1. GEOLOGY

It is the science which is devoted to the study of the earth and its components. It deals with all features of the earth's surface and with origin, composition, structure, and inhabitant of the earth.

1.1 The Science of Geology

The word Geology is derived from the Greek "Gea" the earth and "ology" is the science, thus it is "Earth Science". Geology is the science study and deals with:

- the solid earth that examines the earth, its form and composition and the changes which it has undergone and is going.
- involves studying the materials that make up the earth, the features and structures found on Earth as well as the processes that act upon them.
- deals with the study of the history of all life that's ever lived on or is living on the earth now. Studying how life and our planet have changed over time is an important part of geology.
- deals with many practical questions about our physical environment, what forces produce different geological structures, understanding many processes that operate beneath and upon its surface.
- the explanation of the phenomena, structures in the globe in terms of the general laws recognized by the chemists, physicists, biologists and mathematicians.

1.2 Branches of Geology:

The subject of geology is divided into several branches which are as follows:

1. **Physical Geology**: it is concerned with the work of natural processes which bring changes upon earth's surface.
2. **Petrology**: deals with different kinds of rocks and its formation and properties.
3. **Mineralogy**: it includes the study of minerals.
4. **Structural Geology**: it includes the study of the structures of the rocks in the earth's crust as a mass.
5. **Stratigraphy**: it is concerned with study of stratified rocks and their correlations.
6. **Paleontology**: it deals with the study of fossils. It the study of fossils (preserved bones or shells) as a way of getting information about the history of life on Earth and the structure of rocks.

7. **Historical Geology**: it gives us a picture of the land, seas, climates, and the life of early times upon the earth.
8. **Economic Geology**: it deals with the study of minerals and other earth materials of economic importance.
9. **Mining geology**: it is concerned with the study of application of geology to mining engineering.
10. ***Engineering Geology****: it includes the application of geology in the engineering fields (and specifically in civil engineering).*

1.3 Engineering Geology

Engineering Geology is defined by the association of Engineering Geologists as the discipline of applying geologic data, techniques, and principles to the study of both:

a) Naturally occurring rock and soil materials, and surface and sub-surface fluids.
b) The interaction of introduced materials and processes with the geologic environment.

So that geological factors affecting the planning, design, construction, operation and maintenance of engineering structures (fixed works) and the development, protection and remediation of ground-water resources are adequately recognized, interpreted and presented for use in engineering and related practice.

1.4 Relationship between the Engineering Geologists and Civil Engineers

The geologist presents geological data and interpretations for use by the civil engineer. The civil engineers should deal mostly with the soil and rocks in addition to other construction materials such as timbers, steel, and concrete. In a great majority of civil engineering, projects involve the soils and rocks almost directly in contact with the project.

The importance of engineering geology in civil engineering may briefly be summarized as follows:

1. Geology is important for successful geotechnical engineering practice. One of the primary tasks of a geotechnical engineer is to understand the character of the soil and rocks at a site.

2. Soils, derived from the weathering of rocks, are very complex materials and vary widely. There is no certainty that a soil in one location will have the same properties as the soil just a few centimeters away. Unrealized geological formations and groundwater conditions have been responsible for failures of many geotechnical systems and increased construction costs.

1.5 Development of Engineering Geology

The present science of geology owes much of its origin to the civil engineers working in the eighteenth century. These engineers, while constructing the major engineering works associated with the industrial revolution, had the opportunity to view and explore excavations in rocks and soils. Some, intrigued by what they saw, began to speculate on the origin and nature of rocks, and the relationships between similar rocks found in different places. Their ideas and theories, based on the practical application of their subject, formed the groundwork for the development of geology as a science.

Civil engineers are interest in geology often comes from a 'need to know'. They were confronted with real engineering problems which could only be solved with the help of both a knowledge and understanding of the ground conditions with which they were confronted.

By the end of the nineteenth century the majority of civil engineers knew relatively little about geology, and very few geologists were concerned about, or interested in, its engineering applications. This widening division between geology and engineering was partly bridged in the nineteenth and early twentieth century by the development of soil mechanics by engineers such as Coulomb and Rankine, who developed methods of calculating the deformations of earth masses under the stresses imposed by engineering works.

Failures of some engineering works that there was often a lack of appreciation of the importance of geological conditions in engineering design. Such failures emphasized the need for expert assessment of geological conditions on civil engineering sites and there was, by the 1940s, a trend for civil engineers to employ geologists in an advisory capacity.

1.6 Aims of Engineering Geology

The philosophy of engineering geology is based on three simple premises. These are:

1. All engineering works are built in or on the ground.
2. The ground will always, in some manner, react to the construction of the engineering work.
3. The reaction of the ground (its engineering behavior) to the particular engineering work must be accommodated by that work.

The problem is to assess the magnitude and nature of the reaction of the ground to both the construction and the operation of the project. This ground reaction, the engineering behavior of the ground, could be small and insignificant, or massive and perhaps disastrous, depending on the nature of site geology and the engineering work. It must, however, be known in order to fulfill the third point, namely that the engineering work be designed so that it can be constructed and will operate within the bounds of the site geological conditions without sustaining significant damage as the result of the reaction of the ground.

To determine the engineering behavior of the ground, the engineering properties of the ground mass and the proposed design of the engineering work must be known.

1.7 Relevance of Geology to Civil Engineering

The application of geological principles in engineering investigations has great benefits for engineering sciences and vice versa for geological sciences in case of well drilling. So, both are closely related and important in site investigation. The cooperation between geologists and civil engineers resulted in introduction of "Soil Mechanics" science. Soil mechanics is the branch of science that deals with the study of the physical properties of soil and the behavior of soil masses subjected to various types of forces.

Soils engineering is the application of the principles of soil mechanics to practical problems. Geotechnical engineering is the subdivision of civil engineering related to site investigation that involves natural materials found close to the surface of the earth. It includes the application of the principles of soil mechanics and rock mechanics to the design of foundation, retaining structures and earth structures.

In a major engineering project, geological proposals might be carried out and reported on by a consultant specializing in geology, geophysics or engineering (with a detailed knowledge of soil or rock mechanics). However, even where the services of a specialist consultant are employed, an engineer will have overall supervision and responsibility for the project. Therefore, the civil engineers must therefore have enough understanding of geology for the following reasons:

1. To know how and when to use the expert knowledge of consultant, and to be able to read their reports intelligently, judge their reliability, and evaluate how the conditions described might affect the project.
2. In some cases, the engineer can recognize common rock types and simple geological structures, and knows where he can obtain geological information for his preliminary investigation.
3. When reading reports, or studying geological maps, he must have a complete understanding of the meaning of geological terms and be able to grasp geological concepts and arguments.
4. Most civil engineering projects involve some excavation of soils and rocks, or involve loading the earth by building on it.
5. In some cases, the excavated rocks may be used as construction material, and in others, rocks may dorm a major part of the finished products, such as a motorway cutting or the site for a reservoir.
6. The feasibility, the planning and design, the construction and costing, and the safety of a project may depend critically on the geological conditions where the construction will take place.
7. In modest projects or in those involving the redevelopments of a limited site, the demand on the geological knowledge of the engineer or the need for geological advice will be less, but are never negligible. Site investigation by boring and by testing samples may be an adequate preliminary to construction in such cases.
8. Besides, the knowledge about geological works of rivers and the occurrences of underground water are required.
9. The exploration of a site to assess the feasibility of a project, to plan and design appropriate foundation, and to draw up bills of quantities for excavation.

2. EARTH CRUST AND MINERALS

2.1 Description of the Earth Profile

The Earth has an average radius of 6378 km and a mean mass density of 5.527 g/cm³ compared with a mean mass density of soil particles of 2.7 g/cm³ and water of 1.0 g/cm³. Studies from elastic waves generated by earthquakes have shown that the earth has a ***core*** of heavy metals, mostly iron and nickel, of mass density 8 g/cm³ surrounded by a ***mantle***. As shown in Figure 2-1, the mantle consists of two parts, upper mantle, and lower mantle. The upper mantle lies between (35-650) km depth and made of solid rock while the lower mantle lies between (650-2890) km depths and made of molten rock. Above the upper mantle is the ***crust***, which may be as much as 50 km thick in the continental areas and as little as 7 km thick in oceanic areas.

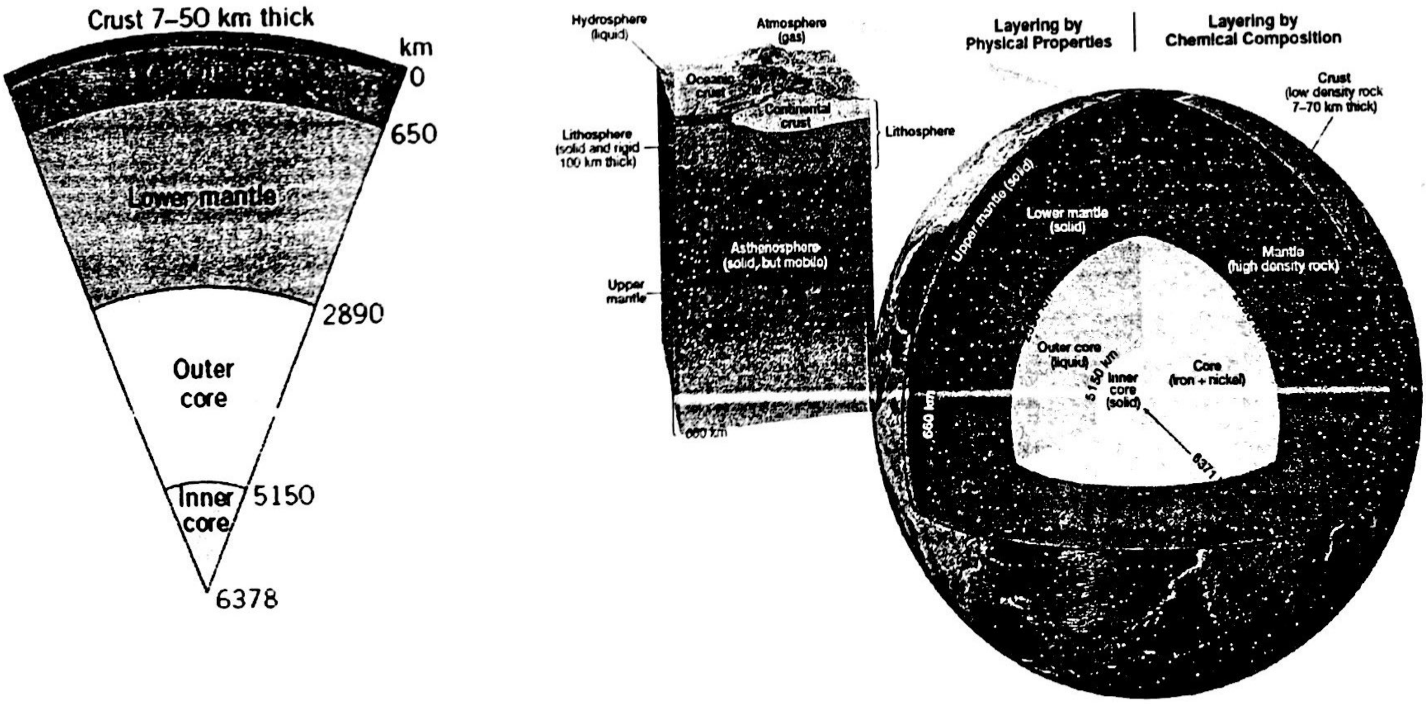


FIGURE 2-1: A SECTOR OF THE EARTH.

2.2 Description of the Earth Crust

The earth crust consists mainly of two layers as shown in Figure 2-2:

- ***Sial or Granitic layer***: is composed of less dense materials. It is rich in silica (SiO_2) and alumina (Al_2O_3) and similar in composition of granite rocks with an average density of 2.7 gm/cm³ and average thickness of 25 km.
- ***Sima or Basaltic layer***: is made up of dense, dark colored materials which is rich in magnesia (MgO) plus silica and it is similar to those which comes out of the volcanoes with an average density of 3.0 gm/m³ and average thickness of 20 km.

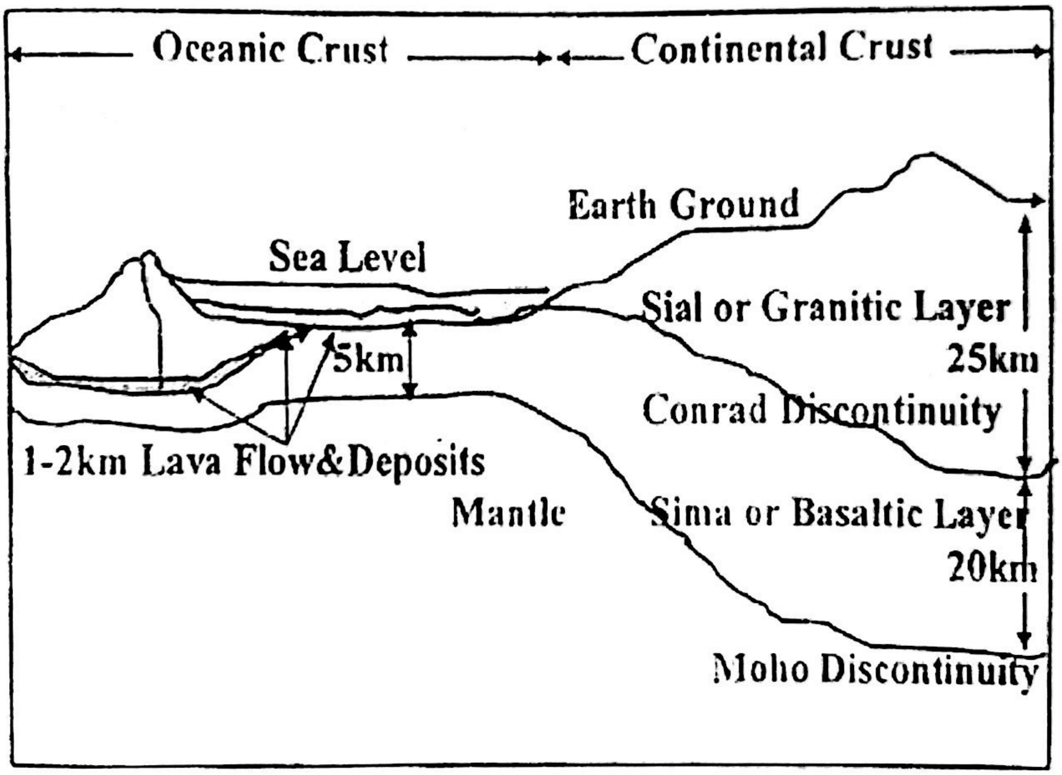


FIGURE 2-2: EARTH CRUST PROFILE

2.3 Minerals

2.3.1 Definition

The mineral is a naturally occurring inorganic substance which has definite chemical composition and definite atomic structure. Minerals are most commonly associated with rocks due to the presence of minerals within rocks. These rocks may consist of one type of mineral, or may be an aggregate of two or more different types of minerals. The minerals may be divided into two groups:

i. Rock forming minerals: are those which are found in abundance in the rocks of the earth's crust
ii. Ore-forming minerals: are those which are of economic value, and which do not occur in abundance in rocks

In nature there are many minerals: around 2000 species are known. Some of them are very rare, while some others are very popular. But only around ***thirty*** of them compose the Earth's crust rocks. The minerals which occur in common rocks are small in numbers and they are divided into the following groups:

1. Oxides: Quartz, Magnetite, Hematite, limonite.
2. ***Carbonates: Calcite ($CaCO_3$).***
3. Sulphides: Pyrite (Galena).
4. ***Sulphates: Gypsum ($CaSO_4.2H_2O$).***
5. ***Chlorides: Rock salt ($NaCl$).***
6. Silicates: Feldspars, Mica, Hornblende, Augite, Olivine.

2.3.2 Identification of minerals

Common minerals can be identified readily, if their ordinary physical properties are known. These include such properties as color, streak, luster, hardness, cleavage, fracture, form, specific gravity, odor, feel, fluorescence, phosphorescence, magnetism, and crystal form.

The correct identification of minerals is made with polarizing microscope. This involves grinding the minerals or rocks into very thin slices and allowing polarized light to pass through them. In this way, their optical properties are studied and the mineral are identified. Opaque minerals are studied under microscope by reflected light. In this course, it will focus on the physical properties of minerals.

- ***Color***

  Some minerals possess a characteristic color e.g. the lead grey of Galena, the black of Magnetite, and the green of Chlorite. But in other cases, such as Quartz, the color is variable and cannot be relied on as a guide to identify minerals. The variation in the color of a mineral may be due to: (a) isomorphs variations in composition, (b) minute colored inclusion, and (c) a small amount of some substance in solid solution.

- ***Streak***

  Streak is the color of mineral powder. The minerals are rubbed against unglazed porcelain plate (called streak plate) to obtain the streak. In some cases, the color of the streak differs remarkably from the color of the mineral. For example, the color of the Pyrite is brass yellow and its streak is dark green.

- ***Luster***

  Luster is the appearance of a mineral surface in reflected light. The various types of luster are as follows:

  i. Metallic luster: it is the luster exhibited by metals, e.g. Pyrite, Galena etc.
  ii. Vitreous luster: it is the luster exhibited by the broken surface of glass, e.g. Quartz.
  iii. Pearly luster: it is the luster exhibited by pearls, e.g. Mica.
  iv. Silky luster: it is the luster exhibited by silk fibers, e.g. Asbestos.
  v. Resinous luster: it is the luster exhibited by resin, e.g. Serpentine.
  vi. Adamantine: it is the luster exhibited by Diamonds.
  vii. Dull or earthy luster: minerals which have no luster, e.g. Kaolin.

- ***Hardness***

  The hardness of a mineral is its resistance to scratching. It is determined by comparison with the standard minerals of the "Mohs Scale of Hardness". In this scale, there are ten minerals which are arranged in the order of their increasing hardness. The Moh's scale of hardness is given in Table 2-1. Note that a finger nail will scratch up to 2.5 (i.e. not Calcite), a window glass will scratch up to 5 (i.e. not Feldspar), and a pen knife will scratch up to about 6.5 (i.e. not Quartz). These can be used conveniently for determining the approximate hardness of minerals.

TABLE 2-1: MOH'S SCALE OF HARDNESS

1	Talc	Scratched by a finger nail
2	Gypsum	
3	Calcite	Scratched by a knife
4	Fluorite	
5	Apatite	
6	Orthoclase	Scarcely scratched by a knife
7	Quartz	Not scratched by a knife
8	Topaz	
9	Corundum	
10	Diamond	

- ***Cleavage***

  It is the property of minerals to break more easily with smooth surfaces in certain directions. Cleavage is the property which is related to the atomic arrangement within the mineral. Galena has three cleavages at right angles forming cubes. Mica cleaves in one direction only, while in Calcite, cleavage planes meet in acute and obtuse angles giving a rhombohedral form. Quartz has no cleavage.

- ***Fracture***

  The nature of a broken surface of a mineral is known as "fracture"; but the breaking should be in any other direction than the cleavage. Unlike cleavage, fracture does not produce smooth planes. The various types of fracture are as follows:

  i. Uneven Fracture: when the broken surface is rough or irregular, e.g. Apatite.
  ii. Even Fracture: when the mineral breaks with a flat surface, e.g. Flint.
  iii. Conchoidal Fracture: when the mineral breaks with curved surfaces often with concentric markings like a shell, e.g. Quartz.
  iv. Hackly Fracture: when the broken surface has a small sharp irregularity like broken metal, e.g. Native Copper.

- ***Form***

  Minerals may occur in the form of well-developed crystals. Besides these, the minerals may occur in a number of different forms. The important forms are as follows:

  i. Acicular: minerals showing needle like crystals, e.g. Natroflint.
  ii. Fibrous: minerals showing an aggregate of fibers, e.g. Asbestos.
  iii. Columnar: minerals which occur as columnar crystals, e.g. Tourmaline.

iv. Bladed: minerals showing this form occur as small knife blades, e.g. Kyanite.

v. Foliated: minerals having thin separable lamelle, e.g. Mica.

vi. Granular: minerals which occur as aggregate of grains, e.g. Chromite.

- ***Specific Gravity, Gs***

  It is the weight of a mineral compared with the weight of an equal volume of water. Thus, a mineral with specific gravity 4, is four times as heavy as water.

- ***Odor***

  Some minerals give a characteristic smell when rubbed, breathed upon, or heated. The chief types of odor are as follows:

  i. Arsenical: like the odor of garlic (Orpiment).

  ii. Sulphurous: like the odor of burning sulphur (Pyrite).

  iii. Argillaceous: like odor of clay.

- ***Feel***

  Feel is the sensation up on touching or handling minerals. The different types of feel are "greasy", "soapy", "rough", and "harsh".

- ***Fluorescence***

  Some minerals when exposed in sunlight or UV light produce a color, quite different from their own, and from that of the existing light. Thus, green, or colorless fluorite shows a blue or purple color in sunlight.

- ***Magnetism***

  A magnet attracts a few minerals. Of these minerals, magnetite is the most common examples, which possesses attracting power and polarity is called lodestone.

3. ROCKS: TYPES, CHARACTERISTICS AND ENGINEERING PROPERTIES

The rocks may be defined as aggregates of minerals. They form a major part of the earth crust. Based on their origin and formation, rocks can be divided into three basic types: ***igneous, sedimentary, and metamorphic***. The rock cycle in nature is illustrated in Figure 3-1 and Figure 3-2.

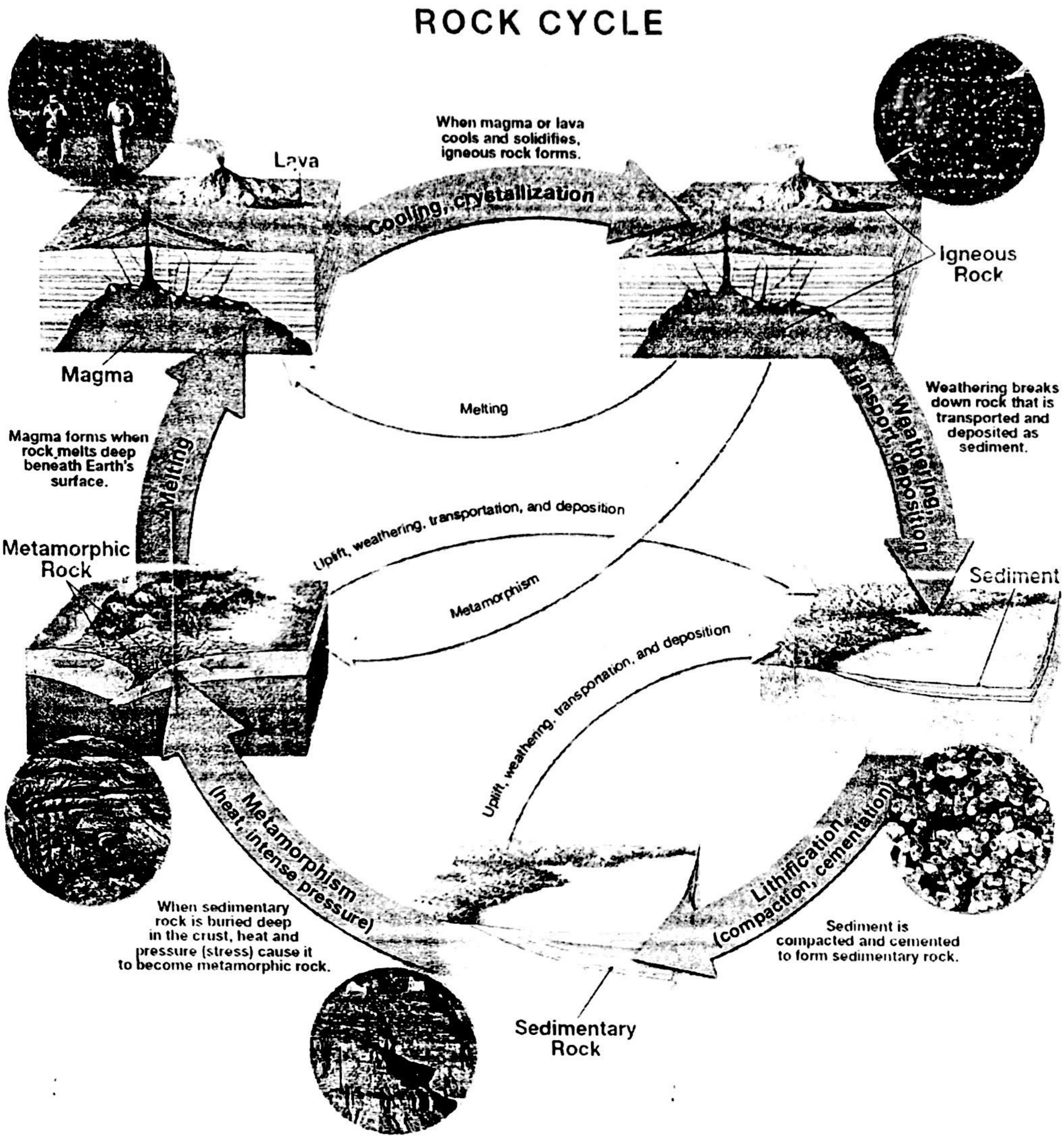


FIGURE 3-1: ROCK CYCLE IN NATURE.

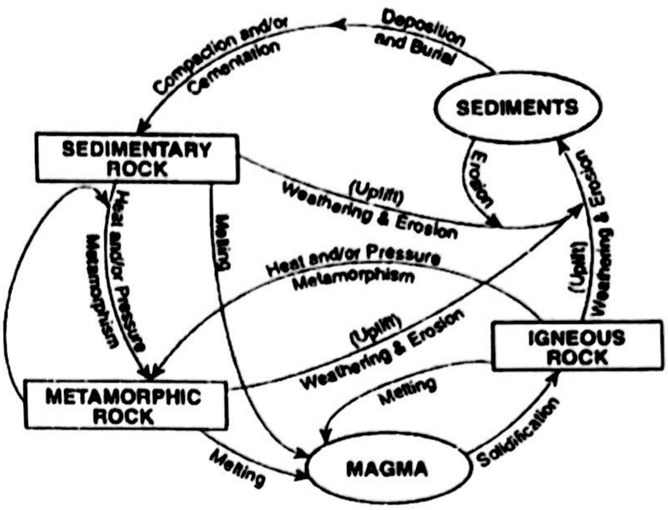


FIGURE 3-2: ROCK CYCLE IN NATURE (SIMPLIFIED SKETCH).

3.1 IGNEOUS ROCKS

Igneous rocks represent about 25% of earth surface rocks but 95% of earth ***crust*** rocks. Those rocks formed by ***cooling*** and ***solidification*** of hot molten mineral matter, known as ***Magma*** below the surface of the earth. If this material comes to the earth surface, it is termed as ***Lava*** which is similar to magma except that most of the gaseous component has escaped.

The process by which crystals are formed after cooling is called ***Crystallization.*** The rocks which result when lava solidifies are classified as ***extrusive or volcanic.*** The magma is not able to reach the surface eventually crystallize at depth and producing ***intrusive or plutonic rocks.***

3.1.1 Acid and Basic Igneous Rocks

The composition of igneous rocks depends upon the composition of the magma; from which they are originated. Magmas are of two types:

- ***Acid Magma:*** It is rich in ***Si, Na, K*** and poor in ***Ca, Mg,*** and ***Fe***. They are light in color, low in specific gravity (2.7), and have high proportion of minerals like quartz, feldspar (alkali felspars) and some mica. An example of acid rock is granite.
- ***Basic Magma:*** It is rich in **Ca**, ***Mg, Fe***, and poor in ***Si, Na,*** and ***K***. They are usually dark in color (often black), relatively high in specific gravity (3.0), and are rich in minerals like Augite, hornblende, plagioclase, and iron. An example of basic rock is basalt.

3.1.2 Igneous Rocks Based on Silica Content

Based on their ***silica content***, the igneous rocks can be divided as:

a) ***Ultra-basic Rocks***: These contain ***less*** than 45% silica, e.g. peridotite.
b) ***Basic Rocks***: These contain silica between 45% and 55%, e.g. basalt.
c) ***Intermediate Rocks***: These contain silica between 55% and 65%, e.g. diorite.
d) ***Acid Rocks***: These contain ***more*** than 65% of silica, e.g. granite.

3.1.3 Textures of Igneous Rock

Texture means the ***size, shape***, and ***arrangement*** of mineral grains in a rock. The ***cooling rate*** of the magma ***governs*** the texture of a rock. In general, ***slower*** is the rate of cooling, ***the coarser*** (large size) is the grain of the rock. It is because; in slow cooling, more opportunity is provided for crystals to grow to a large size. On the other hand, the glassy texture results from extremely rapid cooling. Between these two extremes there are fine grained and cryptocrystalline textures. There is a wide range of size of grains for igneous rocks as shown in Table 3-1. The important textures found in igneous rocks are as follows.

1. **Holo-crystalline**: a rock is made up entirely of crystalline material.
2. ***Coarse Grained**: If the average grains or crystals of the minerals are more than 5 mm in diameter, the rock is said to be coarse grained.*
3. ***Fine Grained**. If the grains are like granulated sugar where their average diameter is less than one millimeter, the rock is said to be fine grained.*
4. **Cryptocrystalline.** If the crystals are invisible to the naked eyes, and visible only under the microscope the rock is said to be cryptocrystalline.
5. **Glassy**: If the magma is consolidated as an amorphous mass without any crystallization, the rock is said to be glassy.
6. **Porphyritic**: sometimes an igneous rock shows relatively large crystals in a matrix, which is more finely crystalline or even glassy. Such a texture is called porphyritic texture and the rock is called a porphyry. The large crystals in a porphyry are called phenocrysts and the finely crystalline uniform background is called the groundmass.
7. **Vesicular**: volcanic rocks which have a glassy matrix often contain gas cavities, called Vesicles. Such rocks are said to have vesicular texture.

TABLE 3-1: THE RELATION OF GRAIN SIZE AND COOLING RATE OF IGNEOUS ROCKS

Grain Size	Dimension	Cooling Rate
Very coarse-grained	> 30 mm	Very slow
Coarse-grained	> 5 mm	Slow
Medium	1-5 mm	Medium
Fine	< 1 mm	Rapid
Very fine	Not seen with eyes	Very rapid
Glassy	Noncrystalline	Intensively very rapid
Vesicular	Noncrystalline	Vesicles

3.1.4 Classification of Igneous Rocks According to Location

Based on texture and mode of occurrence, the igneous rocks have been classified into three groups:

Plutonic (Intrusive) Rocks: Plutonic rocks are formed when ***magma cools*** slowiy at ***great depth*** with the retention of the volatiles. The textures of such rocks are coarse grained.

Volcanic (Extrusive) Rocks: Volcanic rocks are formed when the magma erupts at the earth surface and cools rapidly. The texture of such rocks is fine grained or glassy. Volcanic rocks often contain gas cavities called vesicles.

Hypabyssal Rocks: Hypabyssal rocks are formed when consolidation of ***magma*** takes place ***very close to the earth surface.***

3.1.5 Mode of Occurrence of Igneous Rocks

Batholith: Batholiths are large intrusive igneous bodies which are granitic in composition. In plain view their outline is irregular and the area of outcrop ***exceeds 100 square kilometers.*** Most batholiths increase in size with depth and they are thought to be bottomless (Figure 3-3).

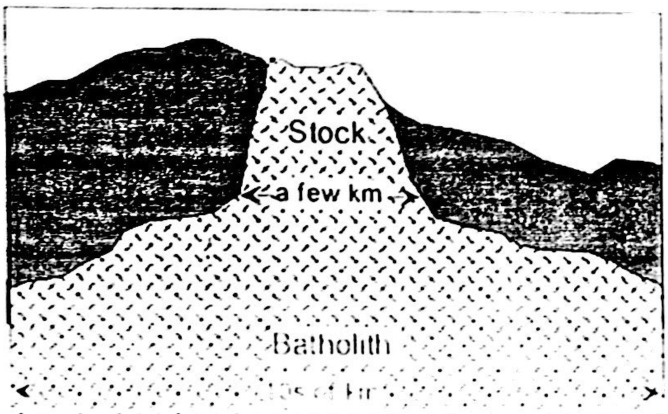


FIGURE 3-3: BATHOLITH.

Stock and Boss: A stock is a small batholith. Its area of outcrop is ***less than100*** square kilometer. A stock having a circular outcrop is called a" boss".

Lopolith: It is a lenticular igneous body which is bent or sagged downward into a basin like shape (Figure 3-4)

Laccolith: Laccoliths arc plano-convex intrusive body which cause the overlying beds to arch in the shape of dome (Figure 3-5). A laccolith may be 2 to 3 km in diameter and several hundred meters in thickness. It differs from batholiths in being much smaller and having a known floor.

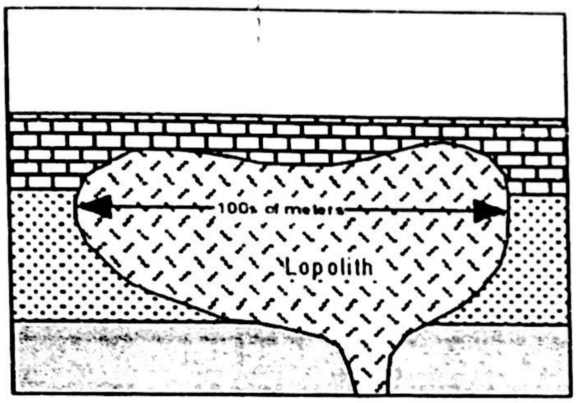


FIGURE 3-4: LOPOLITH.

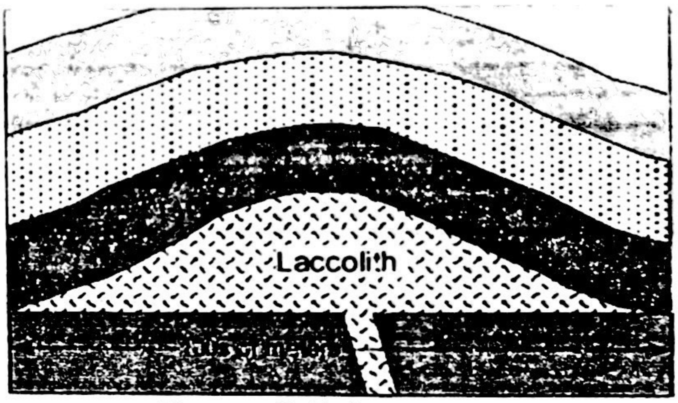


FIGURE 3-5: LACCOLITH

Phacolith: Phacolith is intrusions of igneous rocks which occupy crests and troughs of folded strata as shown in Figure 3-6.

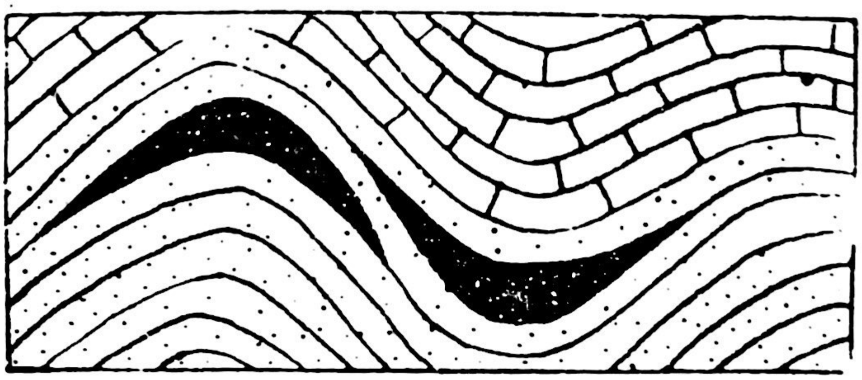


FIGURE 3-6: PHACOLITH

Sill: A sill is a sheet like igneous body which ***runs parallel to the bedding*** of the enclosing rock (Figure 3-7). They may be ***horizontal***, inclined, or vertical depending upon the attitude of the strata. Sills vary in thickness from a few centimeters to several hundred meters, but they are always thin as compared to their length along the beds.

Dyke: A dyke is a vertical wall-like igneous body that cuts across the bedding of the country rocks (Figure 3-7). The thickness of a dyke may vary from a few centimeters to a hundred meter or more.

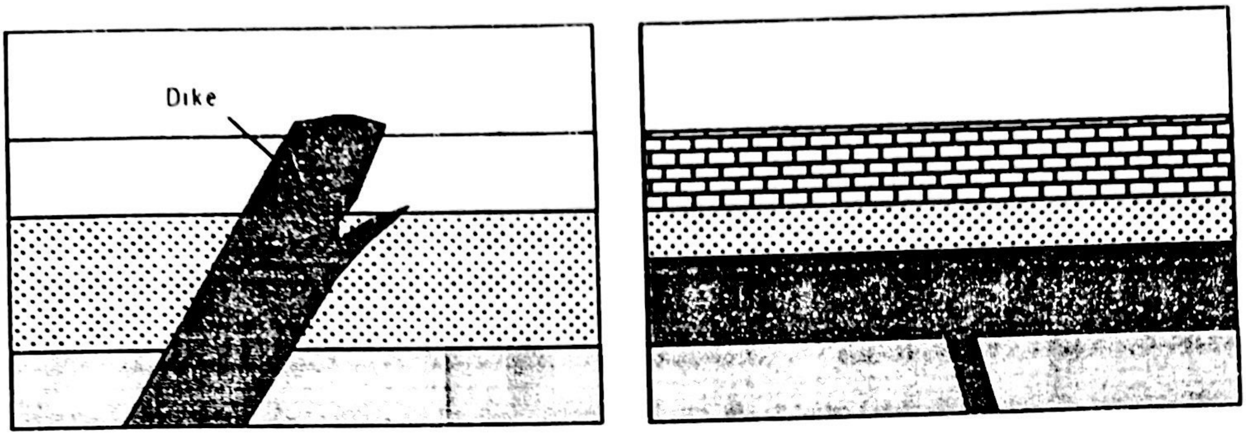


FIGURE 3-7: SILL AND DYKE.

Volcanic Neck or Plug: A volcanic neck or plug is ***a vertical Intrusion of igneous mass*** which has a roughly oval or circular cross section (Figure 3-8). Volcanic necks range in diameter from a few hundred meters to a kilometer or more.

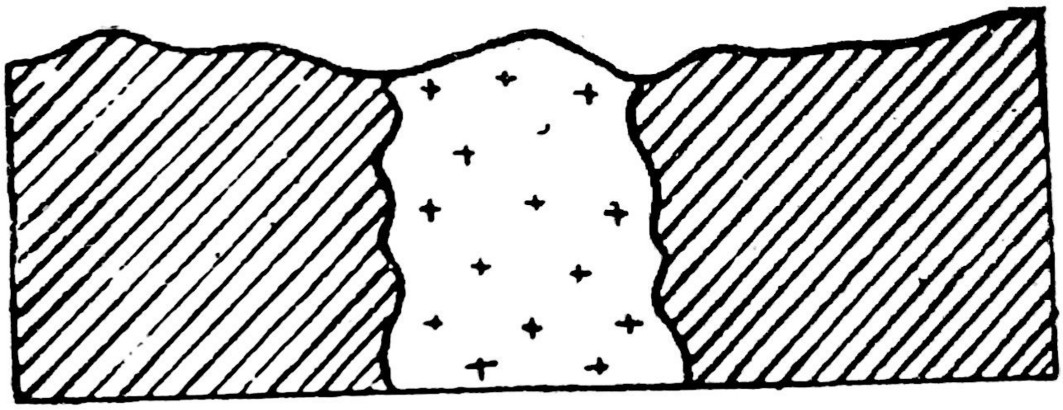
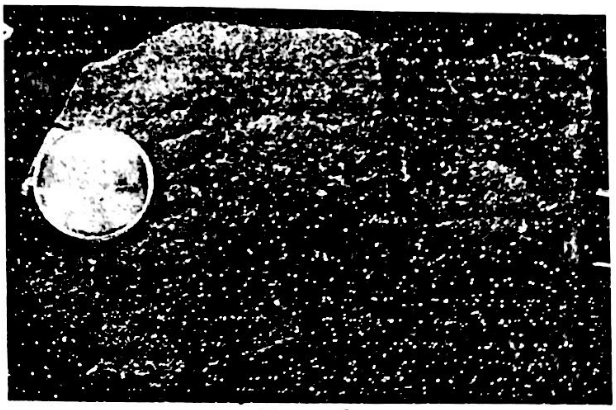


FIGURE 3-8: VOLCANIC NECK.

Lava Flow: The volcanic igneous rocks occur as ***lava flows***. They are ***tabular in shape*** and may range in thickness from a few meters to several hundred meters. Lava flows are formed when lava breaks through the earth crust along fissures kilometers in length, and very large quantities of it are poured out over the land.

3.1.6 Description of Common Rocks

- **Granite:** (see Figure 3-9); It is a coarse-grained rock which is composed of quartz, alkali felspars (orthoclase and microcline), and small amount of biotite or hornblende or both. The average granite contains 60% felspars, 30% quartz, and 10% ferromagnesian minerals. The granites are mostly light in color with a white or pink tint per the color of the feldspar.
- **Basalt:** (see Figure 3-9); Basalt is a dense black volcanic rock. Its texture is fine grained to glassy. It is composed of augite, plagioclase and iron-oxide. Basalt sometimes contains vesicles. Which have become filled with secondary minerals like quartz, calcite, zeolites, etc.



Basalt

Granite

FIGURE 3-9: BASALT AND GRANITE IGNEOUS ROCKS

- **Rhyolite:** Rhyolite is like granite in mineral composition but very different in texture. The texture is often porphyritic, which contains phenocrysts of quartz and felspar, set in a finely crystalline or glassy groundmass, the color of the rock is generally white, grey, or pink. Rhyolites may show "flow structure".
- **Pumice:** It is a cellular, volcanic froth of glassy texture which is so light that it floats on water. It is formed on the surface of acid lava.
- **Diorite:** It is a coarse-grained rock which is mainly composed of plagioclase felspar and hornblende. However, in some varieties augite and biotite may occur. Most diorites contain little or no quartz.
- **Gabbro:** It is a coarse-grained plutonic rock which is dark green or black in color. It is composed of calcic-plagioclase (labradorite), augite (diallage), and magnetite.
- **Dunite**: is a coarse-grained rock which is composed almost entirely of olivine.

3.2 SEDIMENTARY ROCKS

Sedimentary rocks are formed from the ***solid debris and the dissolved mineral matter produced by the mechanical and chemical breakdown of pre-existing rocks***, or in some cases from the ***skeletal material of accumulated plants and animals for very long period***. The processes involved in the disintegration of rocks by weathering and erosion, and the transportation of these deposits to the place where they are deposited, then it gets consolidated and cemented to form sedimentary rocks. Sedimentary rocks occur in ***layers*** and frequently contain ***fossils***.

3.2.1 Major Processes for Sedimentary Rocks Formation

3.2.1.1 Weathering and Erosion

Weathering is the disintegration and decomposition of rock at or near the surface of the earth. Whereas ***erosion is the incorporation of materials transportation in addition to disintegration of pre-existing rocks.***

3.2.1.2 Transportation

It includes the mobile factors to transport materials from a place to another one, such as ***water, wind, and ice (glaciers)***.

3.2.1.3 *Deposition*

It is the site of ***deposition of the materials in a sedimentary basin***. By compaction and cementation, these sediments will transform to solid rocks.

3.2.1.4 *Consolidation*

It is a process by which soft and loose sediments are converted into hard and firm rocks. There are mainly three methods of consolidation:

a) ***Compaction and Dehydration***: When a bed is ***buried under more sediment***, it is consolidated due to the ***pressure of the overlying mass***. The excess of water is squeezed out and the cohesion is developed between the grains of sediments. ***Fine grained sediments like clays*** are consolidated most effectively by this process.

b) ***Cementation: Coarse grained sediments*** are mostly consolidated by cementation. The most common cementing materials are silica, calcium carbonate, iron-oxides, and clay minerals.

c) ***Crystallization: Chemically formed sedimentary*** rocks such as ***salt and gypsum*** are consolidated chiefly by the crystallization of their constituents.

3.2.2 Classification of Sedimentary Rocks

The sedimentary rocks may be classified as follows:

a) ***Mechanically Formed***: Consisting of material (gravel, sand, silt and clay) suspended in flowing water. They are of three types:

- Rudaceous rocks: Bouldery deposit, e.g. conglomerate.
- Arenaceous rocks: Sandy rocks, e.g. sandstone.
- Argillaceous rocks: Clayey rocks, e.g. shale.

b) ***Organically Formed***: Consisting of accumulated animal or plant remains. These are of two types:

- Calcareous rocks: Limestone rocks.
- Carbonaceous rocks: Coal seams.

c) ***Chemically Formed:*** Formed due to precipitation and accumulation of soluble constituents. These are of three types:

- Carbonate rocks: Limestone, dolomites.
- Sulphate rocks: Gypsum rock.
- Chloride rocks: Rock salt.

3.2.3 Particle Size of Sediments

The constituent particles of sediments may be classified into gravel and pebble, sand, silt, and clay, and each of these give rise to a particular type of rock as shown in Table 3-2.

TABLE 3-2: PARTICLE SIZE IN SEDIMENTS

Grade	Grain size (mm)	Type of rock
Gravel or Pebble	> 2.0	Conglomerate
Sand	0.I to 2.0	Sandstone
silt	0.01 to 0.10	Siltstone
Mud or Clay	< 0.01	Mudstone, shale, clay

3.2.4 Factors Affecting the Variety of Sedimentary Rocks

Three main factors are affecting the variety of sedimentary rocks; these are:

1. ***Type of the Original Rock Material***: Where chemical weathering of calcareous rocks produces calcareous rocks too, and physical weathering of sandstone produces sandstone too. Whereas, chemical and physical weathering of igneous and metamorphic rocks produces different rocks.
2. ***Type of Transportation:*** Different deposits formed with different agent of transportation (wind, water and glaciers).
3. ***Environment of Deposition:*** Different environments results in different sedimentations. Thus, it may be described according to the type of environment in which it accumulated:

    (a): Continental deposits: If it were laid down on land or in a lake by rivers, ice or wind. If the agents are rivers, wind and glaciers, their result will be fluviatile deposits, Aeolian deposits and glacial deposits, respectively.

    (b): Transitional (Intermediate) deposits: If it were laid down in an estuary or delta deposits formed in delta (deltaic) and deposits formed in estuaries of rivers (estuarine).

    (c): Marine deposits: These deposits formed along coastlines, shores, continental shelves and deposits formed in the abyssal areas of deep oceans (under greater depth of water) are abyssal deposits.

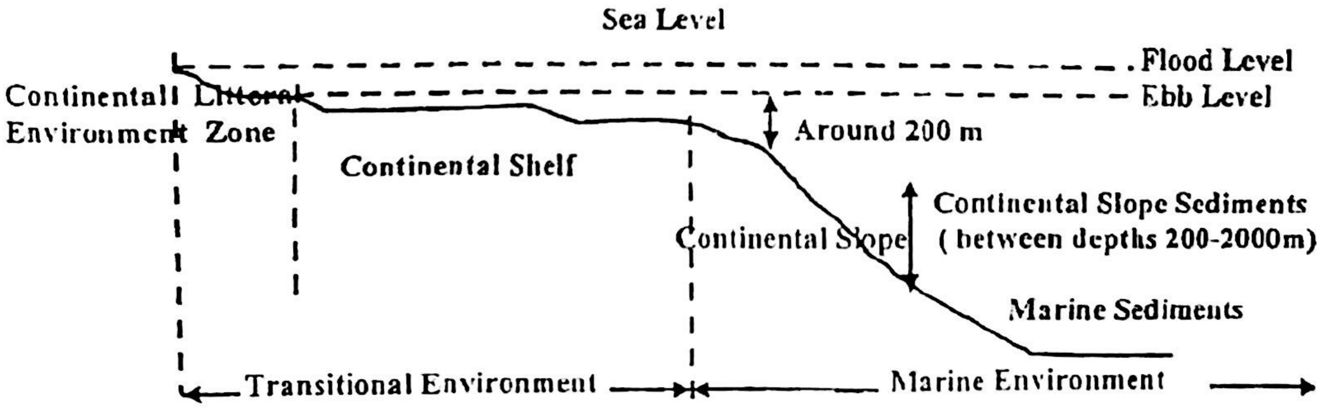


FIGURE 3-10: DEPOSITION ENVIRONMENTS OF SEDIMENTARY ROCKS.

3.2.5 Structural Features

Structural features of sedimentary rocks are of great value in determining their origin. The chief sedimentary structures are as follows:

a. Stratification

The deposition of sediments into layers or beds is called stratification. The thickness of a single bed may vary from a few centimeters to many meters. The stratification is formed due to the following:

- Differences in the kinds and composition of material deposited.
- Differences in the size of particles deposited.
- Differences in the color of the material deposited.

b. Lamination

Thin bedding, less than one centimeter in thickness, are called lamination. It is usually found in fine grained sedimentary rocks like shale.

c. Cross-bedding

Cross bedding are the minor bedding or laminations which lie at an angle to the planes of general stratification. This structure is found in shallow water and wind formed deposits.

d. Graded bedding

When a sedimentary bed shows a gradation in grain size from coarse below to fine above, it is said to be graded. Such type of bedding is called graded bedding.

e. Ripple Marks

Ripple marks are the wavy undulations that may be seen on the surface of some sedimentary deposit. These are produced by the action of waves and currents in shallow water. They may also be formed on the deposits formed by wind.

f. Marks in Desiccated Sediments

The sediments which have undergone repeated wetting and drying may show mud cracks, tracks of terrestrial animals, percussion marks of hail and rain, and impressions of ice or salt crystals.

g. Concretions

Concretions are variously shaped masses or nodules of mineral matter found within a sedimentary rock. Concretions generally consist of calcium carbonate, or silica and often possess an internal radiating or concentric structure. Their shape may be round, elliptical, oval, lenticular, or irregular.

3.2.6 Description of Common Rocks

- ***Conglomerate:*** The pebbles and gravels on consolidation and cementation produce a rock known as conglomerate. The pores of a conglomerate are composed of fine sands, rock particles, and some cementing material.
- ***Breccia:*** A breccia is a rock same as Conglomerate but having ***angular*** fragments instead of rounded pebbles. Sandstone is mainly composed of sand size grains of quartz, which are cemented together. The cementing material may be silica, calcite, iron-oxide or, clay.
- ***Greywacke:*** Greywacke is a grey colored rock. In addition to quartz, it contains fragments of rock and some ferromagnesian minerals, which are embedded in a matrix of clay and chlorite materials.
- ***Shale:*** It is a laminated fine-grained sedimentary rock which is mainly composed of clay minerals and some silt-size grains of quartz. Shale may be calcareous, carbonaceous, and ferruginous depending upon whether they contain calcium carbonate, carbonaceous matter, or iron-oxide. ***Shale are often soft and can be scratched by a knife.***
- ***Limestone:*** Limestone consists mainly of calcite and dolomite with varying amounts of impurities such as chalcedony or clay. Some limestones may also contain calcareous shells of marine organisms. It is very fine grained and can be identified by their softness, their fossil content, and by their excitation in dilute hydrochloric acid.
- ***Marl:*** Impure limestones which contain mixture of clay and calcareous matter.
- ***Dolomite:*** Dolomite is a Magnesian limestone which is composed of double carbonate of calcium and magnesium. It is distinguished from ordinary limestone by its ***greater hardness***, greater specific gravity, and inferior (minimum) solubility in hydrochloric acid.
- ***Flint and Chert:*** These are cryptocrystalline forms of silica found in limestones and chalks in the form of nodules and bands.

3.3 METAMORPHIC ROCKS

When the pre-existing rocks are subjected to increased temperature, pressure, and action of chemically active fluids, metamorphic rocks are formed.

During metamorphism, ***re-crystallization*** of the mineral constituents takes place as a result ***new minerals*** and ***new textures*** are produced.

3.3.1 Agents of Metamorphism

The agents which bring about metamorphism of rocks are as follows:

1. **Physical agents**: Heat, uniform pressure, and directed pressure. ***Physical changes produce new texture.*** The changes in the texture is produced by the process of re-crystallization in which the original minerals undergo a change in their structure, i.e. they are flattened or elongated.
2. **Chemical agents**: Chemically active water and gases. It involves the ***exchange of elements and compounds*** which result in the formation of ***new minerals.***

3.3.2 Types of Metamorphism

The metamorphism process cab be described as given below.

A. Thermal metamorphism

In thermal metamorphism the changes brought about in rocks are mainly due to ***heat*** but heated ***magmatic waters*** or ***vapors*** carrying mineral matter in solution also play important part when the thermal metamorphism occurs in the immediate vicinity of igneous intrusions. In thermal metamorphism ***uniform pressure*** predominates, hence during re-crystallization, the minerals that develop will be ***dense and equidimensional*** and the metamorphic rock thus produced will have ***non-foliated*** even grained texture.

B. Dynamo-thermal metamorphism

This type of metamorphism is also called regional metamorphism. It is caused when ***directed pressure and heat act together***.

The directed pressure involves movement and shearing, and therefore, it is the main factor in forming ***foliated*** rocks. The new minerals that develop under directed pressure are usually flat, tabular, elongated, bladed, or flaky in nature. Dynamo-thermal metamorphism takes place in fold mountain regions.

C. Dynamic metamorphism

In this type of metamorphism mainly ***directed pressure or stress predominates.*** The stress produces shearing movements in the rocks and causes crushing, granulation, and powdering. Therefore, the rocks show mainly mechanical breaking with little new mineral formation. Dynamic (pressure) metamorphism occurs in the higher levels of the earth crust where rocks are mostly hard and brittle.

D. Chemical Metamorphism (Metasomatism)

The metamorphism replacement of rocks is brought about by ***deposition from hydrothermal solutions*** (hot magmatic waters). The replacement takes place ***molecule by molecule so that as new mineral is added***, the old is removed and the volume of the rock remains unchanged. The new rock frequently produces all the textural details of the original rock.

3.3.3 Metamorphic Zones

The degree or intensity of metamorphism generally ***increases with depth*** because as the depth increases temperature and pressure also increase. From the earth surface downwards, there are three metamorphic zones:

a) Upper zone;
b) Intermediate zone, and
c) lower zone.

Upper zone: It lies near the earth surface where temperature is low (300°C) and directed pressure is high. In this zone dynamic metamorphism takes place. The alteration in rocks is weak.

Intermediate zone: It is an intermediate zone where temperature is of the order of 300°C to 500°C. The directed pressure is also high and therefore, ***dynamo-thermal metamorphism takes place.***

Lower zone: It is the bottom most zone where ***directed pressure is absent, uniform pressure is high***, and temperature is also high (500°C to 800°C).

3.3.4 Description of Common Rocks

- ***Quartzite:*** Metamorphosed sandstones having granulose structure are called quartzite. They are mainly composed of quartz with a small amount of mica, tourmaline, graphite or iron-minerals.
- ***Marble:*** Marbles are produced by the metamorphism of limestones and dolomites. They contain interlocking grains of calcite or dolomite minerals and here their structure is said to be granulose.
- ***Schist:*** A rock having well developed schistose structure is known as a schist. Schists arc largely composed of flaky minerals such as muscovite, biotite, hornblende, chlorite, talc etc. Depending upon the type of flaky mineral present, the schists are described as Muscovite-Schist, Biotite-Schist, Hornblende-Schist, Chlorite-Schist, Talc-Schist. When the content of quartz increases, mica-schist passes into quartz-schist and micaceous quartzite.
- ***Slate:*** Slates are produced by the metamorphism of shales. They are fine grained rocks having slats structure due to which they split into thin smooth plates. They are composed of very fine-grained mixture of quartz, chlorite, sericite, and felspar

4. SECONDARY GEOLOGICAL STRUCTURES

4.1 DIP AND STRIKE

Dip: It is the angle of inclination of a rock bed with the horizontal plane. The dip includes both the direction and the angle. The dip direction is measured by its compass bearing, and the angle of dip with a clinometer.

Strike: It is the direction of a line formed by the intersection of the plane of a bed with a horizontal plane. The strike is always at right angles to the true dip. The direction of strike is determined by compass with reference to the true north and south. The illustration of the dip and strike is given in Figure 4-1below.

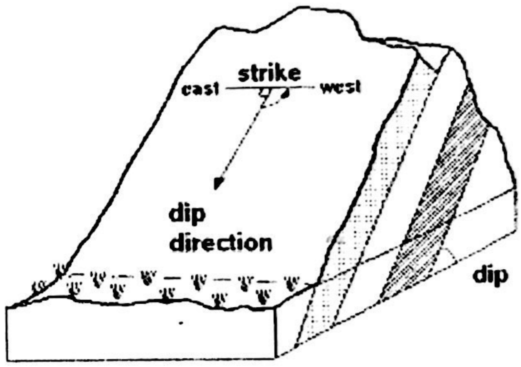


FIGURE 4-1: DIP AND STRIKE

4.2 Folds

The wavy undulations in the rock beds are called folds. They consist of arches and troughs in alternate manner. The size of folds varies greatly. Width of some folds are measured in kilometers while those of others in meters or centimeters. The details of the fold terminology are shown in Figure 4-2.

4.2.1 TERMINOLOGY

- ***Anticline***: It is on up fold where the limbs dip away from the axis.
- ***Syncline:*** It is a down fold where the limbs dip towards the axis.
- ***Limb:*** The sloping side of a fold from crest to trough is called the "limb".
- ***Axial Plane:*** It is an imaginary plane or surface which divides the fold into two equal halves.
- ***Axis:*** The line of intersection of the axial plane with the surface of any of the constituent rock beds is known as the "axis" of the fold.

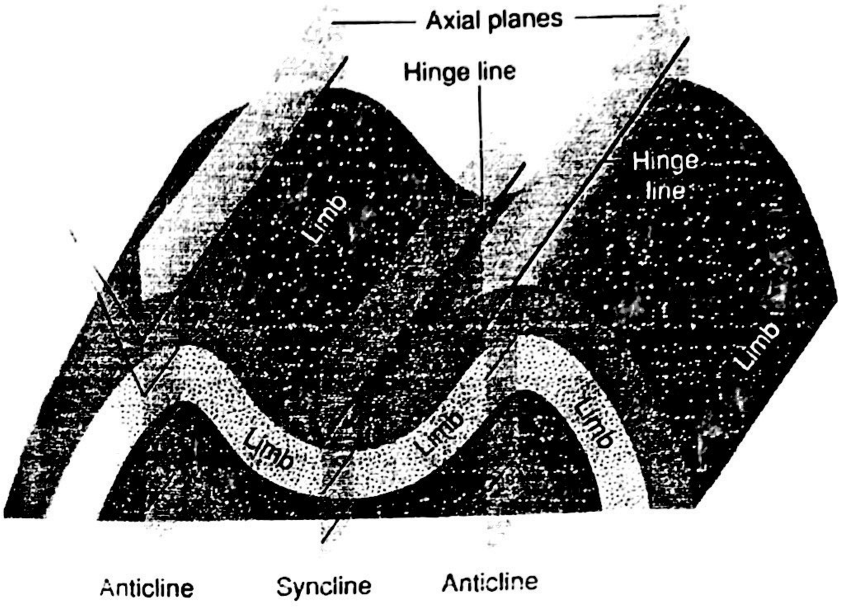


FIGURE 4-2: FOLDS

4.2.2 Types of Fold

- **Symmetrical Fold:** it is one where the axial plane is vertical and the two limbs have the same amount of dip Figure 4-3.
- **Asymmetrical Fold:** it is one where the axial plane is inclined and the limbs dip at different angles, and in opposite directions.
- **Overturned Fold:** it is one in which the axial plane is inclined and one limb is turned past the vertical. In this case both the limbs dip in the same direction and one of the limbs is turned upside down.
- **Recumbent Fold:** the folding is so intense that axial plane becomes almost horizontal and the lower limb, which also becomes nearly flat, gets overturned.

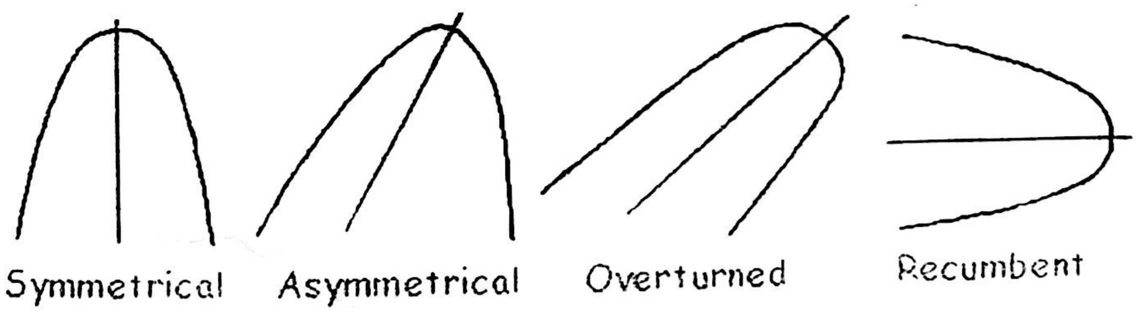


FIGURE 4-3: SOME TYPES OF FOLDS

In such folds, fractures may develop across bends and thrusting of the recumbent rock mass may take place, please see Figure 4-4.

- **Isoclinal Fold:** This type of fold shows parallel limbs which dip at the same angle and in the same direction.
- **Dome and Basin:** When the strata have been subjected to folding in two directions at right angles, each anticline is converted into a "dome", and each syncline is converted into a "basin". In domes the beds dip away from a central point. In basins, the beds dip downwards a central point.

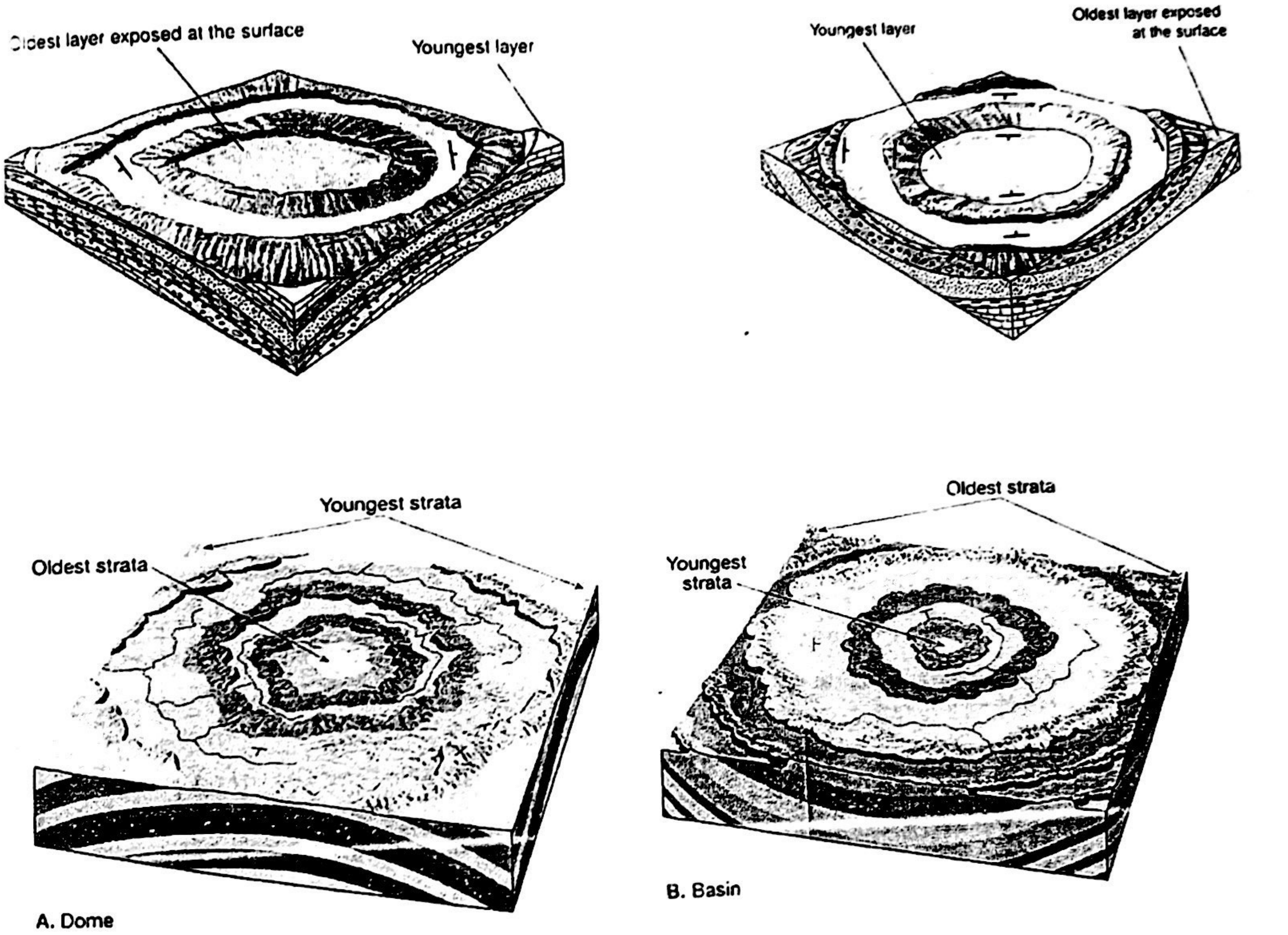


FIGURE 4-4: DOME AND BASIN FOLDS

4.3 FAULTS

A fault is a fracture along which there has been relative displacement of beds, which were once continuous (Figure 4-5). The fracture surface is called fault plane. The displacement along a fault may be less than a meter, several hundred meters, or many kilometers.

4.3.1 TERMINOLOGY

- **Strike of a Fauit:** It is the direction of the line of intersection of a fault plane and horizontal plane.
- **Hade:** The hade of a fault is the angle of inclination of the fault plane measured **from** the vertical (DCE in Figure).
- **Hanging Wall and Foot Wall:** When the fault plane dips at any angle other than 90°, **one** face of the rock mass will lie above the fault, and the other will be below it. The block of rock which is on the upper side of the fault plane, is called the hanging wall, and the block which lies below the fault plane is called foot wall.
- **Throw:** The vertical displacement (CD in Figure 4-5) of the fractured beds is called the **throw** of the fault.
- **Heave:** The horizontal displacement of strata as seen in a section of a fault, is called. **heave** (DE in Figure 4-5).

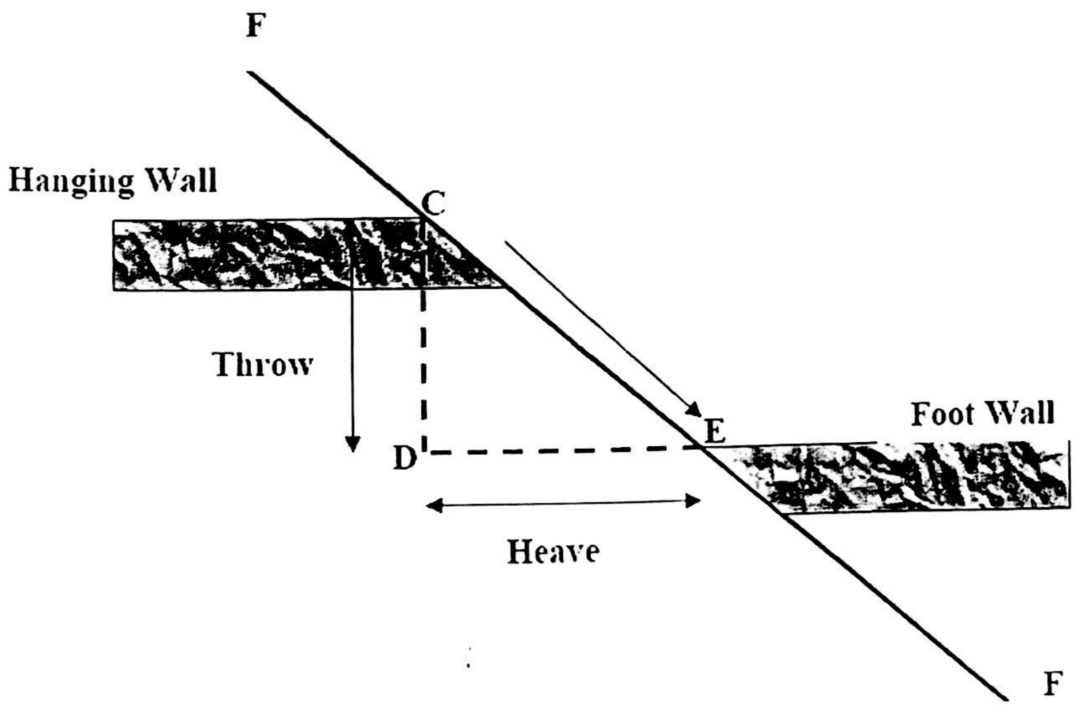


FIGURE 4-5: PARTS OF FAULT.

4.3.2 TYPES OF THE FAULTS

According to the relative movement, faults are classified as follows (Figure 4-6 to Figure 4-9):

1. **Normal Fault:** A normal fault is one in which hanging wall appears to have moved downward relative to foot wall. It is called gravity fault.
2. **Reverse fault:** A reverse fault is one in which hanging wall appears to have moved upward relative to the foot wall.
3. **Graben or rift fault:** when normal faults hade towards each other as shown in Figure 4-8 and the beds between them are thrown down in the form of a wedge, the structure is called "Graben" or "Rift fault".
4. **Horst:** a horst consists of a central block on the both sides of which adjacent beds appear to have been faulted down (Figure 4-9).
5. **Radial Faults:** A number of faults exhibiting a radial pattern are described as "radial faults".

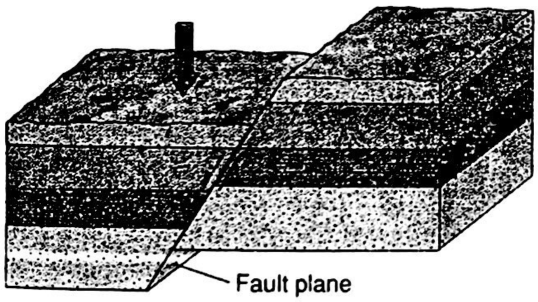


FIGURE 4-6: NORMAL FAULT

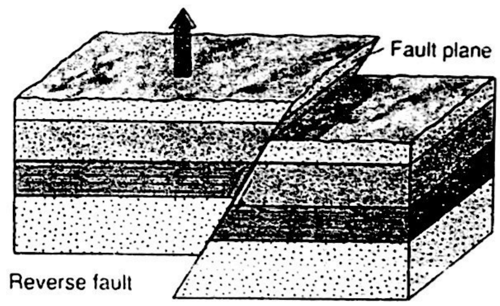


FIGURE 4-7: REVERSE FAULT

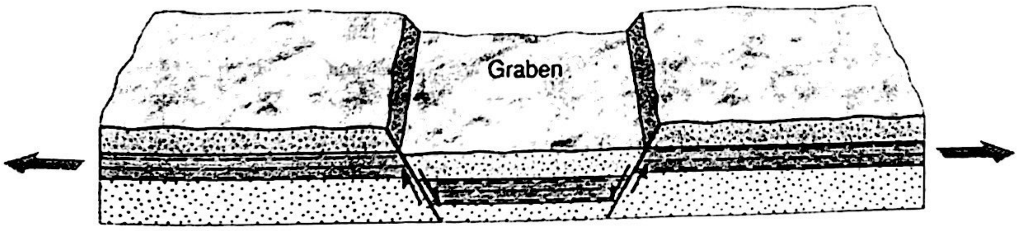


FIGURE 4-8: GRABEN FAULT

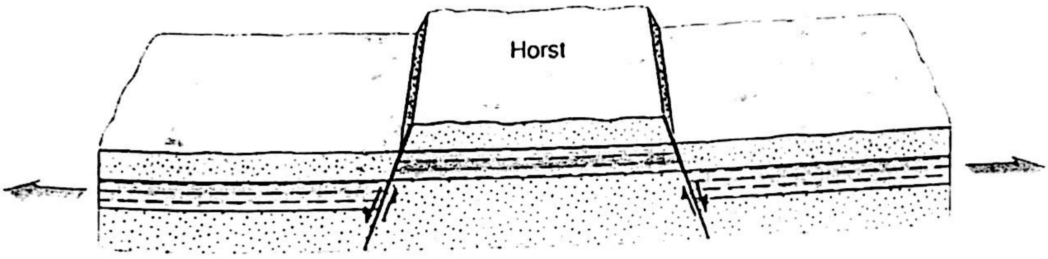


FIGURE 4-9: HORST FAULT

4.4 JOINTS

Joints: Joints are cracks or fractures present in the rocks along which there has been no displacement. Joints occur in all types of rocks. They may be vertical, inclined, or even horizontal.

Joints are formed as a result of contraction due to cooling or consolidation of rocks. They are also formed when the rocks are subjected to compression or tension during earth movements.

Commonly a large number of joints lie parallel to one another. These parallel joints together form a joint set. A joint system consists of two or more joint sets. On the basis of the origin, joints may be classified into two groups:

i. Tension joints, and
ii. Shear joints.

Tension Joints: Tension joints are those which are formed as a result of tensional forces. These joints are relatively open, and have rough and irregular surfaces. The columnar joints in lava flows, and longitudinal joints in the anticlines, that run parallel to the axis of fold.

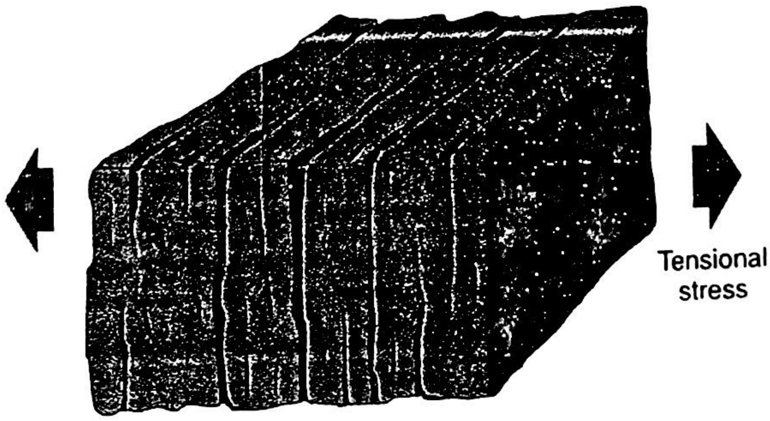


FIGURE 4-10: JOINTS

Shear Joints: Shear joints are those which are formed due to shearing stresses involved in the folding and faulting of rocks. These joints are rather clean cut and tightly closed. Shear joints occur in two sets which intersect at a high angle to form a "conjugate joint system".

6.1 PHYSICAL PROPERTIES OF ROCKS

Rock mass is generally a three-phase system. It consists of solid particles, liquid and gas. For all practical purposes, the liquid may be considered to be water (although in some cases, the water may contain some dissolved salts) and the gas as air. The phase system may be expressed in SI units either in terms of mass-volume or weight-volume relationships. The inter relationships of the different phases are important since they help to define the condition or the physical make-up of the rock.

6.1.1 Volumetric Relations:

- **The void ratio,** $e = \frac{Volume\ of\ voids}{Volume\ of\ solids} = \frac{V_v}{V_s}$
- **The porosity, n=** $\frac{Volume\ of\ voids}{Total\ volume\ of\ sample} \times 100 = \frac{V_v}{V}$ $or\ n = \frac{V_v}{V} \times 100$
- **The degree of saturation, S,** $S = \frac{Volume\ of\ water}{Volume\ of\ voids} \times 100 = \frac{V_w}{V_v} \times 100$

6.1.2 Mass or weight Relations:

Water Content, *w*:

$$water\ content, w\% = \frac{Mass\ of water}{Mass\ of\ solids} \times 100 = \frac{M_w}{M_s} \times 100 = \frac{Mwet - Mdry}{Mdry} \times 100$$

6.1.3 Weight-Volume Relationship:

Specific Gravity: $G_s = \frac{\gamma_s}{\gamma_w} = \frac{\frac{W_s}{V_s}}{\frac{W_w}{V_w}}$ $@certain\ temperature$

6.1.4 Interrelationships of Different Parameters

Relationship between e and n:

$e = \frac{n}{1-n}$ and $n = \frac{e}{1+e}$

Relationship Between e, Gs, ρ_{dry} or γ_{dry} :

$\rho_{dry} = \frac{G_s}{1+e}\rho_{water}$ Or, $\gamma_{dry} = \frac{G_s}{1+e}\gamma_{water}$

Relationship Between e, Gs, w and S:

$$Gs \times w = S \times e$$

Example 6.1:

A sample of wet rock has a mass of 126 kg. The following data were obtained from laboratory tests on the sample: Wet density, ρ_t = 2.1 g/cm³, Gs = 2.7, water content, *w*, 15%. *Determine:* (1) dry density, ρ_d, (2) void ratio, (3) porosity, and (4) degree of saturation.

Solution:

1. $water\ content, w\% = \frac{weight\ of water}{weight\ of\ solids} \times 100$

   $15 = \frac{126-Md}{Md} \times 100$

   $Md = 109.56\ kg$

   $dry\ density = \frac{wet\ density}{1+watercontent}$

   = 2.1/ (1+0.15) =1.83 gm/cm³

2. $dry\ density = \rho_{dry} = \frac{G_s}{1+e}\rho_{water}$

   Void ratio=0.4754

3. $n = \frac{e}{1+e} = 0.322 = 32.2\%$

4. $Gs \times w = S \times e$

   $S = 0.852 = 85.2\%$

Example 6.2:

If the wet weight of a rock has a volume of (0.22m3) equal to (312 kg) and the water content was (12%) and the specific gravity was (2.72). Calculate: Wet density, Weight of water in the sample, Dry density, Void ratio and Porosity.

Solution:

1. $\rho_{wet} = wet\ density = \frac{M\ wet}{V} = \frac{M\ t}{V} = \frac{312\ kg}{0.22\ m3} = 1418.2\frac{kg}{m3}$

2. $w\% = \frac{M_{wet}-M_{dry}}{M_{dry}} \to \frac{12}{100} = \frac{312-M_{dry}}{M_{dry}} \to M_{dry} = 278.57\ kg$

   $M_{water} = M_w = amount\ of\ water = 312 - 278.57 = 33.43\ kg$

   Hence, the weight of water=33.43 × 10 = 334.3 *N*

3. $\rho_{dry} = dry\ density = \frac{M\ dry}{V} = \frac{278.57\ kg}{0.22\ m3} = 1266.23\frac{kg}{m3} = 1.266\ gm/cm3$

4. $\rho_{dry} = \frac{G_s}{1+e} \times \rho_{water} \to e = \left(\frac{2.72}{1.266} \times 1\right) - 1 = 1.148$

5. $n = \frac{e}{1+e} = \frac{1.148}{1+1.148} = 0.5344\ \ or\ 53.44\%$

Example 6.3:

A rock sample has 76 mm height and 38 mm diameter. This sample was tested under standard laboratory condition and it was found that it contains 10cm3 as voids. The mass of the sample was 165 gm and 155 gm in wet and dry case, respectively. Calculate porosity, void ratio, water content as well as dry and wet unit weight.

Solution:

1. $porosity(n) = \frac{V_v}{V} \times 100$, $volume\ of\ cylinder = \frac{\pi D^2}{4} \times h\ or = \pi r^2 \times h$,

$where:$

$D: Diameter\ of\ the\ cylinder$

$r: radius\ of\ the\ cylinder$

$h: height\ of\ the\ cylinder$

$volume = \pi(1.9)^2 \times 7.6 = 86.193\ cm3$

$$\therefore n = \frac{10}{86.193} \times 100 = 11.6\%$$

2. $Void\ ratio, e = \frac{n}{1-n} = \frac{0.116}{1-0.116} = 0.104$

3. $water\ content, w\% = \frac{M_{wet}-M_{dry}}{M_{dry}} \times 100$

$$w, \% = \frac{165-155}{155} \times 100 = 6.4\%$$

4. $\rho_{wet} = wet\ density = \frac{Wet\ Mass}{Volume} = \frac{165\ gm}{86.193\ cm3} = 1.914 \frac{gm}{cm3}$

$$in\ the\ case\ of\ wet\ unit\ weight = \gamma_{wet} = wet\ unit\ weight = \frac{W\ wet}{Volume}$$

$$\gamma_{wet} = \frac{1.914\left(gm \times \frac{1kg}{1000\ gm} \times 10 \frac{m}{sec^2}\right) N \times \frac{1kN}{1000N}}{cm^3 \times \frac{1m^3}{10^6 cm^3}}$$

$$= \frac{1.914 \times 10\ kN}{m^3} = 19.14 \frac{kN}{m3}$$

$$\gamma = unit\ weight = density \times acceleration = \rho\left(\frac{kg}{m3}\right) \times \frac{m}{sec2}$$

5. $\rho_{dry} = dry\ density = \frac{Dry\ Mass}{Volume} = \frac{155\ gm}{86.193\ cm3} = 1.798 \frac{gm}{cm3}$

$$\gamma_{dry} = \frac{1.798\left(gm \times \frac{1kg}{1000\ gm} \times 10 \frac{m}{sec^2}\right) N \times \frac{1kN}{1000N}}{cm^3 \times \frac{1m^3}{10^6 cm^3}} = 17.98 \frac{kN}{m3}$$

Example 6.4:

A rock sample of cylindrical shape with dimensions of (38^{mm}) diameter and (76^{mm}) length, wet mass and water content and degree of saturation are equal to (160 gm, 20% and 70%) respectively. Find the void ratio, porosity and specific gravity of the sample.

Solution:

$V = volume = \pi(1.9)^2 \times 7.6 = 86.193\ cm^3$

$\rho_{wet} = wet\ density = \frac{M\ wet}{V} = \frac{160\ gm}{86.193\ m3} = 1.856\ gm/cm^3$

$\rho_{dry} = \frac{\rho_{wet}}{1+w\%} = \frac{1.856}{1+0.2} = 1.5469 gm/cm^3$

$Se = G_S w \ldots\ldots\ldots (1)$

$0.7e = 0.2G_S$

$\rho_{dry} = \frac{G_s}{1+e} \times \rho_{water} \ldots\ldots\ldots (2)$ by substituting (1) in (2), we get:

$\therefore 1.5469 = \frac{3.5e}{1+e}$

$e = 0.792$

$G_S = 2.772$

The performance of soil and rock under the action of load, water, temperature and tectonics of the earth crust depends upon physical properties and mechanical strength of these materials. Rocks in their natural state are fractured, inhomogeneous, anisotropic and discontinuous. The construction design in rocks requires the knowledge of the resulting deformation, which can be achieved by knowing their mechanical strength properties.

6.2.1 Strength of rocks

The strength of rocks (and any earth material) is defined as the ability of rocks to resist the external applied load. This may be compressive stresses; tension stresses and shear stresses.

6.2.1.1 *Compressive strength*

The stresses are result from compression forces causing contraction (reduction) in the volume of the rocks. There are two types of these stresses.

- Confined (Triaxial) compressive strength (out of the scope of the course)
- Unconfined (uniaxial) compressive strength

It is the most frequently used strength of the rocks in which a load on the rock acts in one direction only as shown in the following Figure 6.1.

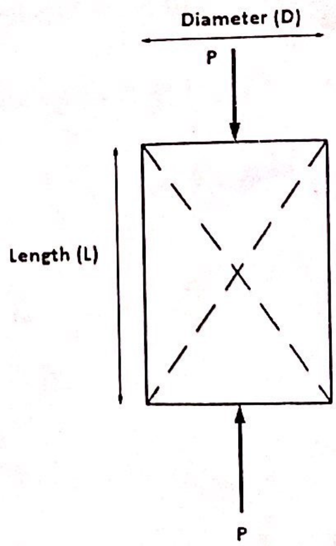


FIGURE 6.1: ILLUSTRATION OF LOAD APPLICATION TO ROCK SAMPLE

$$\sigma_n = P_n/A$$

Where:

$\sigma_n = axial\ or\ normal\ stress\ in = \frac{Forec}{area}\ \frac{F}{L^2}\ such\ as\ \frac{kg}{m^2}\ or \frac{kN}{m^2}$

$P_n = Compression\ force\ (axial)$

$A = cross\ sectional\ \ area$

6.2.1.2 Tensile strength

A material can sustain the maximum tensile stress prior to failure. In general, the tensile strength of rocks is less than the compressive strength of the same rock. For example, the tensile strength of granite is less than quarter than the compressive strength. The tensile strength of a rock sample can be calculated as:

$$\sigma_{n\ tension} = P_n(tension)/A$$

6.2.1.3 Shear strength

It is the capacity of a rock mass to take a shear stress or the maximum resistance to deformation due to shear displacement caused by shear stresses. The shear strength of the rocks results from:

- The cementation between particles of the rock, and
- The type of packing or arrangement of these particles.

In general, the shear strength can be obtained from the following relation:

$$\tau = c + \sigma_n \tan \varphi$$

Where:

$\tau = shear\ strength\ of\ rocks,\qquad take\ a\ unit\ of\ stresses\ such\ as\ \frac{kN}{m^2}$

$c = cohesion\ of\ rocks, take\ a\ unit\ of\ stresses\ such\ as\ \frac{kN}{m^2}$

$\sigma_n = compressive\ stress\ on\ rock, unit\ of\ stresses\ such\ as\ \frac{kN}{m^2}$

$\varphi = angle\ of\ internal\ shearing\ resistance, degree$

Rock	UC Strength (MPa)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Poisson's Ratio	Strain at Failure (%)	Point Load Index $I_{s(50)}$ (MPa)	Fracture Mode I Toughness
Igneous							
Granite	100 – 300	7 – 25	30 – 70	0.17	0.25	5 – 15	0.11 – 0.41
Dolerite	100 – 350	7 – 30	30 – 100	0.10 – 0.20	0.30		>0.41
Gabbro	150 – 250	7 – 30	40 – 100	0.20 – 0.35	0.30	6 – 15	>0.41
Rhyolite	80 – 160	5 – 10	10 – 50	0.2 – 0.4			
Andesite	100 – 300	5 – 15	10 – 70	0.2		10 – 15	
Basalt	100 – 350	10 – 30	40 – 80	0.1 – 0.2	0.35	9 – 15	>0.41
Sedimentary							
Conglomerate	30 – 230	3 – 10	10 – 90	0.10 – 0.15	0.16		
Sandstone	20 – 170	4 – 25	15 – 50	0.14	0.20	1 – 8	0.027 – 0.041
Shale	5 – 100	2 – 10	5 – 30	0.10			0.027 – 0.041
Mudstone	10 – 100	5 – 30	5 – 70	0.15	0.15	0.1 – 6	
Dolomite	20 – 120	6 – 15	30 – 70	0.15	0.17		
Limestone	30 – 250	6 – 25	20 – 70	0.30		3 – 7	0.027 – 0.041
Metamorphic							
Gneiss	100 – 250	7 – 20	30 – 80	0.24	0.12	5 – 15	0.11 – 0.41
Schist	70 – 150	4 – 10	5 – 60	0.15 – 0.25		5 – 10	0.005 – 0.027
Phyllite	5 – 150	6 – 20	10 – 85	0.26			
Slate	50 – 180	7 – 20	20 – 90	0.20 – 0.30	0.35	1 – 9	0.027 – 0.041
Marble	50 – 200	7 – 20	30 – 70	0.15 – 0.30	0.40	4 – 12	0.11 – 0.41
Quartzite	150 – 300	5 – 20	50 – 90	0.17	0.20	5 – 15	>0.41

6.2.2 Deformation and Elasticity of Rocks

Deformation of the rocks means the change in the size and shape of the rock sample and mass that induced by the applied force even though the rock sample does not break or fail.

By referring to Figure (6.2), it can be seen that when uniaxial compression load is applied to a rock sample, the sample become small is the direction of load application and expand in the lateral direction. Furthermore, when the applied load is tension, the sample became longer (the load pulls the sample in the direction of load application).

For both loading conditions, the original length of the sample before deformations denoted as (L), the radius of the sample (r) and the cross-sectional area as (A). The change in the dimensions of the sample would be denoted as (L1), (r1) and (A1).

As a measure of the rock deformations, the axial and lateral strains are introduced as well as the other elastic parameters should be explained.

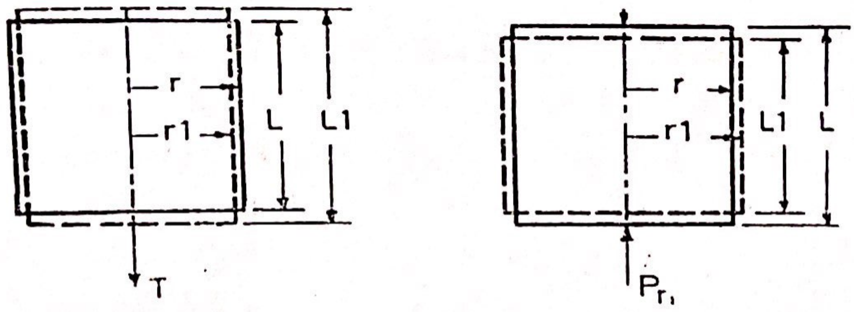


FIGURE (6.2): ROCK SAMPLE UNDER TENSILE AND COMPRESSION FORCES AND THE RESULTING DEFORMATIONS

6.2.2.1 *Axial and Lateral Strains*

The axial and lateral strain is expressed as given below

Tension	Compression
$\varepsilon_n = \dfrac{L_1 - L}{L}$	$\varepsilon_n = \dfrac{L - L_1}{L}$
$\varepsilon_{rT} = \dfrac{r - r_1}{r}$	$\varepsilon_{rn} = \dfrac{r_1 - r}{r}$

In general, the strain= change in length/original length (dimensionless)

6.2.2.2 *Modulus of Elasticity*

is the constant that shows the relation between the axial stress and axial strain. It is a distinguished feature for elastic material and can be calculated from the following relation:

$$Modulus\ of\ Elasticity = E = \frac{axial\ stresses}{axial\ strains} = \frac{\sigma_n}{\varepsilon_n}$$

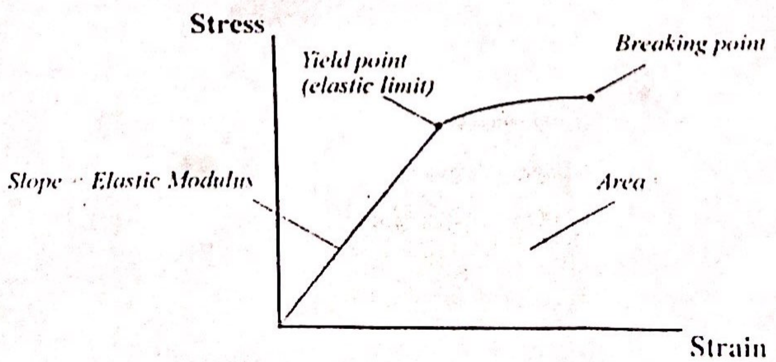


FIGURE (6.3): STRESS-STRAIN RELATIONSHIP AND MODULUS OF ELASTICITY dimensionless. Its value is ranged between (0.0-0.5)

$$Poisson's\ Ratio = \upsilon = \frac{lateral\ strain}{axial\ strain} = \frac{\varepsilon_{rn}}{\varepsilon_n}\ \ from\ compressive\ stress$$

Or

$$\upsilon = \frac{\varepsilon_{rt}}{\varepsilon_t}\ \ from\ tensile\ stress$$

2. **Shear Modulus**: is the ratio between the shear stress and shear strain are expressed as a unit of stress.

$$Shear\ Modulus\ G = \frac{shear\ stress}{shear\ strain} = \frac{\tau}{\varepsilon_{shear}}$$

3. **Bulk Modulus**: is the ratio between the equal all-round stresses to the resulted volumetric strain due to applied stresses and expressed as a unit of stress.

$$Bulk\ Modulus = K_v = \frac{\sigma_n}{\Delta V/_V} = \frac{\sigma_n}{\varepsilon_{Volumetric}} = \frac{\sigma_n}{\varepsilon_V}$$

4. **Compressibility Modulus:** is the magnitude of reduction in sample volume corresponding to the one unit of subjected compression stresses on all parts of the external surface, i.e., is the reciprocal of the Bulk Modulus:

$$compressibility\ Modulus = \frac{\varepsilon_V}{\sigma_n} = \frac{1}{K_v} = \frac{1}{Bulk\ Modulus}$$

Interrelationships of Different Parameters

We can establish relationships between the different parameters:

a) Relationship between Modulus of Elasticity and Shear Modulus in term of Poisson's Ratio:

$$G = Shear\ Modulus = \frac{E}{2(1+\upsilon)}$$

b) Relationship between Modulus of Elasticity and Bulk Modulus in term of Poisson's Ratio:

$$K_v = Bulk\ Modulus = \frac{E}{3(1-2\upsilon)}$$