corrections calculated by a GPS receiver at a known fixed location Differential Global Positioning System (DGPS).

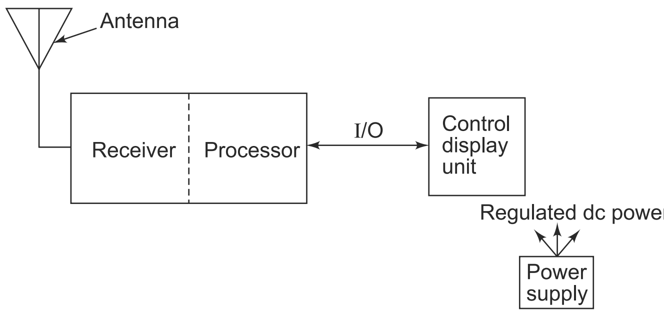


Fig. 15.2 *A schematic representation of GPS receiver*

15.5 APPLICATIONS OF GPS

GPS technology is, nowadays, being used as a tool in most applications at the implementation stage of engineering projects being most sophisticated and accurate. The accuracy and correction factors of the GPS technique can also be applied to give authenticity to geological mapping. In the case of geological mapping with GPS, there is no need to measure horizontal distance and direction as the location of the observation point can be had directly in terms of longitude and latitude. Moreover, the altitude of the observation point can be noted down directly from the GPS reading. However, the accuracy of elevation is not reflected well and fluctuates due to non-uniform satellite signals.

Geological Mapping

The most important application of GPS in geosciences is surveying and mapping. GPS makes it possible for a single surveyor to accomplish in a day what used to take weeks with an entire team of several members, and that too with a much higher level of accuracy. GPS is the only system today to show one's exact position on the earth anytime, in terms of longitudes and latitudes, giving accuracy up to 1 mm to 1 cm. The main advantage of the GPS during geological mapping is the speed of the mapping operation and a large area that can be covered within very less time. GPS includes mapping of

1. Mountains, rivers, forests and other landforms

2. Roads, routes, and city streets
3. Endangered animals, minerals and all natural resources
4. Damage and disasters, trash and archaeological treasures

Geological mapping is the first step in geological investigations. The concept of mapping has altogether changed with the arrival of the modern techniques of investigations like GPS, Geographic Information System and Remote Sensing technique. Apart from geological mapping, some of the other important applications of GPS techniques are as follows:

1. Since global positioning system is most accurate of all the known methods to determine location, it is highly useful for mapping-based operations such as mineral prospecting and exploration, geo-engineering applications such as the construction of tunnel and dam and mapping of ocean floor.
2. GPS techniques are particularly useful in open-pit mining where original, in-progress, and final surveys can easily be performed for quantity estimation and payment purposes.
3. GPS is used for tracking the movement of lithospheric plates, crustal deformation and the geomorphological change with the help of remote sensing satellites.
4. Watershed management projects are being carried out across different parts of the country by using the technique of GPS, being supplemented with GIS and remote sensing technique.
5. Land use pattern of any area can be prepared with high accuracy, if GPS is used along with satellite imagery.
6. GPS are very effective tools for GIS data capture.

15.6 GEOGRAPHIC INFORMATION SYSTEMS (GIS)

A Geographic Information System (GIS) is a specialised data base that preserves locational identities of the information that it records. The subsystems of GIS system are shown in Fig. 15.3. GIS systems can handle both the raster data and vector data. *Vector data* is described as points, lines, surfaces, and volumes that define an object and the object is the entity in GIS system. *Raster data* has the form of a regular grid or cell structure that together defines the object, but each cell is a separate entity in the system. The combination of database and visualization makes a GIS system particularly handy for engineering geology. For example, it should be possible, if the separate items of data necessary for rock mass classification exist, to ask the GIS to produce a particular form of rock mass classification for a specified lithology within a given area.

GIS Systems

Two dimensional (2D) and three-dimensional (3D) GIS systems are prevalent in the country. In 2D systems, the coordinate system in the database can store two coordinates; normally x and y. Properties are then assigned to these coordinates. The 2D systems are basically no more than a map visualisation tool with the capacity to overlay different types of zero- (point), one- (line) and two- (surface) dimensional information. However, their application in engineering geology is limited because it is not possible to represent the subsurface accurately. 2D systems can only handle a projection on a surface of the subsurface boundaries and properties, similar to a map or cross section made by traditional drawing methods. The advantage of the systems is that they are relatively simple and easy to handle.

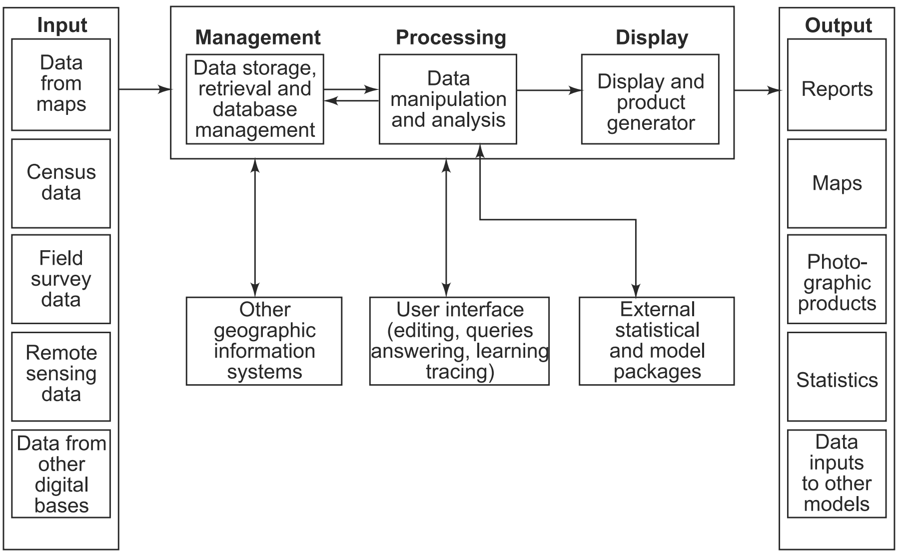


Fig. 15.3 *Component of subsystems of GIS*

In 3D systems, the coordinate system in the database consists of three coordinates, x, y and z. Boundary surfaces can be defined and between the boundaries, properties can be defined for each point leading to the definition of volumes. Manipulation of the properties is similar to that for the 2D systems. The 3D-GIS systems therefore represent the subsurface accurately and precisely.

Four-dimensional systems (e.g. spatial with time) have not yet been made. However, some numerical calculation programs include a 3D-GIS system and can store different realisations of a numerical calculation. This apparently can be considered to be a 4D system, but without 4D data manipulation options, such as property addition.

15.7 APPLICATIONS OF GIS

Geographic Information System has become an indispensable tool for government officials to manage land and natural resources, monitor the environment and formulate economic strategies. In particular, 3D-GIS are able to offer considerable help to the engineering geologist; however, it does not add these qualities in itself. The quality of the output is directly related to the quality of the input and the quality of the manipulation that is done with the data. A full 3D-GIS system is necessary for site-specific analysis in which either an accurate representation of the subsurface is required and/or property distributions are required, or where the geology is more complicated. Another point that should be considered is that GIS software is complex and not always user-friendly. Hence, it is often time consuming to use the programs and this extra time is certainly not always justified for all types of projects. Some of the important applications of GIS are as follows:

15.7.1 Earth Science

- **Applied Geomorphology and Natural Hazards**
  - (a) Hazards, vulnerability and risk analysis
  - (b) Flood hazard analysis using multitemporal satellite
  - (c) Modelling cyclone hazard
  - (d) Modelling erosion potential of catchment
  - (e) Statistical landslide hazard analysis
  - (f) Deterministic landslide hazard zonation
  - (g) Seismic landslide hazard zonation
- **Engineering Geology** Creating an engineering geological database
- **Surface Hydrology**
  - (a) Irrigation water requirement
  - (b) Irrigation area characteristics
  - (c) Determination of peak run-off
  - (d) Morgan approach for erosion modelling
- **Hydro-geology** Assessing aquifer vulnerability to pollution
- **Geology**
  - (a) Remote sensing and GIS techniques applied to geological survey
  - (b) Geological data integration

15.7.2 Land Resources

- **Soil Surveys**
  - (a) The soil erosion issue
  - (b) Soil erosion modelling

Summary

The engineering geological maps are produced from the information collected from various sources such as fieldwork using traditional equipments or GPS, existing maps, aerial photographs, satellite imageries, etc. The remote sensing, global positioning system and geographic information system are introduced. Their applications in engineering geology are presented. With the advancement in technology, the use of these techniques for collecting data precisely and analysing them with accuracy cannot be overemphasized. Applications of GIS where GPS can provide three-dimensional

information about the features such as mapping, watershed prioritisation, land-use planning and management and environmental impact studies are becoming a favourite with the analysts these days.

Terminology

Active Remote Sensing It provides its own source of electromagnetic radiation to illuminate the terrain. Most active systems operate in the microwave portion of the electromagnetic spectrum. Examples of active systems include RADAR, LIDAR, and Laser altimeter.

Active Remote Sensing System A system which utilises human-made sources of energy. For example, taking photographs in dark places with the help of flash bulb.

Electromagnetic Radiation The energy propagated in the form of and advancing interaction between electric and magnetic fields. All electromagnetic radiations move at the speed of light (3×10^8 m/s).

Electromagnetic Spectrum The electromagnetic spectrum is the extent of the electromagnetic energy ranging from cosmic rays, gamma rays, X-rays to ultraviolet, visible and infrared radiation, including microwave energy.

Hydrology The scientific study of the waters of the Earth, especially with relation to the effects of precipitation and evaporation upon the occurrence and character of groundwater.

Image Also called imagery, it is the pictorial representation of a scene recorded by a remote sensing system. Although image is a general term, it is commonly restricted to representations acquired by non-photographic methods.

Image Interpretation The process in which a person extracts information from an image.

Noise The random or repetitive event that obscures or interferes with the desired information.

Passive Remote Sensing It is the remote sensing of energy naturally reflected or radiated from the terrain.

Passive Remote Sensing System A system that uses an existing source of energy. For example, Sun.

Radar An acronym for radio detection and ranging. It is an active form of remote sensing that operates in the microwave and radio wavelength regions.

Exercises

1. (a) Define remote sensing. Discuss briefly the application of remote sensing data in structural and geomorphic studies.
(b) Discuss the role of remote sensing in the site selection of engineering projects.
(c) Discuss the role of remote sensing in the identification of water bodies.

2. (a) Discuss the various applications of remote sensing in Civil Engineering.
(b) How does remote sensing help in conservation and management of mineral resources?

3. Differentiate between the following:
(a) Aerial photograph and satellite imageries
(b) Raster data and vector data

4. Write short notes on the following:
(a) Active and passive remote sensing
(b) Use of remote sensing data useful in land-use planning

5. (a) Describe the application of remote sensing techniques for lithological mapping.
(b) Describe the application of GPS in Earth Science.

6. (a) What is Geographic Information Systems (GIS)? How will it help in engineering geology?
(b) Describe the application of GIS in groundwater studies.

7. How does Global Positioning System (GPS) help to identify geological mapping?

Multiple-Choice Questions

1. In a remotely sensed data of a planet, the presence of hydrous species can be inferred using which region of the electromagnetic spectrum?
(a) Radiowave (b) Gamma
(c) Infrared (d) Visible

2. Which of the following cannot be achieved by remote sensing?
(a) Land use pattern (b) Detection of forest fires
(c) Detection of lineaments (d) Prevention of earthquakes

3. Consider the following with regards to remote sensing system:
1. The sensor used for geologic investigations is active one
2. The sensor used for geologic investigations is passive one
3. The source is Sun

Of the above, the correct statement(s) is(are)
(a) 1 only (b) 1 and 2 only
(b) 2 and 3 (d) all the above

4. Consider the following with regards to GPS system. It consists of
1. satellite constellation
2. operational control system
3. equipment segment

Of the above, the correct statement(s) is(are)

(a) 1 only (b) 1 and 3 only
(c) 2 and 3 (d) all the above

5. Consider the following with regards to input data to a GIS system:
1. from existing maps
2. remote sensing data
3. from GPS

Of the above, the data that can be used for a geological survey is(are)

(a) 1 only (b) 1 and 3 only
(c) 2 and 3 only (d) all 1, 2 and 3

Answers to MCQs

1. (c) 2. (d) 3. (d) 4. (d) 5. (d)

chapter 16

Geological and Geomechanical Laboratory Investigations

16.1 INTRODUCTION

The field and laboratory investigations in engineering geology require meticulous and systematic practical knowledge. For construction of a new civil engineering structure, the detailed study of outcrop of different rocks and their geological and geomechanical properties are needed to ascertain its stability and durability. An attempt has been made to incorporate all the possible field and laboratory investigations in this chapter so as to know the impact of geological and geomechanical properties of different rock formations.

Different types of minerals and rocks require detailed knowledge about their properties. Laboratory investigations consist of proper identification of minerals and rocks adopting different types of techniques. Optical properties of rocks and minerals are determined in the laboratory through an optical microscope. Geological maps and geological models are studied in the laboratory to understand the behaviour of different types of outcrops in field and their interrelationship.

Geomechanical investigations conducted in a laboratory have great bearing on the nature and quality of rocks. The strengths of rocks are measured by different types of experiments for identification and are useful for planning, design and construction of civil engineering projects. In this chapter, the required investigations have been categorized broadly into geological and geomechanical investigations.

16.2 GEOLOGICAL INVESTIGATION

Under the geological investigation, while the identification of different types of minerals and properties of rocks are studied in hand specimens, the optical properties of rocks and minerals are carried out through an optical microscope. Geological maps and geological models are studied in laboratory to understand the behaviour of different types of outcrop in field and their inter-relationship. The procedures to carry out the geological investigations in laboratory are described in sections 16.3 to 16.7.

16.3 IDENTIFICATION OF MINERALS

The physical properties of each mineral include crystal shape, cleavage or fracture, hardness, lustre, colour, specific gravity, streak, tenacity, diaphaneity, reaction to acid, and other less commonly observed properties, such as magnetism, taste, and double refraction. Some properties of same mineral may vary while others may not. For example, the mineral quartz is usually colourless or white, but some specimens may have any colour (due to slight impurities in composition). However, quartz will always scratch glass and fracture conchoidally. Appendix 9 may be referred for identification of minerals. Appendix 10, specifically elaborates the diagnostic properties on the basis of which different minerals are identified.

To identify the minerals as to whether they are rock-forming or ore-forming, the apparatus required are streak plate, hardness box and hand lens.

The following physical properties of minerals are identified in a laboratory:

❑ *Colour*

It is a mineral property in which we observe colour of mineral in reflected light by naked eye. Colour of a mineral is produced by the presence of different types of elements. It also becomes sometime diagnostic property of mineral. For some minerals, it is a very important property. Azurite, for example is always blue, and named for the colour azure, whereas galena is always silvery grey; example being golden yellow colour of chalcopyrite. For most minerals, however, colour should not be used as a significant diagnostic property. Quartz, for example, is usually colourless or white, but may reflect from red (jasper), purple (amethyst) or black (smoky), depending on impurities.

❑ *Streak*

It is the colour of powder produced by the mineral. The streak plate is used to get the colour of minerals which are less hard than streak plate. Streak of mineral is sometimes considered as the diagnostic property of mineral. Many minerals have a different colour when powdered than they do in crystal or massive forms. The streak may be entirely different, or it may be a different shade. Quite a few minerals give a streak that is lighter in colour than the whole crystal or massive pieces. Sometimes when we grind a mineral across a white unglazed porcelain plate, a powdered streak will be left on the plate. The colour of this streak may be very helpful in properly identifying the specimen (especially the metallic or earthy minerals). For example, the mineral hematite is often brown in appearance, but when a streak test is conducted, the powdered streak will be reddish-brown.

❑ *Lustre*

It is the shine of a mineral under reflected light. A brass-yellow pyrite crystal has a metallic lustre. Quartz is said to have a glassy (or vitreous) lustre. The different types of lustre referred to are:

Metallic lustres usually resemble shiny brass or steel. On occasion, though, minerals with metallic lustre will look more like dull metal (like an engine block). Most minerals possessing metallic lustres will also leave a pronounced streak.

Submetallic lustres have the look of a metal that shows dull shine due to weathering or corrosion.

Nonmetallic lustres can be quite variable. With the exception of the earthy minerals, most will leave no streak.

Vitreous lustre that looks like broken glass.

Earthy lustre that looks like a broken brick.

Resinous lustre that looks like resin or shiny cellophane.

Pearly lustre that looks like pearls.

❑ *Cleavage*

This is one of the important mineral properties which is used to identify minerals. It is described the way some minerals break along certain lines of weakness in their structure. The pattern of cleavages is perfect, imperfect, distinct, good, fair, and poor. Mica is a good example of perfect cleavage in one direction and breaking along very closely spaced flat planes that yield thin sheets. Calcite is another good example, breaking along three different planes which yield blocky fragments that look like a rectangular box that has been warped—called a "rhombohedron" or, simply, "rhomb." Galena breaks along three planes at right angles to one another, producing true cubes as fragments.

Cleavage may also be described in terms of crystallographic type, e.g., cubic (galena), octahedral (fluorite), rhombohedral (calcite), prismatic (feldspars) and pinacoidal or basal (micas).

❑ *Hardness*

Hardness denotes how resistant a mineral is to being scratched. It should not be confused with a mineral's overall toughness and mineral's ability to resist abrasion (scratching). A harder substance will scratch a softer one. The relative hardness can be determined by scratching the surface of a crystal or cleavage face with an item of known hardness—and vice versa, scratching the item of known hardness with a sharp point, edge, or grain of the mineral being tested.

■ **By Nail** A mineral can be scratched with a nail to find the relative hardness. The hardness of a mineral is taken as 2.5, if it gets scratched by nail.

■ **By Streak Plate** The mineral can be scratched with a streak plate and relative hardness can be determined. The hardness of a streak plate is 4–5.

■ **By Moho's Hardness Box** The Moho's hardness box has 10 minerals having their hardness from 1–10. The minerals are talc, gypsum, calcite, fluorite, apatite, orthoclase, quartz, topaz, corundum and diamond.

This is now known as *Moho's Scale of Hardness* (Table 16.1) and is almost universally used by all geologists and engineers worldwide.

❑ *Other Objects*

There are few objects which are also used to estimate the hardness of minerals. These objects are shown in Table 16.2.

Table 16.1 *Moho's scale of hardness of minerals*

Hardness	Name of Mineral	Hardness	Name of Mineral
1	Talc (softest)	6	Orthoclase
2	Gypsum	7	Quartz
3	Calcite	8	Topaz
4	Fluorite	9	Corundum
5	Apatite	10	Diamond (hardest)

Table 16.2 *Hardness of other objects*

Hardness	Object	Hardness	Object
2½	Fingernail	6½	Steel file
5½	Window Glass	9½	Carborundum

❑ *Specific Gravity*

Commonly referred to as the weight of a mineral when compared to the weight of an equal volume of water. If a mineral weighs 3 times as much as an equal volume of water, the mineral has a specific gravity of 3. In the field, one can estimate the specific gravity of a mineral by lifting the specimen in hand. After a little practice with various minerals of known specific gravity, such as galena (Sp. gr. = 7.5), pyrite (Sp. gr. = 5) and calcite (Sp. gr. = 2.7), it is possible to estimate the specific gravity of an unknown mineral with reasonable accuracy. If a mineral has less volume and has considerable mass, then specific gravity is considered as high. The specific gravity of a mineral is determined in laboratory and designated into three forms: low, medium and high.

❑ *Fusibility*

It is a measure of how much heat it takes to melt a mineral into a globule, or at least to melt the sharp edges of a sharp splinter and make it round over. Quite a few minerals are easily fusible in the flame of a candle. A small, sharp, splinter held in the flame either melts into a globule or its edges round over easily. So this is a handy test to perform. Minerals such as talc and gypsum are said to have a fusibility of 1 or 2.

❑ *Density*

It is defined as unit mass of mineral per unit volume. A one cm cube of galena is noticeably heavier in the hand than a one cm cube of pyrite. A barite crystal of the same size as other similar glassy crystals is likely to feel noticeably heavier. With a little practice, one can become quite proficient at judging the relative weight of minerals and using that to help establish a sample's identity.

❑ *Diaphaneity*

The way minerals transmit light is referred to as diaphaneity. There are three categories of diaphaneity:

- *Transparent* One can clearly see an image through these minerals, like looking through glass. Some specimens of quartz have transparent diaphaneity.
- *Translucent* Allows some light to transmit through, but not an image. One cannot see anything clearly through these minerals, like looking through a piece of frosted glass. Calcite and fluorite are often translucent.
- *Opaque* No light is transmitted through the specimen. Pyrite and limonite are examples of opaque diaphaneity.

❑ *Tenacity*

The mineral may respond in a variety of ways when placed under stress. This response, or resistance to breakage, is called *tenacity*. The behaviour depends on the rate of stress, the same mineral may respond differently. Thus, sometimes more than one term can be used to describe the tenacity. The types of tenacity are as follows:

- *Elastic* Can be bent and will snap back to its original shape like a rubber band after the deforming pressure is released. Flexible sandstone is the example.
- *Flexible* Can be bent but will not regain its original shape after releasing the deforming pressure, like putty. Selenite gypsum is the example.
- *Brittle* Shatters into fragments, like glass. Quartz and pyrite are the examples.
- *Malleable* Can be smashed into thin sheets without breaking. Gold and native copper are the examples.
- *Sectile* Can be cut with a knife blade into thin shavings, like soap. Talc and native copper are the examples.
- *Ductile* Can be drawn out into wire. Most native metals like copper, gold and silver are the examples.

❑ *Habit*

It is the general appearance a mineral tends to have—whether it is found as blocky crystals, long slender ones, or aggregates of some type. If the crystals are glassy and cubic in shape, it may be concluded that they are not quartz. On the basis of different habit (shape), the minerals are classified as below.

- *Blocky or Equant* Roughly boxlike or ball-like, as in pyrite.
- *Prismatic* Elongated with opposite faces parallel to one another. They may be short and stout, or long and thin as in orthoclase.
- *Bladed* Long thin crystals may be flattened like the blade of a knife as in kyanite.

- *Acicular* Needle-like as in asbestos.

Groups of distinct crystals may be described as following:

- *Druzy* Covering a surface in more-or-less outward pointing clusters of small crystals, such as druzy quartz crystals.
- *Radiating* Growing outward from a point in sprays or starbursts, such as some stibnite exhibits.
- *Reticulated* Interconnected like a lattice or trellis, such as rutile.

Compact parallel or radiating groups of individual crystals may be described as follows:

- *Columnar* Stout parallel clusters with a columnlike appearance, such as some forms of the serpentine.
- *Fibrous* Aggregates of parallel or radiating slender fibers, such as chrysolite.
- *Stellate* Long thin crystals radiating outwards in all directions like a starburst, or in a circular pattern such as astrophyllite.
- *Spherical or Globular* Compact clusters radiating outwards forming rounded ball-like shapes.
- *Botryoidal* Globular or ball-like clusters—like a bunch of grapes—that do not have internally radiating fibers as in chalcedony.
- *Reniform* Radiating compact clusters of crystals ending in rounded, kidney-like surfaces, such as haematite.

A mineral composed of grains is simply said to be granular. Granular minerals may be composed of rounded or semi-rounded grains, or of angular grains.

A few other descriptive terms are as follows:

- *Massive* No crystal structure visible, though the mineral may be crystalline. Some massive minerals may also be granular as in magnesite.
- *Banded* Showing different bands or layers of colour or texture, as in agates and fluorite.
- *Concentric* In rounded masses showing layers around the mass in shells, working outward from the centre, as in some agates.
- *Pisolitic* Roughly pea-size rounded masses as in bauxite.
- *Oolitic* Masses of small round spheres of about the size of fish eggs.

❑ *Other Properties of Minerals*

■ **Magnetism** A few minerals behave as natural magnets; they are able to deflect a compass needle and attract magnets. Magnetite is the most common mineral with this unique property. The mineral pyrrhotite (looks like pyrite but is far less common) is another magnetic mineral. It can easily be distinguished from pyrite and chalcopyrite by its magnetic properties.

■ **Reaction to Acid** Although this test is truly a chemical reaction, it is often utilized in mineral determination. For example, mineral calcite (a common mineral at the Earth's surface) effervesces (fizzes) vigorously when a weak solution of hydrochloric acid (HCl) is dropped on it.

■ **Double Refraction** This property is diagnostic of transparent sections of the mineral calcite. When viewing an object like a line or word through a transparent piece of calcite, the image (light rays passing through it) will be split into two images by the internal structure, and will wobble as the specimen is rotated over the image.

■ **Smell** Some minerals do have a distinctive odour. Minerals containing arsenic for example, have a distinctive odour of garlic when scratched (i.e. arsenopyrite). The mineral sphalerite gives off hydrogen sulphide (smells like rotten eggs) when hydrochloric acid is applied to it, or when rubbed on a streak plate. The mineral sulfur will often have the distinct aroma of matches (which are made with sulphur).

■ **Striations** These are tiny "hairlike" parallel grooves that are sometimes useful in distinguishing plagioclase from potassium feldspar. On plagioclase, they appear on some of the surfaces. Striations on the crystal faces of pyrite help distinguish that mineral from chalcopyrite. These may be identified by a hand lens.

■ **Exsolution/Banding** Usually resembles layers, or wavy or wispy layers of one composition inside another one. Although these bands may look like striations, the striations only appear on the surface of cleavage planes whereas exsolution bands go through the mineral. Exsolution bands should thus appear to go around corners of breaks in the minerals.

■ **Luminescence** The emission of light by a mineral other than the reflected light of the sun or a lamp—the mineral glows due to some other reason. The usual reason is reaction to ultraviolet light, though X-rays and cathode rays may produce it as well. The types of luminescence seen in minerals are *fluorescence* and *phosphorescence*—two closely related phenomena. Fluorescence results from electrons orbiting the mineral's atoms being excited by ultraviolet light; the electrons absorb the energy and jump to higher orbits, then fall back to their original orbits—giving off light in the visible spectrum as they do. Phosphorescence is basically the same thing, but continues for a time after the source of excitation is removed, giving off energy as visible light more slowly. The fact is that most fluorescent minerals exhibit phosphorescence to some extent, though it usually can only be seen carefully. Only a very few minerals phosphoresce well enough to see in a simple darkened room, and the phenomenon is usually rather short-lived. Fluorescence is a useful field identification tool for collectors who have UV lights and a thick blanket when in the field. Where they are present, the UV light can be put to use in identifying them.

16.4 IDENTIFICATION OF ROCK

The rocks are identified by the scientific method based on observations such as its colour, texture, shape, structure and mineral composition, etc. (Appendix 11). Minerals common to the three major rock groups are as given in Table 16.3.

Table 16.3 *Common minerals in rocks*

Igneous	*Sedimentary*	*Metamorphic*
Olivine	Calcite	Garnet
Amphibole (hornblende)	Gypsum	Biotite
Biotite	Quartz	Muscovite
Plagioclase feldspar	Plagioclase feldspar	Plagioclase feldspar
Potassium feldspar	Potassium feldspar	Potassium feldspar
Quartz		Quartz and serpentine

Index Properties

These are the important petrological characters that help description, identification and classification of rocks. These properties are governed by the mode of formation and composition of rock bodies. Following are some of the important index properties helpful in the identification and classification of rocks. These are observed/determined in hand specimens by the naked eye or with the aid of a hand lens (sight identification) and some testing tools like a pen knife, magnet, streak plate and dilute HCl.

(1) Colour (2) Texture
(3) Grain size (4) Mineral composition
(5) Cementing material (6) Specific gravity
(7) Structures (8) Other properties, e.g., acid reaction and magnetism

❑ *Colour*

The colour of rock depends upon the colour of constituent minerals or cementing material and is inferred according to the overall shade.

Since the rocks are composed of different minerals, the colour of the rock is classified as follows:

1. Leucocratic: light in colour
2. Mesocratic: light shades of dark colour, and
3. Melanocratic: dark colour

❑ *Texture*

The mode of aggregation of the component mineral grains, their size, shape and the mutual relationship of the grains is known as texture. The descriptive terminologies for different types of textures in rocks are as follows.

- **Igneous Rocks**
  - *Equigranular Texture* Consists of almost equidimensional grains. Example: Volcanic igneous rocks: Rhyolite and Trachyte
  - *Porphyritic Texture* Consists of large well-developed crystals (phenocrysts) embedded in a crystalline or amorphous groundmass. Examples: Hypabyssal igneous rocks: Diorite.
  - *Graphic Texture* Consists of an intergrowth between irregular grains of quartz and crystalline grains of orthoclase and vice versa.
    Example: Pegmatite.
  - *Ophitic Texture* Consists of small grains of plagioclase enclosed wholly or partially in large dark gray irregular grains of augite.
    Example: Dolerite and basalt
  - *Glassy Texture* Consists of an amorphous surface with or without vesicles and filled with a mineral like zeolite.
    Example: Basalt and rhyolite
- **Sedimentary Rocks**
  - *Rudaceous Texture* Consists of assorted angular or smooth rounded grains. Fragments or pebbles of rocks and minerals cemented together and formed by the mechanical process.
    Example: Breccia and conglomerate
  - *Arenaceous Texture* Consists of sand grains welded or cemented together and characterized by porosity. Bedding is also prominent in sandstone.
    Example: Sandstone
  - *Argillaceous Texture* Consists of fine particles or flakes of clay and mica welded or cemented and frequently laminated. It also gives an odour of wetted soil.
    Example: Shale
  - *Massive Texture* Amorphous or very fine-grained, often bedded and crystallization texture.
    Example: Limestone
  - *Fossiliferous Texture* Consists of fossil which remains cemented together.
    Example: Shely limestone and oolitic limestone

o *Concretionary Texture* Consists of different sizes of hard and soft clots of clay with iron oxide (Fe_2O_3 in red) or alumina (Al_2O_3).
Example: Laterite

- **Metamorphic Rocks**

o *Granulose Texture* Consists of interlocking angular grains or crystalline grains.
Examples: Quartzite and marble

o *Schistose Texture* Consists of flaky, foliated or platy and elongated grains oriented with their longer axes. Frequently twisted or curved.
Examples: Mica schist and chlorite schist

o *Gneissose Texture* Consists of alternate light-coloured granulose and dark coloured schistose layers which are disposed in parallel arrangements. It is characterized by pinching and swelling (Augen structure).
Example: Gneiss

❑ *Grain Size*

This is the diameter of the component mineral grains, expressed as follows in Table 16.4.

Table 16.4 *Classification based on grain size*

Fine-grained	Grain diameter 1 mm or less
Medium-grained	Grain diameter 1 mm to 5 mm
Coarse-grained	Grain diameter 5 mm and above

❑ *Mineral Composition*

It is important to identify minerals in rocks. The mineral after identification can be kept under following two categories.

- **Essential Minerals** Minerals those constitute 90% of the bulk composition of rock are called the essential minerals. Quartz, orthoclase feldspar, plagioclase feldspar, biotite mica, hornblende, augite, olivine, calcite, muscovite mica talc, chlorite and hypersthene are essential minerals.

- **Accessory Minerals** Minerals which are present in small quantities, may or may not be economically valuable, but their presence makes change in physical appearances are called accessary minerals. Magnetite and iron pyrites are the accessary minerals.

Notes

1. In case of glassy volcanic igneous rocks, mineral composition is expressed as equivalent to the corresponding plutonic types.
2. In case of sedimentary rocks, the mineral composition is expressed in terms of constituent sedimentary fragments, grains or particles like pebbles (gravel), sand, clay and fossil remains.

❑ *Cementing Material (Exclusively for Sedimentary Rocks)*

Natural binding material is deposited in between minerals, pebbles, rock fragments and/or fossil remains. The common cementing materials are Fe_2O_3, SiO_2 and $CaCO_3$ (Table 16.5).

Table 16.5 *Determination of cementing material and terminology*

Colour of the Sedimentary Rock	*Cementing Material*	*Description (Terminology)*	*Acid Test*
Pink, reddish brown, brick-red chocolate brown and related red or brown shades	Fe_2O_3	Ferrugenous cement	×
White, grey brown other than reddish brown shades	SiO_2	Siliceous cement	×
White, grey, yellow, green, black and some pink	$CaCO_3$	Calcareous cement	✓

❑ *Specific Gravity*

Specific gravity of minerals present in rock collectively make the overall specific gravity of the rock and is denoted as low, medium and high.

❑ *Structures*

All the rocks have certain structures which are observed by the naked eye in the laboratory and field as well. These structures can be broadly divided into (1) layered and (2) nonlayered structures. Igneous rocks show nonlayered structures while both sedimentary and metamorphic rocks have layered structures. Rockwise structures observed in the laboratory are discussed below.

■ Igneous Rocks

- *Vesicular and Amygdaloidal Structures* Holes, steam cavities in volcanic igneous rocks. Vacant cavities or holes are called vesicles and filled-up vesicles are called amygdaloidal.
  Example: Basalt, pumicite, rhyolite

- *Buoyancy* Floating in water like iceberg—most part submerged, only the tip can be seen floating above water level.
  Example: Pumice

■ Sedimentary Rocks

- *Current or Cross Bedding* Criss-cross series or inclined series in between horizontal beds due to disturbance during deposition by waves and currents. It is observed on the surface of the rocks.
  Example: Sandstone

- *Ripple Marks* Wave like structure due to action of sea waves or wind.
  Example: Sandstone and shale

o *Suncrack Polygons* A network of polygonal cracks. Shrinkage cracks sometimes filled with clay and cakes in between.
Example: Mudstone

o *Graded Bedding* Graduation in grain size from coarsest at bottom and finest at top.
Example: Graded sandstone

❑ ***Metamorphic Rocks***

o *Augen Structure* Eyelike features, white or pink oval-shaped or eye-shaped clusters or grains of quartz and orthoclase (± plagloiclase) surround by dark layers of biotite or hornblende like eyebrows and lashes.
Example: Augen-gneiss

o *Rock Parting* Closely spaced parting planes along which layers of the rocks separate out.
Example: Slate

o *Schistocity* Characterized by layers of foliated minerals.
Example: Mica schist

o *Gneissocity* Alternate layers of granular and foliated minerals.
Example: Gneiss

■ **Other Properties**

o *Acid Reaction* Carbonate rocks readily react with dilute HCl test: similar as in minerals.
Example: Limestone (sedimentary), marble (metamorphic)

o *Magnetism* Some rocks are attracted towards a hand magnet. To test a rock for magnetism, a magnet is placed on the mineral and observed that whether the rock is attracted. Magnetite is the only common mineral that is always strongly magnetic.
Example: Magnetite rich rock

16.5 OPTICAL PROPERTIES OF MINERALS AND ROCKS

Optical properties of non-opaque minerals are studied with a petrological microscope under polarized light. Study of the minerals under the microscope requires an understanding of the construction and working principles of the microscope, together with a background of sound knowledge of optical crystallography. Since the mineral assemblages form the rock, therefore the same procedure is adopted to identify the rocks and their properties as well. The mirror of the microscope is to be tilted to a position which gives the best illumination from ordinary day light (preferably from the northern sky) or light from some artificial source and aperture with an iris diaphragm is usually provided in order to vary the amount of light taken in. The analyzer should be inserted only when the extinction characters, interference colour, twining, etc., are to be studied. Different optical properties have been explained in detail in Chapter 4. The optical properties of some selective minerals and rocks of igneous, sedimentary and metamorphic are given in Appendix 12.

16.6 STUDY OF GEOLOGICAL MODELS

To understand the different geological structures and their relationship with engineering structures, particularly tunnelling, requires the three-dimensional geological models. These models (3D) have been shown in two-dimensional representation. Studies of a few selective geological models have been described below.

Geological Model 1

❑ ***Description***

The geological model 1 shows anticline and syncline. In anticline, the beds are convex in nature and in syncline beds are concave in nature. Oldest beds occur in centre and youngest bed on the periphery in the anticline. Syncline is characterized by the oldest bed in the periphery and youngest in the centre.

■ **Inference** The model represents a simple anticline and syncline fold.

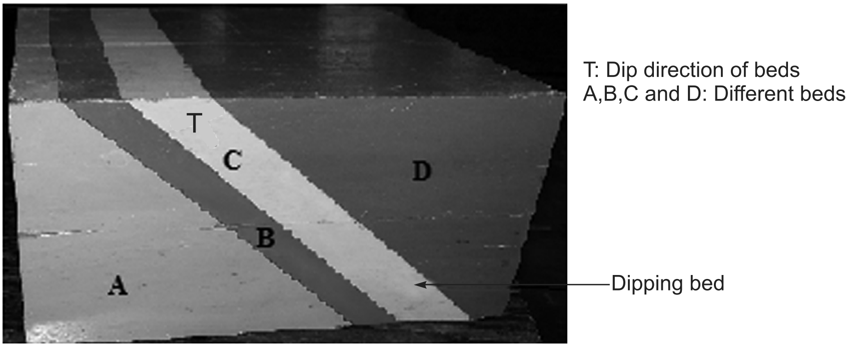
Geological Model 1: *Anticline and syncline folds*

Geological Model 2

❑ ***Description***

The geological model 2 shows simple stratification of different beds having different thicknesses. The beds are dipping towards the south-east direction. The strike of the beds is towards north-east to south-west direction.

■ **Inference** This model reflects the dip and strike of beds.



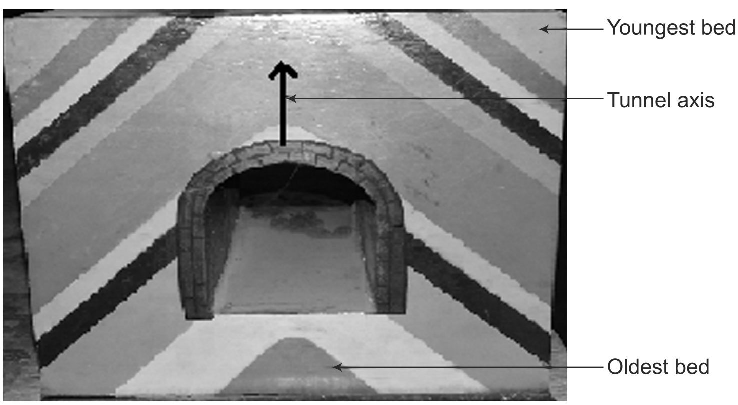
Geological Model 2: *Attitude of beds*

Geological Model 3

❏ *Description*

The geological model 3 reflects the construction of a tunnel in anticline fold. The tunnel axis is parallel to the axial surface of the fold. The tunnel in this condition is not much stable because the tensional stress at crest in anticline fold becomes maximum. Therefore, the cracks are developed at the crest.

■ **Inference** The tunnel is less stable in a given anticline fold.



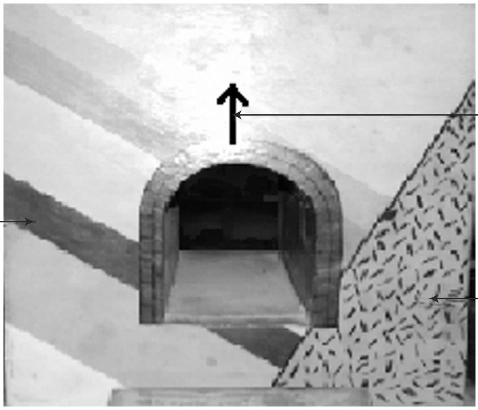
Geological Model 3: *Tunnel in anticline fold*

Geological Model 4

❏ *Description*

The geological model 4 shows the construction of a tunnel in heterogeneous rocks. There are several beds of sedimentary or metamorphic rocks. The igneous rock shown with dotted symbols is situated in the right side of the tunnel. Due to heterogeneity in rock formations, the tunnelling will be difficult and the tunnel will be unstable, particularly at the right limb of tunnel.

■ **Inference** The tunnel in this model is unstable. Therefore, tunnelling should be avoided in such geological conditions.



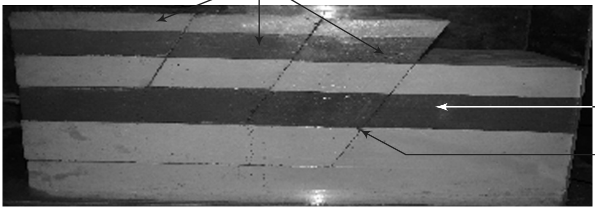
Geological Model 4: *Tunnel in heterogeneous rocks*

Geological Model 5

❑ *Description*

The geological model 5 reflects the development of the faults in simple stratify horizontal beds. Along the fault plane, movement of hanging wall and foot wall has taken place. In this model, the beds have been displaced and moved upward in the hanging wall side.

■ **Inference** Since reverse fault is present, it indicates that the formation of narrow valley will taked place in the area.



Geological Model 5: *Reverse fault in horizontal beds*

Geological Model 6

❑ *Description*

The geological model 6 resembles a fan fold. In the left and right side, sharp anticline and syncline are present, while in the middle, rocks are gently anticline.

In the central part of this model open folds appear while tight fold appears in periphery. Plunging is also visible.

- **Inference** This geological model shows fan folds.

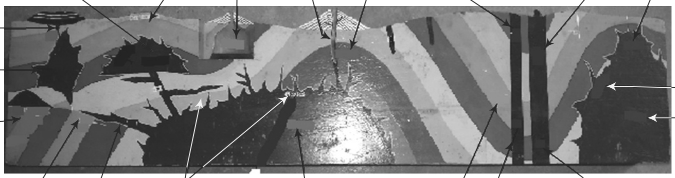
Geological Model 6: *Fan fold*

Geological Model 7

❑ *Description*

The geological model 7 houses most of the geological formations like anticline, syncline and faults. This model also reflects concordant structures like sills and phacolith. The discordant structures like dome, batholiths, chonoliths, apophyse, boss, stock and dykes are dominant and shown in the geological model.

- **Inference** This model shows holistic view of geological forms starting from simple beds to folded beds and then faulted and also characterizes with many igneous activities.



Geological Model 7: *Different forms of igneous rocks*

16.7 PREPARATION OF PROFILE MAP AND GEOLOGICAL CROSS SECTION

To understand the attitude of the beds and different geological structures, existing in three-dimensional shapes, as observed in the field have to be plotted on paper using a suitable scale. In any outcrop, different dip and strike directions are observed as shown in the map. For the preparation of profile map and geological cross section, the procedures are given below.

❑ *Step-by-step Procedure for Drawing a Profile from a Geological Map*

To prepare the profile and cross section of any geological map, the following procedures are adopted.

1. Draw a line across the given point (*X*-*Y*).
2. Observe the intersection point on *X*-*Y* line with the contour line.
3. Select a scale for the *X* and *Y* axes.
4. Mark the actual horizontal distance between the point of intersection on *X*-axis.
5. Draw the height of intersected contour as per selected scale on *Y*-axis.
6. Join all the points with a regular line and it becomes a profile map.

■ **Example 1** Draw the profile map of the geological map of Fig. 16.1(a).

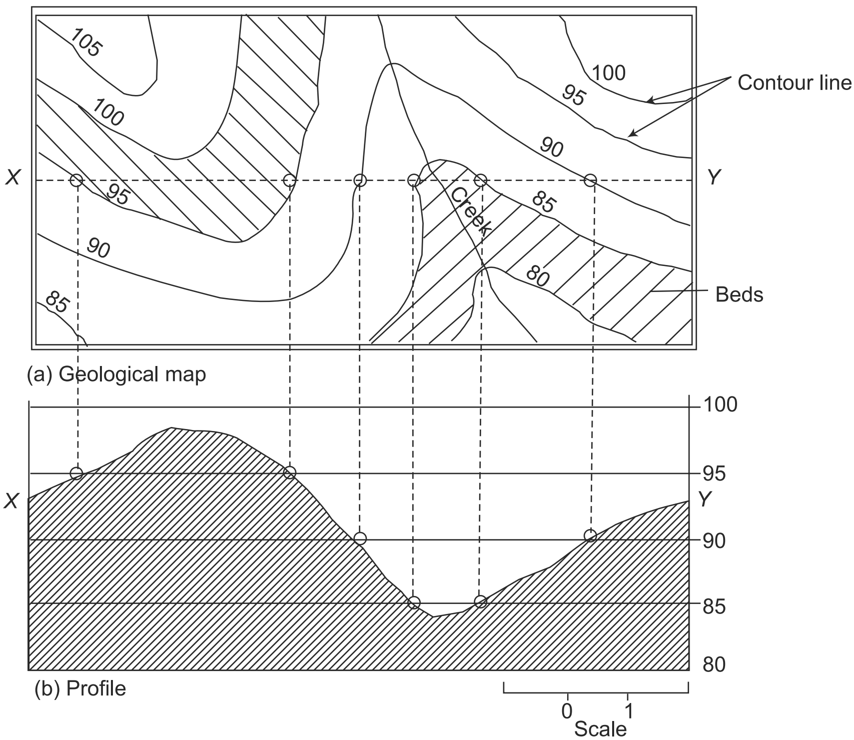


Fig. 16.1 *Geological map and profile*

❑ *Step-by-step Procedure for Drawing Geological Cross Section from a Geological Map*

1. Mark the points on the bedding plane of equal contour height and join them with a line, say strike line-1.

2. Similarly, mark the other point of consecutive contour for the same bed and connect the points with another line, say strike line-2. Strike line-2 should be parallel to strike line-1.
3. The horizontal distance is measured between two consecutive strike lines.
4. Mark the point of intersection of beds with X-Y line and plot them on a profile map.
5. Vertical (contour) interval is divided by the actual distance between strike lines which when multiplied with contour interval i gives the amount of dip

   Amount of dip, $\theta = h/d \times i$

   where, h = Vertical interval
   d = Distance between two consecutive strike lines
   i = Contour interval
6. These amounts of dips for different beds are plotted inside the profile map with the help of a protector.
7. Legends and scale are also made to describe the geological cross section properly.

■ **Example 2** Draw the geological cross section of the given geological map shown in Fig. 16.2.

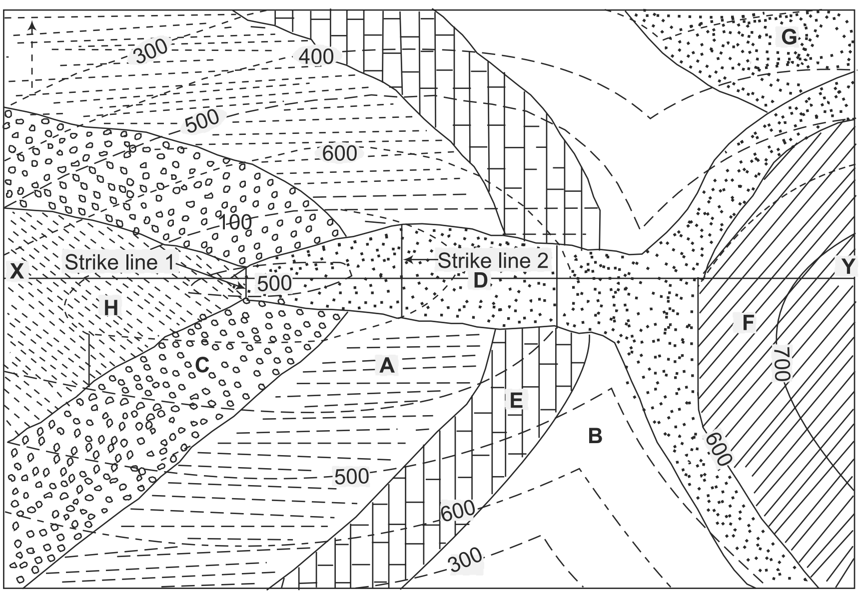


Fig. 16.2 *Geological map*

Amount of dip calculation for different beds

(i) For H bed (d = 1.4)

$$\theta = \frac{1}{1.4} \times 100 = 71.42°$$

(ii) For C bed ($d = 1.45$)

$$\theta = \frac{1}{1.45} \times 100 = 68.96°$$

(iii) For A bed ($d = 1.4$)

$$\theta = \frac{1}{1.4} \times 100 = 71.42°$$

(iv) For E bed ($d = 1.4$)

$$\theta = \frac{1}{1.4} \times 100 = 71.42°$$

(v) For D bed ($d = 2.8$)

$$\theta = \frac{1}{2.8} \times 100 = 35.71°$$

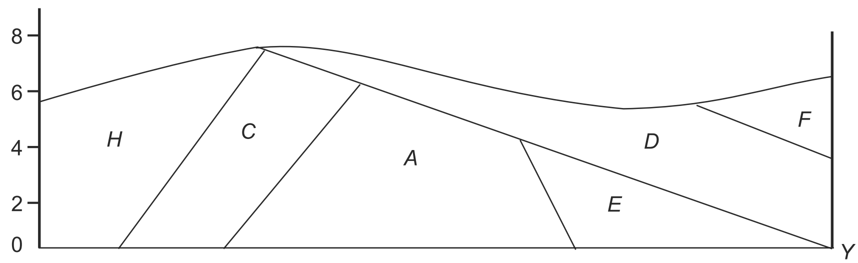


Fig. 16.3 *Cross section of geological map of Fig. 16.2*

16.8 GEOMECHANICAL INVESTIGATIONS

Understanding the physical properties and strength of rocks requires detailed geomechanical investigations. The investigation is carried out in a geotechnical laboratory. Geomechanical properties of different rocks determined in the laboratory are corroborated with geological investigation. Following experiments are conducted in laboratory for proper identification of rocks. To evaluate the geomechanical properties of rock, the rock samples are prepared as per the following procedure.

■ **Objective** To evolve the procedure for the preparation of rock sample to estimate different geomechanical properties in the laboratory.

■ **Equipment Required** The sample represents a small part of rock intended to show the true value of the quality, style, or specimen. The following equipments are required for preparation of samples

- o *Laboratory Coring Drill* A heavy rigid machine with a suitable clamping device for holding the sample should be used for drilling. The drill travel should be sufficient to permit continuous runs of at least 150 mm and preferably 250 to 300 mm without the need for stopping the machine. The feeding arrangement of the drilling machine should be preferably be a constant hydraulic force. Electrical overload breaker should be used to prevent the possible damage due to overload.

- *Diamond Saw* A 400–450 mm dia diamond saw with the provision of mobile trolley to facilitate holding and movement of the sample should be used.

- *Cutting Machine* A precision cut-off machine with 200 mm diameter diamond blade should be used.

- *Lathe* A medium-sized machine shop lathe (if required) should be used for rock working. To reduce the dust nuisance, an extractor may be provided.

- *Lapping Machine* The lapping machine may be a simple rotating iron disc with a minimum of attachments or an automatic one which can handle several specimens simultaneously. Suitable arrangements for clamping the specimens should be provided.

- *Comparator* Comparators should be used for checking the final dimensions of the specimens.

■ **Collection and Storage** The following procedure is used for collection of the sample.

1. Test material should be collected from the field in the form of rough blocks, dressed blocks or drilled cores.
2. The sample should be marked to indicate its original position and orientation with respect to the parent rock mass.
3. Samples intended to be representing intact rock should not be collected from material which has been modified by blasting, contamination or weathering.
4. Samples should be moisture proofed immediately after collection by waxing.
5. Samples should be transported carefully, preferably in a wooden box with sawdust.
6. Samples should be stored in shade to protect them from excessive changes in humidity and temperature.

■ **Shape and Size of Specimens**

The specimen diameter should not be less than ten times the maximum grain size of the rock and preferably more than twenty times the maximum grain size. However, the recommended minimum size is 45 mm and in no case it should be less than 35 mm.

Procedures

- *Coring*
  - (a) Laboratory coring should be done with thin-walled rotary diamond drill bits. The diameter of the core may vary from 35 to 150 mm. The bits should preferably be diamond based.
  - (b) The block should be clamped tightly to a strong base to prevent any movement.
  - (c) Clean water should be used for flushing and cooling the machine. For moisture sensitive rocks, compressed air should be used.
- *Sawing and Cutting*
  - (a) The large diameter diamond saw wheel should be used for heavy sawing. For exact cutting, the precision cut-off machine, if available may be used.
  - (b) For cross cutting, the core should be clamped in a vee-block slotted to permit passage of the wheel. The core should preferably be supported on both sides of the cut to avoid spalling and lip formation at the end.
- *Lathe Grinding*
  - (a) Grinding should preferably be done dry without any cutting or cooling liquids.
  - (b) For edge grinding, a tool-post grinder or a stationary diamond point may be used. The rotation should be fairly slow about 300 rpm.
  - (c) Lathe may also be used for quick grinding of cylindrical samples. Sample should be held directly in the chuck and rotated at 200–300 rpm and the grinding wheel passed against it.
- *Surface Grinding* Surface grinding should be used on broad surfaces of prismatic specimens to achieve closer tolerances.
- *Lapping*
  - (a) Lapping should be done if considered necessary to put a final smooth finish on end surfaces of specimens.
  - (b) The cylindrical specimen should be placed in a steel tube with close tolerance of about 0.05 mm. At the lower end of the steel tube is a steel collar which rests on the lapping wheel.
  - (c) Silicon carbide and aluminium oxide compounds of different grades carried in water should be used as for grinding.

Measurement and Tolerances

(a) Specimen dimensions should be checked during machining with a micrometer or vernier caliper. Final dimensions should be measured nearest 0.1 mm.

(b) The final dimensions and tolerances should be checked with a comparator.

(c) Specimen ends should be flat within 0.05 mm. They should be parallel to each other within 0.002 D, where D is the specimen diameter. The ends should be perpendicular to the axis of the specimen within 0.001 rad (3.5 minutes) or 0.05 mm in 45 mm diameter specimen.

(d) The other surfaces of the specimens (cylindrical surface in the case of cylindrical specimen) should be smooth and free from abrupt irregularities and straight to within 0.3 mm and the dimensions (diameter of cylindrical specimen) of the specimen should not vary by more than 0.2 mm over the length of the specimen.

■ Precautions

(a) The specimens should not be contaminated with oils or other substances at any stage. If contamination cannot be avoided, it should be soaked in a solvent like benzene or acetone and then washed with clean water.

(b) Contamination of external surfaces of finished specimens should be avoided by using gloves for handling and by placing specimens against clean dry surfaces.

Experiment 1

■ Objective To determine water content, porosity and density of rocks.

The procedures for determination of water content, porosity and density of rocks are as follows. Before describing the procedure, few important symbols and protocols are briefly explained.

■ Symbols Used For the purpose, the following symbols should apply:

M_s = Mass of grains (the solid component of the sample)
V_s = Volume of grains
M_w = Mass of pore water
V_w = Volume of pore water
ρ_w = Density of water
V_a = Volume of pore air

■ Formulae

Bulk sample mass $M = M_s + M_w$

Bulk sample volume $V = V_s + V_w$

Pore (Voids) volume $V_v = V_w + V_a$

Water content, $$w = \frac{M_w}{M_S} \times 100(\%)$$

Degree of saturation, $$S_r = \frac{V_w}{V_v} \times 100(\%)$$

Porosity, $$\eta = \frac{V_v}{V} \times 100(\%)$$

Void ratio, $e = \dfrac{V_v}{V_s}$

Density or bulk density or mass density, $\rho = \dfrac{M}{V} = \dfrac{M_s + M_w}{V}$ kg/m^3

Relative density (mass specific gravity), $G_m = \dfrac{\rho}{\rho_w}$

Dry density, $\rho_d = \dfrac{M_s}{V}$ kg/m^3

Dry relative density (dry specific gravity), $G_d = \dfrac{\rho_d}{\rho_w}$

Saturated density, $\rho_{\text{sat}} = \dfrac{M_s + V_v \cdot \rho_w}{V}$ kg/m^3

Saturated relative density (solid specific gravity) $G_s = \dfrac{\rho_s}{\rho_w}$

Unit weight $\gamma = \rho \times g$ N/m^3

■ **Test Sample** A representative sample for testing should generally comprise of several rock lumps, each in order of magnitude larger than the largest grain or pore size. Microfissures of similar size to that of a rock will cause erratic results, their presence should be noted and if possible, the lump size increased or reduced to specifically include or exclude the influence of such fissures.

❑ *Determination of Water Content of a Rock Sample*

■ Apparatus Required

(a) An oven capable of maintaining a temperature of 105 ± 3°C for a period of at least 24 hours.
(b) A sample container non corrodible material including a lid.
(c) A desiccators to hold sample container during cooling.
(d) A balance of adequate capacity, capable of weighing to an accuracy of 0.01% of the sample mass.

■ **Procedure** The following steps are involved in the determination of water content:

1. The container with its lid is cleaned and dried, and its mass *m*, is determined.
2. A representative sample comprising of at least 10 lumps each having either a mass of at least 50 g or minimum dimensions of ten times the maximum grain size, whichever is greater, is selected. To determine in situ water-content sampling, storage and its handling precaution are accounted so that water content remains within 1% of the in situ value.
3. The sample is placed in the container and the mass of the sample plus container determined without lid.

4. The lid is removed and the sample dried to constant mass at a temperature of 105 ± 3°C.
5. The lid is replaced and the sample allowed to cool in the desiccator for 30 minutes. The mass of sample plus container is determined.

■ **Calculation and Reporting of Results** The water content should be calculated from the following formula:

Water content

$$w = \frac{\text{Pore water mass } M_w}{\text{Grain mass } M_s} \times 100$$

$$= \frac{m_2 - m_3}{m_3 - m_1} \times 100(\%)$$

m_1 = Mass in g of the container with its lid at room temperature
m_2 = Mass in g of the container with its lid and the sample at room temperature
m_3 = Mass in g of the container with its lid and the sample after drying

The water content should be reported to within 0.1% stating whether this corresponds to in situ water content, in which case precautions are taken to retain water during sampling and storage should be specified.

❑ *Porosity and Density Determination using Saturation and Caliper Techniques*

This method is for determining the porosity and dry density of rock samples in the form of specimen of regular geometry.

■ Apparatus Required

(a) An oven capable of maintaining a temperature of 105 ± 3°C for a period of at least 24 hours.
(b) A desiccator to hold specimen during cooling.
(c) A measuring instrument such as vernier or micrometer caliper, capable of reading specimen dimensions to an accuracy of 0.1 mm.
(d) Vacuum saturation equipment such that the specimen can be immersed in water under a vacuum of less than 0.8 kPa for a period of at least one hour.
(e) A sample container of non-corrodible material, including a lid.
(f) A balance of adequate capacity for determining the mass of specimen to an accuracy of 0.01% of the specimen mass.

■ Procedure

1. Select at least three specimens from a representative sample of material. Machine each specimen to conform closely to the geometry of a right cylinder or prism. The minimum size of each specimen should either be such that its mass is at least 50 g (for an average density rock, a cube with sides of 27 mm will have sufficient mass) or such that its minimum dimension is at least ten times the maximum grain size, whichever is greater.

2. Repeat the following procedure for each of the specimen in the sample.
   (a) Determine the external dimension and then bulk volume V of each specimen with the vernier calipers. Measurement should be accurate to 0.1 mm. An average of three separate measurements should be obtained for each dimension.
   (b) Place the specimen in an oven and dry at 105 ± 3°C. For this test method, specimens should be of sufficient coherence not to require containers, but these should be used if the rock is at all friable or fissible. The specimen is deemed to be dry when the difference between successive determinations of mass of the cooled specimen at intervals of 4 hours does not exceed 0.1% of the original mass of the specimen.
   (c) Remove the specimen from the oven and place in a desiccator to cool.
   (d) Determine the dry mass, M_s of the specimen.
   (e) Immerse the specimen in a container of water and place the container with the specimen in a vacuum of less than 0.8 kPa for a period of one hour with periodic agitation to remove trapped air.
   (f) Determine the water temperature t to the nearest degree centigrade.
   (g) Remove the specimen from the container and surface dry it using a moist cloth. Care should be taken to remove only surface water and to ensure that no fragments are lost.
   (h) Determine the saturation mass M_{sat} of the specimen.

■ Calculations

(a) For each specimen, calculate the pore volume V_v by the following formula:

$$V_v = \frac{M_{\text{sat}} - M_s}{\rho_w}$$

where ρ_w = Density of water at given temperature

(b) For each specimen, calculate the bulk volume, V, from the external dimensions.

(c) For each specimen, calculate the dry density ρ_d by the following formula:

$$\rho_d = \frac{M_s}{V} (\text{Kg/m}^3)$$

(d) For each specimen, calculate the porosity η by the following formula:

$$\eta = \frac{V_v}{V} \times 100$$

(e) Calculate average values of porosity and dry density for the sample.

■ Reporting of Results

1. Report the individual dry density and porosity values for each specimen in the sample as well as together with the average values of dry density and porosity for the sample. Density values should be given to the nearest 10 kg/m^3 and porosity values to the nearest 0.1%.
2. Report the bulk volume which was obtained by measurement of dimension by caliper or vernier and the pore volume was obtained by water saturation.

3. Record any change in the shape and size of the rock specimen during wetting or drying.

   Record the following general information in the practical notebook.
   a. Project title
   b. Sampling technique and sample identifications number
   c. Dates of sampling and testing
   d. Lithological description of the rock samples

❑ *Porosity and Density Determination using Saturation and Buoyancy Techniques*

This method is applicable for determining the porosity and the dry density of a rock sample in the form of lumps or aggregate of irregular shape-geometry. It may also be applied to a sample in the form of specimens of irregular geometry.

> ***Note*** The method should only be used for rocks that do not appreciably swell or disintegrate when oven-dried and immersed in water.

■ Apparatus Required

1. An oven capable of maintaining a temperature of $105 \pm 3^{\circ}$ C for a period of at least 24 hours.
2. A sample container of noncorrodible material, including an airtight lid.
3. A desiccator to hold sample container during cooling.
4. A vacuum vessel such that the sample can be immersed in water under a vacuum of less than 0.8 kPa for a period of at least 1 ohour.
5. A balance of adequate capacity, capable of weighing to an accuracy of 0.01% of the sample weight.
6. An immersion bath and a wire basket or perforated container, such that the sample immersed in water can be freely suspended from the stirrup of the balance to determine the saturated-submerged weight. The basket should be suspended from the balance by a fine wire so that only the wire intersects the water surface in the immersion bath.

■ Procedure

1. A representative sample comprising at least 10 lumps of regular or irregular geometry, each having either a mass of at least 50 g or a minimum dimension of at least 10 times the maximum grain size, whichever is the greater, is selected. The sample is washed in water to remove dust.
2. The sample is saturated by water immersion in a vacuum of less than 0.8 kPa for a period of at least 1 hour, with periodic agitation to remove trapped air.
3. Determine the temperature t of the water in the immersion bath to the nearest degree centigrade.
4. Determine the mass M_1 of the basket submerged in the immersion bath.
5. Transfer the sample under water to the basket in the immersion bath. Determine the saturated-submerged mass, M_2 of the basket plus sample to an accuracy of 0.01% of the sample mass.

6. Determine the mass M_3 of a clean, dry sample container and lid.
7. Remove the sample from the immersion bath and dry the sample with a moist cloth, care being taken to remove only surface water and to ensure that no rock fragments are lost. Transfer the sample to the sample container and replace the lid. Determine the mass M_4 of the saturated surface dry sample plus container.
8. Remove the lid and place the container with contents and lid in the oven and dry at 105 ± 3°C. The sample is deemed to be dry when the difference between successive determinations of mass of the cooled sample at intervals of 4 hours does not exceed 0.1% of the original mass of the sample.
9. Replace the lid, remove the container from the oven and place the whole in the desiccators to cool for 30 minutes.
10. Determine the dried mass M_5 of container with the oven-dry sample.

■ **Observations** The observations are recorded in a tabular form as below.

Sample No. **Date** **Temperature of Water (t in °C)**			
Determination No.	**1**	**2**	**3**
1. Saturated-submerged mass of basket alone M_1 in kg			
2. Saturated-submerged mass of basket plus specimen M_2 in kg			
3. Mass of the container plus lid, M_3 in kg			
4. Saturated surface dry mass of the sample plus container M_4 in kg			
5. Dry mass of the container with sample M_5 in kg			

■ **Calculations**

1. Calculate the saturated submerged mass M_{sub} of the sample

$$M_{sub} = M_2 - M_1 (\text{kg})$$

2. Calculate the saturated-surface-dry mass M_{sat} of the sample

$$M_{sat} = M_4 - M_3 (\text{kg})$$

3. Calculate the dry mass (grain weight) M_s of the sample

$$M_s = M_5 - M_3 (\text{kg})$$

4. Calculate the bulk volume V of the sample by the following formula:

$$V = \left(\frac{M_{sat} - M_{sub}}{\rho_w} \right) (m^3)$$

5. Calculate the pore volume V_v of the sample by the following formula:

$$V_v = \left(\frac{M_{\text{sat}} - M_s}{\rho_w}\right)(m^3)$$

6. Calculate porosity *n* of the rock sample by the following formula:

$$V_v = \left(\frac{M_{\text{sat}} - M_s}{M_{\text{sat}} - M_{\text{sub}}}\right)\times 100 = \left(\frac{V_v}{V}\right)\times 100$$

7. Calculate the dry density P_d of the rock sample by the following formula:

$$\rho_d = \left(\frac{M_s}{V}\right)(\text{kg/m}^3)$$

■ Reporting of Result

1. Report the porosity and dry density values or the sample to the nearest 0.1% and 10 kg/m^3 respectively.
2. Report that the bulk volume was obtained by a buoyancy technique and that the pore volume was obtained by water saturation.
3. Report the following general information:
   (a) Project title
   (b) Sampling technique and sample identification numbers
   (c) Date of sampling and testing
   (d) Lithological description of the rock samples

❑ *Porosity and Density Determination using Mercury Displacement and Grain Specific Gravity Techniques*

This method is used for determining the porosity and the density of a rock sample in the form of lumps or aggregate of irregular geometry.

> ***Note*** This is particularly suitable if the rock material is liable to swell or disintegrate if immersed in water. The test is also applicable to regularly shaped rock specimens or to coherent rock materials, but other techniques are usually found more convenient in these cases.

■ Apparatus Required

(a) An oven capable of maintaining a temperature of 105 ± 3°C for a period of at least 24 hours. It should have forced ventilation exhausting to outside atmosphere.
(b) Specimen containers of noncorrodible material, including lids.
(c) A desiccator to hold specimen containers during cooling.
(d) A balance of adequate capacity, capable of mass determination to 0.01% of sample mass.
(e) A mercury-displacement volume measuring apparatus capable of measuring specimen volume to 0.5%.
(f) Grinding equipment to reduce the sample to a pulverized powder less than 150 mm in grain size.

(g) A calibrated volumetric flask and stopper.
(h) A constant temperature water bath.
(i) A vacuum apparatus capable of maintaining a vacuum with a pressure of less than 0.8 kPa.
(j) A soft brush of camel hair or of similar softness.

■ Procedure

1. A representative sample is selected comprising of at least ten rock lumps, the shape and size of lumps suiting the capabilities of the volume measuring apparatus. The minimum size of each lump should preferably be either such that its mass exceeds 50 g or such that its minimum dimension is at least 10 times the maximum grain size, whichever is greater. Specimen and swelling of rock should be sampled and stored to retain water content to within 1% of its in situ value prior to testing.
2. Repeat the following procedure for each of the specimens in the sample:
   (a) Brush each specimen to remove loose material and measure its volume V by mercury displacement.
   (b) Carefully remove mercury adhering to the sample, ensuring that no rock fragments are lost.
   (c) Determine the mass M_1 of clean dry container and its lid.
   (d) Place the specimen in the container, replace the lid and determine the mass M_2 of the container plus specimen at initial water content.
   (e) Remove the lid and the specimen which is oven dried to constant mass at a temperature of 105 ± 3°C is allowed to cool for 30 minutes in a desiccator. The mass M_3 of container plus oven dry specimen is determined.
3. Crush all the rock specimens and grind to a grain size not exceeding 150 mm. A number of representative sub-samples of about 15 g of the pulverized material are selected and oven-dried.
4. Determine the mass M_4 of a clean, dry volumetric flask plus stopper to an accuracy of 0.001 g.
5. Fill the flask with a liquid such as kerosene that is nonreactive with the rock.
6. Bring the flask to equilibrium temperature in the constant temperature bath and adjust the liquid level accurately to the 50 cm^3 graduation.
7. Remove the flask from the constant temperature bath, insert the stopper and clean and dry the outside of the flask.
8. Determine the mass, M_5 of the flask and liquid to an accuracy of 0.01% of the total mass.
9. Empty and dry the flask and add the 15 g sample of dry pulverized rock with the aid of a funnel.
10. Determine the mass M_6 of the flask, sample and stopper to an accuracy of 0.001 g.
11. The flask and subsample are evacuated for about 20 minutes and sufficient fluid added to thoroughly wet the sample. Further fluid is then added and

the flask is carefully evacuated to remove air. The flask is replaced in the constant temperature water bath and the liquid level adjusted accurately to the 50 cm^3 graduation.

12. The flask with its contents is allowed to cool and its mass G is determined to 0.01% of the total mass.
13. Steps (5) to (12) are repeated for each sample of pulverized material.

■ Precautions

(a) It is preferable to use self-indicating silica gel as the desiccant.

(b) Metallic mercury is a toxic material and should be handled with considerable care. It is principally absorbed via the respiratory tract as elemental mercury vapour, but there is also some absorption through the gastro-intestinal tract. Spillages are difficult to clean up completely owing to the propensity of the substance, if left, to divide into miniscule globules which can generate unacceptably high levels of mercury vapour in the atmosphere of a room. Tests should be carried out in a fume cupboard to avoid accumulation of vapour, and mercury spillages should be liberally sprinkled with powdered sulphur which takes up the metallic mercury to form the less volatile sulphide.

(c) The density of some non-reactive liquids may vary appreciably. It is essential that a consistent source of liquid is used for each test and that volumes are adjusted in the constant temperature bath.

■ Observations

The observations are recorded in a tabular form as below.

Sample No. **Date**			
Specimen No.	**1**	**2**	**3**
1. Bulk volume of specimen by mercury displacement V in m^3			
2. Mass of dry container plus lid M_1 in kg			
3. Mass of the container and sample plus lid M_2 in Kg			
4. Mass of the container and oven dried sample plus lid M_3 in Kg			
5. Mass of the dry flask (volumetric) and stopper M_4 in kg			
6. Mass of volumetric flask plus liquid stopper M_5 in kg			
7. Mass of flask, stopper and sample M_6 in kg			
8. Mass of flask, stopper and sample liquid M_7 in kg			
9. Wet mass of sample = $M_2 - M_1$ in kg			
10. Dry mass of sample $M_s = M_3 - M_1$ in kg			
11. Mass of water in the sample = $M_2 - M_3$ in kg			
12. Moisture content $w = \left(\dfrac{M_2 - M_3}{M_2 - M_s}\right) \times 100$			

■ Calculations

(a) Calculate the grain density ρ_s of the pulverized rock material by the following formula:

$$\rho_s = \frac{M_6 - M_4}{V_t\left[1 - \left(\dfrac{M_7 - M_6}{M_5 - M_4}\right)\right]} (\text{kg/m}^3)$$

where V_t = Calibrated volume in m^3 of the volumetric flask.

(b) For each specimen in the sample calculate dry density and porosity as follows:

(i) Dry density ρ_d by the following formula:

$$\rho_d = \frac{M_s}{V}$$

(ii) Porosity η by the following formula:

$$\eta = \left[\frac{\rho_s - \rho_d}{\rho_s}\right] \times 100$$

(c) From the values for the individual specimens, calculate the average dry density, porosity, moisture content and grain density for the sample.

❑ *Reporting of Results*

1. Report the individual dry density, porosity and moisture content values for each specimen in the sample, together with the average values of dry density, porosity and moisture content for the sample. Density values should be given to the nearest 10 kg/m^2, porosity values to the nearest 0.1% and moisture content values to the nearest 0.1%.
2. Report that the bulk volume was obtained using a mercury displacement technique, and that the porosity was calculated from grain volume, measurement using a pulverization technique.
3. Record any gross change in the shape or competence of the rock specimens during drying.
4. Record the following general information:
   (i) Project title
   (ii) Sampling technique and sample identification number
   (iii) Dates of sampling and of testing
   (iv) Lithological description of the rock

Experiment 2

■ Objective Determination of hardness of rock by Schmidt impact hammers method.

■ **Apparatus Required**

1. The Schmidt hammers which determines the rebound hardness of rock material. The device is portable and may be used both in the laboratory and field as well (Fig. 16.4).
2. A steel base of minimum weight of 20 kg to which specimen should be securely clamped.

Fig. 16.4 *Schmidt hammer*

■ **Procedure** Prior to each testing sequence, the Schmidt hammer should be calibrated using a calibration test anvil. The average of 10 readings on the test anvil should be obtained. When possible, use larger pieces of rock and not less than 50 mm core or having an edge length of at least 60 mm. The test surface of all specimens should be smooth and flat over the area covered by the plunger. This area and the rock material beneath to a depth of 60 mm should be free from cracks, or any localized discontinuity of the rock mass. Small individual pieces of rocks should be securely clamped to a rigid base to adequately secure the specimen against vibration and movement during the test. The base should be placed on a flat surface that provides firm support. At least 25 individual tests should be conducted of a rock sample. Test locations should be separated by at least twice the diameter of the plunger. Any test that causes cracking or any other visible failure should cause that test and the specimen to be rejected.

■ **Calculations** The correction factor is calculated as

$$\text{Correction factor} = \frac{\text{Specified standard value of the anvil}}{\text{Average of 10 readings on calibration anvil}}$$

The measured test values for the sample should be tabulated in descending order. The lower 50% of the values should be discarded and the average obtained of the upper 50%. This average should be multiplied by the correction factor to obtain the Schmidt rebound hardness.

■ **Results** The following information should be reported:

1. Lithologic description of the rock source of sample, including geographic location, depth and orientations.
2. Type of specimen (core, blasted or broken sample, *in situ*); size and shape of core or block specimen.
3. Date of sampling, date of testing and condition of storage (that is, exposure to temperature extremes, air drying moisture, etc.).
4. Orientation of the hammer axis in the test.
5. Method of clamping sample (V-block or clamps).
6. The Schmidt hardness value.

Experiment 3

■ **Objective** The determination of unconfined compressive strength of rock materials.

■ **Apparatus Required** A suitable loading machine should be used for applying and measuring the axial load to the specimen. It should be of sufficient capacity and capable of applying load at a rate 0.5 to 1 MPa/s. It should be verified and calibrated at suitable intervals depending on the work load. Discs made of steel having a hardness of not less than 30 HRC should be placed at specimen ends. The thickness of the discs should be at least 15 mm. Surfaces of the discs should be ground and their flatness should be within 0.025 mm.

The diameter of the discs should be same as the diameter of the specimen. One of the two discs should incorporate a spherical seat. The spherical seat should be placed on the upper end of the specimen. It should be lightly lubricated with mineral oils. The specimen, the discs and the spherical seat should be accurately centred with respect to one another and the loading frame. The curvature centre of the seat surface should coincide with the centre of the top surface of the specimen.

■ **Test Specimen**

Test material should preferably be a right circular cylinder, although specimen of any shape with regular geometry could be used. The specimen should be tested at a moisture content as close to field conditions as possible.

o *Specimen Dimensions* The samples are prepared in the following manner.

1. The length-to-diameter ratio of cylindrical specimen should preferably be 2 to 3. If ratio is less than 2, usual correction should be applied taking standard slenderness ratio as 2.
2. The diameter of the specimen should be more than ten times the largest mineral grain size in rock, preferably 45 mm, but in no case less than 35 mm.
3. Specimen ends should be flat to within 0.05 mm.
4. The ends should be parallel to each other within 0.002 D, where D is the specimen diameter.
5. The ends should be perpendicular to the axis of the specimen within 0.001 radius (3.5 minutes) or 0.05 mm in a 45 mm diameter specimen.
6. The cylindrical surface should be smooth and free from abrupt irregularities, and straight to within 0.3 mm over the full length of the specimen. The dimensions of the specimen should not vary by more than 0.2 mm over the length of the specimen.
7. The diameter of the test specimen should be measured to the nearest 0.1 mm by averaging two diameters measured at right angles to each other at about the upper height, the mid-height and

the lower height of the specimen. It should not vary by more than 0.3 mm over the length of the specimen.

■ Procedure

1. The ability of the spherical seat to rotate freely should be checked before each test.
2. The surfaces of the two bearing discs and the test specimen should be wiped clean. The specimen should be kept on the lower disc. The axis of the specimen should be carefully aligned with the centre of the thrust of the spherical seat. As the load is gradually brought to bear on the specimen, the movable portion of the spherically seated disc should be adjusted to ensure uniform seating.
3. Load on the specimen should be applied continuously at a constant stress rate such that failure will take place in about 5 to 15 minutes of loading. Alternatively, the stress rate should be within the limits of 0.5 MPa/s to 1 MPa/s.
4. The maximum load on the specimen should be recorded in N within 1% accuracy.
5. The number of specimens to be tested should be determined from practical considerations, but at least five are required to obtain a representative value.

■ Calculation The unconfined compressive strength of the specimen should be calculated by dividing the maximum load carried by the specimen during the test, by the average original cross-sectional area.

■ Result

- The report should give uniaxial compressive strength for each specimen in the sample, expressed to three significant figures, together with the average result for the sample.
- The report of test should include the following information:
  - (a) Number of specimen tested
  - (b) Mode of failure
  - (c) Lithological description of rock
  - (d) Orientation of loading axis with respect to anisotropy, for example, bedding planes, foliations, etc.
  - (e) Source of sample, location, depth and orientation, and date of sampling
  - (f) Storage history and environment
  - (g) Date of testing and type of machine used
  - (h) Specimen diameter and height
  - (i) Moisture content and room temperature
  - (j) Duration of the test and stress rate
  - (k) Other physical properties, such as specific gravity, absorption, permeability, and porosity, citing their method of determination if available
  - (l) Any other observation

Experiment 4

■ **Objective** Determination of tensile strength by indirect tests on a rock sample by Brazilian Test.

■ Preparation of Samples

1. The specimen should be selected to represent a true average of the type of rock.
2. In the laboratory, the rock specimen should be obtained from the same block of rock as on site and drilled in the same direction.
3. In the field, the rock specimen should be obtained from the same bore hole, and geological horizon.
4. The diameter of the disc and ring specimen for the Brazilian test should not be less than 45 mm and thickness should be approximately equal to half of the diameter.
5. The inner radius of the ring in the ring test should be one tenth of the outer radius.
6. The hole in a core for the ring test should be made by drilling on a lathe machine. Then the core should be cut slowly and carefully by a diamond saw to the required thickness.
7. The side of the square rock prism to be used in a line load test should be not be less than 50 mm. The thickness of the square prism should be about 2/3 × side of the square base.
8. The diameter of the core for point load test should be more than 35 mm and not less than 12 mm. Then, length of the core should be more than its diameter.
9. The total number of specimens should be such that at least 10 tests of any one of the types under consideration are possible.
10. The specimen may be air dried in open air for 15 to 20 days after their preparation and then tested.
11. The dimension of the test specimen should be measured to the nearest 0.1 mm. The thickness of the disc ring or prism should be measured at or near the centre.

■ Apparatus Required

1. Two steel loading jaws designed so as to contact a disc-shaped rock sample at diametrically opposed surface over an arc of contact of about 10 degree at failure.
2. Double thickness (0.2 to 0.4 mm) adhesive paper strip with a width equal to or slightly greater than the specimen thickness.
3. A suitable machine for applying and measuring compressive load to the specimens.
4. A spherical seat of the testing machine should be placed in a lock position, the two loading surface of the machine being parallel to each other.

■ Procedure

1. The test specimen should be wrapped around its periphery with one layer of the adhesive paper tape and mounted squarely in the test apparatus such that

the curved plate loads the specimen diametrically with the axis of rotation for specimen and apparatus coincident.

2. Load on the specimen should be applied continuously at a constant rate such that the failure in the weakest rocks occurs within 15 to 30 seconds. A loading rate of 200 N/s is recommended.
3. The maximum load on the specimen should be recorded in newton with 1% accuracy.
4. Where the testing machine is fitted with a force/displacement recorder, a record should be taken during testing so that the load for primary fracture can be determined. If load/displacement recorder is not laboratory on the testing machine, care should be taken by the operator to detect the load at primary failure. At primary failure; there should be a brief pause in the motion of the detector needle. However, the difference between the load of primary failure and ultimate load bearing capacity should be less than 5%.

■ **Calculation** Tensile strength of rock should be calculated from the following expression.

$$q_t = 2P/(\pi Dt)$$

q_t = Tensile strength in MN/m^2
P = Load at failure in N
D = Diameter of test specimen in mm
t = Thickness of test specimen measured at the centre in mm

Experiment 5

■ **Objective** Determination of point load strength of rocks.

■ **Limitation** The testing may be carried out either in the laboratory or in field at the drilling site. These tests are not reliable if point load strength index is less than 1 MPa.

■ **Apparatus** Figure 16.5 shows a schematic diagram of a point-load testing machine.

■ **Sampling** Oven-dried specimens are usually very much stronger than moist ones. At water saturations above 50%, the strength is less influenced by small changes in water content, so that tests in this water content range are recommended unless tests on dry rock are specifically required. All specimens in a sample should be tested at a similar and well-defined water content, and one that is appropriate to the project for which the test data is required. Field testing of chisel-cut samples, not affected by drilling fluids, offers a method for testing at the *in situ* water content. If possible, numerical values should be given for both water content and degree of saturation at the time of testing.

(a) The cores or lumps should be selected so as to represent a true average of the rock type under consideration. The size and shape requirements for diametral, axial, block or irregular lump testing are specified in Fig. 16.6.

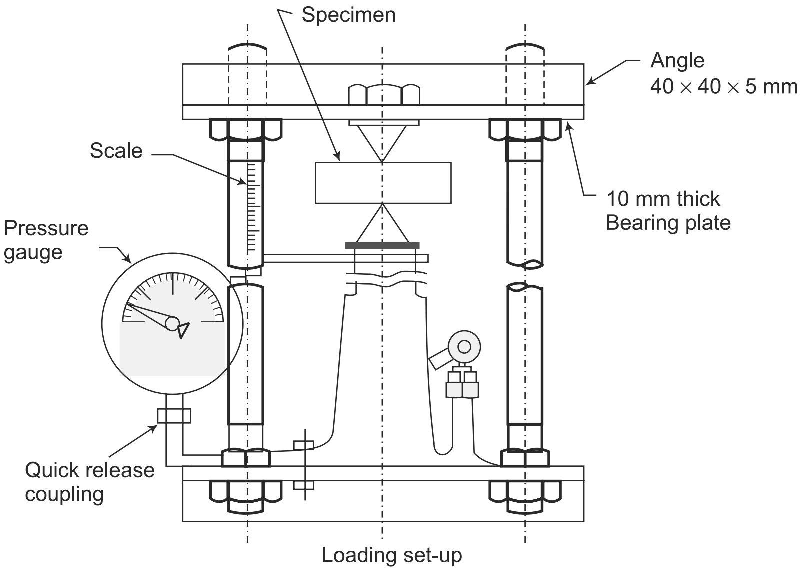


Fig. 16.5 *Point load testing machine*

(b) The diameter of cores should be between 25 mm and 100 mm. The length of the core specimens between ends at their nearest points should not be less than 1.5 times the diameter. However, the ends of core need not be finished.
(c) In the field, these cores should be from the same bore hole, from the same geological horizon and within the shortest possible difference in their elevation in the bore hole.
(d) In the laboratory, these should be from the same block of rock and drilled in the same direction.
(e) As far as strength tests on rocks, point load strength varies with the water content of the specimens. The variations are particularly pronounced for water saturations below 25%.

■ Procedure

(a) The equivalent diameter *D* should be measured in mm.
(b) The specimen core or fragment should be tested at the water content, as obtained in the field and/or after soaking them for 7 days depending on requirement.
(c) The specimen should be held horizontal between the two loading plates.
   i. The correct position of the specimen should be checked first by giving longitudinal rotation to see that the distance between loading points is minimum.
   ii. The correct position of the specimen should also be checked by giving lateral movement to see that the distance between loading plates is maximum.
   iii. The platens should have contact along a single plane of weakness or within the same material in the case of bedded rocks as shown in Fig. 16.7.

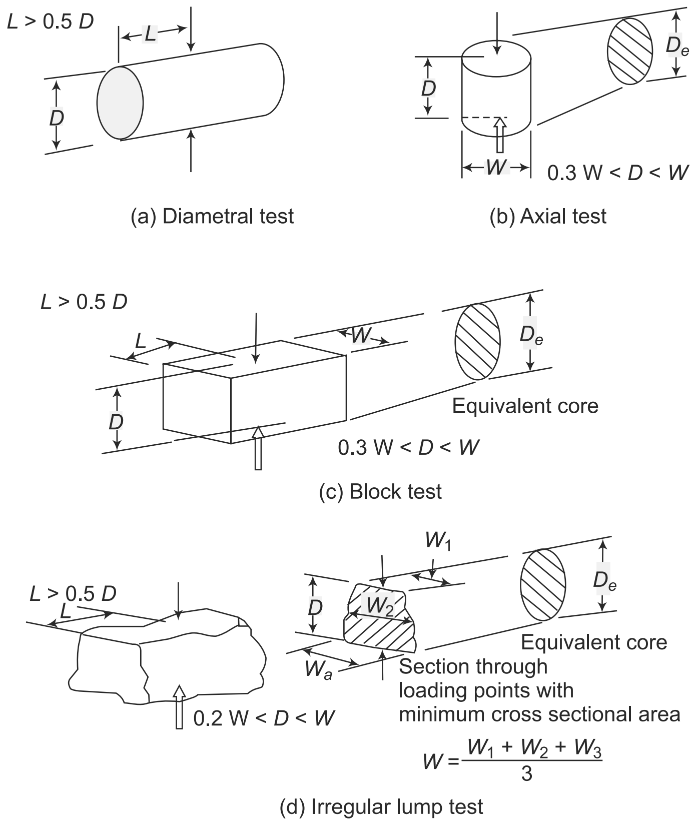


Fig. 16.6 *Specimen shapes under different tests*

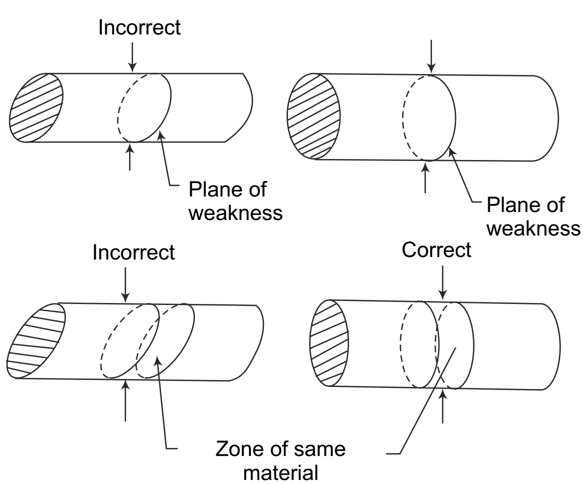


Fig. 16.7 *Orientation of tests specimen for point load test*

■ Diametral Test

1. Core specimens with length/diameter ratio greater than 1.5 are suitable for diametral testing.
2. There should preferably be at least 10 tests per sample and even more, if the sample is heterogeneous or anisotropic.
3. The specimen is inserted in the test machine and the plates closed to make contact along a core diameter, ensuring the distance L between contact point and the nearest free end is at least 0.75 times the core diameter.

> ***Note*** If the ends of the specimens are uneven, the length L. should be measured as the shortest horizontal distance, for many points at the nearest end to the loading point.

4. The distance D between plates contact points is recorded to ±2%. The specimen length L is recorded to ±5%.
5. The load should then be applied to the core specimen such that failure occurs within 10–60 s. and the failure load P is recorded. The test should be rejected as invalid if the fracture surface passes through only one loading point [Fig. 16.8 (d)].
6. Of the four alternative forms of this test, the diametral test and the axial test with saw-cut faces are the most accurate if performed near the standard 50 mm size, and are preferred for strength classification when core is available. Axial test specimens with saw-cut faces can easily be obtained from large block samples by coring in the laboratory. Specimens in this form are particularly suitable when the rock is anisotropic; the direction of weakness planes must be noted.

■ Axial Test

1. Core specimens with length/diameter ratio of 0.3 to 1.0 are suitable for axial testing. Long pieces of core can be tested diametrally to produce suitable length for subsequent axial testing; alternatively, suitable specimen can be obtained by saw cutting or chisel splitting.
2. There should preferably be at least 10 test specimens per sample and even more, if the sample is heterogeneous or anisotropic.
3. The specimen is inserted in the test machine and the plates closed to make contact along a line perpendicular to the core end faces.
4. The distance D between plates contact points is recorded to 2%. The specimen width W perpendicular to the loading direction is recorded to 5%. In axial test, W is equal to the diameter of axial core.
5. The load should then be applied to the specimen such that failure occurs within 40–60 second and the failure load P is recorded. The test should be rejected as invalid if the fracture surface passes through only one loading point [Fig. 16.8(e)].

■ Block and Irregular Lump Tests

1. Rock blocks or lumps of size 50 ± 35 mm and of shape shown in Fig. 16.6 (c) and Fig. 16.6 (d) are suitable for the block and irregular lump tests. The ratio

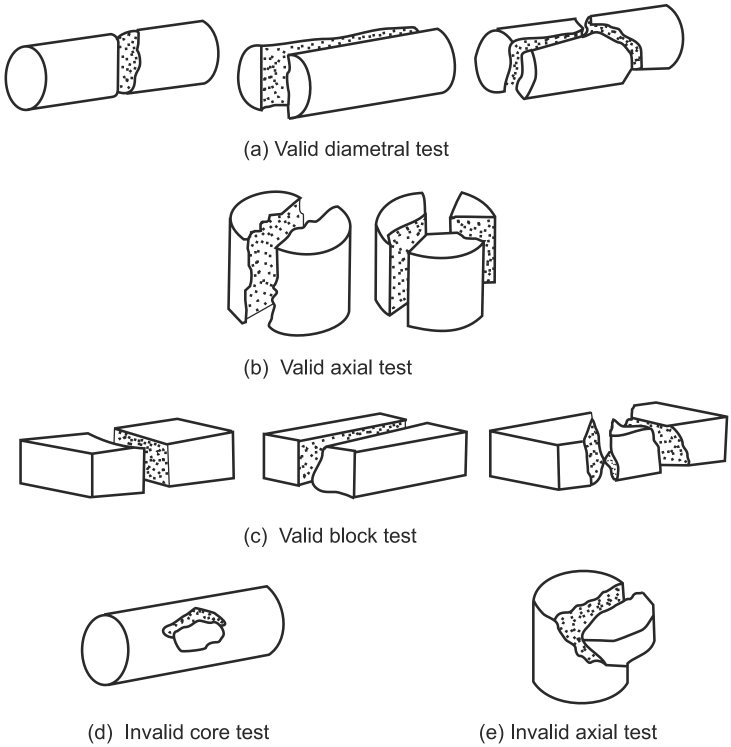


Fig. 16.8 *Typical modes of failures*

of D/W should be between 0.3 and 1.0, preferably close to 1.0. The distance L should be at least 0.5 D.

2. There should preferably be at least 10 test specimens per sample and even more, if the sample is heterogeneous or anisotropic.
3. The specimen is inserted in the test machine and the platens closed to make contact with the smallest dimensions of the block or lump, away from the edges and corners.
4. The distance D between platen contact points is recorded to 2%. The smallest specimen width W perpendicular to the loading direction is recorded to +5%. If the sides are not parallel, then W is obtained from W_1, W_2 and W_3 as given in Fig. 16.6 and, calculated as follows:

$$W = (W_1 + W_2 + W_3)/3$$

5. The load should then be applied to the specimen such that failure occurs within 40–60 second and the failure load P is recorded. The test should be rejected as invalid if the fracture surface passes through only one loading point [Fig. 16.8(d) or Fig. 16.8(e)].

■ Calculations and Size Correction

o *Calculation of Point Load Strength Index of Cores* The point load strength index should be calculated from the following formula:

$$I_s\,(50) = I_s = \frac{P}{\sqrt{(D^{1.5} D^*)}}$$

where $I_s\,(50)$ = Point load strength index (for the standard core size) in MN/m^2

P = Failure load in N

D = Core diameter in mm

D^* = Standard core diameter = 50 mm

The mean value of strength index should be determined by systematically deleting two highest and lowest values from the ten or more valid tests and calculating the mean of the remaining values. If significantly fewer specimens are tested, only the highest and lowest values are to be deleted and the mean calculated from those remaining.

o *Uniaxial Compressive Strength* The uniaxial compressive strength of rock may be predicted from the following correlation:

$$q_c = 22\, I_s(50)$$

where q_c = Uniaxial compressive strength in MN/m^2, and

$I_s(50)$ = corrected point load strength.

o *Point Load Lump Strength Index Test* This test should be conducted on lump pieces of rock material. The depth of the specimen D between the points should be less than the width of the specimen, but should be more than one-third width of the specimen. Point load lump strength index I_L is calculated by the formula:

$$I_L(50) = P/[(DW)^{0.75}\sqrt{D^*}]$$

P = peak load in kgf at failure,

DW = Cross-sectional area of the fractured surface in cm^2 or the minimum cross sectional area,

$I_L(50)$ = Point load lump strength index in MN/m^2, and

D^* = standard size of lump = 50 mm

o *Uniaxial Compressive Strength vs Point Load Lump Strength Index* Uniaxial compressive strength q_c is related to point load lump strength index by:

$$q_c = 15 \times I_L(50)$$

Notes

1. The above correlation is valid for unweathered rocks only.
2. The strength anisotropy index $I_a(50)$ is used to test the anisotropic and laminated rock materials. It is the ratio of mean $I_s(50)$ values measured perpendicular and parallel to planes of weakness that is the ratio of the greatest to the least point load strength indices. $I_a(50)$ assumes values close to 1 for quasi-isotropic rocks and higher values when the rock is anisotropic. Commonly, the shortest dimension of naturally occurring anisotropic rock lumps is perpendicular to the weakness planes.

■ Precautions and Limitations

(a) When a rock sample is shale, bedded, schistose or otherwise observably anisotropic, it should be tested in directions which give the greatest and least strength values, which are in general parallel and normal to the planes of anisotropy.

(b) If the sample consists of a core drilled through the weakness planes, a set of diametral tests may be completed first, spaced at intervals which will yield pieces which can then be tested axially.

(c) Best results are obtained when the core axis is perpendicular to the planes of weakness, so that when possible the core should be drilled in this direction. The angle between the core axis and the normal to the weakness planes should preferably not exceed 30°.

(d) For measurement of the I_s value in the directions of least strength, care should be taken to ensure that load is applied along a single weakness plane. Similarly, when testing for the I_s value in the direction of greatest strength, care should be taken to ensure that the load is applied perpendicularly to the weakness planes.

(e) If the sample consists of blocks or irregular lumps, it should be tested as two sub-samples, with load applied first perpendicular to, then obtained when the platens make contact along a single plane of weakness.

■ Report of the Test Results

- The corrected mean value of the point load strength index $I_s(50)$ or I_L should be reported in MN/m^2.
- Identification of the sample, location, depth and date of sampling and testing should be reported.
- Core or fragment size, length L and width W in mm should be indicated along the observable planes of weakness.

Summary

It is necessary to understand the effects of geological and geomechanical properties of rocks on the civil engineering structures. These properties are assessed or/and determined in field and laboratory. The study of minerals and rocks in hand specimens for their important physical properties has been elaborated in this chapter. Fine-grained rocks are not studied well in hand specimens by naked eyes, while optical studies are of utmost important for mineral identification and their arrangements in rock. These have been dealt in detail with examples given in different appendices.

To make the reader acquainted and have deep knowledge about the interrelationship between geological structures and their properties, different geological models have been presented in the chapter. Preparation of profile map and geological cross sections representing the observations obtained from the field regarding geological structures and rocks have been elaborated.

The chapter presents geomechanical properties like density, porosity, water absorption, uniaxial compressive strength and tensile strength, and procedure for their determination

have been explained. These properties are required to ascertain the quality of rocks and their suitability for foundations of structures and other construction purposes.

Exercises

1. List the common apparatus/equipment which are useful for conducting the geological practicals.

2. Describe the physical properties of hornblende, calcite, orthoclase and chalcopyrite minerals.

3. Explain the optical properties of the following minerals:
(a) Orthoclase
(b) Calcite
(c) Biotite
(d) Quartz

4. What are the important physical properties of the following rocks in hand specimens? Also state the criteria to identify them.
(a) Granite
(b) Basalt
(c) Sandstone
(d) Quartzite
(e) Marble
(f) Limestone

5. What are the different important optical properties required for the identification of rocks?

6. Describe the optical properties of basalt and granite.

7. Write short notes on the following:
(a) Moho's scale of hardness
(b) Optical microscope
(c) Geological models
(d) Schmidt hammer

8. Differentiate between the following.
(a) Geological profile map and geological cross section map
(b) Compressive strength and tensile strength determination
(c) Polarized light and non polarized light

9. Explain the procedure to prepare a geological cross section from any given geological map.

10. Briefly describe the procedure of sample preparation for the determination of geomechanical properties.

11. Draw the profile of the geological map and draw geological cross sections along the *XY* line of Fig. 16.9. Also determine the amount of dip of given beds.

12. Draw the profile and geological cross sections along *XY* line of the geological map of Fig. 16.10. Also determine the amount of dip of given beds.

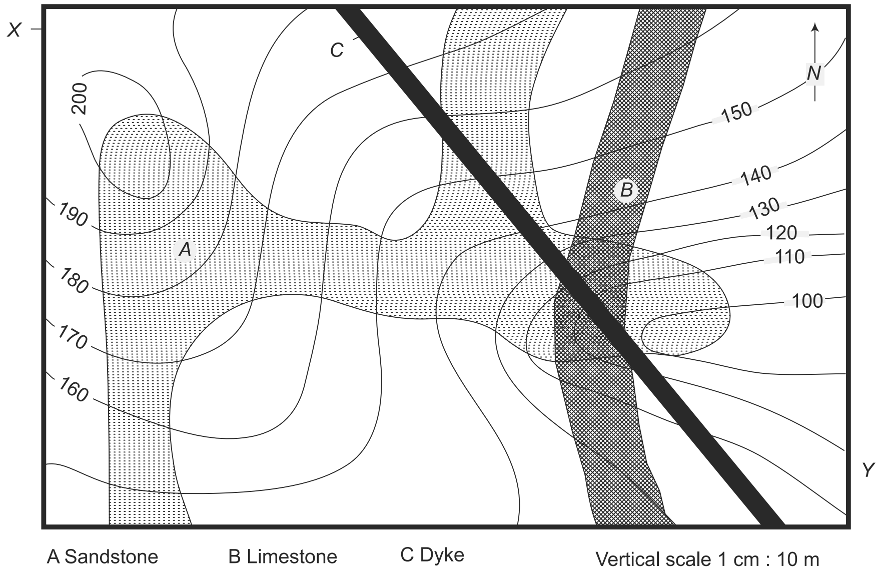


Fig. 16.9 *Geological map*

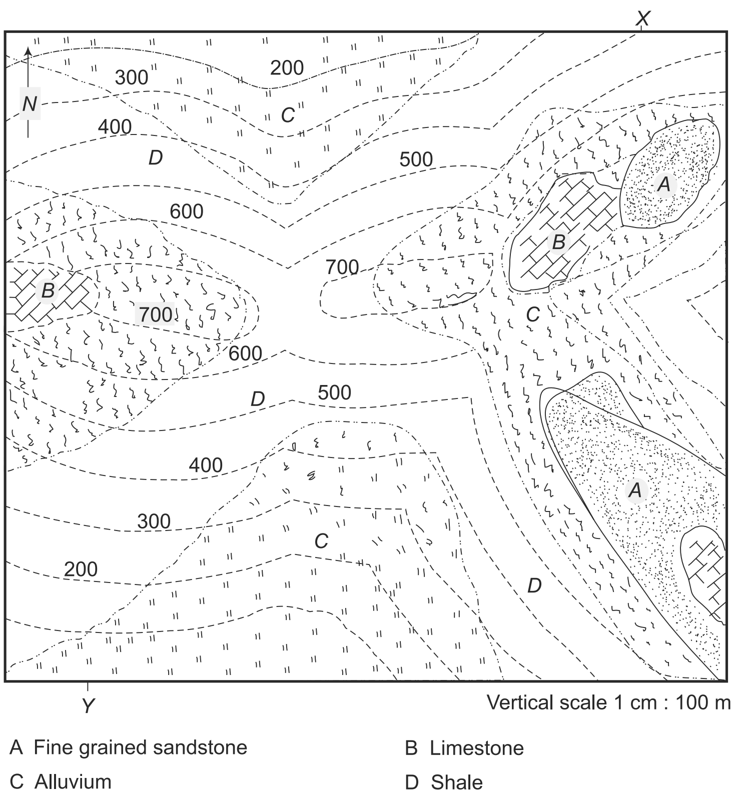
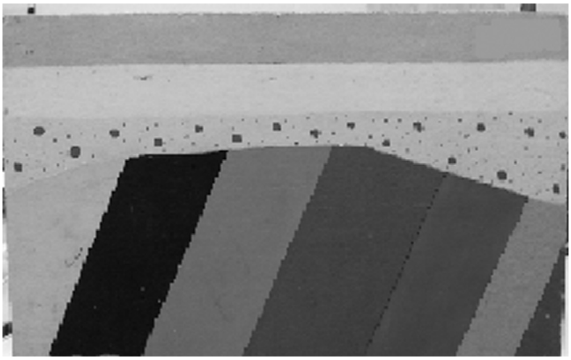


Fig. 16.10 *Geological map*

13. Write down the description of given geological model 1 and also provide the inference.



Geological Model 1

14. Write down the description of the given geological model 2 and explain about the stability of tunnel.

Geological Model 2

Multiple-Choice Questions

1. The dip of beds is calculated from a geological map with the help of
   (a) contour height
   (b) slope beds
   (c) distance between strike line
   (d) distance between strike line and contour interval

2. Basalt is differentiated with gabbro under optical microscope by its
   (a) grain size and texture (b) ground mass
   (c) mineral composition (d) shape of crystals

3. Sandstone is differentiated with quartzite in hand specification by its
   (a) texture (b) mineral composition
   (c) compactness (d) compactness and texture

4. Granite is differentiated with gneiss under optical microscope by
   (a) texture
   (b) mineral composition
   (c) texture and mineral composition
   (d) shape of crystals
5. Geological model explains the behaviour of the rock with different geological structures to explain the
   (a) stability of structure
   (b) physical appearance
   (c) interrelationship
   (d) stability and interrelationship
6. Geological structure appears as a fold in the geological cross section when beds have
   (a) opposite dip direction
   (b) dipping in same direction
   (c) many dips in any direction
   (d) dipping vertically
7. Schimidt hammer is used to estimate
   (a) stress of rock
   (b) hardness of rock
   (c) strain of rock
   (d) brittleness of rock
8. Use of magnet in a geological laboratory is to estimate the
   (a) hardness of mineral and rock
   (b) magnetic properties of mineral and rock
   (c) compactness of mineral and rock
   (d) durability of mineral and rock
9. Geological cross section is useful to
   (a) know the outcrop
   (b) know the outcrop and its behaviour
   (c) know the atitute of beds
   (d) understand the discontinuity
10. Uniaxial compressive strength of rock is determined to understand about
   (a) mineral composition
   (b) compactness of rock
   (c) density
   (d) porosity of rock

Answers to MCQs

1. (d) 2. (a) 3. (d) 4. (c) 5. (d) 6. (a) 7. (b) 8. (b) 9. (b) 10. (b)

Viva–Voce Questions with Answers

Q1. What can be the geological reasons for the failure of major engineering structures, for example dams and bridges?

These structures may fail if at the time of site selection, the lithological characteristics and geological structures have not been properly studied.

Q2. What are the various methods for dating rocks? Which is the most suitable one?

There are methods like biological dating (on the basis of fossils), mineralogical dating (on the basis of particular minerals) and radiometric dating (on the basis of radio isotopes). The most suitable method is the radiometric method.

Q3. How are earthquake waves helpful in determining the interior of the Earth?

They are helpful because the velocity of P-waves can be used to determine the types of material and their density. This helps ascertain the discontinuities inside the Earth.

Q4. What are the different parts of the interior of the Earth?

These are the crust, mantle and core.

Q5. Where and how is magma formed?

Magma is formed in asthenosphere due to partial melting of the crust.

Q6. What is the role of volatile matters present in magma?

Volatile matters facilitate the magma to blow out on the Earth's surface and form low-density rocks.

Q7. How do we know that magma is not originated in the core?

Presence of many volatile gases indicates that they have not been formed in the core.

Q8. Why is quartz the most abundant mineral in the Earth's crust?

It is so because most of the Earth's crust is made up of SiO_2.

Q9. What is the diagnostic property of a mineral?

The properties by which minerals are easily distinguished with those of other minerals are known as diagnostic properties.

Q10. How will you differentiate calcite mineral from quartz mineral in a hand specimen?

The two minerals can be differentiated by observing hardness and cleavage. Quartz has a hardness of 6 and calcite has 3 under Moho's scale. Quartz has no cleavage but calcite has three sets of cleavages.

Q11. The crystallization of quartz takes place in which crystal system?

Quartz crystallizes in the hexagonal crystal system.

Q12. The mica group of minerals are characterized by platy minerals. To which crystal system does mica belong?

It belongs to the hexagonal crystal system and sheet structure.

Q13. What is the most important difference between pyroxene and amphiboles group of minerals?

Pyroxene forms the single-chain silicate structure with two sets of cleavage (87° and 93°), while amphiboles form the double-chain silicate with two sets of cleavage (124° and 56°).

Q14. What are ore-forming minerals and rock-forming minerals? What is their importance?

Minerals which are economically exploitable are called ore-forming minerals. These minerals are generally utilized to extract metals, while the aggregation of minerals forming rocks are known as rock-forming minerals. Theses do not have any economic value.

Q15. What is the benefit of optical studies of a mineral under a thin section?

The physical properties like mineral composition and cleavage, etc., which are not clearly visible by the naked eye, can be well studied under an optical microscope.

Q16. Name some important igneous rocks used in civil engineering projects.

Granite, basalt, gabbro, rhyolite and dolerite are commonly used as building stone, and rock aggregate in civil engineering projects.

Q17. Why do acidic igneous rocks have lower specific gravity than basic igneous rocks?

It is so because acidic igneous rocks are composed of mainly minerals like quartz and feldspar which have low specific gravity, while basic igneous rocks are composed of minerals like olivine, hornblende and plagioclase having high specific gravity.

Q18. What are the parameters that control the classification of igneous rocks?

The controlling parameters are mineralogical composition, chemical composition and depth of formation.

Q19. How are igneous rocks distinguished from metamorphic and sedimentary rocks in a hand specimen?

Igneous rocks do not have layering and are generally characterized by random arrangement of mineral grains.

Q20. Which rock is more suitable as a foundation for construction of dams and why?

Quartzite is the most suitable rock for foundation of a dam because it has the highest bearing capacity.

Q21. Narrate the important sources for the formation of igneous and sedimentary rocks.

Igneous rocks are formed from the magma after solidification while sedimentary rocks are formed from disintegration of either sedimentary or metamorphic rocks.

Q22. Why is limestone not used as building material?

Because it contains $CaCO_3$ which disintegrates upon coming in contact with water.

Q23. How do optical studies of fine-grained rocks help us know about the alkali aggregate reaction?

By identifying the presence of silica-rich minerals under the microscope, we can determine the probability of alkali aggregate reaction.

Q24. How are folds developed?

Folds are developed due to compressional forces in the ductile rocks.

Q25. In which types of rocks, folds are generally observed and why?

Folds are mostly observed in metamorphic and sedimentary rocks due to their higher plastic limits.

Q26. How are folds identified in a field?

These are identified by repetition of beds and opposite dip direction in the traverse taken along the strike direction.

Q27. Which part of the fold has maximum tensile strength?

Maximum tensile strength in a fold lies at the hinge point.

Q28. How are the faults recognized in a field?

While traversing along the strike direction, the beds are found not repeating and these dip in the same direction. Presence of angular breccia also indicates a fault.

Q29. What is a reverse fault? Give an example of a reverse fault in India.

When the hanging wall moves upwards and the footwall downwards, the fault is known as a reverse fault. The Narmada valley is a major example of a reverse fault.

Q30. What is a thrust fault and where do these exist dominantly in India?

A low-angle ($< 10°$) reverse fault is known as thrust fault. It is commonly observed in the Himalayan region.

Q31. With which type of faulting are earthquakes mostly associated?

Earthquakes are associated with reverse fault and are more reactivated along the thrust fault.

Q32. How is remote sensing useful in geology?

It reveals about the topographical features and geological structures like faults and joints in inaccessible areas.

Q33. How is earthquake zonation made? How many zones have been identified in India?

Earthquake zonation is done on the basis of intensity and magnitude of earthquakes. There are four zones in India.

Q34. Why are tunnels not constructed in faulted regions?

It is so because a faulted region is not stable and the strength of rocks falls down to a very low value. Therefore, construction of tunnels is not recommended in faulted regions.

Q35. In what conditions are tunnels stable?

Tunnels are most stable when the beds are horizontal and are free from fractures and joints.

Q36. What are suitable geological conditions for selection of a dam site?

Upstream dip direction of beds, freedom from fault and joints and presence of stronger rocks having higher bearing capacity are the most suitable conditions.

Q37. In which part of a fold is the construction of a dam safest and most stable?

It is safest and most stable if constructed at the limb of the fold facing the upstream side.

Q38. Explain the nature of rocks in scouring of a dam.

The weathered rocks existing at the dam site indurate at a faster rate and erosion of underlying rocks take place.

Q39. How do you identify unconformity in outcrops?

An abrupt change in lithology and presence of conglomerates on the top of the bed indicates the presence of unconformity.

Q40. How are shale and slate rocks differentiated in a hand specimen?

In shale, there is a soil-like odour but in slate it is missing, otherwise most of the properties may be similar in a hand specimen.

Q41. How are schist and gneiss types of rock differentiated in a hand specimen?

In schist, a layering of flaky or platy minerals is present, while in gneiss, alternate layers of quartz and platy minerals like mica and chlorite are present.

Q42. How do we differentiate between granite and basalt?

Granite is characterized by coarse-grained minerals like quartz and feldspar, while basalt has fine-grained minerals like augite, plagioclase and zeolite.

Q43. By which method are the textures and micro-textures of rocks best studied?

These are best studied under an optical microscope and the method is known as optical mineralogy.

Q44. Which geophysical method is most suitable to explore groundwater?

The resistivity method is the most suitable geophysical method to explore groundwater and its quality as well.

Q45. Which geophysical method is most suitable to explore deposits of oil and natural gas?

The seismic method is the most suitable method to search for deposits of oil and gas.

Q46. Why is Rock Quality Designation (RQD) considered one of the most important criteria to select a site for tunnels?

Because, it consists of most geological and geo-mechanical properties.

Q47. Which instrument is used to measure the dip and strike of rock beds in outcrops?

The Brunton Compass is used to measure the dip and strike of rock beds in outcrops.

Q48. What is the relationship between dip and strike?

Strike is perpendicular to the true dip.

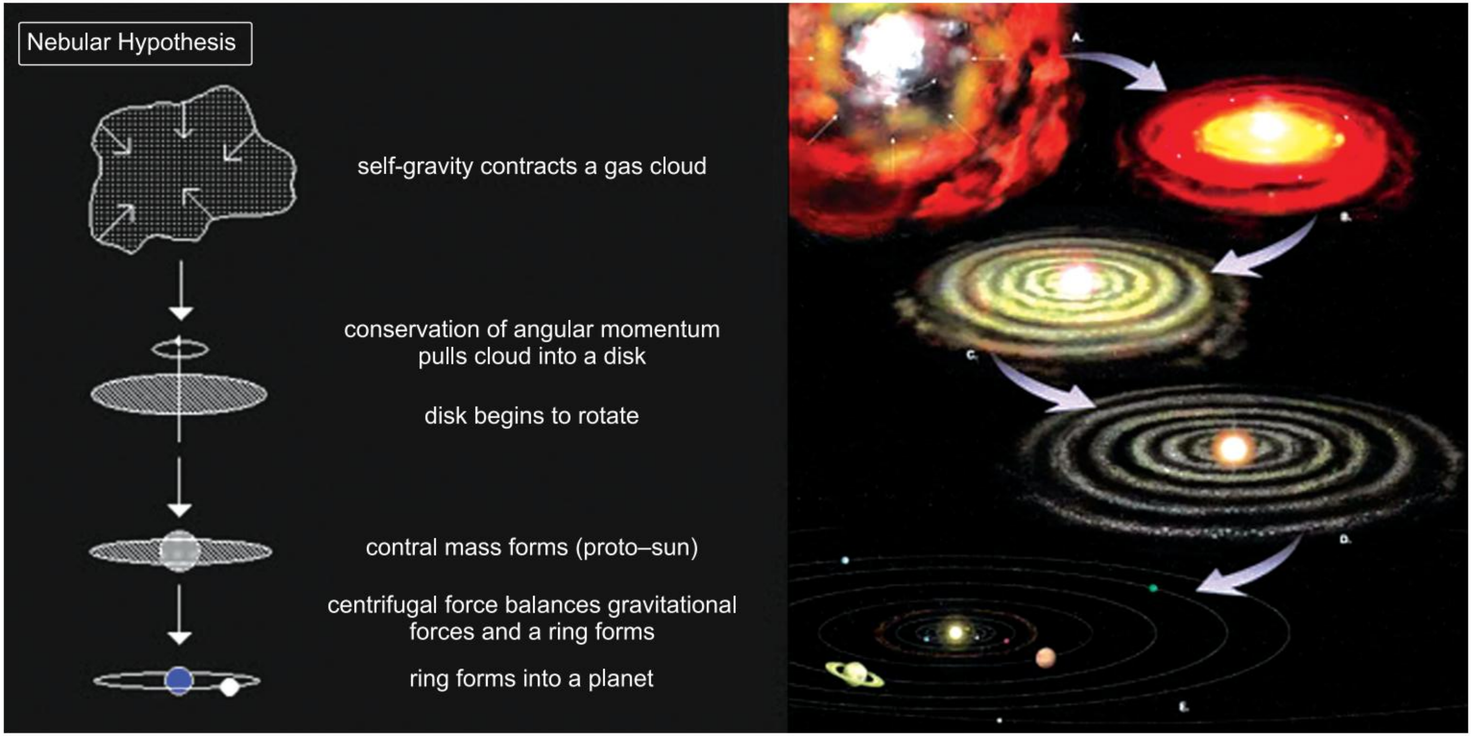
Q49. Explain true dip and differentiate it from apparent dip.

True dip is maximum inclination of a particular bed with the plane of strike. Apparent dips can be many in number for a particular bed. An apparent dip is always less than the true dip.

Q50. Why is a traverse in field generally taken along the strike direction of a rock bed?

Because the nature of bed varies maximum along strike direction.

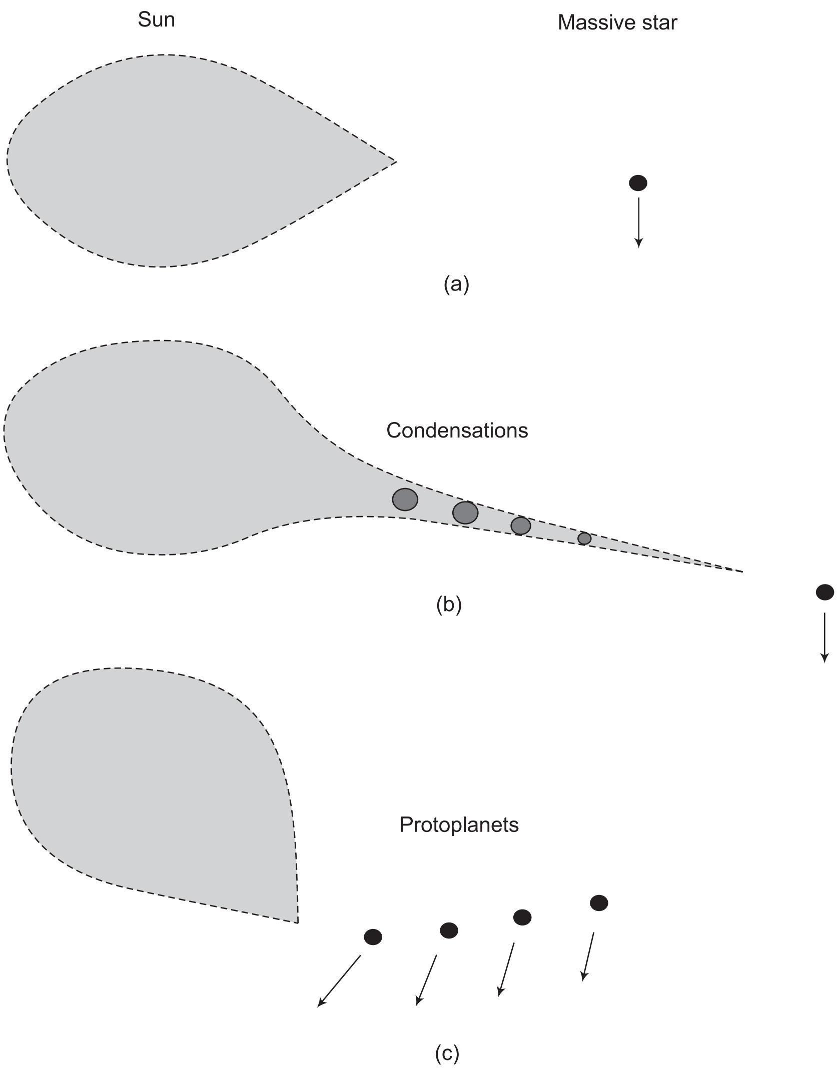
PLATE – 1



http://fineartmeetsscience.blogspot.in/

Nebular Hypothesis

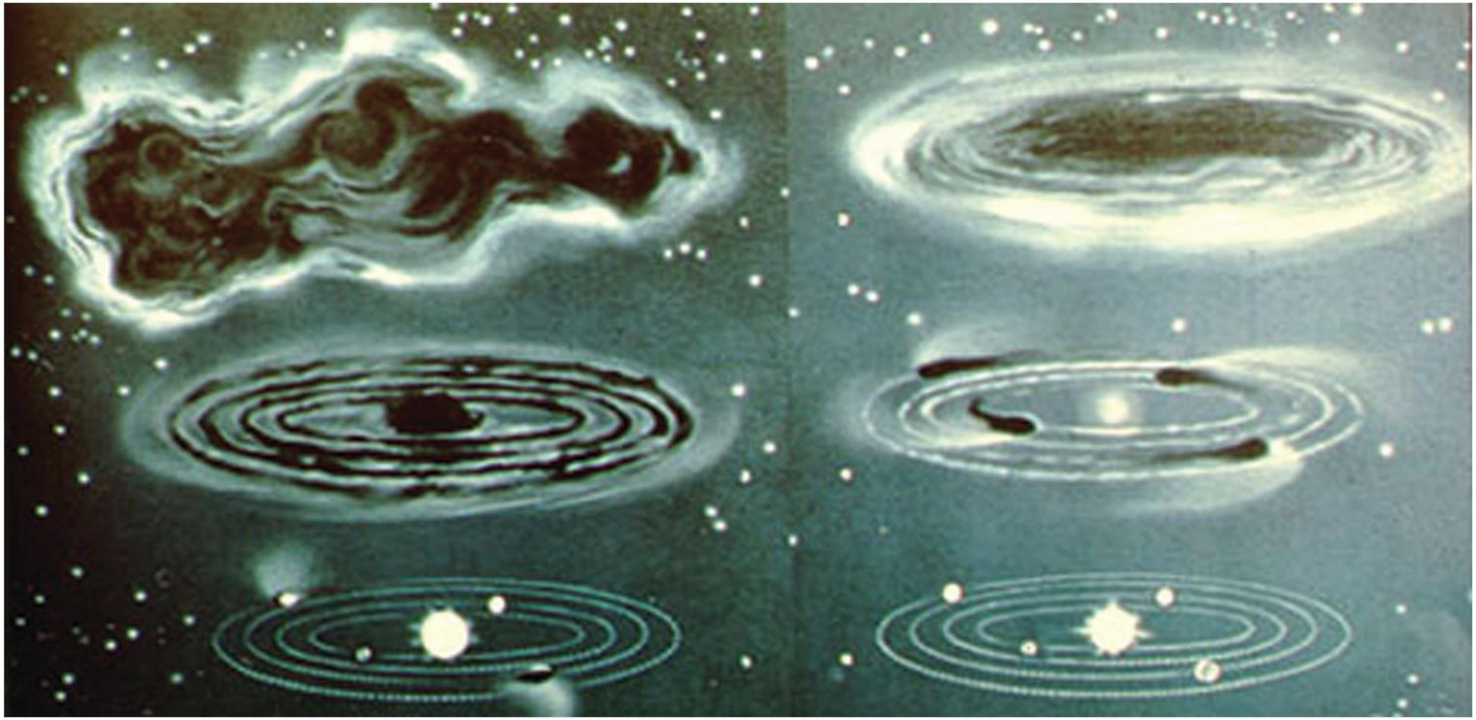
PLATE-2



http://www.daviddarling.info/encyclopedia/J/JeansJefftidal.html

Tidal Hypothesis

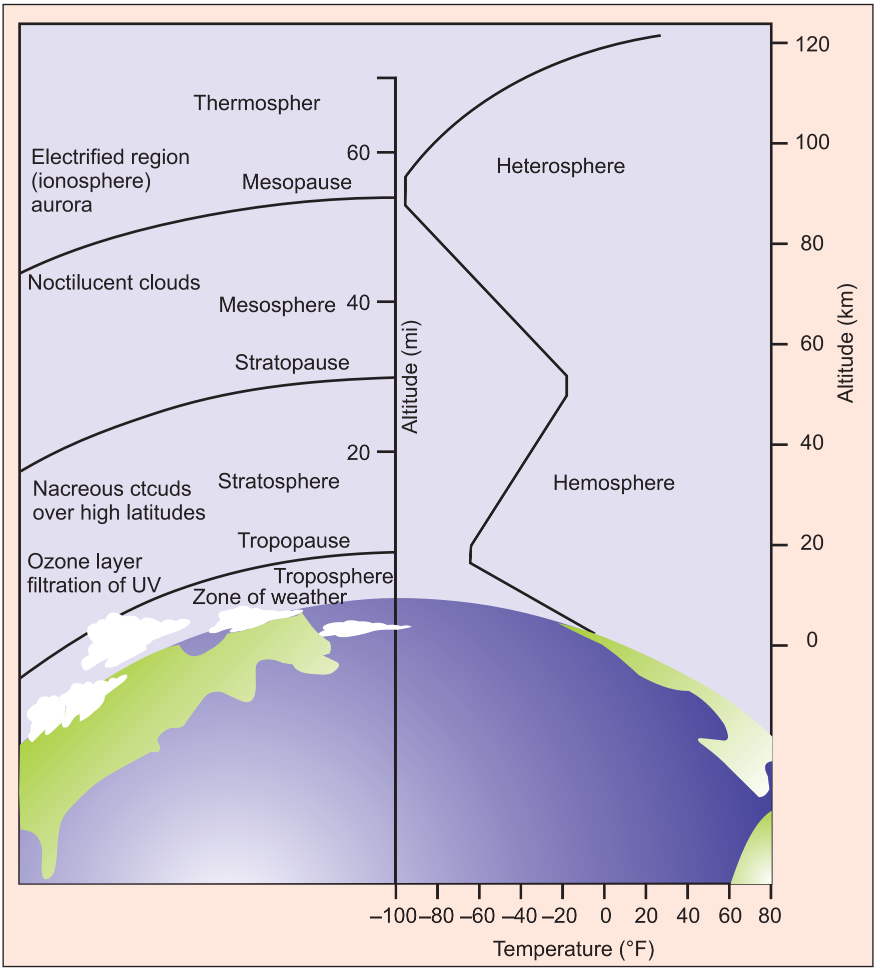
PLATE–3



http://www.fas.org/irp/imint/docs/rst/Sect19/Sect19_2a.html

Gas-dust Cloud Hypothesis

PLATE–4



http://astro.wsu.edu/worthey/earth/html/lecture07.html

Structure of Atmosphere

PLATE-5

pacificislandparks.com

(a) Eruption of Lava

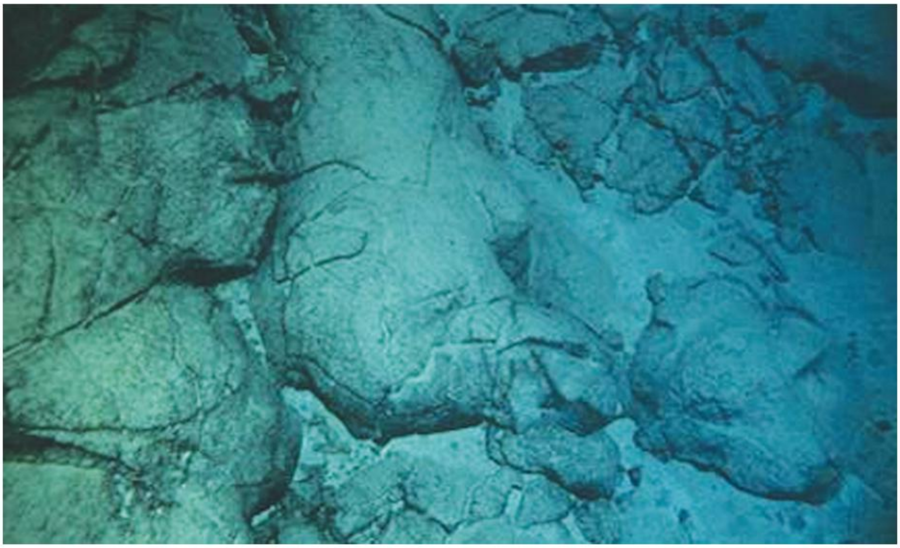
pacificislandparks.com

(b) Flow of Lava

PLATE-6

http://volcano.oregonstate.edu

(a) Ropy lava showing finer grain with smooth surface of lava layers



http://volcano.oregonstate.edu

(b) Blocky lava showing coarse grain with rough surface

Types of Lava

PLATE-7

Hornblende (amphibole group)

Augite (pyroxene group)

Stibnite (sulphide group)

Bauxite (oxide group)

Ore-forming Minerals (In Hand Specimen)

PLATE–8


Orthoclase (feldspar group)


Hexagonal quartz (quartz group)

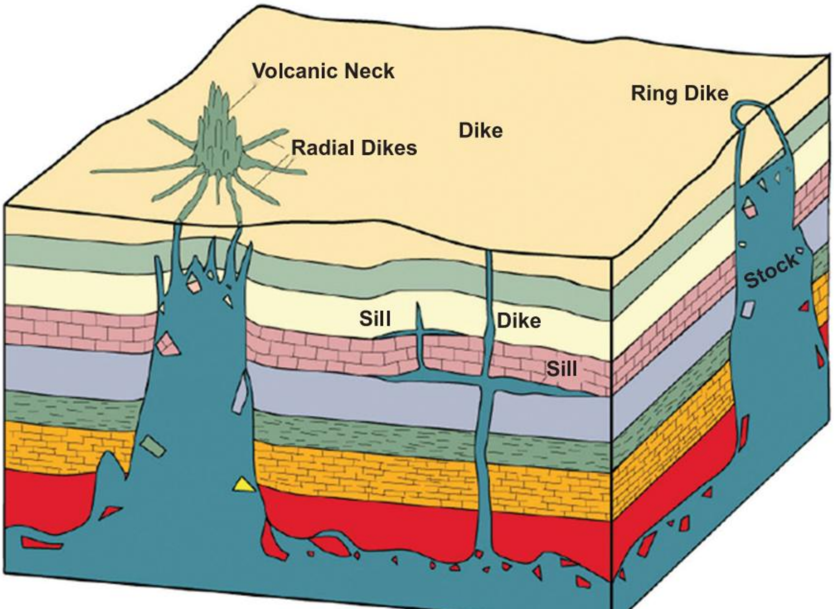

Calcite (carbonate group)


Biotite (mica group)

Rock-forming Minerals (In Hand Specimen)

PLATE-9

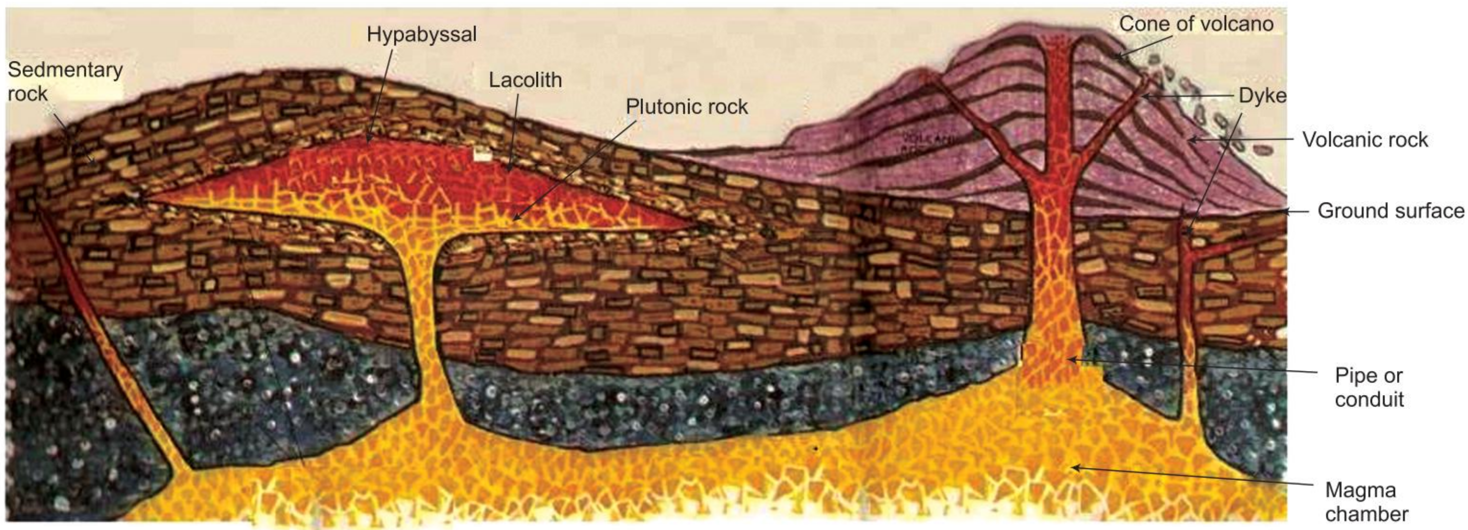
(a) Dyke



(b) Batholith

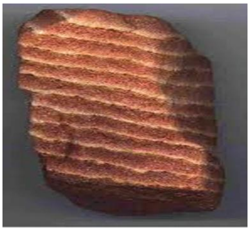
Major Discordant Igneous Structures

PLATE– 10



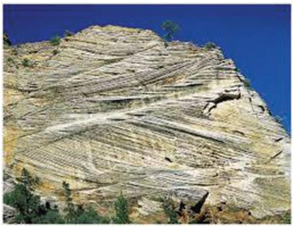
Major Subgroup of Igneous Rocks

PLATE-11

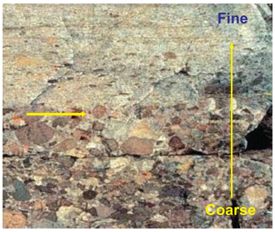


Stratification

Lamination



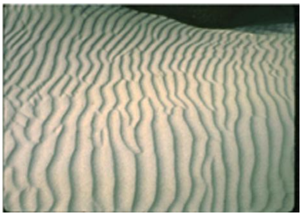
Cross-bedding



Graded Bedding

Mud Cracks

Rain Prints



Ripple Marks

(a) Mechanical structures

Concretionary Structure

Nodular Structure

Geode Structure

(b) Chemical structures

Structures of Sedimentary Rocks

PLATE-12

Breccia

Conglomerates

Sandstones

Shale

Limestones

Dolostone

Coals (Anthracite)

Iron Ores

Gypsum

Rock Salt

Important Sedimentary Rocks

PLATE – 13

Slate

Schist

Phyllite

Gneiss

Mylonite

Quartzite

Marble

Hornfels

Important Metamorphic Rocks

PLATE-14

(a) Tehri Dam, Uttarakhand

(b) Bhakra Nangal Dam, Punjab

(c) Hirakund Dam, Orissa

(d) Nagarjun Sagar Dam, Andhra Pradesh

(e) Sardar Sarovar Dam, Gujrat

Major Dams of India

PLATE-15

(a) Jawahar tunnel, Kashmir

(b) Bhatan tunnel, Mumbai-Pune Express way

(c) Karbude tunnel, Maharastra

(d) Gandhi Setu, Bihar

(e) Jadukata Bridge, Meghalaya

(f) Naini Bridge, Allahabad

Important Bridges and Tunnels

PLATE-16

(a) Kedarnath view after landslide

(b) Scar and its shifting position

(c) Kedarnath glacier before landslide, 2013

(d) Kedarnath glacier after landslide, 2013

Kedarnath Landslides

appendix 1

Physical Properties of the Feldspar Group of Minerals

Properties of the Mineral	*MICROCLINE*	*ORTHOCLASE*	*ALBITE*	*ANORTHITE*
Crystal system	Triclinic; resembles closely with orthoclase in crystal habits.	Monoclinic ; crystals commonly occur in prismatic shapes.	Triclinic. It is the first member of the isomorphous plagioclase series of feldspar the albite–anorthite series.	Triclinic. It is the last member of the isomorphous plagioclase series of feldspar. Crystals are commonly prismatic.
Cleavage	In two directions; the one parallel to basal pinacoid (001) is perfect.	Shows cleavage in two directions. The one parallel to basal pinacoid (001) is perfect. The cleavage angle is 90°.	Present in two directions, the one parallel to basal pinacoid (001) is perfect.	Present in two directions, the one parallel to basal pinacoid (001) is perfect.
Colour	Similar to orthoclase; in addition, may occur as a greenish feldspar, when it is called amazonite.	Various shades of pink and red, such as flesh red, reddish white, light pink. The transparent variety is called *adularia*.	Commonly whitish or pinkish white but shows shades of grey, green and blue.	Generally white, may also occur in reddish and light grey shades.

(*Contd.*)

Properties of the Mineral	*MICROCLINE*	*ORTHOCLASE*	*ALBITE*	*ANORTHITE*
Lustre	Vitreous to semi-vitreous	Vitreous to semi-vitreous	Vitreous to pearly. Some varieties, show play of colours on the cleavage surface.	Semi-vitreous
Streak	Colourless	White	Colourless	Colourless
Hardness	6–6.5	6–6.5	6–6.5	$CaAl_2Si_2O_8$
Specific gravity	2.54–2.57	2.56–2.58	2.60–2.62	2.5–2.65
Composition	$KAlSi_3O_8$	$KAlSi_3O_8$	Sodium aluminium silicate, $NaAlSi_3O_{8\,(1}$00–90 percent and $CaAl_2Si_2O_8$ (0–10 %). $NaAlSi_3O_5$ and $CaAl_2Si_2O_8$	$CaAl_2Si_2O_8$ and $AlSi_3O_5$
Occurrence	It occurs along with orthoclase in granites and other igneous rocks. In coarse-grained igneous rock called pegmatites, microcline is the prominent variety of feldspar. Also occurs as an intergrowth with albite.	A most common and essential constituent of many igneous rocks, especially granites.	An essential constituent of many igneous rocks, such as granites, syenites, rhyolites and dacites	An important constituent of many basic types of igneous rocks
Economic use	(i) As a ceramic material (ii) As a semi-precious stone (amazonite)	As a ceramic material	(i) As a ceramic material (ii) As an ornamental stone.	(i) As a ceramic material (ii) As an ornamental stone.
Varieties	Anorthoclase (meaning *not orthoclase*). It is a triclinic feldspar also containing sodium aluminium silicate.	As a ceramic material. (i) *Adularia:* A transparent orthoclase. (ii) *Sanidine:* High-temperature variety, stable above 900°C.	These may be broadly considered the varieties of plagioclase feldspars.	These may be broadly considered the varieties of plagioclase feldspars.

appendix 2

Physical Properties of the Pyroxene Group of Minerals

Properties of the Mineral	*AEGIRINE (ACMITE)*	*JAEDITE*	*SPODUMENE*
Crystal system	Monoclinic	Monoclinic	Monoclinic
Cleavage	Prismatic	Prismatic	Prismatic
Colour	Green to black in colour	Green	White and violet
Lustre	Vitreous to pearly. Some varieties are translucent.	Vitreous to pearly. Some varieties are translucent.	Vitreous to pearly. Some varieties are translucent.
Streak	Grey	Colourless	Grey
Hardness	6	6–7	6.5
Specific gravity	3.5–3.6	3.25–3.35	3.1–3.2
Composition	$NaFeSi_2O_6$	$NaAlSi_2O_6$	$LiAlSi_2O_6$
Occurrence	A common constituent of igneous rocks, i.e. nepheline, syenite	As boulder in metamorphic rocks	A common constituent of igneous rocks, i.e. pegmatite

(*Contd.*)

Properties of the Mineral	*ENSTATITE*	*HYPERSTHENE*	*DIOSPIDE*	*AUGITE*
Crystal system	Orthorhombic. But, the mineral mostly occurs in massive and sometimes fibrous form.	Orthorhombic; an isomorphic variety of enstatite; occurs commonly in massive form	Monoclinic, occurs in short columnar crystals	Monoclinic, occurs usually in short prismatic crystals and as a granular mass
Cleavage	Two sets (prismatic-110)	Two sets (prismatic)	Prismatic	Prismatic [110]. Commonly shows parting parallel to base (001)
Colour	Variable between greyish white to greenish white	Commonly green but also occurs in olive green to greenish black	Light green and grey	Variable, depending on chemical composition, occurs in shades of greyish green and black.
Lustre	Vitreous to pearly. Some varieties are translucent.	Pearly to vitreous	Sub-vitreous	Commonly vitreous
Streak	—	Grey	—	Grey
Hardness	5.5	5–6	5–6	5–6
Specific gravity	3.1–3.3	3.4–3.5	3.27–3.38	3.25–3.55
Composition	$MgSiO_3$	$(Fe, Mg)\ SiO_3$	Calcium magnesium silicate with some Fe and Mg	$Ca(Mg, Fe, Al)\ (Al, Si)_2O_6$
Occurrence	A common constituent of many igneous rocks and some metamorphic rocks.	A more common constituent of volcanic igneous rocks like andesites and trachytes; also found in plutonic rocks like jubbros and norites.	A common constituent of basic and ultrabasic igneous rocks.	A very common ferro-magnesian mineral of igneous rocks. The basic and ultrabasic rocks are especially rich in augite.

appendix 3

Physical Properties of the Amphibole Group of Minerals

Properties of the Mineral	*ANTHOPHYLLITE*	*TREMOLITE*	*ACTINOLITE*	*HORNBLENDE*
Crystal system	Orthorhombic; commonly occurs in thin, slender fibres	Monoclinic; crystals are long, bladed	Monoclinic	Monoclinic, crystals long, slender and prismatic.
Cleavage	Perfect (prismatic)	Prismatic and perfect	Perfect (prismatic)	Perfect, prismatic, parallel to [110],
Colour	Grey, brownish or green-ish.	Commonly white to light grey	Mostly a green amphibole. The green colour is due to ferrous iron.	Dark green, dark brown and black.
Lustre	Vitreous	Vitreous		Vitreous
Streak	------	----		White with greenish tint
Hardness	5.5–6	5.5–6.0	5.5–6.0	5.5–6
Specific gravity	2.85–3.20	2.9–3.0	3.1–3.3	3.0–3.47
Composition	$(Mg, Fe)_3\ [Si_4O_{11}]_2\ [OH]_2$	$Ca_2\ Mg_5(Si_4O_{11})_2(OH)_2$	$Ca\ (Mg\ Fe)_2\ (Si_4O_{11})_2(OH)_2$	$Ca_2Na(Mg, Fe)(Al, Fe)$ $[(SiAl)_4O_{11}]_2[OH]_2$

(*Contd.*)

Occurrence	Found only in metamorphic rocks described as crystalline schist.	Igneous and metamorphic rocks, especially in metamorphosed limestone and dolomites.	Actinolite is confined in its occurrence to metamorphic rocks such as crystalline schists.	Hornblende is a common rock-forming mineral in igneous and metamorphic rocks.
Varieties			Asbestos: Actinolite and tremolite and other minerals of the amphibole group often occur in fibrous from when they are grouped as asbestos. They form long and flexible fibres.	About half a dozen varieties of hornblende have been differentiated on the basis of variation in its chemical composition

Properties of the Mineral	***GLAUCOPHANE***	***ARFVEDSONITE***
Crystal system	Monoclinic	Monoclinic
Cleavage	Prismatic	Prismatic
Colour	Various shades of blue, e.g. bright blue, blue-black, greyish-blue, etc.	Black
Lustre	Vitreous	Vitreous
Streak	—	Deep blue
Hardness	6–6.5	6
Specific gravity	3.1–3.2	3.4
Composition	$Na_2 (Mg, Fe)_3A1_2 [Si_4O_n]_2 [OH, F]_2$	$Na_3 (Mg, Fe)_4 (Fe, Al) [Si_4O_{11}]_2 [OH, F]_2$

appendix 4

Physical Properties of the Mica Group of Minerals

Properties of the Mineral	*MUSCOVITE*	*BIOTITE*	*PHLOGOPITE*	*LEPIDOLITE*
Crystal system	Monoclinic; commonly occurs in platy form with pseudo symmetry of hexagonal or orthorhombic type	Occurs in tabular sheets or short prismatic flakes; monoclinic; commonly occurs in platy form with pseudo symmetry of hexagonal or orthorhombic type	Monoclinic	Monoclinic; occurs in the form of granular mass
Cleavage	Perfect (one set), basal (001)	Perfect (one set), basal (001)	Perfect	Perfect (one set)
Colour	Colourless in thin sheets; as a mass may appear pale yellow	Black and deep green	Yellow, brown and yellow	Dark green, dark brown and black
Lustre	Pearly on cleavage faces, vitreous	Pearly on cleavage faces, vitreous	Pearly	Pearly
Streak	Colourless	Colourless	Brown	—
Hardness	2.5–3.0	2.5–3.0	2.5–3.0	2.4–5
Specific gravity	2.7–3.1	2.7–3.1	2.7–2.85	2.5–3.3

(*Contd.*)

Properties of the Mineral	*MUSCOVITE*	*BIOTITE*	*PHLOGOPITE*	*LEPIDOLITE*
Composition	$KAl_2AlSi_2O_{10}$	$K(Mg, Fe)_3$, $(AlSi_3O_{10})$ $(OH)_2$	KMg_3 $(A1_3Si_3O_{10})(OH)_2I$	KLiAl (Si_4O_{10}) $(OH)_2$
Occurrence	It is the most common variety of all the micas and occurs in abundance in acidic igneous rocks such as granites and pegmatities and also in metamorphic rocks (mica schists). It is a common accessory mineral of sedimentary rocks.	Commonly found in igneous rocks and metamorphic rocks like gneisses. It is rare in sedimentary rocks compared with muscovite.	Occurs in limestone and dolomite	Lepidolite is confined mostly to igneous rocks.
Varieties	Muscovite is a good electrical insulator and finds extensive use in the electrical industry and for making fireproof material.	—	—	—

appendix 5

Physical Properties of the Oxide Group of Minerals

Properties of the Mineral	*QUARTZ*	*CORUNDUM*	*SPINEL*
Crystal system	Hexagonal (rhombohedral). Crystals common, some crystals weighing many tones have been reported. Twinned, right-handed and left-handed crystals are common.	Hexagonal-trigonal columnar crystals	Monoclinic; crystals are long, bladed
Cleavage/Fracture	Absent/Choncoidal	The mineral shows parting parallel to (0001) rather than cleavage	Prismatic and perfect
Colour	Colourless when pure, quartz also occurs in coloured varieties: red, green, blue and mixed	Greyish brown, occurs in many other colours also mentioned below	Commonly white to light grey
Lustre	Vitreous	Dull	Vitreous
Streak	White in coloured varieties	Colourless	Colourless
Hardness	7	9	5.5–6.0
Specific gravity	2.65–2.66	3.9–4.1	2.9–3.0
Composition	SiO_2	Al_2O_3	$MgAl_2O_4$

(Contd.)

Properties of the Mineral	*QUARTZ*	*CORUNDUM*	*SPINEL*
Occurrence	It occurs in all types of rocks but more dominant in igneous rocks.	The common dull grayish brown variety of corundum is found distributed widely in metamorphic rocks like gneisses, schists and crystalline limestone. Corundum also occurs in some igneous rocks. The gem varieties are very rare.	Igneous and metamorphic rocks, especially in metamorphosed limestones and dolomites.
Varieties	A few common varieties are chalcedony, agate, chert. jasper.	The mineral occurs in quite a few coloured varieties, some of which are highly valued as gemstones. 1. *Ruby*: Transparent, red variety of corundum 2. *Sapphire*: Transparent, blue variety of corundum. 3. *Oriental Emerald*: Green variety of corundum. 4. *Oriental Topaz*: Yellow variety of corundum	—

appendix 6

Physical Properties of the Carbonate Group of Minerals

Properties of the Mineral	*CALCITE*	*DOLOMITE*	*MAGNESITE*
Crystal System	Hexagonal–rhombohedral; occurs in a great variety of crystals: tabular, rhombohedral, prismatic, thin and elongated	Hexagonal and rhombohedral	Hexagonal–rhombohedral
Cleavage/Fracture	Highly perfect (3 sets)	Perfect	One set (hexagonal)
Colour	Pure calcite is white and transparent. Milky white, opaque varieties are also common. Small proportions of impurities give various tints to calcite: pink, red, violet, blue, green and black.	White when pure; also occurs in shades of brown, red, grey, green and black	White when pure; shades of grey and brown are also common
Lustre	Vitreous	Vitreous	Vitreous to silky in fibrous varieties
Streak	White	White	White
Hardness	3	3.3–4	3.3–4
Specific gravity	2.71	2.8–2.9	3.0–3.1
Composition	$CaCO_3$	$CaMgCO_3$	$MgCO_3$

(*Contd.*)

Properties of the Mineral	*CALCITE*	*DOLOMITE*	*MAGNESITE*
Occurrence	Calcite is one of the most common rock-forming minerals in sedimentary rock. Limestones are almost entirely made up of calcite and the dolomites contain this mineral to a good proportion. The recrystallized variety of calcite makes the well-known metamorphic rocks–marbles. Calcite is principally a secondary mineral formed from the carbonate-rich water of seas and oceans.	Dolomite commonly occurs in massive forms making layers extending several kilometres across. As a mineral, it is found in veins when its igneous origin is in no doubt. As a rock constituent, however, it is believed to have been formed by action of magnesium-rich sea water on original limestone deposit. This process is called in-petrology dolomitization.	Magnesite is formed from magnesium-bearing sea waters on their coming in contact with other carbonate rocks. Large deposits of this mineral take the form of rock bodies and become the source of commercial rock.

appendix 7

Physical Properties of the Sulphide Group of Minerals

Properties of the Mineral	*GALENA*	*PYRITE (FOOL'S GOLD)*	*CHALCOPYRITE*
Form	Crystalline	Radiating	Crystalline
Colour	Lead gray	Brass yellow	Brass yellow
Streak	Lead gray	Black	Black
Lustre	Metallic	Metallic	Metallic
Hardness	Medium (2.5)	Medium (6.0)	Medium (3.5 to 4)
Sp.Gr.	High (7.58)	High (5.02)	High (4.2)
Chemical composition	PbS	FeS_2	CuFeS
Occurrence	Occurs in veins in sedimentary rocks of Rajasthan, Bihar	Occurs in metamorphic rocks, Ajmer (Rajasthan), Ingaldhal (Karnataka), Taradevi (Punjab).	Occurs in the metamorphic rocks of Rajasthan, Bihar.
Uses	Galena is the most important lead ore containing 66% of lead, found in combined state with zinc. Also used in lead piping.		Copper ore having 34.5% of copper

appendix 8

Groundwater Management

A.8.1 GROUNDWATER MANAGEMENT

Groundwater resources management in the Indian context is an extremely complex proposition as it deals with the interactions between the human society and the physical environment. The highly uneven distribution of groundwater availability and its utilization indicates that no single management strategy can be adopted for the country as a whole. On the other hand, each situation demands a solution which takes into account the geomorphic set up, climatic, hydrologic and hydrogeologic settings, groundwater availability, water utilization pattern for various sectors and the socio economic setup of the region.

Any strategy for scientific management of groundwater resources involves a combination of

1. supply side measures aimed at increasing extraction of groundwater depending on its availability, and
2. demand side measures aimed at controlling, protecting and conserving available resources.

Various options falling under these categories are described under the subheads of supply-side and demand-side measures as follows.

A.8.1.1 Supply-Side Measures

These measures are aimed at increasing the groundwater availability, taking the environmental, social and economic factors into considerations. Development of additional groundwater resources through suitable means and their augmentation has to take place together. The artificial recharge and rainwater harvesting fall under this category. For an effective supply-side management, it is imperative to have complete knowledge of the hydrologic and hydrogeological controls that govern the yield of aquifers and behaviour of groundwater level under abstraction stress. Interaction of surface and groundwater and changes in flow and recharge rates are also important considerations in this regard.

❑ ***Scientific Development of Groundwater Resources***

The groundwater development has taken place since time immemorial in the country, but in recent decades the use of groundwater technology has accelerated the groundwater withdrawal without giving much scientific emphasis. To develop the groundwater resources, the country has been divided into four categories as described below. All these categories have different geological settings, occurrences and potential of groundwater.

(a) Groundwater development in alluvial plains
(b) Groundwater development in coastal areas
(c) Groundwater development in hard rock area
(d) Groundwater development in water logged areas

❑ *Rainwater Harvesting and Artificial Recharge*

To manage the groundwater resource as supply side, apart from scientific development of groundwater, rainwater harvesting and artificial recharge have to be implemented. Supply of groundwater is dependent on the availability of freshwater in different aquifers. The depletion in water level and squeezing of aquifer resource situation warrants the implementation of rainwater harvesting so that supply side management is looked after.

A.8.1.2 Demand-Side Measures

Besides scientific development of available resources, the proper groundwater resource management requires to focus on the judicious utilization of the resources for ensuring their long term sustainability. Ownership of groundwater, need-based allocation, pricing of resources, involvement of stake holders in various aspects of planning, execution and monitoring of projects and effective implementation of regulatory measures wherever necessary are the important considerations with regards to demand-side groundwater management.

❑ *Groundwater Development Prospects*

The analysis of available data indicates that contribution made by groundwater to the agricultural economy of India has grown steadily since the early 1970’s. In the past two decades, the groundwater irrigated lands in India has increased by nearly 105%, this change was most striking in northern India.

Close examination of the groundwater resource availability in different geomorphological terrains of the country and its utilization indicates that out of the total of 433 billion cubic meter of replenishable groundwater resources available in the country, the share of alluvial areas covering Eastern Plain states of Bihar, Orissa (part), Eastern Uttar Pradesh and West Bengal; and North Western plain states of Delhi, Haryana, Punjab, Western Uttar Pradesh, Chandigarh; is about 192 billion cubic metres which works out to be 44% of the total available resource. In the eastern plain states, the overall stage of groundwater development is about 44%, whereas the overall stage of groundwater development in North Western Plain states covering Punjab, Delhi and Haryana is 98%. Western part of Uttar Pradesh, is a major part where groundwater is overexploited. Therefore, the prospects of groundwater development are quite bright in the states where the amount of groundwater development has not come under over-exploited category.

❑ *Groundwater Regulation and Pricing*

Regulation of overexploitation of groundwater through legal means can be effective under extreme situations if implemented with caution. Groundwater regulatory measures in India are implemented both at Central and State levels. The Central Groundwater Authority, constituted under Environment (Protection) Act of 1986 is playing a key role in regulation and control of groundwater development in the country. Central Groundwater Authority initially notifies over-exploited areas in a phase manner for registration of groundwater abstraction structures. Based on data thus generated, the vulnerable areas are notified for the purpose of groundwater regulation. In these areas, construction of new groundwater abstraction structures is regulated. As water is a State subject, the management of groundwater resources is a prerogative of the concerned State Government.

Ministry of Water resources has prepared and circulated Model Bills to all States and Union Territories during 2005. The main thrust of these bills is to ensure that all the States and Union Territories form their own State Groundwater Authorities for proper control and regulation of groundwater resources. As water is a basic need and thereby an important social issue, the regulatory mechanism needs to be transparent and people friendly. Continuous monitoring of groundwater regime is required in notified areas. Micro-level studies need to be taken up in such areas on a regular basis to assess the impacts of the regulatory measures on the groundwater regime.

Real-time dissemination of information on the groundwater situation in the affected areas is to be provided to the stakeholders. Involving local people in the administrative process as social volunteers may also help. Experience indicates that enforcement of legislative measures for groundwater regulation and management would be meaningful only when stakeholders are motivated through local self-governing bodies and directly involved in the decision making and enforcement process.

❑ *Rainwater Harvesting and Artificial Recharge*

Rainwater harvesting and artificial recharge have now been accepted worldwide as cost effective methods for augmenting groundwater resources and for arresting/reversing the declining trends of groundwater levels. Artificial recharge techniques are highly site-specific. Need, suitability of area in terms of availability of sub-surface storage space and availability of surplus monsoon run-off are important considerations for successful implementation of artificial recharge schemes.

Rainwater harvesting and artificial recharge schemes implemented by various organizations in the country have shown encouraging results in terms of augmentation of groundwater recharge, check in rate of decline of groundwater levels and reduction of surplus run-off. Increased sustainability of existing abstraction structures, increase in irrigation potential, revival of springs, soil conservation through increase in soil moisture and improvement in groundwater quality are among the other benefits of the schemes. In the coastal tracts, tidal regulators, constructed to impound the freshwater upstream and enhance the natural recharge are effective in controlling salinity ingress.

Experience gained from pilot artificial recharge schemes implemented by a number of State and Central Government agencies, in different hydrogeological settings in the country indicates that optimal benefits can be achieved when various recharge structures are constructed at suitable locations in complete hydrological units such as watersheds, sub-basins, etc.

The Central Groundwater Board (CGWB) has also carried out studies for demarcating areas of long term decline of groundwater levels and for exploring the possibility of augmenting the groundwater resources in these aquifers using available surplus monsoon run-off. An area of about 4.5 lakh sq km has been identified in the country where such augmentation measures are considered necessary.

It has also been estimated that about 36 billion cubic metres of surplus monsoon run-off can be recharged into these aquifers annually (CGWB, 2002). Modification of natural movement of surface water into the aquifers through various structures like check dams, percolation ponds, recharge pits, shafts or wells are considered suitable in rural areas. On the other hand, roof top rainwater harvesting, either for storage and direct use or for recharge into the aquifers is suited for urban habitations with its characteristic space constraints. There is a need to shift the initiative from institutional endeavour and make it into a mass movement. Community based programmes on rain water harvesting and artificial recharge would inculcate a sense of responsibility among the stake holders, thereby enhancing the efficiency level of maintenance of the schemes.

A.8.2 ARTIFICIAL RECHARGE TECHNIQUES

There are different methods of recharging to groundwater artificially. The methods primarily depend upon parameters like need for artificial recharge to groundwater, availability of source water and its distribution with time, and hydrogeology of the area. The most common method for alluvial areas is harvesting rooftop rainwater and recharging it to the groundwater through a recharge well. The recharge well is similar to a discharge well except that in case of discharge well, water is taken out and a cone of depression is formed and in case of recharge well a cone of impression is formed.

A.8.2.1 Surface Methods

These methods are used only in the areas where sufficient land is available and in case shallow unconfined aquifer is to be recharged. Recharge is accomplished by applying the water on the permeable ground surface where it infiltrates through the unsaturated zone to slowly reach the groundwater table. Surface methods, particularly the spreading methods, are a widely used artificial recharge technique. It is achieved through basin, trenches, ditches and flooding.

❑ *Basin Method*

A basin is constructed by excavation. The area is divided into small sub-basins. The basins are arranged in a series so that the overflow from the upper basin to the lower basin is carried out and from the lower basin excess water is returned to the main channel. The shape and size of a basin depends upon the topography and availability of land. The water released to basins should have minimum sediments so as to reduce deposition and sealing of cracks and joints (in hard rock areas) or pores of permeable material of basin surface. It is essential to have a sufficient knowledge of the unsaturated zone between ground surface and water table.

The artificial recharge by basin method has the following advantages:

1. Basin utilizes the maximum area of spreading 75 to 80%.
2. Irregular and gullied surfaces can be used with minimum preparation.
3. Silt laden water can be used in multibasin system.
4. Considerable surface storage capacity is available to store flash floods.
5. Expenses for maintenance are low.

The main disadvantage is that a large area is required which may not be used for any other purpose.

❑ *Trench and Ditches Method*

In irregular terrain, water is spread through a series of trenches. These are flat bottomed and can be of 1 m to 300 m long (Fig. A.8.1). The depth can be 1m to 3 m depending on the thickness of upper clay layer. These are filled with inverted filter material grading from boulder to fine gravel. In this method, water is distributed to a series of ditches or furrows, which are shallow, flat bottomed and closely spaced to obtain maximum water contact area.

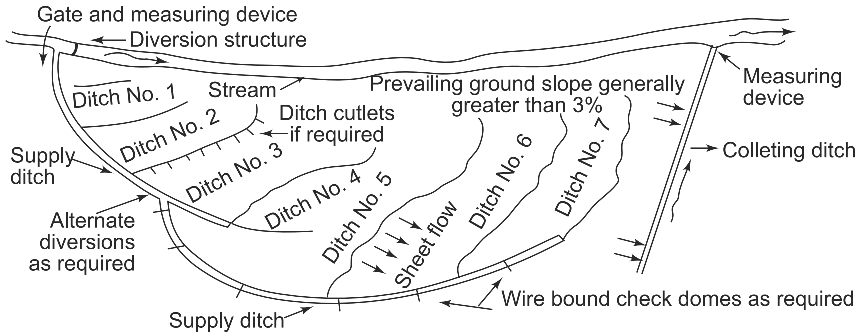


Fig. A.8.1 *Ditch and furrow method*

The method may be adopted in comparatively undulating topography. If the top layer is clayey or impervious, artificial recharge can be attempted by scrapping the top clayey layer by making the furrows and exposing a higher area of high permeability. Series of ditches can also be made to recharge groundwater. The design of the ditch is governed by the topography and size of the area. Common ones are the contour, lateral and T-shaped types. Gradient is also maintained so that suspended material may not clog the sand opening.

❑ *Flooding Method*

This method is employed only in the gently slopping topography. The flooding method involves diversion of rain water, surplus canal water to the local depression. The velocity of flow should be a minimum so that it may not disturb soil cover. The method is least costly, assuming the land is available without cost. However, lot of land is needed and the land cannot be put to use for cultivation.

A.8.2.2 Subsurface Methods

The most common methods are recharge well, shaft, dug-cum-bore well and shaft-cum recharge well. These methods are most suitable for the areas where sufficient land is not available. In case semiconfined/confined aquifers are to be recharged, subsurface methods are the only options suitable. In the areas where thickness of overlying burden is more than 3 m and clay layer occurs between the ground surface and water level, surface methods of recharge are not applicable. In order to recharge the saturated unconfined aquifer below water level, the artificial recharge should be taken up by recharging water under gravity using this method.

A.8.3 TYPES OF ARTIFICIAL RECHARGE STRUCTURES

A.8.3.1 Percolation Tanks/Spreading Basin

These are the most prevalent structures in India as a measure to recharge the groundwater reservoir both in alluvial as well as hard rock formations. The efficacy and feasibility of these structures is more in hard rock formation where the rocks are highly fractured and weathered. In the States of Maharashtra, Andhra Pradesh, Madhya Pradesh, Karnataka and Gujarat, the percolation tanks have been constructed in plenty in basaltic lava flows and crystalline rocks. The percolation tanks are, however, also feasible in mountain fronts occupied by talus creep deposits. These are found to be very effective in Satpura Mountain frontal area in Maharashtra. The percolation tanks can also be constructed in the Bhabar zone. Percolation tanks with wells or shafts are also constructed to recharge deeper aquifers where shallow or superficial formations are highly impermeable or clayey with certain modification.

A.8.3.2 Check Dams/Nala Bunds

Check dams are constructed across small streams having gentle slope and are feasible both in hard rock as well as alluvial formation. The site selected for check dam should have sufficient thickness of permeable bed or weathered formation to facilitate recharge of stored water within a short span of time. The water stored in these structures is mostly confined to stream course and the height is normally less than 2 m (Fig. A.8.2). These are designed based on stream width and excess water is allowed to flow over the wall. In order to avoid scouring from excess run-off, water cushions are provided at downstream side.

To harness the maximum run-off in the stream, series of such check dams can be constructed to have recharge on regional scale. A series of small bunds or weirs are made across selected nala sections such that the flow of surface water in the stream channel is impeded and water is retained on pervious soil/rock surface for longer body. Nala bunds are constructed across bigger nalas of second order streams in areas having gentler slopes. A nala bund acts like a mini percolation tank recharge well.

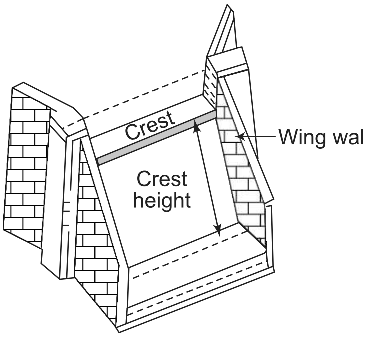


Fig. A.8.2 *Check dam*

A.8.3.3 Recharge Well

A recharge well is one, which admits water from the surface to aquifer. The recharging well may be abandoned open wells/tubewells, or specially designed wells having vertical or horizontal intake slotted pipes, double purpose which can be used both for pumping and recharging (Fig. A.8.3). It is suitable for groundwater recharge in areas where water levels are deep. This hydraulic

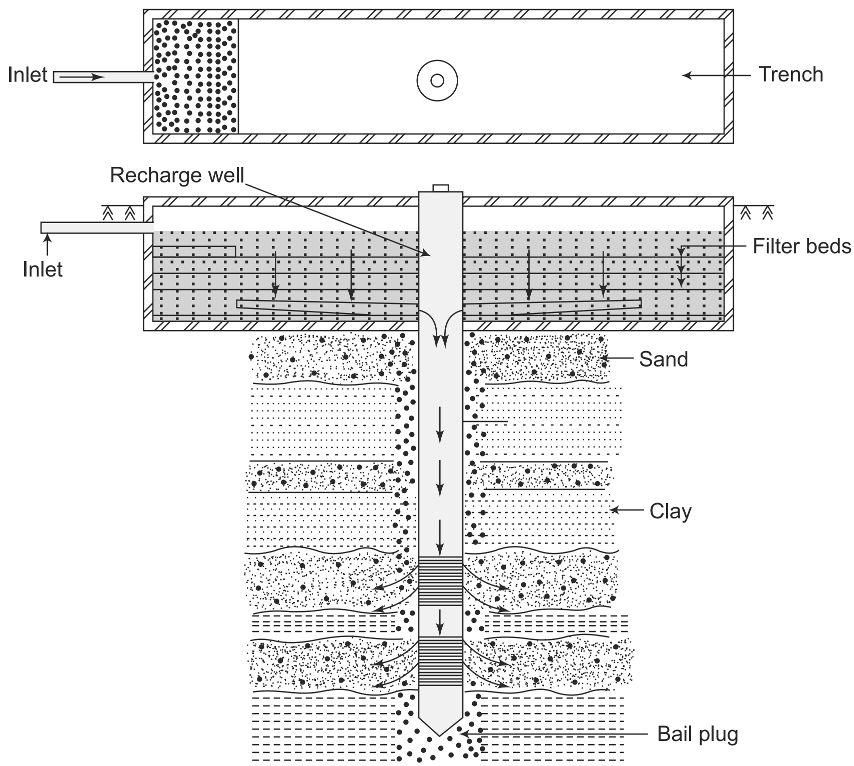


Fig. A.8.3 *Recharge well inside recharge trench* structure is akin to a pumping well with a slight change in construction design as it is used for recharging groundwater rather than pumping. In case of a recharge well, single-diameter pipe assembly is used and it should have a provision of slotted pipes against the filter media for entering filter water into the well. Recharge well is ideally suited for those locations where land availability is limited, and/or aquifer is deep and overlying by thick impermeable stratum (clay). The roof-top rainwater or filtered water is channelled to the well under gravity flow condition. A number of recharging structures can be constructed in limited area around a building. Number of recharge wells to be installed depends upon roof top area and aquifer characteristics.

A.8.3.4 Recharge Trench

The recharge trench is suitable for ephemeral rivers, drains beds or around a building using harvested rainwater. Recharge trench can be of any dimensions, generally it is 2–3 m deep, 3–4 m wide and of any length. It can be straight, zig-zag, L-shaped, or U-shaped and is filled with filter media which can grade from gravel to boulder. The sides of the trench should slope at low angle for stability. It is constructed when permeable strata of adequate thickness are available at shallow depth. The recharge trench should be filled with gravel, pebbles and boulder for filtration of water. These are constructed across the land slope.

A.8.3.5 Recharge Shaft

This is like an open well but filled with filter media (graded boulder, coarse gravel, fine gravel). A recharge shaft is dug manually or drilled by the reverse/direct rotary drilling machines. Diameter of recharge shaft generally varies from 1 to 3 m depending upon the availability of water to be recharged. It is constructed where the aquifer to be recharged is located at shallow depth. Recharge shaft is back filled with boulders, coarse gravel and fine gravel for filtration. The recharge shaft should end in permeable strata (sand) to be recharged. Depth of recharge shaft varies from 2 to 12 m below ground level as construction of deeper shafts is difficult and is not economical. These are filled with filter material to remove silt and other suspended particles. Recharge shaft should be constructed 10 to 15 m away from buildings for the safety of the building. The shaft should be cleaned periodically by scraping the top layer of fine sediments deposited.

A.8.3.6 Recharge Pit

It is constructed in areas where sandy formation occurs within 1–2 m from ground surface. It can be circular, square or rectangular in shape. Recharge pits are suitable for recharging very shallow aquifer. These are constructed generally 1 to 2 m wide and 2 to 3 m deep. After excavation, the pits are refilled with pebbles and boulders. Water to be recharged should be silt free. Cleaning of the pit should be done periodically. It is suitable for small buildings having the roof top area up to 100 sq.m.

A.8.3.7 Cavity Wells

Cavity wells form good recharge structures. Cavity wells are constructed by drilling boreholes with hand boring and pipes are driven up to the bottom of clay beds. Cavity is formed within the underlying sand bed with the help of high capacity pump. Screen is not used in these wells and the bottom of the pipe is not closed but kept open for entering water. The filtered water is recharged under gravity through these wells. The cavity well can be constructed in the area where overlying aquifer layer to be charged is hard and plastic in nature. The recharge capacity of cavity well is generally 5–10 litres per second. It is cheap structure as compared to recharge well. It can also be used as pumping well. The water to be recharged should be silt-free. The cavity should be developed periodically whenever it is found that its recharge capacity is reduced.

A.8.3.8 Groundwater Dams

Also known as *subsurface dykes* (South India) or *underground bandharas* (Rajasthan and Gujarat) are basically groundwater conservation structures and are effective to provide sustainability to groundwater structures by arresting subsurface flow. A groundwater dam is a subsurface barrier across stream, which retards the natural groundwater flow of the system and stores water below ground surface to meet the demands during the period of need. The main purpose of groundwater dam is to arrest the flow of groundwater out of the sub-basin and increase the storage within the aquifer. By doing so, the water level in upstream part of groundwater dam rises, saturating the otherwise dry part of aquifer.

A.8.3.9 Dug cum Bore Well

There are a number of abandoned dug wells all over the country which have gone dry or covered with concrete slab for protection. These can be used as artificial recharge structures after modifying them by constructing a recharge well at the bottom (Fig. A.8.4). Before using the dug well as recharge structure, its bottom should be cleaned and all the fine deposits should be removed.

A filtration chamber may be constructed so that water can be made free from silt before water enters into the dug well. The recharge water is guided through a pipe to the bottom of well to avoid scouring of bottom. In order to enhance the rate of recharge, a borehole is drilled at the bottom of the dug well and it is converted into dug-cum bore well. It is suitable for large buildings, preferably having the roof area more than 1,000 sq m from where rainwater can be diverted and recharged.

A.8.3.10 Filter Media and Desilting Chambers

Filtration of water to be recharged is essential before it enters the recharge structure. Otherwise silt, colloidal clays and suspended material is likely to clog the slot openings of screens of recharge wells. The finer material, if passed through the screen, may ultimately reduce the permeability of the formation material tapped in the recharge well. Thus, gradually the recharge capacity of the wells is reduced and ultimately the structure becomes defunct. Roof top rainwater contains negligible amount of suspended particles but over a period of time, finer particles gets deposited in the bail plug of the recharge wells and the well assembly gradually gets filled up with finer material and with time it chokes the screen, hence recharge capacity gets reduced. In case of roof top rainwater harvesting schemes, gravel of 2 mm to 4 mm size should be provided in between the recharge structure and conveyance system. Small desilting chambers are also constructed at each rainwater outlet. For utilizing waste water like swimming pools, recreation places gravel of 2 mm to 4 mm can be used as filter material.

While diverting surface run-off, canal water, pond water, or dam water to recharge structure, the top layer of filter media should contain gravel of 1.5 mm to 3 mm size to remove clay particles in colloidal forms. As described above, the top layer of filter media may be of gravel of 2 mm to 4 mm or 1.5 mm to 3 mm

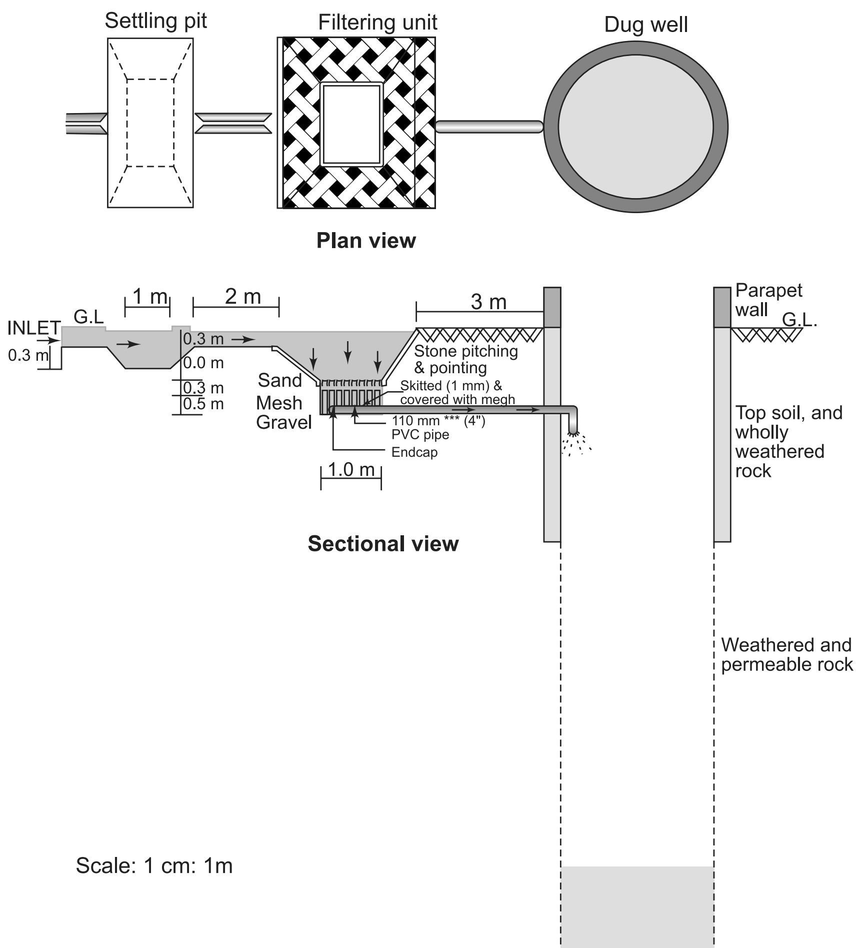


Fig. A.8.4 *Dugwell recharge structure* and should be 0.5 m thick so that finer particles may be retained in this layer. The second layer should of coarse gravel of 5 mm to 10 mm size of 0.5 m thickness and third layer of 50 mm to 100 mm boulder size to store the filtered water. The thickness of each layer can vary as per the need. The coarse sand layer may not be provided at the top as a major proportion of the material contains fine particles and filter media gets choked in shorter time.

A.8.4 IMPORTANT CONSIDERATIONS FOR ARTIFICIAL RECHARGE

Implementation of artificial recharge methods, as described above, to augment groundwater requires certain important considerations. These are briefly highlighted below.

1. Artificial recharge should be taken up in only those areas where water level is more than 10 m below land surface.
2. Long-term post-monsoon trend should be declining.
3. The aquifer to be recharged should be moderately thick and extensive.
4. It is essential to drill a 75 mm diameter test borehole with a hand boring to know the subsurface lithology of the site for construction of recharge structures. The borehole should be drilled down to at least water level. This will give an idea of thickness of unsaturated zone to be recharged.
5. In case of recharging of confined aquifer, the aquifers to be recharged should be identified on the basis of strata chart of nearest borehole drilled.
6. In some of the areas, the water levels in unconfined shallow aquifer are showing rising trend but in deeper confined aquifers these are receding at fast rate. These are falling at an alarming rate. In such areas, unconfined shallow aquifer should not be recharged. The recharge wells should be constructed tapping only deeper water bearing zones.
7. The sand filter media should not be used at the top of trench as it does not allow water to pass through it because it contains more percentage of finer material. Hence, fine gravel should be filled at the top surface. In case of roof top rain water harvesting, the size of gravel should be 2 mm–4 mm. If surface run-off is tapped, then it may be kept 1.5–3 mm to remove the silt from the water to be recharged.
8. The uncased recharge wells (i.e. borehole filled with gravel) are not very effective recharge structures since intake capacity is much less as compared to cased recharge wells. In case of uncased wells, the hydrostatic pressure is not built up.
9. The recharge well will accept water if the water level in the well stands at least below 10 m, i.e. one atmospheric pressure.
10. The slotted pipes should not be wrapped with nylon net which is in practice in case of pumping wells. It reduces the effective open area, thus the intake capacity of the recharge well decreases considerably.

11. The galvanized Vee wire screen is more effective as compared to conventional slotted pipes because 30% open area is available against 10% in MS slotted pipes.
12. The boreholes for the construction of deep recharge wells should be drilled with reverse circulation rotary method. However, in case of shallow recharge well drilling can be carried out with mechanized hand boring.
13. Direct Rotary method should not be deployed for drilling as it chokes the formation with mud cake and thereby reduces the recharge capacity of the structure. In case the recharge well is not pumped properly, the clay particles may choke the screen of the recharge well and surrounding formation material.
14. The water should be made silt-free before it enters into the recharge well. For this purpose, water should be allowed to pass through the inverted filter media. The water loaded with silt, chokes the gravel shrouded around the well and enters the sandy formations, thus reducing the permeability of the formations. The recharge well should be pumped now and then but preferably during the non-recharge times to maintain the efficiency of the well.
15. The slot openings of the slotted pipes or Vee wire screen used for construction of recharging wells should be 1.5 mm or 2 mm, as percentage of open area is more as compared to pipes having finer slot openings.
16. The gravel used for filling the annular space around the well should be 3–6 mm. The finer gravel reduces the intake capacity of the well and there are more chances of getting it choked with silt.
17. The recharge wells should not be constructed closely spaced as cone of impression starts interfering with passage of time. Hence, the recharge capacity of the wells reduce gradually. However in case of confined aquifers, these can be constructed tapping different aquifers.
18. In areas where thin water-bearing zones occur, alternating with thick clay beds, the zones to be tapped should be deciphered with electric logging. In case screen is not properly placed against the aquifers, the intake capacity of the recharge well is likely to reduce considerably.
19. The trench can be brick lined or it can be RCC. The walls of brick lined trench sometimes collapse due to earth pressure. The life span of RCC trench is more as compared to brick lined trench.

Note In order to avoid decline in recharge capacity of structures, regular maintenance of recharge structures is a must.

appendix 9

Physical Properties of Minerals

Metallic and Submetallic Minerals

Fracture Cleavage	*Streak*	*Colour*	*Hardness*	*Fracture Cleavage*	*Lustre*	*Diaphaneity*	*Other Properties*	*Specific Gravity*	*Mineral Name*
Cleavage	Yellow	Yellow, Brown, Black	5–5.5	One Direction Indistinct	Submetallic	Translucent	Silky, Fibrous Appearance	3.3–4.3	Goethite
	Brown	White, Red Yellow, Brown, Green, Black	3.5–4	Perfect Cleavage in 6 directions	Submetallic	Translucent	Brittle, Looks like Resin	3.9–4.1	Sphalerite
	Brown	Dark Green, Dark Brown, or Black	2.5–3	Perfect Cleavage in One direction	Submetallic	Translucent	Thin flakes, Tough, Flexible	2.8–3.2	Biotite
	Black	Black, Silver, or Grey	1–2	Cleavage Sometimes Indistinct	Metallic or Submetallic	Opaque	Marks paper, Soils fingers, Slippery	2.23	Graphite

(*Contd.*)

Fracture Cleavage	*Streak*	*Colour*	*Hardness*	*Fracture Cleavage*	*Lustre*	*Diaphaneity*	*Other Properties*	*Specific Gravity*	*Mineral Name*
	Black	Brassy yellow	6–6.5	Conchoidal Fracture	Metallic	Opaque	Sometimes in Crystal Shapes	5.02	Pyrite
	Reddish	Red-brown, Black, Silver	5–6.5	Fracture	Metallic or Submetallic	Opaque	Sometimes Oolitic or Magnetic	5.56	Haematite
Fracture	Black	Black	6	Fracture	Metallic or Submetallic	Opaque	Strongly Magnetic	5.18	Magnetite
	Black	Brownish	4	Fracture	Metallic	Opaque	Weakly magnetic	4.58–4.65	Pyrrhotite
	Greenish Black	Brassy yellow	3.5–4	Fracture	Metallic	Opaque	Brittle	4.1–4.3	Chalcopyrite
	Black	Brassy with Iridescent Colours	3	Indistinct Cleavage	Metallic	Opaque	Iridescent Peacock Colours	5.0 –5.1	Bornite

Non-Metallic Minerals

Fracture Cleavage	*Streak*	*Colour*	*Hardness*	*Fracture Cleavage*	*Lustre*	*Diaphaneity*	*Other Properties*	*Specific Gravity*	*Mineral Name*
Cleavage	White or Colourless	Green to Black	6–7	One Direction Indistinct	Vitreous to dull	Transparent, Translucent	Typically Pistachio Green	3.35–3.4	Epidote
	Colourless	White, Grey, Pink, Clear, Green, Yellow	6–6.5	Two Directions At 90 degrees	Vitreous	Transparent, Translucent	Few if Any Striations	2.5–2.6	Orthoclase
	White	White, Grey Clear, Blue Green	6	Two Directions At 90 degrees	Vitreous	Transparent, Translucent	Striations On cleavage Faces	2.6–2.8	Plagioclase
	White	Colourless, Grey, White	5.5–6	One Direction Indistinct	Greasy to Vitreous	Transparent, Translucent	Softer than Quartz, Cleavage	2.6–2.65	Nepheline
	Greenish	Green, Grey Brown, Black	5–5.5	Two directions Intersects at 90 degrees	Vitreous to Dull	Translucent	Brittle	3.2–3.6	Augite
	Colourless	Brown, Dark green, Black	5–6	Two directions Intersects at 56 & 124 degrees	Vitreous	Translucent	Appears Fibrous or silky	3.0–3.4	Hornblende
	Yellow	Yellow, Brown	5–5.5	One Direction Indistinct	Dull to Admantine	Translucent	Appears Fibrous or silky	3.3–4.3	Goethite
	White	Green, brown Yellow, Pink Violet	5	Poor Cleavage in One direction	Vitreous	Transparent, Translucent	Brittle, Fractured Masses	3.1–3.2	Apatite
	White	Greenish	3–5	One Direction Indistinct	Greasy to Waxy	Transparent, Translucent	Variegated, Sometimes Fibrous	2.3	Serpentine

(*Contd.*)

Fracture Cleavage	*Streak*	*Colour*	*Hardness*	*Fracture Cleavage*	*Lustre*	*Diaphaneity*	*Other Properties*	*Specific Gravity*	*Mineral Name*
Cleavage	Brown	Green, Black	3.5–4	Perfect Cleavage in 6 directions	Resinous to Adamantine	Translucent	Brittle, Looks like Resin	3.9–4.1	Sphalerite
	White	Pink, White Grey, and others	3.5–4	3 direction, Rhombic Indistinct	Vitreous to Pearly	Transparent, Translucent	HCl fizz Only with Powder	2.85	Dolomite
	White	Any colour: Clear, Yellow Purple, Blue	4	Perfect Four Directions	Vitreous	Transparent, Translucent	Sometimes Fluorescent	3.18	Fluorite
	White	White, Grey	3–3.5	Perfect 3 directions Small faces	Vitreous to pearly	Transparent, Translucent	Very heavy for A non-metallic Mineral	4.3–4.6	Barite
	White	White	3	Perfect 3 directions, "rhombic"	Vitreous to pearly	Transparent, Translucent	Breaks rhombic Hcl reaction Double refraction	2.71	Calcite
	Brown	Dark green, Dark brown, Black	2.5–3	Perfect Cleavage in One direction	Non-metallic	Translucent	Thin flakes, Tough, Flexible	2.8–3.2	Biotite
	White	Yellow to Brown in thin sheets	2.5–3	Perfect in One direction	Vitreous to Pearly	Transparent	Frequently a Copper-like Lustre	2.68	Phlogopite
	Green	Greenish, Grey	2–2.5	Perfect in One direction Indistinct	Vitreous to Dull pearly	Transparent, Translucent	Foliated or Scaly Appearance	2.6–3.3	Chlorite
	White	White Yellowish, Silvery, etc.	2–2.5	Perfect Cleavage in One direction	Vitreous to Pearly	Transparent	Splits Into thin Sheets	2.7–3.0	Muscovite
	White	White, Grey, Yellowish	2–2.5	One direction But usually Indistinct	Dull, earthy	Translucent	Plastic when wet Crumbly when Dry	2.6	Kaolinite

(*Contd.*)

Fracture Cleavage	Streak	Colour	Hardness	Fracture Cleavage	Lustre	Diaphaneity	Other Properties	Specific Gravity	Mineral Name
Cleavage	White	White, Grey	2–2.5	Perfect 3 directions at 90 degrees	Vitreous to Pearly	Transparent, Translucent	Water soluble, Tastes salty	2.16	Halite
	White	White, Grey	1.5 – 2	Perfect in One direction 2 indistinct	Vitreous to Pearly	Transparent, Translucent	Sometimes as Fibrous Masses	2.3–2.4	Gypsum
	White	White	1	One direction But usually Indistinct	Pearly to Greasy	Translucent, Opaque	Feels greasy, Tiny flakes Upon rubbing	2.7–2.8	Talc
Fracture	Colourless	Brown, Pink	9	Fracture, Sometimes with parting	Vitreous to Adamantine	Transparent, Translucent	Sometimes has Hexagonal Crystals	4.02	Corundum
	Colourless	Black	7–7.5	Fracture	Vitreous	Transparent, to Opaque	Sometimes Striations	3.02–3.2	Tourmaline
	Colourless	Usually red, Green, Black or any colour	6.5–7.5	Fracture	Vitreous to Resinous	Transparent, to Opaque	Sometimes Isometric Crystals	3.5–4.3	Garnet
	Colourless	Any colour	7	Conchoidal Fracture	Vitreous to Greasy	Transparent to Translucent	Sometimes has Hexagonal Crystals	2.65	Quartz
Fracture	Colourless	Olive, Green	6.5–7	Conchoidal Fracture	Vitreous	Transparent to Translucent	Frequently as granular Masses	3.27–4.27	Olivine
	Reddish	Red-brown, Silver, Black	5–6.5	Fracture	Dull	Opaque	Sometimes Oolitic or Magnetic	5.26	Heamatite
	Yellowish brown	Yellow, Brown	4–5.5	Fracture	Dull	Translucent, Opaque	Earthy Colour and Appearance	2.7–4.3	Limonite
	White	Yellow, Red, Brown	1 – 3	Fracture	Dull earthy	Translucent, Opaque	Pisolitic	2.00 - 2.55	Bauxite

appendix 10

Distinctive Properties of Metallic and Non-Metallic Minerals

Hardness, cleavage and other physical properties have been taken into consideration to draw a distinction between the metallic and non metallic minerals.

Metallic Minerals

Mineral	*Hardness*	*Streak*	*Other Properties*
Pyrite	> 5.5; scratches glass, steel	Dark grey	Dark grey colour, cubic crystals
Magnetite	> 5.5; scratches glass, steel	Dark grey	Grey colour, magnetism
Haematite	> 5.5; scratches glass, steel	Red-brown	Various colours,
Chalcopyrite	> 3.5, < 5.5; scratched by steel, but not by penny	Dark grey	Golden yellow colour No cleavage
Galena	> 2.5, < 3.5; scratched by penny, but not fingernail	Dark grey	High density, Cubic cleavage
Graphite	< 2.5, scratched by fingernail	Dark grey	Greasy feel

Nonmetallic Minerals

Mineral	*Hardness*	*Cleavage*	*Other Properties*
Quartz	> 5.5; scratches glass	None, conchoidal fracture	Six-sided prisms occur, translucent to transparent, many colours, vitreous lustre
Garnet	> 5.5; scratches glass	None	Small, equant crystals; red, brown, green, or pink
Plagioclase Feldspar	> 5.5; scratches glass	Two directions 90°	Blocky crystals; striations on some cleavage planes; white to dark
Potassium Feldspar	> 5.5; scratches glass	Two directions 90°	Blocky crystals; exsolution lamellae, white to pink
Olivine	> 5.5; scratches glass	None	Always green, equant crystals
Amphibole (Hornblende)	< 5.5, > 3.5; scratched by steel, but not by penny	None	Crystals with prismatic cleavage

(*Contd.*)

Mineral	*Hardness*	*Cleavage*	*Other Properties*
Serpentine	< 5.5, > 3.5; scratched by steel, but not by penny	None	Variable hardness; white to green to black, greasy
Fluorite	< 5.5, > 3.5; scratched by steel, but not by penny	Cleavage in four directions	Cubic crystals; many colours
Calcite	< 3.5, > 2.5; scratched by penny, but not fingernail	Three sets of cleavage in different direction	Vitreous; effervesces in HCl
Biotite	< 3.5, > 2.5; scratched by penny, but not fingernail	Two sets of cleavage	Dark colour
Muscovite	< 3.5, > 2.5; scratched by penny, but not fingernail	Two sets of cleavage	White in colour and may be softer.
Gypsum	< 2.5, scratched by fingernail	One set of cleavage	Milky white

appendix 11

Identification of Rocks in Hand Specimen

Igneous Rocks

Grain Size	*Colour*	*Other properties*	*Mineral Composition*	*Name of rock*
Fine	Melanocratic	Glassy appearance	Lava glass	Obsidian
Fine	Leucocratic	Many small bubbles	Lava froth from sticky lava	Pumice
Fine or mixed	Leucocratic	Contains quartz	High-silica lava	Felsite
Fine or mixed	Mesocratic	Between felsite and basalt	Mesocratic-silica lava	Andesite
Fine or mixed	Melanocratic	Has no quartz	Low-silica lava	Basalt
Mixed	Mesocratic	Large grains in fine-grained matrix	Large grains of feldspar, quartz, pyroxene or olivine	Lamphrophyre
Coarse	Leucocratic	Wide range of colour and grain size	Feldspar and quartz with minor mica, amphibole or tourmaline	Granite
Coarse	Leucocratic	Like granite but without quartz	Feldspar with minor mica, amphibole or pyroxene	Syenite
Coarse	Leucocratic to mesocratic	Little or no alkali_feldspar	plagioclase and quartz with melanocratic minerals	Tonalite
Coarse	Mesocratic to melanocratic	Little quartz	Low-calcium plagioclase and melanocratic miner-als	Diorite
Coarse	Mesocratic to melanocratic	No quartz; may have olivine	High-calcium plagioclase and melanocratic miner-als	Gabbro
Coarse	Melanocratic	Dense; always has olivine	Olivine with amphibole and/or pyroxene	Peridotite
Coarse	Melanocratic	Dense	Mostly pyroxene with olivine and amphibole	Pyroxenite
Coarse	Green	Dense	At least 90% olivine	Dunite
Very coarse	Mesocratic	Usually in small intrusive bodies	Typically granitic	Pegmatite

Sedimentary Rocks

Hardness	*Grain Size*	*Composition*	*Other Properties*	*Name of Rock*
Hard	Coarse	Quartz and feldspar	White to brown	Sandstone
Hard	Coarse	Quartz and feldspar	Usually very coarse clastic texture	Arkose
Hard or soft	Mixed	Mixed sediment with rock grains and clay	Grey or melanocratic and “dirty”, clastic texture	Wacke/greywacke
Hard or soft	Mixed	Mixed rocks and sediment	Round rocks in finer sediment matrix, clastic texture	Conglomerate
Hard or soft	Mixed	Mixed rocks and sediment	Sharp pieces in finer sediment matrix, clastic texture	Breccia
Hard	Fine	Very fine sand and no clay	Feels gritty on teeth, clastic texture	Siltstone
Hard	Fine	Chalcedony	No fizzing with acid, clastic texture	Chert
Soft	Fine	Clay minerals	Splits in layers, clastic texture	Shale
Soft	Fine	Carbon	Black; burns with tarry smoke, clastic texture	Coal
Soft	Fine	calcite	fizzes with acid, non-clastic texture	Limestone
Soft	Coarse fine	dolomite	no fizzing with acid unless powdered, non-clastic texture	Dolomite
Soft	Coarse	Fossil shells	Mostly pieces, non-clastic texture	Coquina
Very soft	Coarse	halite	Salt taste, non-clastic texture	Rock salt
Very soft	Coarse	gypsum	White, tan or pink, non-clastic texture	Gypsum

Metamorphic Rocks

Foliation	*Grain Size*	*Colour*	*Other Properties*	*Name of Rock*
Foliated	Fine	Leucocratic	Very soft; greasy feel	Soapstone
Foliated	Fine	Melanocratic	Soft; strong cleavage	Slate
Nonfoliated	Fine	Melanocratic	Soft; massive structure	Argillite
Foliated	Fine	Melanocratic	Shiny; crinkly foliation	Phyllite
Foliated	Coarse	Mixed melanocratic and leucocratic	Crushed and stretched fabric; deformed large crystals	Mylonite
Foliated	Coarse	Mixed melanocratic and leucocratic	Wrinkled foliation; often has large crystals	Schist
Foliated	Coarse	Melanocratic	Banded	Gneiss
Foliated	Coarse	Melanocratic	Distorted "melted" layers	Migmatite
Foliated	Coarse	Melanocratic	Mostly hornblende and plagioclase	Amphibolite
Non-foliated	Fine	Melanocratic	Soft; shiny, mottled surface	Serpentinite
Non-foliated	Fine or coarse	Melanocratic	Dull and opaque colours, found near intrusions	Hornfels
Non-foliated	Coarse	Melanocratic	Dense; garnet and pyroxene	Eclogite
Non-foliated	Coarse	Leucocratic	Soft; calcite or dolomite by the acid test	Marble
Non-foliated	Coarse	Leucocratic	Quartz with granoblastic texture	Quartzite

appendix 12

Optical Properties of Some Selective Minerals and Rocks

Optical Properties	*Minerals*				
	Quartz	*Orthoclase*	*Microcline*	*Plagioclage*	*Muscovite*
Colour	Colourless	Colourless	Colourless	Colourless	Colourless
Refractive Index (RI)	Low	Low	Low	Moderate	Moderate
Cleavage	Absent	2 sets	2 sets	2 sets	1 set
Shape	Usually anhedral	Usually anhedral to subhedral	Usually anhedral	Subhedral (tabular)	Subhedral (flaky)
Alteration	Absent	Kaolinised	Kaolinised	Kaolinised	Cholritization
Isotropic/Anisotropic	Anisotropic	Anisotropic	Anisotropic	Anisotropic	Anisotropic
Interference Colour	First order/ yellow	First order/ grey	First order/ grey	First order/ yellow	High order
Birefringence	Low	Low	Low	Low	High
Extinction	Cannot be measured	Inclined	Inclined	Inclined	Straight
Twinning	Absent	Absent	Cross hatching	Lamillar	Absent

Optical Properties	*Minerals*				
	Hornblende	*Calcite*	*Augite*	*Garnet*	*Kyanite*
Colour	Dark green	Colourless	Colourless	Pink	Colourless
Refractive Index (RI)	Moderate to high	Low and high twinkling effect	High	Very high	High
Cleavage	2 set (56°/124°)	3 sets	2 sets (87°/93°)	Absent	1 set
Shape	Usually subhedral	Usually anhedral	Usually anhedral	Anhedral	Subhedral
Alteration	Absent	Absent	Absent	Absent	Altered
Isotropic/Anisotropic	Anisotropic	Anisotropic	Anisotropic	Isotropic	Anisotropic
Interference Colour	High order	High order	High order	High order	Second order blue
Birefringence	High	Very high	Moderate	Moderate	Moderate
Extinction	Straight	Symmetrical	Inclined	Inclined	Inclined
Twinning	Absent	Absent	Absent	Absent	Absent

Optical Properties	*Igneous Rocks*				
	Granite	*Rhyolite*	*Gabbro*	*Basalt*	*Dolerite*
Colour	Leucocratic	Melanocratic	Melenocratic	Melenocratic	Mesocratic
Shape	Subhedral anhedral	Usually anhedral	Subhedral to anhedral	Subhedral	Subhedral to anhedral
Alteration	Present	Absent	Present	Present	Present
Mineral composition	Quartz, feldspar, biotite and hornblende	Quartz, feldspar,	Augite, plagioclase and olvine	Augite, plagioclase and olvine	Augite and plagioclase
Texture	Panidiomorphic	Directive	Ophitic	Sub-ophitic	Sub-ophitic
Ground mass	Medium to fine-grained	Fine-grained	Medium to coarse-grained	Fine-grained	Medium- to fine-grained
Mode of origin	Plutonic	Volcanic	Plutonic	Volcanic	Hypabassal

Optical Properties	*Sedimentary Rocks*				
	Sandstone	*Limestone*	*Shale*	*Breccia*	*Calogramerate*
Colour	Leucocratic	Mesocratic	Melenocratic	Mesocratic	Mesocratic
Shape	Subhedral to anhedral	Subhedral to anhedral	Anhedral	Anhedral	Subhedral to anhedral
Alteration	Present	Present	Negligible	Negligible	Present
Mineral composition	Quartz, feldspar and subordinate biotite	Calcite, dolomite and very little quartz	Kaoline, illite and quartz	Quartz and feldspar	Quartz, feldspar, haematite and very little kaoline
Texture	Clastic (heterogeneous)	Non-clastic (homogeneous)	Clastic (homogeneous)	Clastic (heterogeneous)	Clastic (heterogeneous)
Matrix	Present (feldspar)	Absent	Present (kaoline, feldspar)	Present (feldspar, quartz)	Present (feldspar, quartz)
Cement	Absent	Present	Absent	Absent	Absent
Mode of origin	Clastic	Non clastic	Clastic	Clastic	Clastic

Optical Properties	*Metamorphic Rocks*				
	Quartize	*Marble*	*Mica schist*	*Gneiss*	*Slate*
Colour	Leucocratic	Mesocratic	Melanocratic	Mesocratic	Leucocratic
Shape	Anhedral	Subhedral to anhedral	Subhedral	Subhedral to anhedral	Subhedral
Alteration	Absent	Present	Present	Negligible	Present
Mineral composition	Quartz and little feldspar	Calcite, dolomite and very little quartz	Muscovite, biotite and quartz	Quartz, feldspar and mica	Quartz, feldspar and kaoline
Texture	Granoblastic	Granoblastic (crystalline)	Schistose	Gneissose	Slaty
Binding minerals	Quartz	Calcite	Muscovite and biotite	Quartz	Feldspar
Mode of origin	Regional metamorphism	Regional metamorphism and recrystallization	Regional metamorphism	Regional and contact metamorphism	Regional metamorphism

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