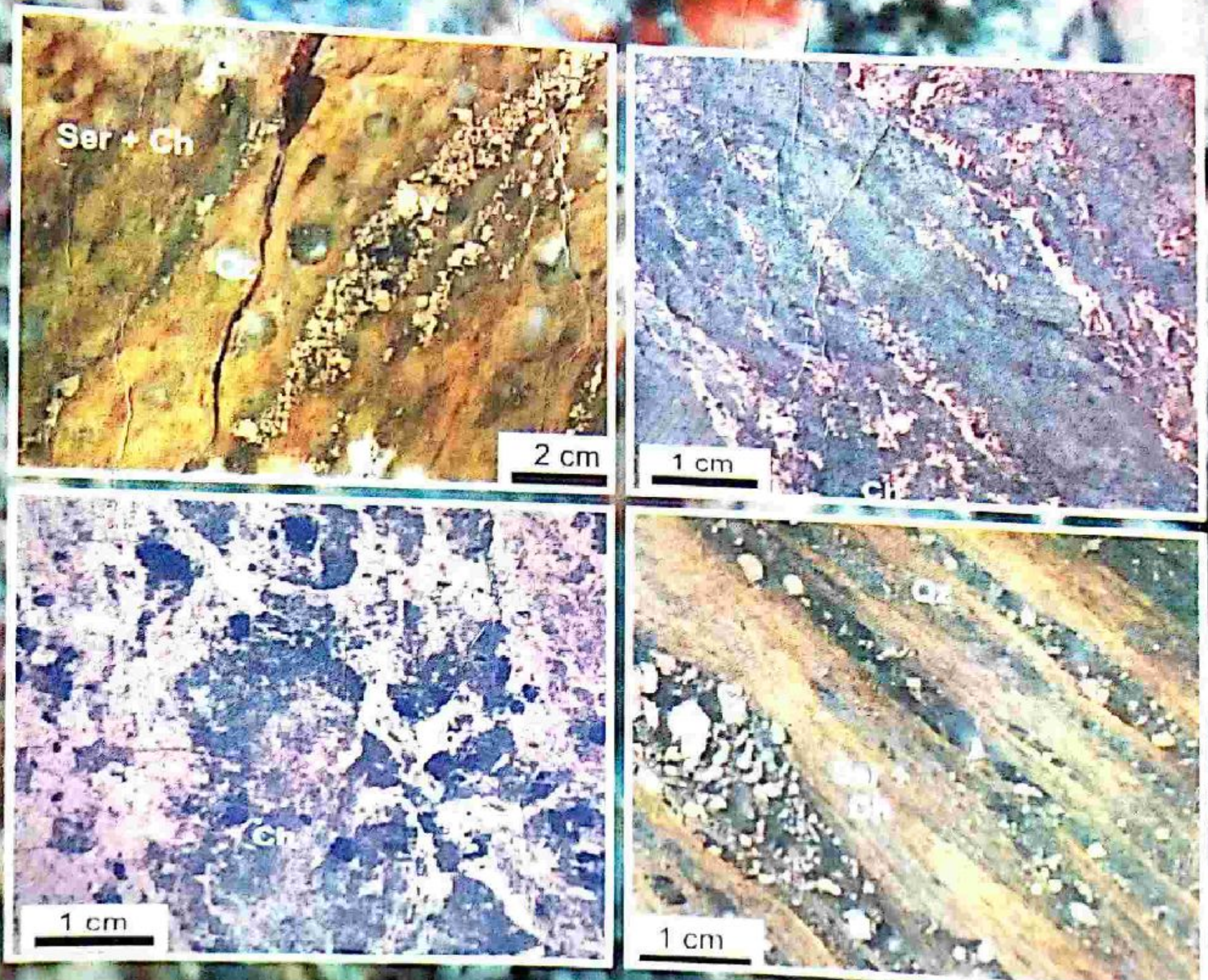
PRINCIPLES OF ENGINEERING GEOLOGY



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GEOLOGY

CONTENTS

1 Introduction

1.1. SCIENCE OF GEOLOGY

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

1.1.1. Branches of Geology

The field of geology is very large and it is divided into several branches.

(*i*) **Physical Geology.** Physical geology is concerned with the work of natural processes which bring about changes upon the earth's surface.

(*ii*) **Petrology.** The discussion of the different kinds of rocks is known as petrology. It deals with the study of composition, structure and origin of rocks.

(*iii*) **Mineralogy.** Mineralogy includes the study of mineral composition, structure, appearance, stability, occurrence and associations.

(*iv*) **Structural Geology.** This branch of geology deals with the study of structures of rocks in the earth's crust.

(*v*) **Stratigraphy.** It is the science of the description, correlation and classification of strata in sedimentary rocks including the interpretation of the depositional environments of those strata.

(*vi*) **Palaeontology.** Palaeontology is the science of fossils of ancient life forms and their evolution.

(*vii*) **Historical Geology.** The study of stratigraphy and palaeontology is included under the historical geology. It gives us a picture of the land and seas, the climate and life of early times upon the earth.

(*viii*) **Economic Geology**. The economic geology deals with the study of minerals, ores and fossil fuels of economic importance.

(*ix*) **Mining Geology.** This branch of geology is concerned with the study of application of geology to mining engineering.

(*x*) **Engineering Geology**. The engineering geology includes the study of application of geology to civil engineering.

1.1.2. Scope of Geology

Geology is of practical importance to mankind. It plays a very useful part in the search of coal, petrolium and minerals used as atomic fuels. It is directly concerned with the ore minerals, industrial minerals and mining industry. The importance of geology has also been recognized in the field of civil engineering. Many engineering projects such as water supply, construction of dams, reservoirs, tunnels, bridges, etc. require geological advice.

1.2. SOLAR SYSTEM

The earth is a planet. It is a member of the solar system. Nine planets and the sun are the main bodies of the "*solar system*". The planets in the order of increasing distance from the sun are Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune and Pluto. Each planet moves around the sun and maintains an elliptical orbit. The orbits of all the planets are almost in the same plane which is close to the equitorial plane of the sun. The planets also rotate about their axes. About 99.85% of the mass of the solar system is contained within the sun while the planets collectively make up most of the remaining 0.15%. On the basis of their location, the planets can be divided into two groups: (*i*) "*inner planets*" which include Mercury, Venus, Mars and Earth, and (*ii*) "*outer planets*" which include Jupiter, Saturn, Uranus, Neptune and Pluto. The planets of the two groups differ markedly in size, density, composition and rate of rotation.

Size. The members of the inner planet group are small in size. On the other hand, the members of the outer planet group are so large that they are often called giants.

Density. The inner planets are generally dense, their density being 4×10^{-3} kgm^{-3} or more. The density of outer planets is much lower. For example, the Saturn has a density less than that of water.

Composition. The low density of the outer planets suggests that they consist mostly of substances like hydrogen, helium, water, ammonia and methane. The high density planets consist almost entirely of silicates and metals.

Rate of Rotation. The planet Mercury is nearest to the sun. It has the fastest orbital motion (48 km/sec) and the shortest period of revolution (88 days). Pluto, the most distant planet, has an orbital speed of 5 km/sec and requires 248 years to complete one revolution.

1.3. ORIGIN OF THE EARTH

In general the theories of origin of the solar system can be divided into two groups : (*i*) *evolutionary theories*, and (*ii*) *catastrophic thories*.

Evolutionary Theories. The theories which suggest that planets are formed during the evolution of the sun, are called "*evolutionary theories*". Nebular hypothesis is an example of these theories.

Catastrophic Theories. "*Catastrophic theories*" are those which imagine that planets are formed by some special accident or catastrophe, such as the close approach of two stars or by collision of two stars. However, as the stars are so far apart in the galaxy, the possibility of such a catastrophe is extremely rare. The examples of catastrophic theories are the planetesimal and gaseous tidal hypothesises.

The best known hypothesises for the origin of the earth and other planets of the solar system are as follows.

1. Nebular hypothesis.
2. Planetesimal hypothesis.
3. Gaseous tidal hypothesis.
4. Binary star hypothesis.
5. Gas dust cloud hypothesis.

1.3.1. Nebular Hypothesis

The nebular hypothesis was put forward by Kant, the German philosopher in 1755 and Laplace, the French mathematician in 1796. This hypothesis suggests that the sun and planets, including the earth have formed from a disc-shaped rotating nebula. A vast cloud of hot gas is called "*nebula*". The nebular hypothesis may be summarized as follows.

1. Originally there was a large, hot, gaseous nebula which rotated along its axis [Fig. 1.1 (*a*)].
2. As the gas lost energy by radiation, it became cooler. As a result the nebula contracted inward and its speed of rotation about its axis increased to conserve angular momentum. Due to this the centrifugal force in the equitorial zone also increased thereby causing the nebula to bulge out in the equitorial zone.
3. The cooling and contraction of the nebula continued and ultimately a stage came when the centrifugal force became greater than

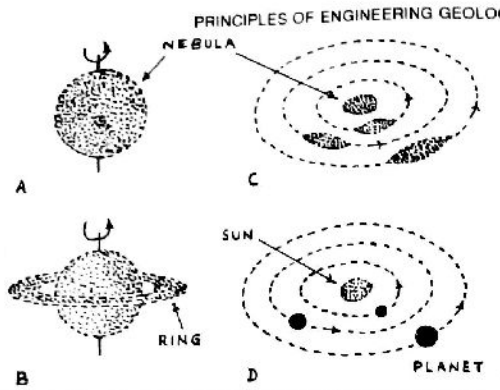


Fig. 1.1. Nebular Hypothesis. (*a*) Nebula. (*b*) A gaseous ring with nebula, (*c*) Formation of severed rings. (*d*) The rings condense into planets.

the gravitational attraction acting inward. As a result a gaseous ring was separated out [Fig. 1.1 (*b*)].

4. The above process was repeated and successive rings of gaseous material were thrown off from the central mass [Fig. 1.1 (*c*)]
5. In the final stages the rings condensed into planets [Fig. 1.1 (*d*)]. Planetoids were formed when one such ring broke into many small fragments.
6. The central mass of the nebula continued to shrink and finally formed the sun.

The nebular hypothesis was not favoured because it had the following defects.

(*i*) This hypothesis could not explain the energy distribution within the solar system. The sun which possesses most of the mass (about 99.9%) of the solar system, should have gathered maximum angular momentum. However, 98% of the angular momentum is concentrated in the planets and the remaining 2% is present in the sun. In other words, the sun does not rotate fast enough. It should have much higher speed of rotation.

(*ii*) There was not enough mass in the rings to provide the gravitational attraction for condensation into individual planets.

1.3.2. Planetesimal Hypothesis

The planetesimal hypothesis was proposed by Chamberlin and Moulton in 1904. The main points of this hypothesis are as follows.

1. The sun existed before the formation of planets. A large passing star approached very close to the sun.
2. Due to the disruptive forces of the sun and the strong gravitational pull of the passing star, giant masses of gas were torn from the surface of the pre-existing sun (Fig. 1.2).

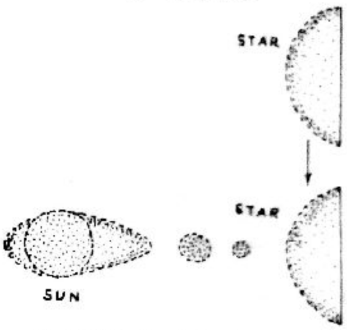


Fig. 1.2. Planetesimal Hypothesis

3. The giant masses of gas broke into a large number of small chunks which on cooling gave rise to solid particles, called "*planetesimals*".
4. The planetesimals started flying as cold bodies into orbits around the sun in the plane of the passing star. By collision and gravitational attraction, the larger planetesimals swept up the smaller pieces and thus planets were formed.

The main flaws in the planetesimal hypothesis are as follows.

(*i*) Most of the material which was ejected by the explosive action of the sun would come from the interior. It would be so hot that the gasses would disperse in the space rather than condense into planets.

(*ii*) Although the angular momentum imparted to the planets by a passing star would be greater than that produced the rotation of a nebula, the amount is still less than that observed.

(*iii*) The space is vast and therefore the probability of a close approach of two stars is extremely unlikely.

1.3.3. Gaseous Tidal Hypothesis

This hypothesis was proposed by Jeans and Jeffreys in 1925. The gaseous tidal hypothesis may be summarized as follows.

1. A very large star progressively approached close to the sun. Due to the gravitational pull of the star, a gaseous tide was raised on the surface of the sun. As the star came nearer , the tide increased in size.

2. When the star began to move away, the gaseous tide was detached from the sun. Its shape was like a spindle being thickest in the middle (Fig. 1.3).

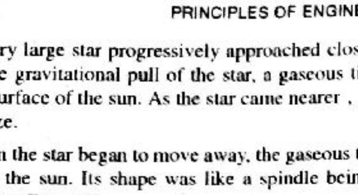


Fig. 1.3. Gaseous Tidal Hypothesis.

3. This spindle-shaped gaseous mass soon broke into ten pieces, nine of which condensed into planets and the remaining one which further broke into small pieces, formed the group of planetoids.

The main objections to the gaseous tidal hypothesis are as follows.

(i) The passing star is unable to impart the proper angular momentum to the detached gaseous masses.

(ii) The hot gaseous mass pulled away from the sun would not form solid planets but would dissipate into the space.

1.3.4. Binary Star Hypothesis

This hypothesis was proposed by Lyttleton in 1938. Before the formation of planets, the sun had a companion star. Another star approached close to these double stars and dragged the companion star away. A gaseous filament was torn from the companion star and it remained close to the sun. The planets were originated from this gaseous filament in the same way as described in the gaseous tidal hypothesis.

1.3.5. Recent Theories

Since 1943 there has been a tendency to swing back to theories of Laplacian type. These theories seem to explain well the observed variations in the chemical compositions and densities of the planets. The objection to Laplacian theory, that the sun's angular momentum is too small, has now been removed. The main points of the recent theories are as follows.

1. There was a disc-shaped cloud of gas and dust around the sun.

2. The planets were formed by gradual aggregation of the dispersed matter in the cloud.

   (i) Close to the sun where temperatures were highest, only those materials condensed which had high melting points such as metals and rockforming compounds. Hence the denser planets grew in the hot region lying closer to the sun.

   (ii) Volatile materials such as water, methane and ammonia were blown away. They condensed in the cold outer zone of the solar system thereby forming low density planets.

3. The primitive sun had a considerable magnetic field. It acted as a rotating magnet and accelerated the hydrogen ions present in the dust cloud. Due to this acceleration the gases moved outwards away from the sun carrying the fine dust with them and leaving only larger solid masses in the region of inner planets. Thus there was the transfer of momentum from the sun to the gas ions which slowed down the sun's rotation. This process also explains how the dust cloud was divided into two regions, an inner gas-free region of solid particles and an outer region rich in gases.

1.4. AGE OF THE EARTH

The age of the earth as determined by current methods of radiometric dating is about 4600 million years. Before the discovery of radiometric dating, several attempts were made to determine the age of the earth. The important ones are as follows.

1. From history of organic evolution.
2. From rate of sedimentation.
3. From salinity of sea water.
4. From rate of cooling.

1.4.1. From History of Organic Evolution

As soon as the earth cooled and solidified, life apeared on it. Initially the organisms had a simple body structure. The complexity increased with the passage of time. Man which has evolved quite recently, possesses the most complex structure. From the history of organic evolution, the biologists have determined the age of the earth to be about 1000 million years.

1.4.2. From Rate of Sedimentation

The formation of sedimentary rocks started with the solidification of the earth. Hence efforts were made to calculate the age of the earth from the rate of sedimentation in the ocean. The method involved was to determine the total thickness of sedimentary rocks that had been deposited during the earth's history, and then to divide it by the rate of sedimentation. This method gave an age of around 500 million years. This method had many difficulties some of which are as follows.

1. Different sediments accumulate at different rates under varying conditions.
2. A rate of sedimentation determined for recent sediments can not necessarily be applied to the past.

1.4.3. From Salinity of Sea Water

It is assumed that the oceans originally had fresh water. If the amount of salts carried to the ocean each year by rivers is known, it can be calculated how much time it took to accumulate the salt now present in the ocean. This method gave an age of about 120 million years. This estimate was not accurate as the rate of accumulation of salts could never have been uniform all through the history of the earth.

1.4.4. From Rate of Cooling

In 1897, the British physicist Lord Kelvin calculated the age of the earth from the temperature difference between the initial molten planet and its present state. He assumed that the rate of heat loss was constant throughout. This method gave an age of 20 to 40 million years which was more than 100 times lower than current estimates.

Kelvin also made estimates based on assumptions concerning the origin of the sun's heat. The age of the earth calculated by this method gave similar results, that is the figures ranged from 20 to 40 million years. Kelvin's estimates for the sun and the earth were wrong because he did not take into account the fierce heat generated by the decay of radioactive elements.

1.5. RADIOMETRIC DATING

The methods of radiometric dating are based on the radioactive decay of certain isotopes that have very long half-lives. The radioactive isotope is often referred to as the "*parent*" and the elements resulting from the decay of the parent are called the "*daughter products*". The age of rocks and minerals that contain radioactive isotopes is determined by measuring the accumulation of the daughter products in them. This procedure is called "*radiometric dating*". Radiometric dating is very reliable because the radioactive decay proceeds at a constant rate and it remains unaffected by any physical or chemical agents.

A commonly used term in radometric dating is "*half-life*". It is a common way of expressing the rate of radioactive decay. Half-life may be

defined as the time required for a given amount of radioactive substance to decay to one-half of its initial value. For example, the half life period of uranium – 238 is 4500 million years. This means that in 4500 million years one gramme of U – 238 would be reduced to half gramme, the rest having been transformed into the lead - 206.

Of the many radioactive isotopes that exist in nature, only three have proved useful in providing radiometric ages for ancient rocks. These three isotopes are given in Table 1.1. The methods which are commonly used for dating rocks include Potassium - Argon, Rubidium - Strontium and Uranium - Lead. The basic equation for calculating the age of a rock sample is as follows.

$$\text{Age of a rock} = 3.323\, T \log_{10}\left(1 + \frac{Nd}{Np}\right)$$

Where Nd is the number of atoms of the daughter product, Np is the number of atoms of the parent radioactive substance present today and T is the half life of the radioactive substance.

Table 1.1. Radioactive Isotopes Used in Radiometric Dating

Radioactive Parent	*Half-life in million years*	*Daughter Product*	*Minerals and rocks commonly dated*
Uranium-238	4500 m.y.	Lead-206	Zircon, Sphene
Potassium-40	11900 m.y.	Argon-40	Muscovite, Biotite, Hornblende, Glauconite, Volcanic rock.
Rubidium-87	47000 m.y.	Strontium-87	Muscovite, Biotite, Microcline, Metamorphic rock.

In practice mass spectrometers are used to measure precisely and accurately the quantities of parent and daughter radioactive substance in rocks. In radioactive dating, it is assumed that none of the daughter product has been leached out from the rock and that none has been introduced from outside.

Radiometric dating methods give a figure of some 3500 million years for the oldest rocks of the earth's crust. The radioactive analysis of meteorites has yielded dates of upto 4600 million years which probably correspond to the age of the earth.

1.6. COMMON RADIOMETRIC METHODS

1.6.1. Potassium—Argon Method

Potassium-40 has a half life of 11900 million years. It is commonly found in many rocks. It decays into argon-40, an inert gas found in the atmosphere. The K—Ar method can be used to date rocks that are millions of years old, including meteorites (age 4600 million years). However rocks younger than 0.1 million years are difficult to date because they contain very little radiogenic argon. The minerals that are suitable for K—Ar dating include biotite, muscovite, hornblende and nepheline. The potassium felspars, such as orthoclase and microcline are unsuitable for K-Ar dating because they are likely to loose argon readily at atmospheric temperatures.

1.6.2. Rubidium—Strontium Method

Rubidium-87 has a half life of 50,000 million years. The Rb—Sr method can be applied to rocks of almost any geological age. However rocks younger than 20 to 30 million years may create analytical difficulties because of the minute amount of radiogenic Sr-87 present. The Rb-Sr method can be used to date such common rockforming minerals as muscovite, biotite and all types of potassium felspars including ortho-clase and microcline.

1.6.3. Uranium—Lead Method

The half life of Uranium-238 is 4500 million years. Uranium and thorium frequently occur in the same mineral and it is therefore possible to make two independent age determinations on one mineral sample.

The U—Pb method can be applied over the greater part of the geological age range, although their usefulness decreases sharply for rocks younger than 100—200 million years. This method is less commonly used than the K—Ar and Rb—Sr methods but may be used to date rare minerals in which uranium and thorium are major constituents. It is frequently applied to minerals such as zircon and sphene.

It should be noted that the U—Pb methods are of much greater value than the Th—Pb method. The latter is now only rarely used.

1.6.4. Radiocarbon Dating

There are three isotopes of carbon : C-12, C-13, and C-14. Of these C-14 is radioactive. Since it has a half life of only 5730 years, it can be used to date events of recent geological history. Although C-14 is only useful in dating the last small fraction of geological time (75,000 years), it has become an important means for dating Ice Age and archaeological material.

Radiocarbon (C-14) is produced in the atmosphere by cosmic ray bombardment of nitrogen - 14. The C-14 combines with oxygen to form carbondioxide which is absorbed by living organisms. A constant ratio of C-14 to C-12 is established in each organism during its life. After death no more carbondioxide is absorbed and the C-14 decays steadily by emitting beta particles to N-14.

1.7. INTERIOR OF THE EARTH

The study of the passage of seismic waves through the earth have helped in knowing the structure of the earth's interior and in defining the physical properties of various layers. The seismic waves travel at different velocities

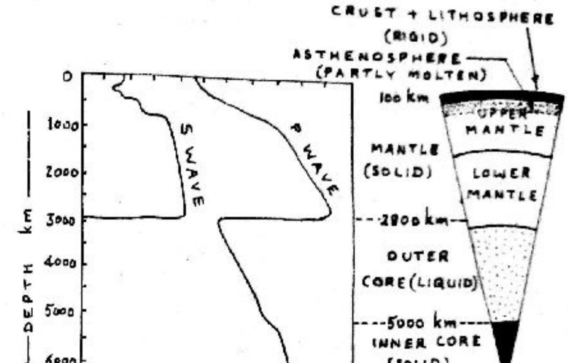


Fig. 1.4. (*a*) Showing variation of P and S wave velocity in the earth's mantle and core; (*b*) showing internal structure of the earth.

depending on the nature of the layer in which they are travelling. Thus they not only indicate the position of each layer but also give clues as to its composition. Fig. 1.4 shows the velocities of earthquake waves at various depths below the earth's surface. The velocity curve shows sharp changes at various discontinuity surfaces. On the basis of seismic investigations, the earth can be divided into four major layers : (*i*) crust, (*ii*) mantle, (*iii*) outer core, and (*iv*) inner core (Fig. 1.5).

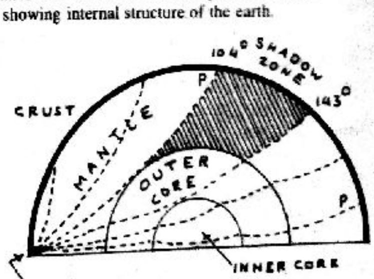


Fig. 1.5. Earth's internal structure and some typical seismic rays.

1.7.1. Crust

The outer superficial layer of the earth is called the "*crust*". It extends down to 30 or 40 kilometer beneath continents and to about 10 km beneath ocean basins. At the bottom of the crust, the velocity of earthquake waves increases abruptly as they enter into a denser layer called "*mantle*". The crust-mantle boundary is known as the "*Mohorovicic discontinuity*".

In the continental regions, the crust can be divided into two layers. The upper layer which is less dense (sp. gr. 2.65) and granitic in character, is known as "*sial*", while the lower layer which is basaltic in character (sp. gr. 3.0) is known as "*sima*". The term sial represents rocks rich in silica and alumina, and term sima represents rocks containing silica and magnesia. Under oceans only sima layer is found and the sial layer is absent.

1.7.2. Mantle

The mantle is located beneath the earth's crust and has a thickness of about 2900 km (Fig. 1.4). It has been divided into two layers : (*i*) upper mantle, and (*ii*) lower mantle. The boundary between these is at about 700 km depth. The average mineral composition of the upper mantle is similar to ultrabasic rocks like "*peridotite*" (sp. gr. 3.3). This zone provides lava for oceanic eruptions. In the lower mantle the density of the material increases rapidly to 4.3×10^3 kgm^{-3} and in the deeper parts it rises to about 5.5×10^3 kgm^{-3}. It has been suggested that the lower mantle consists of a mixture of peridotite and minerals of higher density.

The upper mantle contains a most important zone called "*asthenosphere*". It is located at depths between 50 to 100 km. In the asthenosphere the velocity of S-waves decreases thereby indicating that this zone consists partly of melted rocks. Most basalts originate in this zone. It is believed that the plastic material of the asthenosphere moves and carries along the lithospheric plates. The outer solid portion of the earth existing above the asthenosphere is called the "*lithosphere*". The lithosphere includes part of the upper mantle and the crust.

1.7.3. Core

The boundary between the mantle and the core is at a depth of about 2900 km. This boundary is marked by an abrupt reduction in the velocity of P-waves as well as by the disappearance of the S-waves (Fig. 1.4).

The "*outer core*" was discovered when it was found that P-waves were bent inwards thereby producing a "*shadow zone*" at the surface (Fig. 1.5). Since the S-waves do not pass through the outer core, it is concluded that it may be in the liquid state.

The "*inner core*" extends from about 5150 km to the earth's centre at 6371 km. It transmits P-waves at a higher velocity which indicates that it is in the solid state. Both the solid and liquid portions of the core are believed to consist of iron and nickel similar to iron meteorites and have a density about 1.2×10^3 kgm^{-3}.

1.8. ISOSTASY

C.E. Dutton, in 1889, suggested that a gravitational balance exists between the elevated masses (*i.e.* continents) and ocean basins of the earth's crust. It is believed that the lithosphere floats on the top of the partially molten substratum (asthenosphere) much like logs float on water. Mountains stand high because they are composed of rocks of low density and ocean basins are low because they are made up of rocks of higher density. This gravitational balance of the floating lithosphere is called "*isostasy*".

In the isostatic adjustment mainly vertical movements of the crustal blocks take place. For example, when material is removed from the top of a mountain by erosion, it rises upwards and when sediments derived from it accumulate in a depositional basin, it is depressed due to increased weight.

Zone of Compensation. At depths between 96 and 200 kilometers below the surface, the rocks exist in the plastic state. Here pressures due to elevated masses and depressed areas are equal. This zone is called the "*zone of compensation*".

In the 19th century, while doing the trigonometrical survey, it was found that the deflection of the plumb line towards the Himalayas was not proportional to the gravitational attraction of the mass of the mountain range. It was very much less than the estimated value. As a result in 1855, both J.H. Pratt and G.B. Airy proposed that the continents consisted of lighter material floating on a denser substratum.

1.8.1. Pratt's Hypothesis

Pratt suggested that the different heights of mountains were due to blocks of different densities floating at the same base level. This idea can be illustrated with the help of Fig. 1.6. Blocks of metals having different densities are immersed in the mercury. They have equal weight and cross sections but different length. These blocks sink to the same level in the mercury but their upper surfaces stand out at different heights. The lighter the block, the higher it stands. Here the longer blocks represent mountains and lower blocks ocean basins.

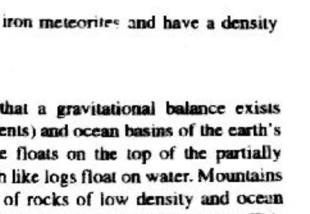


Fig. 1.6. Pratt's hypothesis of isostasy.

1.8.2. Airy's Hypothesis

Airy considered that the different heights of land masses were due to blocks of different thickness and of the same density floating at different depths. Fig. 1.7 illustrates the Airy's hypothesis. Here all the blocks are of the same material but they have different lengths. The bases of the blocks will not be even and their tops will also be irregular. The high columns will have deep extensions downward and low columns will have short ones, and therefore, the level of compensation will be uneven.

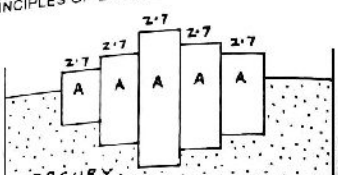


Fig. 1.7. Airy's hypothesis of isosatsy.

Today the Airy's hypothesis is generally accepted as it explains very well the following features.

(*i*) The mountains which are composed of light material have deep "*roots*" extending into the mantle below. The existence of these roots has been confirmed by seismic and gravitational data.

(*ii*) The thickness of sial under plains near sea level is only about 30 km.

(*iii*) Beneath the oceans the sial layer is absent altogether and the crust is thinner than that of the continents.

1.8.3. Evidence of Isostasy

If the isostatic theory is correct, we would expect that if weight is added to the crust, it will respond by subsiding and when weight is removed, there will be uplifting. Evidence of this type exists.

1. Parts of Norway and Sweden which were covered by the thick Pleistocene ice sheets, are rising following the melting of the ice.
2. When erosion strips off the tops of mountains, the mountains themselves rise up. The processes of uplifting and erosion continue untill the root of the mountain reaches the same height as the surrounding crust.

1.9. CONTINENTAL DRIFT

The theory of continental drift was proposed by Alfred Wegener in 1910. He suggested that at the beginning of the Mesozoic era (about 200 million years ago) all the continents of the earth were united together to form a single supercontinent which he called "*Pangaea*" (Fig. 1.10). The huge ocean which surrounded it, was called "*Panthalassa*". Wegener proposed that this vast continent began to break up into smaller continents at the beginning of the Mesozoic era which then drifted to their present positions just like pieces of wood floating on water. The continents were drifted westward and equatorward under the "*differential gravitational forces*". The term "*Gondwana land*" was used for the southern huge landmass which included Africa, South America, Australia, Antarctica and India, and

"*Laurasia*" for the northern landmass which included North America, Greenland and Eurasia (Fig. 1.10). To support his theory, Wegener gave many geological evidences, such as similarities in geological structure, distribution of rock types and fossils, and similar shapes of coast lines on either side of the Atlantic ocean. The theory of continental drift was not accepted for over 40 years. It received support only in 1950's and 60's when geomagnetic evidences were discovered in its favour.

1.10. EVIDENCES FOR GONDWANALAND

1.10.1. Similarities in Shape of Coastlines

The Atlantic coasts of South America and Africa have a roughly similar shape. They would fit-in nicely if they are brought in contact with each other (Fig. 1.8). However, the coast lines are not reliable geological features because their shape changes with the rise and fall of the sea level relative to the land. The real edge of a continent occurs at the continental slope where sea bottom falls rapidly down to deep ocean floor. The mapping of the continental slopes of eastern South America and west Africa has indicated that their contours match excellently. This strongly suggests that these two continents were once joined together.

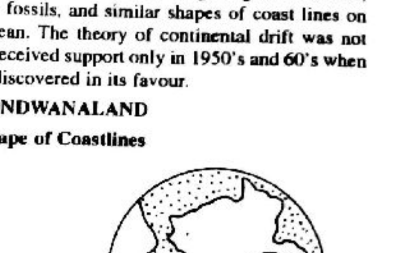


Fig. 1.8. Showing similarities in the shape of the east coast of South Africa and west coast of Africa.

1.10.2. Similar Orogenic Belts

If the eastern coast of South America and the western coast of Africa are fitted together, the orogenic belts of the two continents which have the same range of ages and similar structural trend, are found to align themselves across the join. For example, in Ghana near Accra (west Africa) there is a clear boundary between 2ooo million year old rocks and the much younger (about 400 million year old) rocks. This boundary runs into the Atlantic ocean in the southwest direction. The same boundary occurs in Brazil (eastern South America) at Sao Luis. These data provide some of the best evidence supporting their original continuity.

1.10.3. Permo-Carboniferous Glaciation

In the Parana basin in eastern Brazil (South Africa) glacial deposits of Permo-Carboniferous age are widespread. Their average thickness is about 600 meters. The direction of ice movement suggests that the source area of these glacial deposits lies to southeast of the present Brazilian coast. In southwest Africa, though the glacial deposits are meagre, there is abundant evidence for ice erosion. The direction of ice flow recorded is from east to west. This suggests that southwest Africa was covered by an actively eroding ice sheet which dumped its load further west in Brazil (South Africa). This evidence proves the original continuity between Africa and South America (Fig. 1.9).

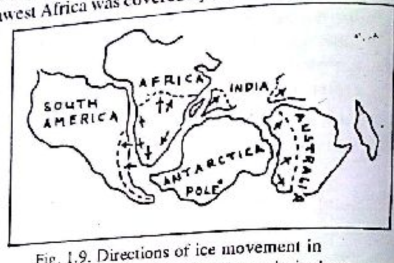


Fig. 1.9. Directions of ice movement in Gondwana land. India is also shown in its best fitting position against northwest Australia.

Evidences of Permo-Carboniferous glaciation have been found in all the continents of southern hemisphere, such as South America, Africa, Australia, India, Antarctica and Madagascar. The till deposits and fossil plants found in these continents have been examined and correlated. If these landmasses had always been in the tropical lattitude, as they are today, it would mean that glaciation extended from the polar regions to the equator. This idea is apparently unreasonable. The only explaination for this puzzle is that all these continents were joined together to form a single landmass, Gondwanaland, which was located over the south pole (Fig. 1.9).

1.10.4. Glossopteris Flora

The remains of the "*glossopteris flora*" occur in rock beds of the Gondwana Series in South America, South Africa, India, Australia and Antarctica. These flora reached their maximum development in the Permo-Corboniferous period. The nature of their species distribution can only be explained if all the southern continents were joined together.

1.10.5. Land Bridges

To account for the distribution of some plants and animals in the fossil record, the land bridges were postulated between the continents. It was assumed that these land bridges were later disappeared by subsidence. The detailed study of ocean floors in recent years has ruled out this idea. If the existence of "*Gondwanaland*" is accepted, the distribution of many animals and plants can easily be explained. For example, remains of the reptile "*mesosaurus*" which could not have swum an ocean, have been found in western South Africa and in Brazil.

1.10.6. Palaeomagnetic Evidence

Igneous rocks record the earth's magnetic field present at the time of their formation. A study of fossil magnetism in a region where several volcanic eruptions had occurred on a widely separated occassions, has led to an interesting discovery. The orientation of the earth's magnetic field in each of the separate lavaflows is found to be different. This suggests that between volcanic eruptions, the magnetic poles have moved to a new location. Thus palaeomagnetic techniques which locate the magnetic pole of any stage in the past, give consistant results on each continent only when they are placed in the proposed framework of the Gondwanaland.

1.11. EVIDENCE FOR LAURASIA

Laurasia was the northern landmass which consisted of North America, Greenland and Eurasia. The geometrical fit of these continents is quite good. To confirm the existence of Laurasia, geologists have shown that the now widely separated Norwegian, Caledonian, Appalachian and east Greenland mountains were originally formed as a single chain. This match suggests that the northern continents were a single unit some time in the interval 260 to 70 million years ago.

1.12. POSTION OF INDIA

In order to fit Australia, Antarctica and India together, the geology is used as a guide. The Palaeozoic mountain belts in Antarctica and Australia indicate the way in which they were joined together. The same pattern of belts also continues into Africa and South America. Further, the edges of Antarctica and Australia at 500 fathom (1000 meter) line also match nicely. However there is doubt about the proper position of India (Fig. 1.9). Ahmad, an Indian geologist, has suggested that close links exist between the geology of southeast India and northwest Australia. He reached to this conclusion when he studied the sedimentary basins of Permian age in these two continents and found them very similar. The main objections for fitting India against northwest Australia are as follows.

(*i*) The Upper Carboniferous tillite pattern does not match across the join.

(*ii*) A recently published fit based entirely on palaeomagnetic data, does not support the placing of India against northwest Australia.

Thus except for the link between India and Antarctica, there is positive evidence that Gondwanaland existed as a supercontinent untill Jurassic time (about 190 million year ago). If the evidence of sea floor spreading and plate tectonic are added to the argument, the continental drift may be regarded as an established fact.

1.13. BREAKUP OF PANGAEA

The chief events of the breakup of the supercontinent Pangaea, are as follows.

1. Fig. 1.10 shows the Pangaea which existed in the Permian times, a little more than 200 million years ago. It was surrounded by a

Fig. 1.10. The Ancient Landmass Pangea.

huge ocean called Panthalassa. The Tethys Sea existed between Africa and Eurasia.

2. The breakup of Pangaea began in the Triassic period (about 200 million years ago) with the formation of rifts. At the end of Triassic period (about 180 million years ago), the significant features of the geography of the world were as follows.

   (i) The "*North Atlantic ocean*" was formed as North America was separated from Africa. Due to this the Tethys sea contracted.

   (ii) The Laurasia was separated from the Gondwanaland.

   (iii) A Y-shaped rift was formed in the southern Pangaea which separated Antarctica—Australia from Africa—South America and sent India on its northward journey.

3. By the end of the Jurassic period (about 135 million years ago), South America broke from Africa thereby forming the "*South Atlantic*" ocean. The North Atlantic and Indian oceans were enlarged but the Tethys Sea continued to close. India moved further northward (Fig. 1.11).

4. At the close of the Cretaceous period (about 65 million years age), Madagascar was separated from Africa and the South Atlantic widened. The Tethys closed further to form an inland sea, the Mediterranean.

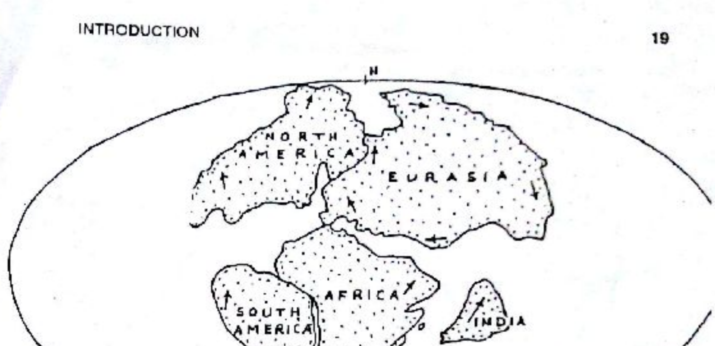


Fig. 1.11. Position of continents at the end of the Jurassic period. Arrows indicate direction of drift.

5. About 40 million years ago, India collided with Asia and produced the Himalayan mountains, Greenland has separated quite recently from North America.

1.14. PLATE TECTONICS

The theory of plate tectonics has evolved from Harry Hess's concept of a "*sea floor spreading*". He proposed this concept in the early 1960's. The Hess's hypothesis was accepted when Vine and Mathews used it in explaining linear magnetic anomalies of the ocean basins. In 1967, W.J. Morgan and J.T. Wilson extended the idea of Hess and produced the theory of plate tectonics. The factors which led to the theory of plate tectonics were : (*i*) mapping of the ocean floor, (*ii*) study of seismic data, and (*iii*) pattern of anomalies of the earth's magnetic field. This theory has now offered explaination for many of the complex geological processes such as volcanic activity, earthquakes, mountain building and continental drift.

1.14.1. Crustal Plates

The entire earth's surface is composed of several rigid but relatively thin plates. These plates are between 100 and 150 kilometer thick and carry both continental and oceanic crust with them. They are continuously in motion with respect to each other.

The plates vary in size. There are about 20 crustal plates on the earth's surface, out of which seven are very large. The large plates are : (*i*) the North American plate, (*ii*) the South American plate, (*iii*) the Eurasian plate, (*iv*) the African plate, (*v*) the Indo-Australian plate, (*vi*) the Pacific plate, and (*vii*) the Antarctic plate (Fig. 1.12). These plates are separated by ridges, transform faults and trenches.

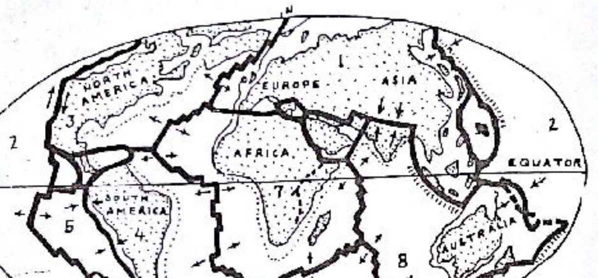


Fig. 1.12. Earth's moving plates. 1. Eurasian plate, 2. Pacific plate, 3. North American plate, 4. South American plate, 5. Nazca plate, 6. Antarctica plate, 7. African plate, 8. Australian plate, 9. Philippine plate.

The plates slide over a partially molten plastic layer called the "*asthenosphere*". The asthenosphere occurs below the lithosphere in the upper mantle at depths between 100–200 km [Fig. 1.4 (*b*)]. In this zone the velocity of shear waves drops to a minimum. Its plastic behaviour may be due to increased temperatures and pressures existing at greater depths. The asthen sphere is believed to be the site of convection cells (Fig. 1.15).

1.14.2. Plate Boundaries

Almost all seismicity, volcanicity and tectonic activity is localized around plate margins. Hence boundaries between different plates are of perticular interest. Depending on the relative motions of adjacent plates, the plate boundaries are classified into three groups : (*i*) "*divergent boundaries*", (*ii*) "*convergent boundaries*", and (*iii*) "*transform fault boundaries*". Let us stinguish between a plate boundary and a plate margin. The zone of motion tween two plates is called the "*plate boundary*" and the marginal part of a single plate is called the "*plate margin*". Two plate margins meet at a common plate boundary.

(*i*) **Divergent Boundaries.** Divergent boundaries are also called the "*constructive zones*" because in these zones the new crust is continuously created. Divergent boundaries occur at oceanic

ridges. The "*divergent boundaries*" are boundaries along which plates move away from each other [Fig. 1.13 (*a*)]. In the process

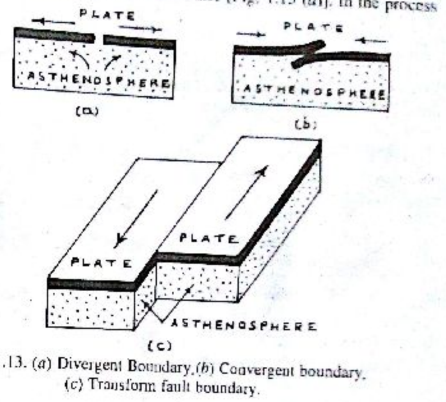


Fig. 1.13. (*a*) Divergent Boundary, (*b*) Convergent boundary, (c) Transform fault boundary.

of plate separation, the magma rises up from the asthenosphere and fills the gap thus created. In this way new crust is created along the trailing edges of the diverging plates. This phenomenon is called "*sea floor spreading*". Such boundaries are characterized by basaltic igneous activity, shallow focus earthquakes and high rates of heat flow.

Thus the oceanic ridges are the newest part of the earth's crust. The oldest crust is found near the oceanic trenches where it slides down into the mantle. The plates move from ridges and travel like a conveyor belt towards trenches where they are destroyed. Plate boundaries at which the net effect of motion is to generate crust are called "*sources*". The rate of sea floor spreading at ridges ranges from less than 1.0 centimeter to 6.0 centimeter per year.

(*ii*) **Convergent Boundaries.** The "*convergent boundaries*" are boundaries along which two plates approach each other and the leading edge of one slips down under the other at an angle of about 45° [Fig. 1.13 (*b*) and 1.14). These boundaries are also called the "*destructive boundaries*" or "*subduction zones*". They occur at the deep trenches. The dipping plate sinks into the asthenosphere where lithosphere melts to produce magma. Thus trenches are the areas where plate edges are destroyed. The plate boundaries at which the net effect of the motions is to destroy surface area are called "*sinks*". Since the surface area of the earth does not change,

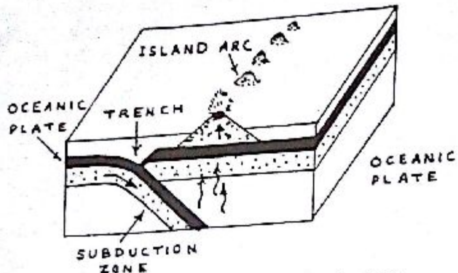


Fig. 1.14. Showing convergence of two oceanic plates.

the amount of crust created at the oceanic ridges is balanced by that destroyed at the trenches.

The convergent boundaries are characterized by basaltic and andesitic volcanism, deep focus earthquakes and fold mountain ranges.

(*iii*) **Transform Fault Boundaries.** "*Transform fault boundaries*" are boundaries along which plates slide past one another and there is no production or destruction of lithosphere [Fig. 1.13 (*c*)]. The transform faults run in the direction of the plate movement and offset oceanic ridges. The margins at which the plates neither gain nor loose surface area, are called "*conservative boundaries*". The transform faults are characterized by shallow focus earthquakes with horizontal slips.

Although most of the transform faults occur in the oceanic crust, a few are found within continents, such as the San Andreas fault (southwestern U.S.A.).

1.14.3. Plate Margins

A plate may carry either continental or oceanic crust or both. However only those margins which have oceanic crust can participate in the main process of plate growth and destruction. The important events associated with plate margins are as follows.

1. The continental crust can not be subducted. It tends to remain floating because this crust is thicker and more buoyant. Where two plates with continents at their leading edges converge, a collision takes place. As a result the crust thickens to form great mountain ranges like the Himalayas [Fig. 7.52 (*b*)]. In such a case the relative motion between the two plates ceases and they unite to form a larger single plate.

2. Where a continental crust converges with the oceanic crust, the less dense continental mass remains floating while the more dense oceanic crust sinks into the mantle along the line of the oceanic trench [Fig. 7.52 (*c*)]. Such a process operates at the Peru-Chile trench where the Nazca plate (oceanic) sinks under the continental plate of South America.
3. Where two oceanic plates converge, one of them is subducted. The magma produced due to melting of the dipping plate, rises to the surface (ocean floor) creating volcanoes. Island arcs are produced as a result of the continuation of this activity (Fig. 1.14).
4. The spreading process which operates at oceanic ridges, produces only the thin oceanic crust and not the thick and mineralogically different crust of the continents.

1.15. CHANGE OF SHAPE AND SIZE OF PLATES

Normally plates change both in size and shape. However there are two conditions in which their size will not alter : (*i*) when the rates of growth and destruction on opposite sides of a plate exactly balance each other, and (*ii*) when a plate is surrounded on all sides by conservative boundaries.

A plate which has constructive margins on the two opposite sides, will expand in size and therefore its shape will change. The African plate is a good example of this type. This plate is bounded on the west by the Mid Atlantic Ridge and on the east by the Indian Oceanic Ridge. Both of these ridges are active centres of spreading. Thus this plate must be expanding in an E—W direction.

The earth is of a constant surface area. It demands that if the area of some plates increases, that of others must decrease. Hence in theory, it is possible that a plate may be completely destroyed, and mid oceanic ridges and deep ocean trenches may migrate freely with respect to each other.

1.16. OPENING AND CLOSING OF OCEANS

Plates change both in size and shape. This means that new plates can form by the breaking up or welding together of other plates. This results in the birth and death of oceans. The process of opening and closing of oceans may be outlined as follow.

(*i*) An ocean grows where the process of sea floor spreading is under progress and shrinks where continents force the ocean floor to slide down into the trench. The Atlantic in an example of growing ocean while the Mediterranean is that of shrinking.

(*ii*) A shrinking ocean disappears altogether when the continental masses converge and join with each other (Fig. 7.52).

(*iii*) The birth of a new ocean takes place with the breaking of a continent. This breaking occurs due to the formation of a new spreading centre. The Red sea is believed to be the site of a recently formed spreading centre. The birth of the Red sea took place when the Arabian Peninsula separated from Africa and moved towards the northwest.

1.17. CONVECTION CURRENT HYPOTHESIS

The high heat flow associated with the oceanic ridges suggests that convection currents exist within the earth. These currents are believed to be responsible for the movement of crustal plates. The idea of convection current was first suggested by the British geologist A. Holmes in 1927 when he tried to explain the driving mechanism for the continental drift. Holmes proposed that subcrustal convection currents dragged the two halves of the original continent apart. The mountain chains were formed on the front portion of the moving land masses where the currents were descending, and ocean floor was developed on the site of the gap where the currents were ascending.

It is generally accepted that most of the mantle is a hot solid. Seismology suggests that the asthenosphere is partly molten (temperature about 1200°C). Due to unequal distribution of heat, convection currents generate in it (Fig. 1.15). Under the mid oceanic ridges, the ascending hot plume spreads laterally. As it spreads away it cools, solidifies and becomes attached to the oceanic plates. At trenches the cold plume sinks back into the mantle where it is reheated. Thus the cycle of convection is completed. This convective transport impart motion to the crustal plates.

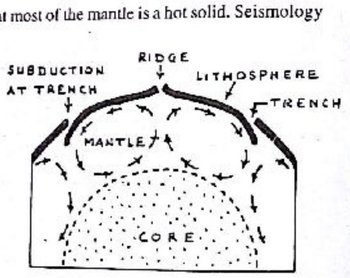


Fig. 1.15. Showing convection currents in the earth's mantle.

Thus the convection current hypothesis has provided an important mechanism for explaining the continental drift, sea floor spreading and plate tectonics.

1.18. THEORY OF SEA FLOOR SPREADING

The theory of "*sea floor spreading*" was first proposed by Harry Hess in 1960. The two fundamental facts that led to him to postulate this theory are : (*i*) the mid ocean ridges occur in all major ocean basins, and (*ii*) the oceanic crust has a thickness of 6 to 7 kilometer only whereas the typical thickness of continental crust is 30—40 km.

Hess postulated that the mid oceanic ridges are situated over the rising limbs of convection currents of the earth's mantle and that thin oceanic crust is formed due to cooling and solidification of lava rising from the mantle. The ocean progressively widens as the new oceanic crust is created along a crack that runs along the crest of mid ocean ridges. This mechanism is called the "*sea floor spreading*". The floor of the Atlantic ocean has formed by this process during the past 200 million years. The typical rate of spreading at oceanic ridges has been estimated to be 5.0 centimeters per year.

The new oceanic crust created at ridges spreads laterally away and is ultimately destroyed in the oceanic trench systems. The oceanic trenches are the sites where convection currents descend down into the mantle. In these areas, the oceanic crust is thrust down in the mantle where it is largely resorbed. Continents are not liable to destruction and hence have great age. They only passively drift apart floating on convection cells of the mantle.

1.18.1. Evidences

The evidences which support the theory of sea floor spreading are as follows.

(*i*) Drilling into the ocean floor has been done to study the sediments occuring there. Cores obtained from near the oceanic ridges have shown, that only thin layer of young sediment overlie the oceanic crust. With an increase in distance from the ridge, the sediment generally thickens and the age of the sediment also increases.

(*ii*) Magnetic surveys taken across the oceanic ridges have disclosed symmetrically distributed strips of positive and negative magnetic anomalies. The axis of symmetry coincides with the crest of the mid oceanic ridge. These strips of magnetic anomalies provide proof for the theory of sea floor spreading. At the oceanic ridges new sea floor is being produced. This new sea floor records the reversals in the earth's magnetic field. The time elasped between the reversals ranges from thousands to hundreds of thousands of years. By determining the amount of new sea floor produced during a magnetic reversal of known length, the rate of spreading can be calculated.

(*iii*) The occurrence of earthquakes and active volcanic islands along the crests of mid oceanic ridges also provide evidences which are in favour of the theory of sea floor spreading.

REVIEW QUESTIONS

1. Enumerate the various hypothesises of the origin of the earth. Describe the Nebular and Gaseous tidal hypothesises in detail.

2. Describe the radioactive methods for dating the earth. How old is the earth according to these estimates ? Why is radiometric dating the most reliable method of dating ?
3. Give a brief account of the internal structure of the earth. What are the major characterstics of each region?
4. What information does the theory of earthquake provide with regards to the interior of the earth ?
5. Give an account of the internal structure and constitution of the earth?
6. Give an outline of the various methods advanced to evaluate the age of the earth and discuss the merits and demerits of each one of them.
7. What is isostasy ? Explain the hypothesises proposed by Pratt and Airy. Give some evidences of isostasy.
8. Explain in brief the Wegener's theory of continental drift and give evidences that support this theory.
9. What is plate tectonics ? Describe the various types of plate boundaries.
10. Explain the following in the context of plate tectonics.

    (*i*) Convection current hypothesis.

    (*ii*) Theory of sea floor spreading.
11. Write short notes on any four of the following.

    (*i*) Protoplanet hypothesis, (*ii*) Solar system, (*iii*) Mohorovicic discontinuity, (*iv*) Isostasy, (*v*) Radiometric dating.

2 Physical Geology

2.1. WEATHERING

The rocks break and undergo decay under the influence of the atmospheric agencies like wind, sun, frost, water and organisms, and produce soil. This phenomenon is called *"weathering"*. Weathering and erosion together lowers the mountains and produces sediments. The weathering may be defined as a process which tends to break and decompose rocks in place. It includes two processes : (*i*) *"disintegration"* or physical breaking, and (*ii*) *"decomposition"* or chemical decay. In nature these two processes work simultaneously.

Erosion. *"Erosion"* is a process which includes the destruction of existing rocks and removal of the product from the site of destruction. Transport is the important aspect of erosion. It is usually done by water, wind or ice.

Denudation. The combined effect of weathering and erosion is called *"denudation"*. It involves the general wearing down of the earth's surface.

Exfoliation. It is mainly a physical weathering process in which large sheets of rock peel off from an outcrop. In exfoliation, reduction in pressure due to removal of the overlying rock plays an important part. As each slab breaks off, it releases weight from the underlying mass. As a result its outer layers expand and separate from the rockmass. Exfoliation is commonly seen in homogeneous rocks like granite.

Spheroidal Weathering. If an outcrop of jointed rock is subjected to chemical weathering, the rounded boulders are produced. This process is called *"spheroidal weathering"*. The spheroidal weathering resembles exfoliation except that it takes place on a much smaller scale. In spheroidal weathering, the hydration which is accompanied by increase in volume, plays an important part. As the minerals in the rock weather to clay, they increase in size because of the addition of water into their structure. This increase in volume exerts an outward force due to which the concentric layers of rock break loose and fall off.

2.2. PHYSICAL WEATHERING

Physical weathering or disintegration involves application of mechanical forces. In physical weathering a rock breaks into smaller pieces without any chemical change. Thus by breaking rocks into smaller pieces, physical weathering increases the amount of surface area for chemical attack. The principal agents of physical weathering are : (*i*) frost, (*ii*) heating and cooling, and (*iii*) organisms.

2.2.1. Frost

When water freezes, it expands about 9 percent of its volume. In nature water enters into cracks of rocks. Upon freezing it expands and exerts great pressure on the walls of cracks. As a result, the rock breaks into pieces. This process is called *"frost wedging"*. By this process angular fragments of rock are broken off from the high mountain ranges. These rock fragments roll down the hill slope and accumulate at the base to form *"talus deposits"*.

2.2.2. Heating and Cooling

It is believed that daily cycle of temperature change weakens rocks, particularly in hot dry regions. Heating a rock causes it to expand and cooling causes it to contract. The repeated expansion and contraction tend to develop cracks in rocks. In desert areas the coarse grained rocks like granite, disintegrate soon into their constituent crystals and become desert sands as a result of temperature variation.

2.2.3. Organisms

Plants, burrowing animals and men play an important part in the disintegration of rocks. Plant roots grow into rock joints. As the roots grow thicker, they exert mechanical pressure and wedge the rock apart. The burrowing animals, such as earth-worms, ants and rodents also contribute to the disintegration of rocks. Men also break rocks by making road cuts, tunneling, quarrying, mining and cultivating the land.

2.3. CHEMICAL WEATHERING

Chemical weathering or decomposition is a process in which rocks are broken down by chemical decay of minerals. During chemical weathering, a set of chemical reactions act on rocks which changes their minerals to more stable forms. The principal agents of chemical weathering are : (*i*) water, and (*ii*) organisms.

2.3.1. Water

Water is the main agent of chemical weathering. Although water in pure form is inactive, it becomes a powerful chemical agent when a small amount of oxygen and carbon dioxide are dissolved in it. Rain water usually contains these gases. The main reactions involved in the chemical weathering are : (*i*) oxidation, (*ii*) hydration, (*iii*) carbonation, and (*iv*) solution.

Oxidation. The oxygen present in the water in dissolved state oxidizes some minerals. Mafic minerals like pyroxenes, amphiboles and olivines contain some iron. During weathering the oxygen unites with the iron producing insoluble iron oxides. Limonite and hematite are the very common products of oxidation which impart red and yellow colours to soils.

Hydration. In hydration water molecules combine chemically with minerals to produce new compounds. The formation of gypsum ($CaSO_4 \cdot 2H_2O$) from anhydrite ($CaSO_4$) is a good example of hydration. Carbonation frequently operates along with hydration. The orthoclase felspar, a mineral which is abundant in granite, is decomposed and converted into kaolin by hydration and carbonation. Other hydrous silicates formed by hydration of the primary silicates, such as pyroxenes, amphiboles and olivine are chlorite, serpentine, talc and zeolites.

Carbonation. Carbon dioxide dissolves in water to form carbonic acid (H_2O_3). Carbonic acid is an effective weathering agent. Granite is the most abundant continental rock. Under the influence of carbonic acid it weathers into clay. Let us examine this process in detail.

(*i*) The granite consists mainly of quartz and potassium felspar. Quartz is very resistant to chemical weathering. Hence it remains unaltered.

(*ii*) The reaction between carbonic acid and potassium felspar is as follows.

$$2KAlSi_3O_8 + 2H_2CO_3 + H_2O \longrightarrow Al_2Si_2O_5(OH)_4 + 2KHCO_3 + 4SiO_2$$

(*iii*) The products of this reaction are potassium bicarbonate and clay minerals. The potassium bicarbonate being soluble is removed by ground-water, while clay minerals accumulate near the surface.

The weathered products of important silicate minerals are shown in Table 2.1. When minerals containing calcium, magnesium, sodium or potassium react with carbonic acid, carbonates and bicarbonates are formed. These soluble products are removed by groundwater. The three remaining elements, aluminium, silicon and oxygen join with water to produce stable clay minerals.

Table 2.1. Products of Weathering

Mineral	*Residual Product*	*Material in Solution*
Quartz	Quartz grains	Silica
Felspars	Clay minerals	Silica, K^+, Na^+, Ca^{++}
Hornblende	Clay minerals, Limonite, Hematite	Silica, Ca^{++}, Mg^{++}
Olivine	Limonite, Hematite	Silica, Mg^{++}

Solution. The process of solution and carbonation goes on together. The limestones, dolomites, rocksalt, and gypsum are particularly susceptible to solution when they are attacked by water containing carbon dioxide.

2.3.2. Organisms

Many dead organisms produce organic acids as they decay. These acids increase the solvent power of water. For example, the solubility of silica, alumina and iron is much greater in the presence of organic acids.

2.4. RATES OF WEATHERING

The rate at which a rock weathers depends on the following factors.

1. The particle size influences the rate of weathering. The smaller the particle, the greater the surface area for chemical attack.
2. The mineral composition of a rock is also very important. The slate which is mainly composed of clay minerals is very resistant to weathering while this is not true for marble.
3. The order in which the silicate minerals weather is the same as their order of crystallization. From Bowen reaction series (*Fig. 5.15*) it is clear that olivine crystallizes first and it is the least resistant to weathering, while quartz which crystallizes last, is the most resistant.
4. The rate of weathering is also affected by the climatic factors. Chemical weathering is most active is warm humid regions and least active in cold or arid regions.

2.5. SOIL

Regolith. Any solid unconsolidated material lying on top of bedrock is called *"regolith"*. It includes soil, alluvium, and rock fragments weathered from the bedrock. The thickness of this mantle varies from nil over rock exposures to very deep in areas protected from erosion.

Soil. A portion of the regolith which supports the growth of plants is called *"soil"*. Thus soil is a combination of minerals, organic matter, water d air.

2.5.1. Soil Profile

If we examine the walls of a trench, they are found to contain a series of horizontal layers. These layers are called *"horizons"*. All horizons together form the *"soil profile" (Fig. 2.1)*. The three basic horizons from top to bottom are *A*, *B*, and *C*.

Fig. 2.1. Soil profile

(*i*) *A-Horizon.* It is the upper most layer of the soil profile. It is also called *"surface soil"*. This layer contains organic matter and micro-organisms. In this layer the greatest biological activity takes place.

(*ii*) *B-Horizon.* The B-horizon is also called *"subsoil"*. This intermediate zone is also called the *"zone of accumulation"* as much of the material which is leached out from A-horizon, is deposited here.

(*iii*) *C-Horizon.* The lower horizon is called *"C-horizon"*. It mainly consists of the partly altered parent rock material.

2.6. CLIMATE AND SOIL FORMATION

In *"arid regions"* where days are very hot and nights are cool, the rocks shatter mainly by the influence of unequal expansion and contraction. The soils thus produced contain the grains of minerals which are disintegrated from the original rock. The surface layers of such soils often become hard due to the crystallization of salts. The evaporation of water brings dissolved salts to the surface by capillary action which cements the upper layer of the soil. The lime crust is found in the desert soils of Texas, New Mexico and north Africa, while the gypsum crust occurs in Egypt and central Australia deserts.

In *"arctic regions"* the ice and frost activity take part in rock disintegration and produce a soil consisting of undecomposed mineral and rock particles. The soil mantle which is usually shallow, is characterized by abundant silt, peat and water in a permanently frozen state.

In *"humid temperate climate"* the rocks are weathered predominantly by a combination of both disintegration and decomposition. Here *"podzol"* type of soil is formed. This soil shows the characterstic development of soil profile having A, B and C horizons.

In *"tropical climate"* the chemical weathering plays an active role and rocks are weathered thoroughly upto a great depth. The most common soil of the tropical areas is *"laterite"* which develops as a result of weathering of silicate rocks. During weathering most of the silica is leached out and the insoluble hydroxides of iron and aluminium accumulate near the surface to give rise a reddish brown residual deposit. Laterite is a very useful construction material. When moist, it is soft and can be cut easily into bricks which become very hard on drying.

The soils of both the temperate and tropical regions may develop *"hard pan"* at some depth below the surface. The downwardly moving rain water may bring leached silica from the upper horizons to lower horizons where it is redeposited. It causes cementation of the soil layer. This type of hard, well cemented and impervious layer of soil is called *"hard pan"*. Such hard pans present very useful horizon for the foundation of buildings and other structures.

2.7. SOIL TYPES

Depending upon their mode of formation, the soil deposits have been broadly grouped into two classes : (*i*) residual soil deposits, and (*ii*) transported soil deposits.

Residual Soil. In plain areas the products of rock weathering continue to accumulate in place over the parent rock masses and give rise to a *"residual soil deposit"*. As the action of weathering decreases with depth, such soil deposits gradually change from soil at the surface to broken rock fragments and merge with fresh rock underneath. The common examples of residual soils are laterite, terra-rosa, and peat bogs.

Transported Soil. The weathered and broken rock materials are eroded and transported from one place to another by natural agencies such as wind, water, ice or gravity. The deposits of soil formed in this manner are called *"transported soil deposits"*. Such soils generally have no relation with the underlying rock mass. The transported soils have been classified according to the nature of the transporting agency responsible for their formation. This classification has been given in *Table. 2.2.*

Table 2.2. Transported Soil

Transporting Agency	*Nature of Soil*
Rivers	Alluvial deposits
Lakes	Lacustrine deposits
Sea	Marine deposits
Wind	Eolian deposits
Glacier	Glacial deposits

The size of the soil particles are extremely variable. It ranges from a big boulder to fine clays. As per the Indian Standard Institution (1948-1951) the nomenclature of soil particles according to size is given in *Table 2.3*. The soil containing mixture of clay and sand is called *"loam"*, and the clayey soil having appreciable lime content is called *"marl"*.

Table 2.3. Nomenclature of Soil Particles

Sediment Name	*Size Range*
Boulder	60 mm or more
Gravel	Between 60–2.0 mm
Coarse sand	Between 2.0–0.6 mm
Medium sand	Between 0.6–0.2 mm
Fine sand	Between 0.2–0.06 mm
Silt	Between 0.06–0.002 mm
Clay	Less than 0.002 mm

2.8. WORK OF WIND

The air currents in motion is called *"wind"*. The wind is an important agent of erosion, transport and deposition. Its work is particularly seen in arid regions.

2.8.1. Wind Erosion

Although wind erosion is not restricted to arid and semiarid regions, it does its most effective work in these areas. Wind does erosion in three ways : (*i*) deflation, (*ii*) abrasion, and (*iii*) attrition.

(*i*) **Deflation.** Lifting and removal of loose material by wind is called *"deflation"*. By this process the land surface is gradually lowered. In many desert areas deflation produces hollows or basins with their bottoms at water table. Such basins containing some water are called *"oases"*.

(*ii*) **Abrasion.** During dust stroms the wind carries minute grains of sand in suspension. They dash and collide against the exposed rock masses and cause erosion. This process in which sand grains are used as tools for eroding rocks, is called *"abrasion"*.

(*iii*) **Attrition.** The particles that travel with wind, collide against one another. These mutual collisions lead to their further break down and the process is called *"attrition"*.

2.8.2. Erosional Features

The important features of wind erosion are polishing of rock faces and formation of ventifacts and pedestal rocks.

Ventifacts. Wind armed with sand abrades rocks near the ground surface. This effect is called *"sand blasting"*. When pebbles and boulders are subjected to sand blasting they develop flat sides and sharp edges. If these stones contain coarse crystals of unequal hardness, they become pitted. Such stones which are polished, pitted and contain sharp edges are called *"ventifacts"*. These stones are faceted by erosion of their windward side.

Pedestal Rocks. Pedestal rocks are the undercut vertical columns of rocks which have wider tops and narrower bases. When wind blows, the sand particles being heavy travel near the surface and cause undercutting of rock faces (*Fig. 2.2*).

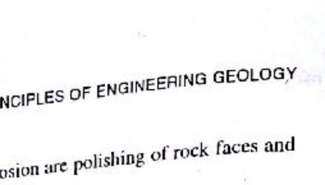


Fig. 2.2. Pedestal rock.

2.8.3. Wind Transport

Turbulent wind can easily sweep small dust particles and carry them to great distances in suspension. Sands, however, are transported in a series of jumps or these merely roll along the ground. The process by which sand particles travel in a series of jumps is called *"saltation"*. The greater part of the sand grains are transported very near the ground surface and they are seldom lifted more than a meter above the ground.

2.8.4 Wind Deposits

The wind deposits are commonly called the *"eolian deposits"*. The rock particles in the eolian deposits are generally well rounded and are sorted according to their size and weight. Wind deposits are of two types : (*i*) accumulations of sand, called *"sand dunes"*, and (*ii*) deposits of silt, called *"loess"*.

Sand Dunes. The wind generally deposits sand in mounds. These mounds are called *"sand dunes"*. The sand travelling as bed load in wind accumulates wherever it meets any obstruction, such as a boulder or a bush. As the accumulation of sand grows, it traps even more sand. In this manner

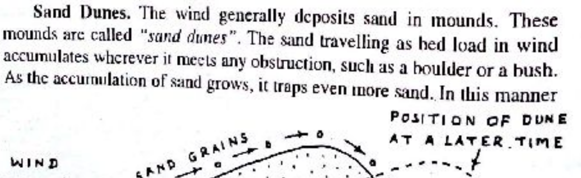


Fig. 2.3. Sand dune migrating with wind.

dunes are created. Sand dunes have a gentle slope (5° to 15°) on the windward side and a steeper slope (20° to 30°) on the lee side. The height of sand dunes depends on the wind speed and the size of sand grains. Dune heights of 30 meters are not uncommon. The sand dunes migrate slowly in the direction of wind movement (*Fig. 2.3*). In some cases they move as much as 20 meters per year. The migrating sand dunes may advance and cover farm land, rail roads, highways and other valuable property. Their movement may be checked by planting vegetation. The sand dunes are of four types : (*i*) transverse dunes, (*ii*) barchans, (*iii*) longitudinal dunes, and (*iv*) complex dunes.

(*i*) **Transverse Dunes.** Transverse dunes have their longer axis at right angles to the direction of wind. They are formed in areas with strong winds where more sand is available.

(*ii*) **Barchans.** *"Barchans"* are crescent shaped dunes the convex side of which faces the wind direction. The horns or wings of the crescent point in the direction of wind flow (*Fig. 2.4*). Barchans are formed where wind is nearly unidirectional. They occur in groups in areas of greatest sand supply. The height of large dunes does not exceed 30 meters and their point to point length is generally 300 meters.

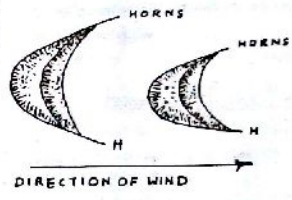


Fig. 2.4. Barchans

(*iii*) **Longitudinal Dunes.** The dunes which are elongated in the wind direction, are called *"longitudinal dunes"*. These dunes usually develop in strong winds in areas where small amount of sand is available. The longitudinal dunes may reach heights of 100 meters and may extend for about 90 kilometers. In the Arab countries these dunes are called *"seifs"* because they appear similar to an Arab sword.

(*iv*) **Complex Dunes.** In areas where the direction of wind varies, *"complex dunes"* are formed. They are of irregular shape.

Loess. The suspended load transported by wind consists mainly of silt and dust particles. When it settles, it forms a blanket deposit of silt, known as *"loess"*. These deposits are typically nonstratified and have a grayish yellow colour. Loess is composed of many minerals including quartz, felspar, hornblende and calcite. These materials are derived by wind from deserts or from flood plains of rivers. Deposits of loess are very fertile. Loess deposits in some parts of China approach a thickness of 300 meters or more.

2.9. WORK OF STREAMS

The term *"stream"* includes the channelized flow of any size, from the smallest brook to a very large river like Ganga. Although the term *"river"* and *"stream"* are used synonymously, the term *" river"* is preferably used to denote a main stream into which several tributaries flow.

The geological work of streams is to *"erode"* the valleys, *"transport"* the material thus eroded, and *"deposit"* the same in the lower reaches at favourable sites.

2.9.1. Stream Erosion

The streams cause erosion in four ways : (*i*) chemical action, (*ii*) hydraulic action, (*iii*) abrasion, and (*iv*) attrition.

Chemical Action. It includes the solvent and chemical action of water on country rocks. The chemical decay works along joints and cracks and thus helps in breaking the bedrocks.

Hydraulic Action. The swiftly flowing water hammers the uneven faces of jointed rocks exposed along its channel and removes the jointed blocks. This process of erosion is called *"hydraulic action"*. At the bottom of waterfalls, the channels are eroded at an enormously rapid rate by the hydraulic action.

Abrasion. The flowing water uses rock fragments such as pebbles, gravels, and sands as a tool for scratching and grinding the sides and floor of the valley. This process of erosion is called *"abrasion"*.

Attrition. It is the breaking of the transported materials themselves due to mutual collision. The attrition causes the rock fragments to become more rounded and smaller in size.

In addition to the above, the streams acquire their load by many other means. Much of the material carried by a stream is contributed by underground water, overland flow and mass wasting.

2.9.2. Stream Transportation

The amount of solid material transported by a stream is called its *"load"*. The streams transport it in three ways : (*i*) in solution (dissolved load), (*ii*) in suspension (suspended load), and (*iii*) along the bottom (bed load).

Dissolved Load. The dissolved load is brought to the stream by groundwater. Some amount of it is also acquired directly from soluble rocks which occur along the stream's course.

Suspended Load. Suspended load forms the major portion of the load carried by streams. Usually only smaller particles such as clay and silt travel in suspension, but during floods much larger particles are carried this way.

Bed Load. The forward force of moving water acts more directly on the larger grains at the bottom, pushing, rolling and sliding them along. The particles moved in this way constitute the *"bed load"* of a stream. Locally the medium size material may travel partly by rolling as bed load and partly in suspension. This process of intermittent jumping is called *"saltation"*. In saltation, the heavy particles are lifted occasionally for a few seconds by a swift eddy.

The velocity of a stream is affected by a number of factors, including gradient, channel size and shape, load, and discharge. The increase of velocity increases the transporting power of a river as much as the 6th power of the velocity.

$$\text{Transporting Power} \propto V^6$$

It means that during floods the transporting power of a stream suddenly rises very much and it becomes capable of moving big boulders which would otherwise remain quite immovable.

2.9.3. Deposition

The loose rock materials transported by a stream downstream, are deposited where the velocity of flowing water is reduced. The sorting of the material takes place automatically as the large and heavier particles settle quickly while the smaller and lighter ones continue their journey further ahead. The material which a stream deposits as sediment is called *"alluvium"* or *"alluvial deposits"*.

2.10. FEATURES OF STREAM EROSION

Pot Holes. *"Pot holes"* are the circular and deep holes, cut into solid rocks by sand grains and pebbles, swirling in fast eddies. They are commonly found on the channel floor.

Waterfalls. The falling of stream water from a height is called a *"waterfall"*. Waterfalls occur at places where the stream profile makes a vertical drop. Such a situation is usually found where gently inclined, erosion resistant beds overlie the nonresistant beds. The softer rock is eroded fast while the harder one offers resistance and forms a ledge at a height, from which the stream's water falls down deep into the gorge (*Fig. 2.5*). When the water falls over the ledge, it erodes the less

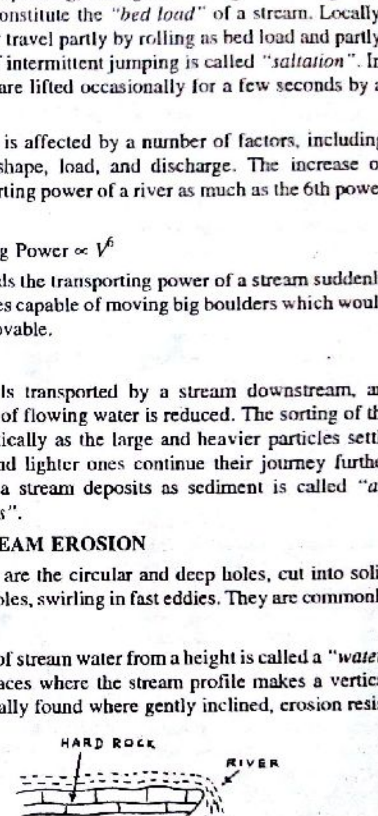


Fig. 2.5. Water fall.

resistant beds of the cliff. Due to this undercutting a portion of the upper resistant bed breaks off and the waterfall retains its vertical cliff while it gradually moves upstream. Niagara Falls (U.S.A.) have retreated approximately 11 kilometers upstream since its formation.

Gorges. Narrow and deep river valleys which develop in hard rocks are called *"gorges"*.

Meanders. The symmetrical S-shaped loops found in the course of a river, are called *"meanders"*. Meanders develop in mature rivers. Mature rivers are those which have cut down to an approximately graded profile. In such rivers side cutting becomes very prominent which results in the development of meanders. The meanders grow due to deposition of sediment along the slipoff side and erosion at the undercut side (*Fig. 2.6*).

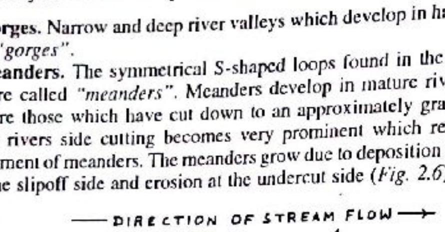


Fig. 2.6. Meanders.

Meanders continually change their position. They move both downstream and to the side (*Fig. 2.7*). The sideways movement occurs because at bends the swiftest currents shift toward the outside bank causing erosion at the outside of the curve and deposition on inside of the curve. In this way a stream migrates sideways and slightly downstream by eroding its outer bank and depositing a sand bar at the inner bank.

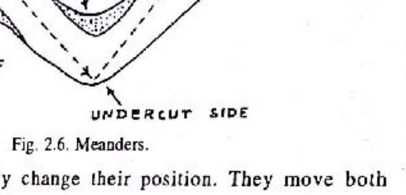


Fig. 2.7. Lateral movement of meanders. 1, 2 and 3 are three stages in the meander movement.

Oxbow Lake. The meanders grow by eroding its outer bank and depositing sediments at the inner bank. During this process the sharpness of the river bends increases progressively and the neck of meander becomes narrow and narrow. Finally a stage comes when the river cuts through the neck and starts flowing straight leaving behind its roundabout course. Such left out old meanders which remain filled with stagnant water, are called *"oxbow lakes: (Fig. 2.8)*.

Entrenched Meanders. On many occasions, the land is uplifted. The uplifting of a mature stream would cause it to give up lateral erosion and revert to downcutting. Rivers of this type are said to be *"rejuvenated"* (*Fig. 2.9*). When a meandering river is rejuvenated, it starts downcutting again. As a result the meandering channel is deepened and the old meanders get entrenched into the bedrock. Such meanders are called *"entrenched meanders"*.

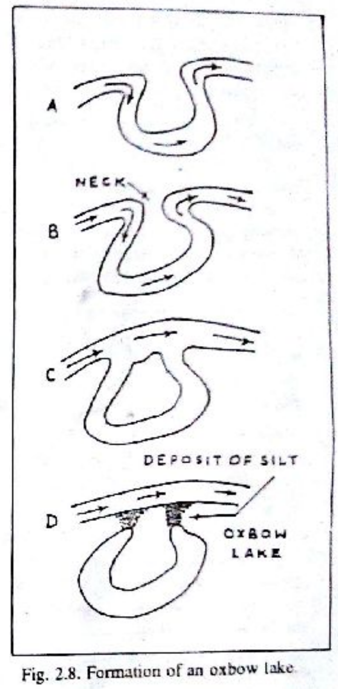


Fig. 2.8. Formation of an oxbow lake.

2.11. DEPOSITIONAL LANDFORMS

Alluvial Fans. The alluvial material which flows down from mountains, accumulates at foot hills where the stream enters a plain. The deposition occurs due to abrupt change in the gradient of river valley. Such deposits spread out in the shape of flat fans and are called *"alluvial fans"*. Usually the coarse material is dropped near the base of the slope while finer material is carried further out on the plain. Alluvial fans from many adjacent streams along a mountain may merge to form a long wedge of sediment called *"alluvial aprons"*.

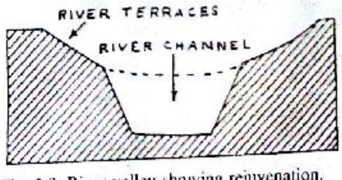


Fig. 2.9. River valley showing rejuvenation.

Flood Plains. During floods a river overflows its bank and submerges the adjacent lowlying areas where deposition of alluvial material takes place. A wide belt of alluvial plain formed in this way on either side of a stream, is called *"flood plain"*. Its name is appropriate, because the flood plain gets submerged only when a river overflows its bank at flood stages (*Fig. 2.10*).

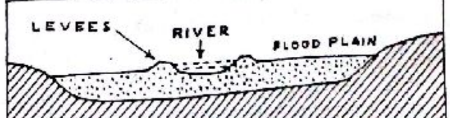


Fig. 2.10. Flood plain and Natural levees.

Natural Levees. *"Natural levees"* are the low ridges which are formed on both sides of a river channel by the accumulation of sediment. They tend to confine the flow of river water into its channel between flood stages. The natural levees occur in rivers which have broad flood plains. During floods the river overflows its bank and its velocity decreases rapidly. As a result most of the coarse sediment is deposited along the area bordering the river channel and finer sediments are deposited more widely over the flood plain. In this way, successive floods build up ridges on both sides of a river channel, which are called *"natural levees"* (*Fig. 2.10*). The natural levees of the lower Mississippi river rise 6 meters above the valley floor.

The area behind the levees are poorly drained as water can not flow up the leevees to join the river. The marshes thus formed, are called *"back swamps"*. A tribulary stream often has to flow parallel to the main stream untill it can breach the levee. Such streams are called : *"yazoo tributaries"*.

Point Bars. In meandering rivers, sediment deposits occur as point bars. The *"point bars"* are the crescent shaped deposits which occur at inside bends of a river channel (*Fig. 2.6*).

Deltas. *"Deltas"* are deposits built at the mouths of streams. The deltas are usually triangular in shape with their apex pointed upstream. When a stream enters an ocean or lake, the currents of the flowing water dissipate quickly. This results in the deposition of the series of sedimentary layers which make up the delta. The material of most deltas is well sorted and many deltas are uniformly graded. The structure of a delta deposit is shown in *Fig. 2.11*. It consists of three sets of beds : (*i*) bottomset beds, (*ii*) foreset beds, and (*iii*) top-set beds.

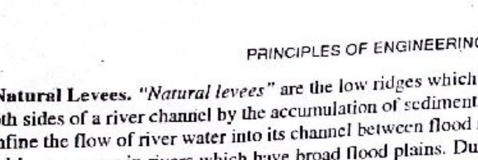


Fig. 2.11. Structure of delta. T-Top set beds, F-Fore set beds, B-Bottom set beds.

(*i*) *Bottomset Beds.* The thin horizontal beds which overlie the ocean bottom, are called *"bottomset beds"*. They are mainly composed of fine grained sediment, such as silts and clays.

(*ii*) *Foreset Beds.* Foreset beds begin to form prior to the accumulation of bottomset beds. These beds are composed of coarse sediment which is dropped almost immediately when a river enters a lake or ocean. The foreset beds appear similar to crossbedding and their angle of slope varies from 12° to 32° depending on the grain size of the material.

(*iii*) *Topset Beds.* Foreset beds are covered by thin nearly horizontal topset beds. These beds occupy the upper surface of the delta. They are composed of a mixture of coarse and fine materials.

Major rivers, such as the Ganga, form large deltas thousands of square kilometers in area. On large deltas the main channel of river divides to form several smaller branches, called *"distributaries"*. They discharge water in various paths to the sea.

2.12. BASE LEVEL AND GRADED STREAMS

Longitudinal Profile. Plot of the relative elevation of a stream bed from headwaters to mouth is called its *"longitudinal profile"*. The longitudinal profile of a stream is generally concave upward which is in accordance with the steady downstream decrease in slope.

Base Level. The level which controls the depth of stream erosion is called a *"base level"*. As base level is the lower limit of the longitudinal profile, streams can not cut below this level. There are two types of base level : (*i*) ultimate base level, and (*ii*) local base level. The *"ultimate base level"* represents the lowest level to which a stream can erode its valley. It is therefore the level at which the mouth of a stream enters a lake or the ocean. Resistant rockbeds, waterfalls, lakes or artificial dams which lie along a river course form *"local base levels"*. They act as limiting levels for the stretches that exist immediately upstream. Thus local base levels are temporary obstructions to downcutting encountered by a stream.

Any change in base level causes a stream to change its characterstics. Lowering of base level increases the stream's gradient. As a result the velocities increase and downcutting is accelerated. The erosion first starts from near the mouth and then works upstream untill the stream profile is adjusted along its full length. Thus the bedrock channel is deepened and parts of the old valley floor are left as a terrace along the walls of the new valley. Such steps-like features are called *"river terraces"* (*Fig. 2.9 and 2.12*).

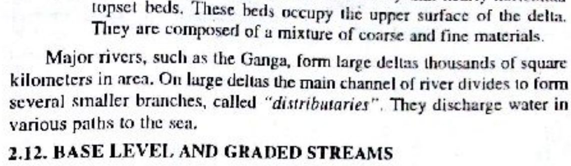


Fig. 2.12. River terraces.

A rise in base level reduces the stream's sediment transporting capacity. As a result the stream deposits sediment thereby building up its channel. Sometimes the capacity of a loaded stream is lowered to such an extent that heavy aggradation takes place. Now the single river channel can no longer carry its load. In such circumstances the individual channel subdivides itself into a series of smaller channels. These channels are separated by many low islands which are the products of heavy deposition. Such a stream is called *"braided stream.*

Profile of Equilibrium. Streams have tendency to cut and remove the material from high gradient regions and deposit it in the low gradient areas. In due course of time when a uniform longitudinal slope is developed throughout the stream course, the process of erosion and deposition ceases. Such a slope is called the *"profile of equilibrium"* or *"graded profile"* of a stream (*Fig. 2.13*). Thus a greaded stream will not erode or deposit material but will simply transport it. As a matter of fact this stage is never reached due to many disturbances.

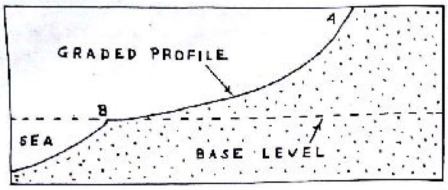


Fig. 2.13. Graded profile and base level.

2.13. DRAINAGE SYSTEM

Drainage Basin. A land area surrounded by divides which contributes water to a river, is called *"drainage basin"*.

Divide. It is a ridge of high ground which separates two drainage basins. Divides range in size from a ridge separating two small gullies to *"continental divides"* which divide continents into large drainage basins.

River Capture. *"River capture"* is a process by which a part of the drainage of one river is diverted into another. Due to greater discharge, slope or other factors, the stream on one side of a divide may erode its valley more actively than the stream on the opposite side. While lengthening its valley headward, it may reach the less active river

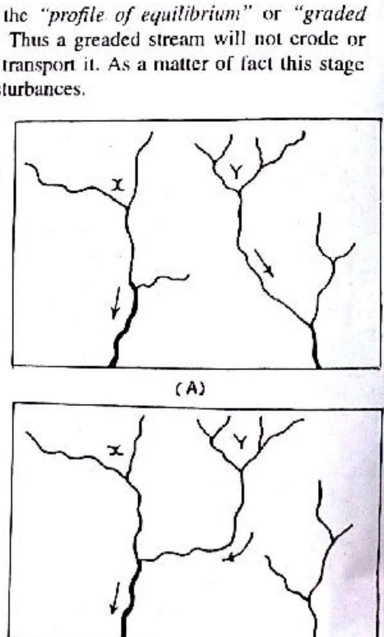


Fig. 2.14. River capture. (*a*) Showing two rivers *x* and *y*. (*b*) Showing a part of the river *y* captured by *x*.

by breaking down the divide between the two and divert a part or all of its drainage into its own channel (*Fig. 2.14*). The river capture commonly occurs in the youth stage. It becomes less common as streams grow larger and is rare in large rivers.

2.13.1. Drainage Pattern

Although all drainage networks branch in the same way, the shape of their patterns varies greatly from one kind of terrain to another, depending upon the rock type or structure. The chief drainage patterns are : (*i*) dendritic, (*ii*) trellis, (*iii*) rectangular, (*iv*) radial, and (*v*) parallel.

(*i*) **Dendritic Pattern.** In *"dendritic pattern"* the streams show a branching tree like arrangement [*Fig. 2.15 (a)*]. This pattern develops in terrains covered with uniform rock types, such as horizontal sedimentary rocks or massive igneous or metamorphic rocks.

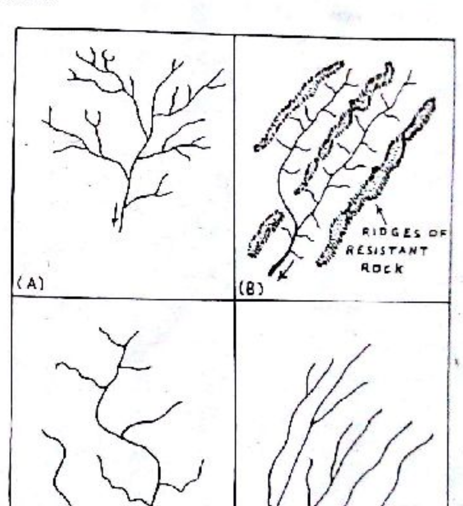


Fig. 2.15. Drainage patterns. (*a*) Dendritic, (*b*) Trellis, (*c*) Rectangular, (*d*) Parallel.

(*ii*) **Trellis Pattern.** A *"trellis drainage pattern"* is one in which major streams are parallel and short tributaries join the main stream at nearly right angles [*Fig. 2.15 (b)*]. This type of drainage pattern develops in regions containing folded or tilted strata. Here the main stream develops in the strike valleys cut into the soft rocks, while tributaries flow down the resistant ridges.

(*iii*) **Rectangular Pattern.** Differential weathering of faults or joint systems in bedrocks localizes the stream flow producing a more ordered rectangular drainage. In a *"rectangular drainage pattern"* angular deflection of stream courses are apparent [*Fig. 2.15 (c)*].

(*iv*) **Radial Pattern.** In a *"radial drainage pattern"*, streams flow outward in different directions from a central high point. This pattern commonly develops on an elevated structure such as a volcano or dome.

(*v*) **Parallel Pattern.** This type of drainage pattern develops in a terrain containing tilted rockbeds and parallel faults. The major stream occupies the fault while tributaries which are parallel, meet the stream approximately at the same angle [*Fig. 2.15 (d)*].

2.14. TYPES OF STREAMS

On the basis of development and origin, the streams have been classified into four groups : (*i*) consequent streams, (*ii*) subsequent streams, (*iii*) antecedent streams, and (*iv*) superposed streams.

(*i*) **Consequent Streams.** Consequent streams are those which follow the slope of the initial land surface.

(*ii*) **Subsequent Streams.** These are tributary streams which develop on

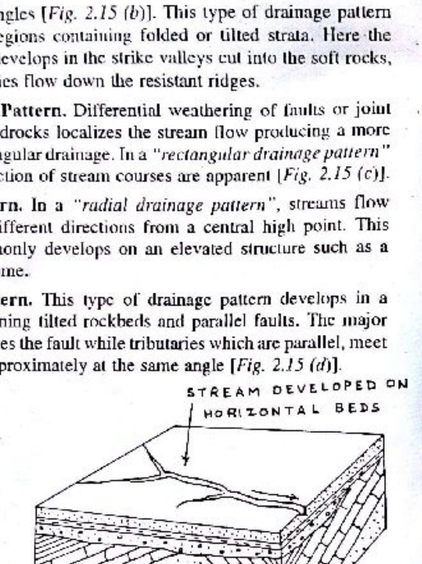


Fig. 2.16. Development of a superposed stream. (*a*) Stream developed on horizontal beds. (*b*) Stream developed on folded beds.

the sloping sides of a stream valley. Subsequent streams generally take their course along the weak and easily erodible zones, such as rock boundaries, fault zones, joints, etc. These weak zones are discovered and eroded after the development of the consequent streams.

(*iii*) **Antecedent Streams.** Antecedent streams are those which are able to maintain their original course across the area of uplift.

(*iv*) **Superposed Streams.** Geologic events may strongly control the course of a stream. Streams flowing in a dendritic pattern on horizontally bedded younger formation may erode through it to expose the underlying, strongly folded and faulted older rocks of varying hardness. Over the older rocks, the stream courses will not easily adjust to form a wholly new drainage pattern appropriate to the structure of rocks. Such streams are called *"superposed streams"* (*Fig. 2.16*). Superposed streams do not show any relation to the structure of the underlying rocks.

2.15. STAGES OF VALLEY DEVELOPMENT

The development of stream valleys takes place in a orderly fashion. A valley passes through three stages during its evolution. The three stages are: (*i*) youth stage, (*ii*) mature stage, and (*iii*) old stage.

(*i*) **Youth Stage.** A stream is said to be in the youth stage when it cuts its valley downward to establish a graded condition with its base level. [*Fig. 2.17 (a)*].

(*a*) *Position.* The youth stage is commonly found in mountainous regions from where a stream starts its journey.

(*b*) *Erosion.* Downcutting is dominent.

(*c*) *Valley.* Narrow V-shaped valley.

(*d*) *Longitudinal Profile.* Longitudinal profile is ungraded. The gradient is steep and waterfalls and rapids are common.

(*e*) *Valley Floor.* The stream occupies most of the width of the valley floor as a result there is little or no flood plain.

(*f*) *Stream Pattern.* The stream course is angular and without meanders. Tributaries are short and few.

(*ii*) **Mature Stage.** A stream is said to be in a mature stage when downward erosion diminishes and lateral erosion dominates [*Fig. 2.17 (b)*].

(*a*) *Position.* Mature stage is found in the plains lying adjacent to the mountain region.

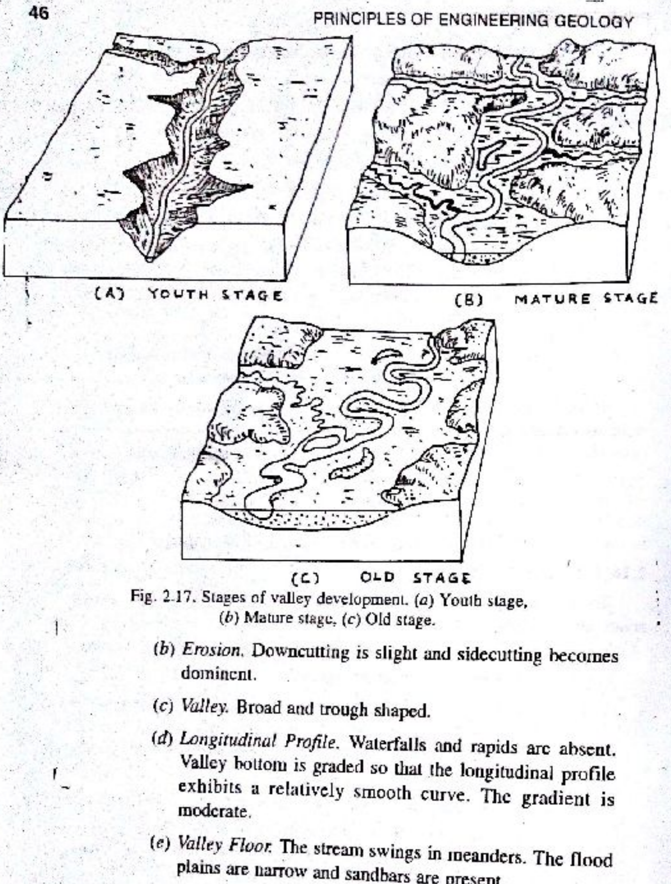


Fig. 2.17. Stages of valley development. (*a*) Youth stage, (*b*) Mature stage, (*c*) Old stage.

(*b*) *Erosion.* Downcutting is slight and sidecutting becomes dominent.

(*c*) *Valley.* Broad and trough shaped.

(*d*) *Longitudinal Profile.* Waterfalls and rapids are absent. Valley bottom is graded so that the longitudinal profile exhibits a relatively smooth curve. The gradient is moderate.

(*e*) *Valley Floor.* The stream swings in meanders. The flood plains are narrow and sandbars are present.

(*f*) *Stream Pattern.* The stream moves in meanders. The tributaries are many.

Old Stage. In old stage, the flood plain of a stream becomes several times wider then its meander belt [*Fig. 2.17 (c)*].

(*a*) *Position.* The old stage is found near the month of streams.

(*b*) *Erosion.* In the old stage, the stream ceases to enlarge the flood plain. The main work of a steam is to rework the unconsolidated sediment of the flood plain.

(*c*) *Valley.* Valleys become wide and open with low boundaries which may be indistinct.

(*d*) *Longitudinal Profile.* The gradient becomes very low. The stream approaches base level and it aggrades strongly.

(*e*) *Valley Floor.* Oxbow lakes are common. Natural levees are also present. They are accompanied by back swamps and yazoo tributaries. The meander belt is narrower than the valley floor.

(*f*) *Stream Pattern.* The stream pattern is meandering with oxbow lakes. The tributaries are few and large.

In the above discussion it is assumed that the base level of a stream remains constant as a river progresses from youth to old stage. On many occassions, however, the land is uplifted. The effect of uplifting on a mature stream is to abandon lateral erosion and revert to downcutting. Such rivers are said to be "*rejuvenated*". Mature streams readjust to uplift by cutting a new flood plain at a level below the old one. This produces step-like features in the river valley which are called "*river terraces*" (*Fig. 2.12*).

2.16. CYCLE OF EROSION

To understand the cycle of evolution of a landscape, let us start with a relatively flat upland area in a humid region.

1. During the youth stage, the area remains more or less flat. The stream valleys are generally narrow.
2. In mature stage, the relief of the land increases and the landscape is changed into one consisting of hills and valleys. The "*relief*" of an area may be defined as the maximum difference in the elevation.
3. In old stage, the streams will approach base level and the land will be reduced to a peneplain. The "*peneplain*" is an undulating plain which lies nearly at base level. Some mounds or hillocks of hard rocks still persist. These hillocks are called "*monadnocks*".

2.17. RIVERS AND ENGINEERING

Rivers present many practical problems to civil engineers, some of which are as follows.

(*i*) Rivers require construction of bridges across them for carrying highways and railways.

(*ii*) Water power of rivers can be utilized to generate hydroelectricity.

(*iii*) Dams are built on rivers to store water for irrigation, flood control, and water supply purposes.

(*iv*) Regulation of river channels are done for navigation and flood control.

(*v*) River deposits are the important sources of the construction material.

(*vi*) The life of some artificial reservoirs is reduced considerably by river deposits.

2.17.1. Flood Control

During floods, the rivers cause destruction of life and property and therefore flood control is a very important problem for a civil engineer. The various methods which are used to control floods are as follows.

(*i*) **Construction of Levees.** The levees are longitudinal embankments which are built along the river banks to check the overflow of the excess water during floods. The levees not only confine the river water into its channel but they also increase bed erosion and keep the channel clean.

(*ii*) **Dredging.** It is the process of removing the sediment deposited at the bottom of the river channel. Dredging is a costly affair as it has to be carried out all the time.

(*iii*) **Construction of Check Dams.** The construction of dams for controlling floods is a very useful method. The check dams are usually built on small tributary streams which regulate the flow of main river.

(*iv*) **Diversion of River Water.** During floods a part of the river water is diverted and made to flow through a newly constructed channel. Thus the river water gets divided and the effect of flood reduces.

(*v*) **Shortening Course of Meandering Rivers.** In meandering rivers artificial cutoffs are made to straighten the course. This increases the efficiency of rivers.

2.17.2. River Training

The river training is mainly connected with the improvement of the river channel for navigation. The various river training measures are as follows.

(*i*) Dredging is done to remove sand, silt, etc. and to deepen the river channel.

(*ii*) Training walls are constructed which restrict the flow of water to a given channel. It enhances the scouring effect of the water currents and keeps the channel clean.

(*iii*) Low groynes are constructed which concentrate the flow of river water in the required portion of the channel.

2.18. WORK OF GLACIER

A *"glacier"* is a thick mass of ice which moves over the ground under the influence of gravity. It originates on land from the compaction and recrystallization of snow. Glaciers form in places where more snow accumulates each year than that melts away. They are found chiefly in high lattitudes as in the Arctic region, or at high elevations as on the Himalayan mountains above the snow-line. The *"snowline"* is the lower limit of accumulating snow. Below the snowline the snow melts in summer. The elevation of the snowline varies considerably. In polar regions it may be at sea level, whereas in areas near the equator, the snowline may occur at 6000 meters. In the Himalayas the snowline lies at altitudes varying between 4200 to 5700 meters.

2.18.1. Types of Glaciers

There are three kinds of glaciers : (*i*) valley glaciers, (*ii*) piedmont glaciers, and (*iii*) ice sheets.

(*i*) **Valley Glaciers.** The glaciers which originate near the crests of high mountains and move along the valleys just like rivers, are called *"valley glaciers"*.

(*ii*) **Piedmont Glaciers.** At the end of a hilly region, a number of valley glaciers may unite to form a comparatively thick sheet of ice. Such a compound glacier is called *"piedmont glacier"*.

(*iii*) **Ice Sheets.** These are massive accumulations of ice covering extensive areas. Two such glaciers that exist today are the Greenland and Antarctic ice sheets. The Greenland ice sheet covers an area of about 1.7 million square kilometers and is over 1500 meter thick.

2.19. MOVEMENT OF GLACIERS

Most of glaciers move at the rate of a few meters per day. They move partly by plastic flow and partly by shear movements. In the high gradient valleys a mountain glacier flows down the slope much like a stream of water under gravity. But in basin-shaped, flat or upland areas where the ice can not move under gravity, the glaciers move as a result of differential pressure within the ice mass. The first type of movement is called the *"gravity flow"* and the second *"extrusion flow"*. A mountain glacier may have gravity flow in one part of its course and extrusion flow in another, depending upon the irregularities present in the path.

In a moving glacier two zones can be identified : (*i*) zone of flow, and (*ii*) zone of fracture. The *"zone of flow"* is found in the deeper layers of ice. Here the weight of the overlying ice is great, and the ice behaves plastically. However, the upper layers of a glacier have little pressure on them and therefore the surface ice behaves as a brittle mass. It often develops cracks known as *"crevasses"*. This upper zone is called the *"zone of fracture"*.

2.20. GLACIAL EROSION

The glaciers cause erosion in three ways : (*i*) by plucking or quarrying, (*ii*) by abrasion, and (*iii*) by frost wedging.

(*i*) **Plucking or Quarrying.** While flowing over a jointed rock surface, the glacial ice adheres to blocks of jointed bedrock, pulls them out and carries them along.

(*ii*) **Abrasion.** The moving ice grinds and polishes the rock surface with the help of rock fragments which are held firmly within the body of the glacier. The abrasion produces striations and grooves in the bedrock surface. A polished surface results when the glacier performs abrasion by fine silt-sized sediment. The ground up rock produced by the grinding effect of the glacier is called *"rock flour"*.

(*iii*) **Frost Wedging.** Thawing and freezing of water in the cracks and joints of rocks break them by wedge action. In this manner rock fragments of all sizes are added into the glacier.

2.20.1. Features of Glacial Erosion

Striations. Glaciers carry rock fragments firmly embeded in the ice. They scratch, grind or groove the rock surface over which they move. These scratches and grooves left on bedrock and boulders, are called *"striations"*. The striations indicate the direction of ice movement.

U-Shaped Valleys. Glaciers occupy valleys and flow downhill. As they erode their valleys both laterally and vertically, U-shaped valleys with steep walls and flat floor are produced (*Fig. 2.18*).

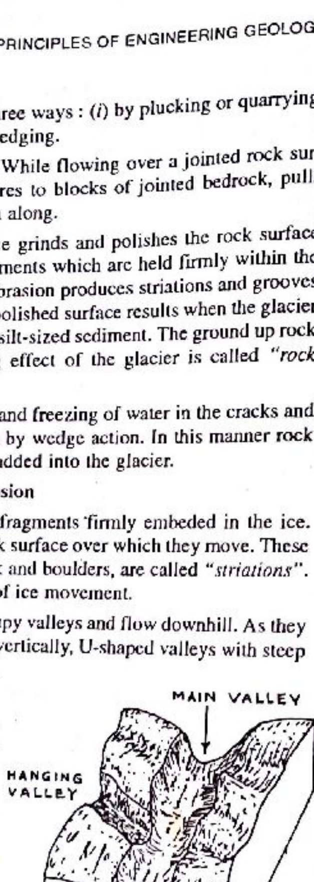


Fig. 2.18. Hanging valleys.

Hanging Valleys. Since the magnitude of the glacial erosion depends upon the thickness of the ice, main glaciers cut their valleys deeper than those of their tributaries. As a result, at the junction where a tributary joints the main glacier, the floors of their valleys do not meet at the same level. The valley of the tributary stands at a higher elevation than that of the main valley (*Fig. 2.18*). Such valleys are called *"hanging valleys"*. When the glaciers disappear, the hanging valleys are occupied by streams which discharge into the main valley forming waterfalls.

Where a valley glacier terminate on land, the streams of melt-water flowing on and under the glacier meet downstream to form a single river.

The glaciers that end at the sea coast, discharge huge cliffs of ice into the sea. Because ice is less dense than water, it floats. Such floating ice hills are called *"icebergs"*.

Cirques. The bowl-shaped hollows present at the glacier valley heads in the mountains, are called *"cirques"*. They are formed mainly be the quarrying and frost-wedging action of ice. In cirques, a little gap is generally left between the head of the glaciated valley and the mass of the glacier ice. This gap is known as the *"bergschrund"* (*Fig. 2.19*).

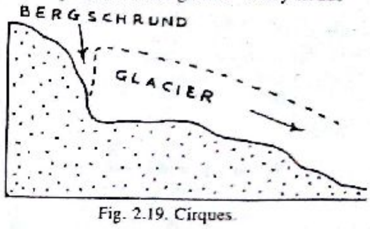


Fig. 2.19. Cirques.

Serrate Ridges. As the adjacent cirques, along the opposite side of a mountain are enlarged, the space between them becomes narrow. As a result sharp divides are formed. Such divides which have jagged, serrated and linear crest are called *"serrate ridges"*. When three or more cirques surround a mountain summit, a pyramid-like peak is formed. Such a peak is called *"horn"*.

Roche Moutonnees. These are small mounds of resistant bedrock which have a typically asymmetrical appearance. The side facing the direction of ice advance is gentle and smooth, while the leeward side is steep and rough [*Fig. 2.20 (a)*]. This form results from the plucking action on the leeward side and abrasion on the opposite side.

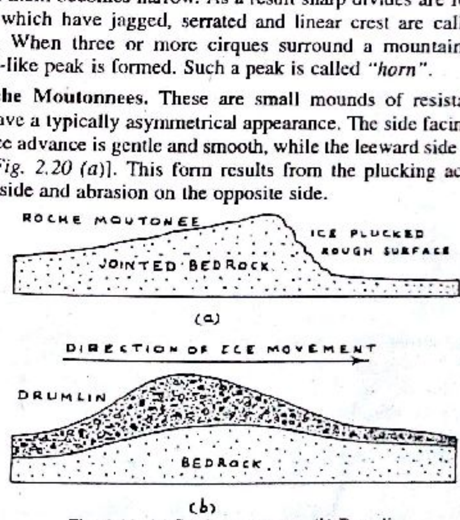


Fig. 2.20. (*a*) Roche moutonee, (*b*) Drumlin.

Fiords. The glaciers that descend from coastal mountains may cut their valleys below sea level. Such valleys produces *"fiords"*. Fiords are highly over-deepened narrow channels of glacial origin along which the sea encroaches inland. Fiords are found along many coasts including those of Norway, British Columbia and Alaska.

2.21. TRANSPORT BY GLACIERS

Glaciers acquire a huge amount of rock debris by plucking, abrasion, and frost wedging. This material is transported in three ways.

(*i*) **Super Glacial Load.** The debris that falls from the valley walls on the surface of the glacier, is transported as a conveyor belt. Such debris is called *"super glacial load"*.

(*ii*) **Englacial Load.** Sooner or later a part of the debris is engulfed into crevases. This material which is enclosed within the ice is called *"englacial load"*.

(*iii*) **Subglacial Load.** The debris present at the bottom of the glacier is called *"subglacial load"*. The subglacial load includes the material plucked from the rocky floor and a portion of the debris that reaches the base from above.

2.22. GLACIAL DEPOSITS

The regions that were formerly covered by ice are characterized by the following features.

1. The topography generally lack organised drainage network.
2. There are hollows with no outlets some of which form lakes.
3. In some places there are isolated hills, in others long and winding ridges, none of which seem to have much relation to the underlying bedrock.
4. In some places, the bedrock is deeply buried, sometimes 50 meters or more, below the glacial drift.
5. The ground over the bedrock is mostly a heterogeneous mixture of sand, clay, pebbles and boulders. Many of the pebbles and boulders differ entirely in composition from the bedrock.

Glacial deposits are of two types : (*i*) those deposited directly by the glacier, are known as *"till"*, and (*ii*) materials deposited by glacial meltwater, are called *"fluvioglacial deposits"*. Deposits of till are a mixture of sand, clay, pebbles and boulders. This material, in general, is heterogeneous and unassorted with no stratification. The pebbles and boulders are commonly striated and they differ markedly in composition from the bedrock. The glacial drift does not exhibit chemical weathering.

Glaciers may transport huge rock boulders, many thousands of tonnes in weight. When ice melts, they are left behind great distances away from their natural bedrock. Such boulders are called *"erratic boulders"*.

The fluvioglacial deposits are also called *"outwash deposits"*. These deposits are usually well sorted and stratified accumulations of silt, sand and gravel.

2.22.1. Depositional Landforms

Moraines. Ridges or layers of till are called *"moraines"*, they are of four types : (*i*) ground moraines, (*ii*) lateral moraines, (*iii*) medial moraines, and (*iv*) terminal moraines.

(*i*) *Ground Moraines.* A layer of till deposited beneath the moving ice on the ground is called the *"ground moraine"*. Ground moraines fill low spots and old stream channels thereby creating a lavelling effect.

(*ii*) *Lateral Moraines.* The material that falls from the valley walls, accumulates on the sides of a glacier. When the glacier disappears, these materials are left as ridges along the sides of the valley. Such deposits are called *"lateral moraines"*.

(*iii*) *Medial Moraines.* When two glaciers meet, a *"medial moraine"* is formed by the union of two laterel moraines.

(*iv*) *Terminal Moraines.* At the terminus of a glacier where the ice starts melting, the rock debris is deposited in the form of a ridge which extends across the valley. Such deposits are called *"terminal moraines"* or *"end moraines"* (*Fig. 2.21*)

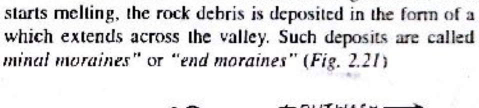


Fig. 2.21. End moraine and outwash plain.

Outwash Plains. In front of the end moraines, streams of meltwater deposit sediment producing stratified deposits of sand,silt and gravel. Such deposits constitute *"outwash plains"* (*Fig. 2.21*).

Kettle Holes. These are basin-like depressions found in areas of both till and outwash plains. The diameter of kettle holes ranges from a few meters to a few kilometers. They commonly contain water. These depressions are created when the masses of buried ice melt (*Fig. 2.21*).

Drumlins. *"Drumlins"* are small, smooth, elliptical hills of till that lie parallel to the direction of ice movement. Unlike roche mountonnees the uphill sides of the drumlins are steep and the downhill sides are gently sloping (*Fig. 2.20*). They may be 20-30 meters high and a kilometer long. Drumlins are not found singly but they occur in clusters thereby forming drumlin fields. They are believed to have formed by a subglacial shaping of an accumulated till into streamlined forms.

Eskers. Eskers are long winding ridges of stratified drift found in the middle of ground moraines. They run for kilometers in a direction more or loss parallel to the direction in which ice moved. Eskers are formed due to deposition of gravels and sand by the englacial and subglacial streams. In many areas they are mined for sand and gravel.

Local melting of ice of glaciers produces streams of water. If these streams flow beneath the glaciers, they are called *"subglacial streams"* and if these flow on or within the glaciers, they are called *"englacial streams"*.

Kames. Kames are hillocks of stratified drift which are formed at the edge of the retreating ice by glacial streams. These streams fall from a height and deposit sand and gravel along the margin of the glacier as alluvial cones (*Fig. 2.22*).

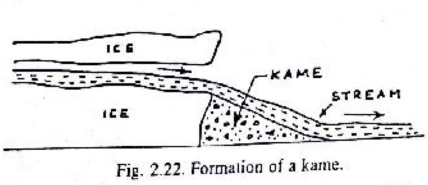


Fig. 2.22. Formation of a kame.

Varves. Varves are thinly laminated deposits formed in glacial lakes. They consist of alternation of light coloured bands of silt and dark coloured bands of clays. The former gets deposited during the summer season while the later in winter. Thus each pair of varves corresponds to one year of deposition. The thickness of a varve may vary from a very small fraction of a centimeter to 0.75 centimeter.

Buried Valley. Buried valleys are the ancient deep valleys which are excavated in the bedrock by glacial erosion and are filled back subsequently with glacial drift. The present day surface topography gives no clue to their existance. The rivers which are flowing in these areas may have no relation to the buried valleys (*Fig. 2.23*). Such valleys creat unexpected problems for the civil engineers.

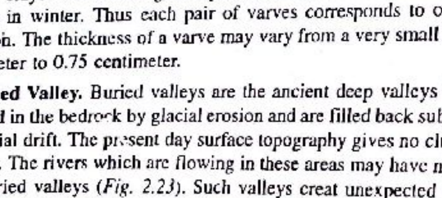


Fig. 2.23. Buried valley.

2.23. ICE AGE

The Pleistocene epoch is called an *"Ice Age"*. The Ice age began at least 2.5 million years ago and had a duration perhaps of a million years. The most recent retreat of ice had taken place between 10,000 and 15,000 years ago. The areas which were extensively buried by ice sheets included northern North America, northern Europe, and northwest Asia. In these areas ice sheets do not exist today.

The Pleistocene epoch, however, was not a period of continuous glaciation. During this period, the continental glaciers alternately advanced and retreated. The time spans between glacial advances are called *"interglacial periods"*. During these periods warm climates returned to most of the formerly glaciated lands. Some of the interglacial periods lasted longer than the glacial ones. Four major periods of glacial advance and retreat have been identified in North America and upto six in Europe.

2.24. WORK OF SEA

Sea Coast. The meeting place of land and sea is called the *"coast"*. Sea coasts may have many kinds of shape. Chief types of sea coasts are : (*i*) steep rocky cliffs, (*ii*) broad low beaches, (*iii*) small bays alternating with rocky headlands, and (*iv*) sandy tidal flats.

2.24.1. Shorelines

A *"shoreline"* is the line along which the water meets the land. The shorelines are classified into three groups : (*i*) shorelines of emergence, (*ii*) shorelines of submergence, and (*iii*) compound shorelines. A shoreline may be uplifted or it may subside with respect to sea level. In some cases uplift and subsidence may operate simultaneously in different parts of the same region.

(*i*) **Shorelines of Emergence.** These shorelines are formed when sea coasts are uplifted or the sea level is lowered. The shorelines of emergence are characterised by a relatively straight shoreline, raised beaches, and elevated shore features like sea cliffs, sea caves, etc.

(*ii*) **Shorelines of Submergence.** These shorelines are formed when either the coastal lands have subsided relative to the sea level or the sea level has risen with respect to the coastal lands. Such shorelines are generally very irregular with drowned valleys, deep bays, headlands and islands. Fiords are formed in the glaciated areas.

(*iii*) **Compound Shorelines.** The shorelines having a complex history of up and down movements relative to sea level, are called compound shorelines.

2.25. EROSION BY SEA

The forces that shape coasts are : (*i*) erosion caused by sea waves, (*ii*) transportation and deposition of the rock debris, and (*iii*) tectonic forces that cause uplift or subsidence of the coastal lands. The major agent of erosion at the shoreline is sea waves. They cause erosion in four ways : (*i*) hydraulic impact, (*ii*) abrasion, (*iii*) attrition, and (*iv*) chemical action.

(*i*) **Hydraulic Impact.** The impact force of high waves breaking against a rocky cliff during a storm can be very great. This force is enough to dislodge blocks of rocks as well as to enlarge preexisting fractures.

(*ii*) **Abrasion.** The sea waves become more destructive when they pick up rock fragments like pebbles and sands, and strike them against the cliffs. A great deal of erosion is done in this way.

(*iii*) **Attrition.** The pebbles and sands moving to and fro along with the sea waves are further broken down to smaller sizes due to mutual collision.

(*iv*) **Chemical Action of Water.** The physical destructiveness of the waves is enhanced greatly by the chemical action of sea water. The chemical decay extends and widens the cracks in rocks and prepares them for the disintegration by waves. The chemical action of sea water is particularly seen where coasts are composed of readily soluble rocks, such as limestones and dolomites.

2.25.1. Shoreline Erosional Features

Wave Cut Cliff. The sea waves dash against the rocky shore and cut it actively. Due to continuous erosion at the base of coastal land, a cliff is formed. This cliff is called *"wave cut cliff"* (*Fig. 2.24*).

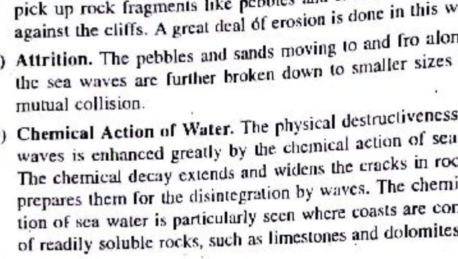


Fig. 2.24. Sea shore profile.

Wave Cut Bench. The sea waves undercut the cliffs and produce a notch at the base. This causes the overhanging rocks to fall into the water. In this way the cliff gradually retreats towards land leaving a submerged rocky platform which is called *"wave cut bench"* (*Fig. 2.24*).

Sea Arch and Sea Stack. Headlands that extend into the sea are vigorously attacked by the waves. The waves erode the rock selectively thereby destroying the softer or more highly fractured rocks at the fastest rate. At first cave like features are produced at the base of the cliff which are called *"sea caves"*. When two caves on opposite sides of a headland unite, a gateway like structure is formed. Such a structure is called *"sea arch"*. When the arch falls, a piller like structure of rocks is left standing in the sea. Such a remnant piller of rock is called *"sea stack"*.

2.26. TRANSPORTATION BY SEA

Most waves approach a shoreline at an angle. Consequently the *"uprush"* of water from each breaking wave is oblique. However the *"back-flow"* is straight down the slope of the beach. The effect of this pattern of water movement is to transport particles of sediment in a zig-zag pattern in a direction along the shore. This movement is called *"beach drift"*. The beach drift can transport sand and pebbles hundreds of meters each day.

When a wave strikes a shoreline at an angle, the kinetic energy of the wave is only partly spent in the impact, the remaining energy is used up in forming currents that flow parallel to the shore. These currents are called *"longshore currents"*. The longshore currents transport sediments along the shore. When the sediment transported by longshore current is added to the quantity moved by beach-drift, the total amount can be very large.

Where the oncoming waves strike at right angles to the shoreline, the undertow currents are formed. The *"undertow currents"* are returning currents which are formed below the oncoming waves. They transport finer sediment out to the sea.

2.27. DEPOSITION BY SEA

Where beach drift and longshore currents are active, several depositional features may develop along the shore. The principal depositional features are as follows.

Beach. A beach is the flat mass of sand and gravel that is deposited on sea shores. The sediment of the beach is derived from erosion of adjacent cliffs and from alluvium contributed by rivers.

Wave Built Terrace. Under suitable conditions a part of the sediment is carried beyond the rock bench and is deposited there. In this way a flat platform like feature is formed which is called *"wave built terrace"* (*Fig. 2.24*). Towards shore it merges with the beach.

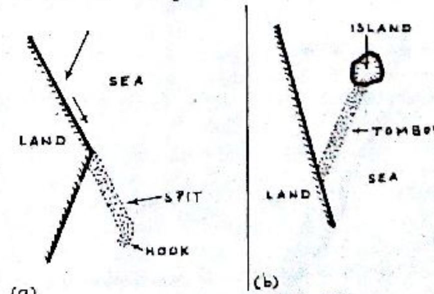


Fig. 2.25. (*a*) Spit, (*b*) Tombolo.

Spits. Where a straight shoreline takes a sharp turn, the longshore currents are not able to flow parallel to it. Such a shore directs the currents into water of increasing depth, where deposition takes place. This results in the formation of a submerged bar, one end of which is attached to the main land. This bar is called *"spit"*. The end of the spit often becomes curved landward in response to the wave action. Such a spit is called *"hooked spit"* or *"hook"* [*Fig. 2.25 (a)*].

Sand Bars. *"Sand bars"* are the low offshore ridges of sand which extend parallel to the coast. They commonly enclose a lagoon.

Tombolo. In the lee side of islands spits are often formed. If such a ridge connects an island to the main land or joins two islands together, it is called a "tombolo" [*Fig. 2.25 (b)*].

2.28. SEA AND ENGINEERING

Engineers build shoreline structures mainly for two purposes : (*i*) for prevention of destruction of sea coast by waves and currents, and (*ii*) for improvement of navigation. The chief shoreline structures are as follows.

Sea Walls. *"Sea walls"* are massive structures built to protect the areas lying immediately in their rear from the damaging wave action. They are built parallel to the coastline. The sea walls range from a simple rip rap deposit to regular masonry retaining walls.

Groynes. A *"groyne"* is a wall like structure which is built at right angles to the coastline. It checks littoral drift and causes deposition. In this way a beach is created which protects the coast against wave action. Groynes are generally made up of steel sheets, concrete blocks, stones and creosoted wood.

Jetties. These are large massive groynes which project into deeper water. They are used to protect mouth of rivers for navigation. Jetties deflect the longshore currents to deeper water and stop the sediment outside the channel way.

2.29. DEPTH ZONES OF SEA

The profile of the sea floor from coast up to the deep sea, has been divided into four zones : (*i*) littoral zone, (*ii*) continental shelf, (*iii*) continental slope, and (*iv*) deep sea zone (*Fig. 2.26*).

(*i*) **Littoral Zone.** The littoral zone is also called *"shore zone"*. This zone includes the area between the levels of the high tide and low tide. The littoral zone separates the coastal landmass from the sea. This zone contains the sediment derived from the land (terrigenous sediment).

(*ii*) **Continental Shelf.** It is a gently sloping submerged platform that extends form the edge of the continent to a depth of about 200 meters. The outer edge of the continental shelf is marked by rapid steepening of the gradient. Since it is underlain by continental type crust, it is clearly a flooded extension of the continental mass. Continental shelves vary in width, the average width being about 65 kilometers. The sediment on it is mostly terrigenous. Coral islands are commonly formed in this zone.

(*iii*) **Continental Slope.** The continental slope lies between the continental shelf and deep sea zone. The depth of water varies from 200 to 900 meters. Beyond the shelf, the downward slope increases abruptly to form continental slope (*Fig. 2.26*). The continental slope marks the boundary between the continental crust and the oceanic crust. The sediments here are very fine which include black mud, blue mud, green mud, coral mud and volcanic mud. These sediments are derived mainly from continental erosion.

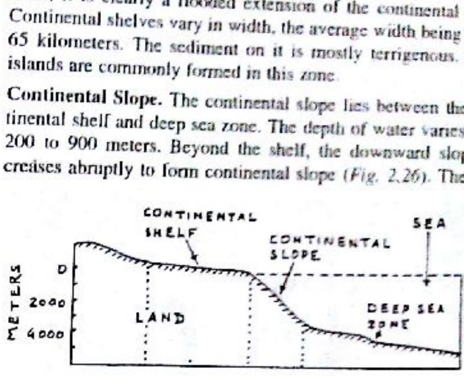


Fig. 2.26. Sea shore profile.

Along some mountainous coasts, the continental slope merges into deep oceanic trenches. In such cases, the shelf is very narrow or does not exist at all. Such a situation occurs along the west coast of South America. Here the vertical distance from the high peaks of the Andes Mountains to the floor of the Peru-Chile trench exceeds 12,200 meters.

(*iv*) **Deep Sea Zone.** This zone includes the deep sea floor which lies at a depth of about 4000 meters. The deep sea zone contains very fine sediments of inorganic and organic origin which are called *"ooze"*. Radiolarian ooze, foraminiferal ooze, diatom ooze, and red clay are the important types of deep sea deposits.

2.30. FEATURES OF OCEAN BASIN FLOOR

Mid Ocean Ridges. Mid ocean ridges are found in all of the major oceans. They are the most prominent linear topographic feature of the sea floor. The axes of the ridges are marked by frequent earthquakes and are characterized by a much higher heat flow through the crust. Deep rifts occur at the crests of the ridges. It is a site where two crustal plates are being pulled apart and new oceanic crust is being created.

Deep Ocean Trenches. A deep ocean trench is a long and narrow deep trough which represents the deepest part of the ocean. Several trenches in the western Pacific ocean have a depth of about 10,000 meters. Trenches are the site where crustal plates plunge down into the mantle. Volcanic island arcs are found associated with trenches in the open ocean while volcanic mountains, like the Andes, may be found along trenches that are adjacent to continents.

Abyssal Plains. The extremely flat areas of the deep ocean floor are called *"abyssal plains"*. They contain thick accumulations of sediment.

Sea Mounts. Isolated volcanic islands dot the ocean floors. Those volcanic mountains which rise at least 1000 meters above the surrounding topography, are called *"sea mounts"*.

2.31. SEDIMENTS OF DEEP SEA

On the basis of their origin, the sea floor sediments may be classified into three groups : (*i*) terrigenous sediment, (*ii*) biogenous sediment, and (*iii*) hydrogenous sediment.

(*i*) **Terrigenous Sediment.** The most common sediment that covers deep ocean floor, is grey and brownish mud. This mud mainly conists of mineral grains derived from the erosion of land.

(*ii*) **Biogenous Sediment.** This sediment is derived mainly from the shells and skeletons of marine animals and plants. *"Calcarious ooze"* is the most common biogenous sediment. This sediment is produced by organisms that live in the surface waters of the sea. Other biogenous sediments include *"siliceous ooze"* and phosphate rich materials. Oozes of silica are derived from the silica shells of diatoms (single celled algae), and radiolaria (single celled animals). The phosphate rich sediment is formed due to accumulation of bones, teeth and scales of fishes and other animals.

(*iii*) **Hydrogenous Sediment.** This sediment contains minerals that crystallize directly from sea water through various chemical processes. For example, some limestone is formed in this way. From economic point of view, *"manganese nodules"* are the most important hydrogenous sediment. These rounded, blakish, potato-sized nodules contain a complex mixture of minerals which include Mn, Fe, Cu, Ni and Co.

2.32. CORAL REEFS

Coral reefs are island-like structures found in the ocean. They are built by corals and many other lime secreting marine organisms under tropical and subtropical climatic conditions. They occur mainly in the warm water of the Pacific and Indian oceans. The conditions which favour the development of coral reefs are as follows.

1. Reef building corals grow best in waters with an average annual temperature of about 24°C. Coral reefs, therefore, develop only between 28°N and 28°S lattitudes.
2. Corals can not grow at depths where sunlight can not penetrate. This limits the depth of active coral reef growth to about 45 meters.
3. Clear water is necessary for the growth of corals. They do not survive in muddy water.

2.32.1. Types of Coral Reefs

Coral reefs are of three types : (*i*) fringing reefs, (*ii*) barrier reefs, and (*iii*) atolls.

(*i*) **Fringing Reefs.** A *"fringing reef"* is formed on the margin of an island in continuity with the shore. It encircles the island almost completely [*Fig. 2.27 (a)*].

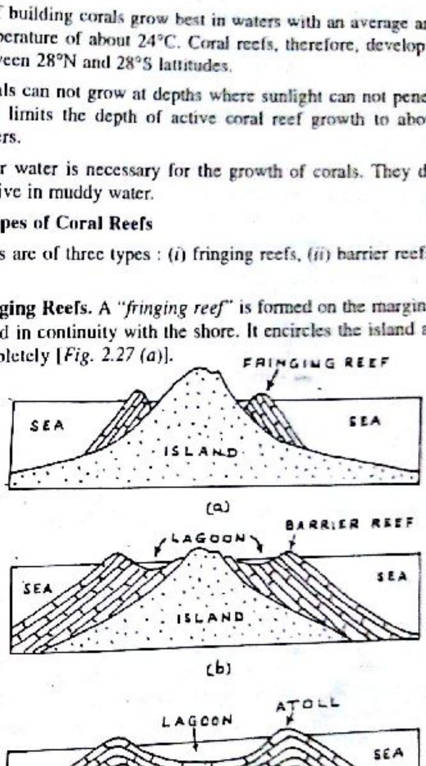


Fig. 2.27. Formation of a coral reef. (*a*) Fringing reef. (*b*) Barrier reef. (*c*) Atoll.

(*ii*) **Barrier Reefs.** Barrier reefs are built away from the island and therefore they enclose a lagoon between the central landmass and themselves [*Fig. 2.27 (b)*]. The Great Barrier Reef along the northeast coast of Australia is the famous example of this type.

(*iii*) **Atolls.** An atoll is a circular reef the central portion of which is occupied by a relatively shallow lagoon [*Fig. 2.27 (c)*].

2.32.2. Origin of Coral Reefs

The formation of coral reefs was explained by Charles Darwin in 1836. He said that coral reefs form on the flanks of sinking volcanic islands. Darwin's theory is known as the *"subsidence theory"*. This theory is still considered to be a most probable explanation. It may be summarized as follows.

1. The process starts with the formation of a volcanic island on the sea floor. The corals grow around the edge of the volcanic island and build a *"fringing reef"* [*Fig. 2.27 (a)*].
2. Then the island slowly sinks beneath the sea as a result of some tectonic movement. The actively growing corals may keep pace with this sinking and continue to build the reef upwards and outwards. In this way a *"barrier reef"* is formed which is separated from the island by a lagoon [Fig. 2.27 (*b*)].
3. With further subsidence, the central island disappears below the sea level and an *"atoll"* is formed [*Fig. 2.27 (c)*].

The confirmation of Darwin's theory was found only after World War II when United States selected two atolls for testing atomic bombs. During deep drilling of these atolls volcanic rock was found beneath the thick coral reef structure. Recently the theory of plate tectonics has offered a reasonable explaination for the gradual subsidence of volcanic islands on oceanic crust. This subsidence takes place when crustal plates slowly move away from the higher oceanic ridge to the lower oceanic basin floor.

2.33. GROUNDWATER

All water occuring beneath the ground surface is called *"groundwater"*. It has been estimated that the volume of water in the upper 0.8 kilometer of the continental crust is nearly 20 times greater than the combined volume of water in all lakes and rivers. The chief source of groundwater is the downward percolation of the rain water (meteoric water). Some groundwater may also be derived from juvenile and connate water. The *"juvenile water"* is the term used for magmatic water while *"connate water"* is that water which was entrapped in the sedimentary rocks during their deposition.

2.33.1. Hydrological Cycle

Hydrological cycle is a simplified description of the ways in which water moves from one place to another and how much is transported. The water in the atmosphere condenses to form clouds and then falls as rain or snow. The rain water divides itself into four parts.

1. Much of the rain soaks into the ground by *"infiltration"* and forms groundwater.
2. Another part flows over the surface as *"runoff"* and finds its way into rivers. Ultimately it reaches the sea.

3. Some of the water in the ground returns directly to the atmosphere by *"evaporation"*.
4. Another part is absorbed by plant roots. It is carried up to leaves and returned to the atmosphere by *"transpiration"*.

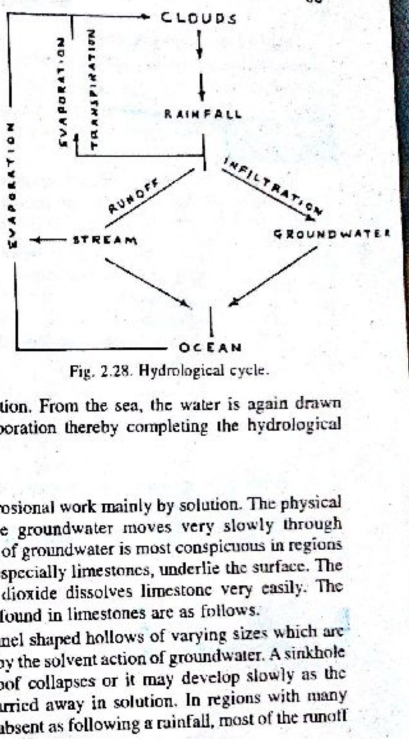


Fig. 2.28. Hydrological cycle.

Some of the groundwater may come out upon the surface again as springs or through wells but a large part of it reaches the sea through underground circulation. From the sea, the water is again drawn into the atmosphere by evaporation thereby completing the hydrological cycle (*Fig. 2.28*).

2.33.2. Erosion

The groundwater does erosional work mainly by solution. The physical erosion is negligible as the groundwater moves very slowly through bedrocks. The erosive action of groundwater is most conspicuous in regions where easily soluble rocks, especially limestones, underlie the surface. The water charged with carbon dioxide dissolves limestone very easily. The common solution structures found in limestones are as follows.

Sinkhole. These are funnel shaped hollows of varying sizes which are made in the carbonate rocks by the solvent action of groundwater. A sinkhole may form when a cavern roof collapses or it may develop slowly as the material is dissolved and carried away in solution. In regions with many sinkholes, streams are often absent as following a rainfall, most of the runoff is funneled below the ground.

Caverns. The tunnels and underground chambers which are formed in limestones by the solution of rock by groundwater are called *"caverns"*. These stand without collapsing the roofs. Joints are the natural avenues through which groundwater moves. The dissolution of rock gradually enlarges the joints and produces a complex system of caverns. The caverns are believed to have formed at or just below the water table. The stream's water may sometimes flow through these underground caverns.

Solution Valleys. With continued solution of limestones, the closely spaced sinks and solution basins are enlarged into a big valley called *"solution valley"*.

Karst Topography. The irregular terrain produced largely by the underground solution of limestones, is called *"karst topography"*. The karst topography is characterized by numerous sinkholes, caverns and underground channels. This topography develops in humid climate.

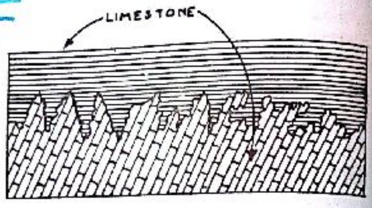


Fig. 2.29. Stylolites.

Stylolites. When groundwater percolates through bedding planes of limestones, the more soluble parts are dissolved easily leaving the less soluble parts as ridges. In adjacent beds these ridges project into each other forming a zig zag line along the junction of the bedding plane. Such a structure is called *"stylolite"* (*Fig. 2.29*).

2.33.3. Transportation and Deposition

The materials dissolved by groundwater are carried in solution untill they are deposited. Some materials may also reach sea through underground percolation thereby increasing the salinity of sea water. The deposition of the dissolved materials from the groundwater takes place by : (*i*) loss of carbon dioxide from water, (*ii*) evaporation (*iii*) decrease of temperature, (*iv*) fall of pressure, or (*v*) chemical reaction.

2.33.4. Depositional Features

Stalactite and Stalagmite. These features are found in caverns. As water drips from the roof of a cavern, evaporation leaves a small deposit of calcite behind. Gradually a cone shaped piller of calcium carbonate, hanging from the cavern roof develops. Such a deposit is called *"stalactite"* (Fig. 2.30). Similar deposits also grow from the floor of the caverns where water drops. Such piller-like forms which grow upwards from the cavern floor, are called *"stalagmite"*. When a stalactite and a stalagmite meet, a *"column"* is formed.

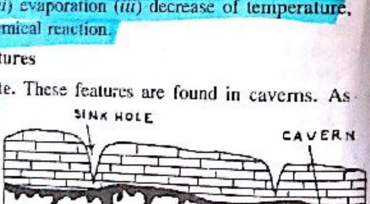


Fig. 2.30. (S) Stalactite, (M) Stalagmite, (D) Piller or column.

Geode. Sometimes in the cavities of rocks the groundwater deposits crystals of quartz, calcite, or other minerals. These deposits are called *"geodes"*.

Replacement. The groundwater generally contains silica or calcium carbonate in solution. This solution sometimes replaces a portion of the country rock or any other substance it may meet. The replacement involves the solution of preexisting substance and deposition of an equal volume of silica or calcium carbonate from the solution. In replacement the origional structure of the dissolved substance is commonly preserved. For example, in petrified wood the cellulose is replaced by silica and its woody structure remains intact.

2.34. OCCURRENCE OF GROUNDWATER

Beneath most land areas the groundwater occurs in three zones : (*i*) zone of aeration, (*ii*) capillary fringe, and (*iii*) zone of saturation (*Fig. 2.31*).

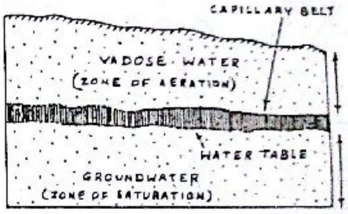


Fig. 2.31. Zones of groundwater below the ground surface.

(*i*) **Zone of Aeration.** The zone of aeration extends from the ground surface down upto the capillary fringe. This is the unsaturated zone in which the pore spaces of the rock are partly filled with water and partly with air. The rain water moving vertically downwards to the water table, passes through this zone. A certain amount of water is always held in smaller pore spaces due to molecular attraction. All the water which exists in the zone of aeration is called *"vadose water"*.

(*ii*) **Capillary Fringe.** The position of the capillary fringe is in between the zone of aeration and the zone of saturation. The water in this zone is connected with the zone of saturation and is raised above it by capillary forces. In coarse grained soils the capillary water rises only a few centimeters above the water table, but in fine grained soils or clays it may rise to a height of 10 to 15 meters.

(*iii*) **Zone of Saturation.** This zone extends from the water table downwards. In this zone all the pore spaces of rocks are completely filled with water. As the openings in the rocks decrease with depth, the lower limit of the zone of saturation is commonly found within a few hundred meters of the earth's surface.

2.34.1. Water Table

The upper limit of the zone of saturation is known a the *"water table"*. The water table may be defined as a gently curved surface below the ground at which the vadose zone ends and the saturation zone begins. It represents the level to which a well would fill with water.

The water table surface is obtained by connecting the levels of water in wells. It is not a horizontal surface. It generally follows the surface topography in a subdued form. The water table fluctuates with the amount of precipitation. The outcrops of the water table are springs and beds of rivers. In these places the water drains out of land. Swamps occur when the water table is right at the surface. In desert regions the water table may lie hundreds of meters below the surface.

The depth of water table at a place represents a balance between the rate of infiltration (recharge) and the rate of discharge at rivers, springs or pumped wells. Any imbalance, such as seasonal fluctuation of rainfall, raises or lowers the water table.

2.34.2. Perched Water Table

At some places a local impervious bed (aquiclude), such as a lens-shaped bed of clay, occurs in a permeable rock formation above the main water table. An isolated body of groundwater may occur above this impervious layer in the zone of aeration. Such groundwater is called *"perched groundwater"*. The local water table thus formed is called *"perched water table"* and the water bearing rock is called *"perched aquifer"* (*Fig. 2.32*).

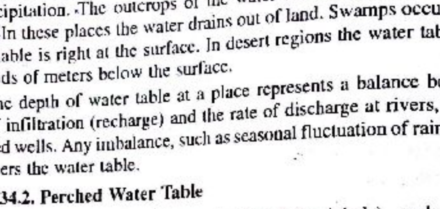


Fig. 2.32. Perched water table.

2.34.3. Water Table Maps

The water table is not a horizontal surface. Its form and slope very depending upon : (*i*) the area of recharge and discharge, (*ii*) pumpage from the wells, and (*iii*) permeability of the aquifer. The configuration of the water table surface may be shown by contour lines. In this case all points on a given contour will represent an equal elevation of the water table. Such a map is called *"water table contour map"*. These maps are used in analyzing the direction and the rate of groundwater movements.

2.34.4. Aquifers

Permeable rockformations which store groundwater and transmit sufficient quantity of it to a pumping well, are called *"aquifers"*. The impermeable beds that do not yield water and hinder or prevent water movement are called *"aquicludes"*. The aquifers are divided into two groups : (*i*) unconfined aquifers, and (*ii*) confined aquifers.

(*i*) **Unconfined Aquifers.** The aquifers in which groundwater occurs under atmospheric pressure are called *"unconfined aquifers"*. If a well is drilled in an unconfined aquifer, the water level in it will represent the water table.

(*ii*) **Confined Aquifers.** A confined aquifer is that in which aquicludes lie both above and below it. The aquicludes restrict the movement of groundwater and as a result in the confined aquifer the groundwater moves under pressure. The water pressure in such an aquifer depends on the difference in height between it and the recharge area. If the difference is enough, the water will readily flow out of a well drilled into it. Such wells are called *"artesian wells"*. A region supplying water to a confined aquifer is called *"recharge area"*. In the recharge area, the rain water infiltrates underground though the soil.

2.34.5. Pressure Surface.

In confined aquifers, because groundwater exists under pressure, the *"pressure surface"* is found in place of water table. The pressure surface is an imaginary surface which coincides with the hydrostatic pressure level of the groundwater in the aquifer (*Fig. 2.33*). If the pressure surface lies above the ground surface, the wells will be *"flowing artesian wells"* and if the pressure surface is below the ground level, the wells will be artesian but *"nonflowing"*, that is water will rise above the level where it is initially encountered but it will not rise upto the ground surface.

2.34.6. Artesian Well

When a well is drilled in a confined aquifer, the groundwater in it rises towards the surface. Such a well is called *"artesian well"*. The conditions necessary for the artesian flow are as follows.

1. Presence of an aquifer which must be confined between two impermeable beds. These beds prevent the water from escaping.
2. The aquifer must be inclined so that one end of it is exposed at the surface from where it can receive water.

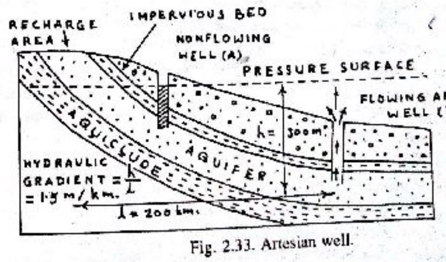


Fig. 2.33. Artesian well.

When such an aquifer is tapped, the pressure created due to difference between the height of the water table in the recharge area and the bottom of the well, will cause the water to rise. The friction reduces the height of the pressure surface. The greater the distance from the recharge area, the greater the friction and less the rise of water. In *Fig. 2.33*, well *A* is a nonflowing artesian well while well *B* is a flowing artesian well.

2.35. MOVEMENT OF GROUNDWATER

The groundwater moves very slowly through pore spaces or other openings in rocks. The movement of groundwater is measured in meters or centimeters per day. Although rates of tens of meters per day have been measured, a rate of 12 to 15 meters per day is considered high.

2.35.1. Openings in Rocks

The open spaces contained in the rocks are of fundamental importance because groundwater occurs in them and moves through them. The openings in rocks are of two types : (*i*) primary openings, and (*ii*) secondary openings. The "*primary openings*" are those which existed when the rock was formed. The intergranular pores in sedimentary rocks and gas cavities in lavas are the examples of primary openings. The "*secondary openings*" are those which develop after the formation of rocks. The joints, fractures and solution channels belong to this category. The secondary openings are found in most igneous and metamorphic rocks, and also in some sedimentary rocks.

2.35.2. Porosity

The quantity of groundwater that can be stored in a rock depends on its porosity. "*Porosity*" is a measure of pore spaces in rocks. It is defined as the percentage of pore spaces existing in a given volume of rock. Rocks vary widely in porosity. The loose sand and gravel may have porosity up to 50%, sandstones upto 15%, while porosity of igneous rocks is of the order of 2% to 3%.

2.35.3. Permeability

The "*permeability*" of a rock is its ability to transmit water. It is measured by the quantity of water passing through a unit cross-section of an aquifer in a unit time under 100% hydraulic gradient. The permeability in which full depth and unit width of the aquifer is considered, is called "*transmissibility*".

All porous rocks are not equally permeable. The permeability is closely related to the size of pore spaces and the degree to which they are interconnected. If the pores are small, the rock will transmit water very slowly. If they are large and interconnected, the rock will transmit water readily. Some clays have high porosities but they yield little or no water. The reason is that the openings in clays are very small and water in them is held by molecular attraction and therefore it is not free to move. Many rocks with low porosity may be fractured and thus have good permeability.

2.35.4. Darcy's Law of Groundwater Motion

From the observations of heights of water level in wells, Darcy proposed that for a given aquifer, the rate of water flow is directly proportional to the hydraulic gradient. The "*hydraulic gradient*" is the ratio between the difference in levels (h) of two points on the slope of the water table and the distance (l) between them, Mathematically, the Darcy's law can be expressed as follows

$$Q = K\frac{h}{l}$$

where Q is discharge per unit area and K is permeability. The hydraulic gradient (h/l) provides the driving force that keeps the groundwater in motion against internal friction.

2.35.5. Specific Yield and Specific Retention

All the water that exists in an aquifer can not be recovered. A part which is held there by molecular attraction is not free to move. The terms "*specific yield*" and "*specific retention*" have been used to designate respectively the water which can be drained out freely under gravity and the water which is held in the aquifer. The specific yield may be defined as the ratio of the volume of water that can be drained and the total volume of the aquifer. The specific retention is the ratio of the volume of water which is retained and the total volume of the aquifer.

$$\text{Specific yield} = \frac{\text{Volume of water drained}}{\text{Total volume of aquifer}} \times 100$$

$$\text{Specific retention} = \frac{\text{Volume of water retained}}{\text{Total volume of aquifer}} \times 100$$

2.36. PUMPING OF WELL

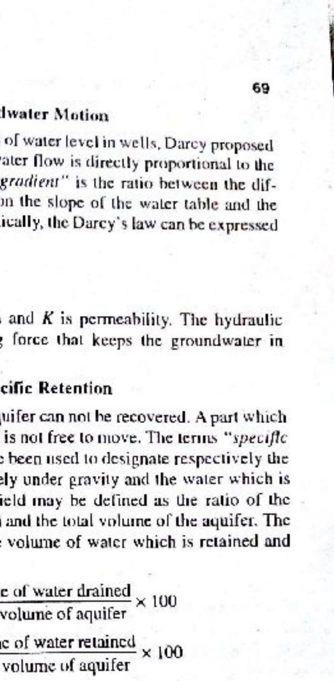


Fig. 2.34. Cone of depression around a pumping well.

In a well drilled to an unconfined aquifer, the water will always stand in it at the level of the water table when the pump is not operating. As soon as the pump starts, the water level in the well drops. The distance by which the level in the well is lowered below the water table by pumping, is called the "*drawdown*". Around the well the water table assumes a form which is comparable to an inverted cone. This cone shaped water table around a pumping well is called "*cone of depres-*

sion". Frequently the cone is found to be elliptical rather than circular in cross-section because the material of the aquifer is seldom homogeneous and the water table is usually inclined. The distance from the pumped well upto the outer limit of the cone of depression on the ground surface is termed the "*radius of influence*" (*Fig. 2.34*).

As pumping is continued at a constant rate, the drawdown increases and the radius of influence expands untill the flow of water from the aquifer into the well becomes equal to the withdrawal by pump. An increase or decrease in the rate of pumping will have a corresponding increase of decrease in the amount of drawdown. The relation of drawdown to the yield of a formation, both for artesian and nonartesian wells is shown in *Fig. 2.35*. This figure

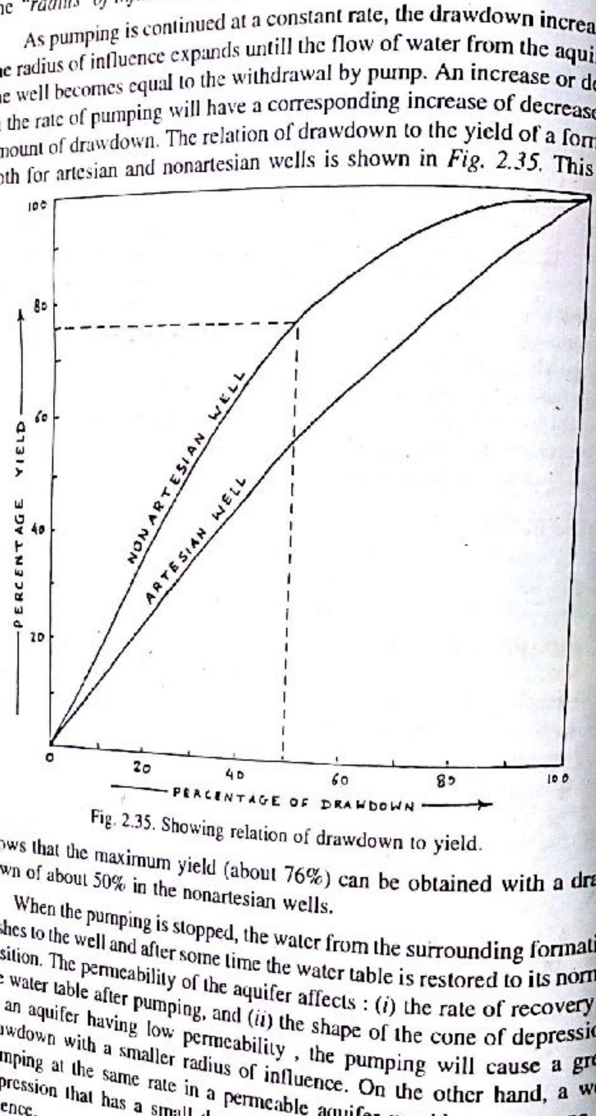


Fig. 2.35. Showing relation of drawdown to yield.

shows that the maximum yield (about 76%) can be obtained with a drawdown of about 50% in the nonartesian wells.

When the pumping is stopped, the water from the surrounding formation rushes to the well and after some time the water table is restored to its normal position. The permeability of the aquifer affects : (*i*) the rate of recovery of the water table after pumping, and (*ii*) the shape of the cone of depression. In an aquifer having low permeability, the pumping will cause a great drawdown with a smaller radius of influence. On the other hand, a well pumping at the same rate in a permeable aquifer would cause a cone of depression that has a small drawdown and relatively large radius of influence.

2.37. GROUNDWATER IN COASTAL AREAS

Under islands and near sea coasts, the fresh water extends to a considerable depth in the aquifers below the sea level. As a result the underground boundary between the fresh water and salt water of the sea is inclined as

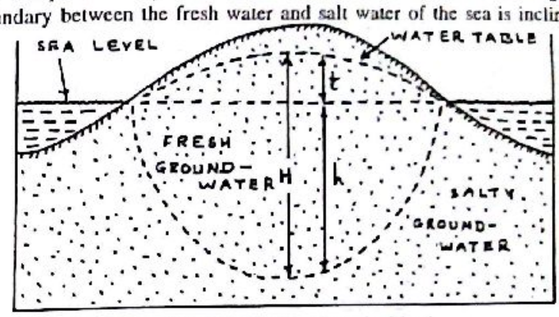


Fig. 2.36. Water table under islands.

shown in *Fig. 2.36*. If withdrawals by pumping are not excessive, the recharge of fresh water on the land is enough to keep the water table elevated above sea level and maintain a reservoir of fresh water which bulges into the sea water at depth. But if the withdrawals exceed recharge, the water table is lowered and the pressure of fresh water on the bulge decreases thereby allowing the sea water to move in. There is no solution to the incursion of sea water except to reduce the pumping or artificially increase the recharge.

On an island the fresh water occurs in a lens shaped area the major part of which extends below sea level. By the Herzburg formula it is possible to determine the amount of fresh water present in this lens below sea level. In *Fig. 2.36* at a certain well, "t" is the height of the water table above sea level, and "h" is the depth below sea level upto which the fresh water extends. The total thickness of the fresh water column is "H", which is equal to "$h + t$". According to the law of floating objects, the weight of the column of fresh water H is equal to the weight of the column of salt water h which is displaced. Thus,

$$H = h + t$$

But H is also equal to hg where "g" is the specific gravity of salt water

Then,
$$t = h(g - 1)$$

or,
$$h = \frac{t}{g - 1}$$

The average specific gravity of sea water is 1.025. By substituting this value in the above formula, we have :

$$h = 40\,t.$$

2.38. WELLS

The most common device used by men for tapping groundwater is the well. The *"well"* is a vertical opening or shaft excavated into the zone of saturation. Wells serve as reservoirs into which groundwater moves and from which it can be pumped to the surface. The amount of water that a well will yield depends chiefly on (*i*) the permeability of the aquifer, (*ii*) thickness of the aquifer, and (*iii*) diameter of the well.

2.38.1. Types of Well

Depending upon the method of construction, the wells may be classified into the following groups.

Dug Wells. Dug wells are excavated by means of picks and shovels and their diameter is usually more than one meter. These wells seldom exceed a depth of 20 meters.

Driven Wells. The wells in the unconsolidated materials may be constructed by driving a pipe at the end of which there is a drive point. The diameter of such wells seldom exceeds 7.0 centimeters.

Bored Wells. The bored wells are constructed in the unconsolidated materials by means of hand or power augers.

Jetted Wells. These wells are excavated in the loose earth materials by the force of the jet of water which is produced by pumping water through hollow drill rods.

Drilled Wells. The water from consolidated aquifers is extracted by drilling deep wells. These wells are generally constructed by hydraulic rotary drill methods. The drilled wells may attain a depth of 70 meters or more.

2.39. SPRINGS

When the groundwater flows out at the ground surface, it is called a *"spring"*. The springs are formed at places where water table intersects the ground surface.

2.39.1. Types of Springs

Water Table Spring. The water table springs are found in depressions where the ground level is below the water table (*Fig. 2.37*).

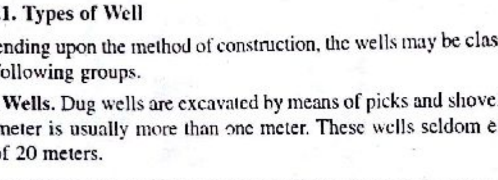


Fig. 2.37. Water table spring.

Contact Spring. Where an impervious bed underlies a permeable bed, the groundwater flows out along the contact if the same is exposed by erosion (*Fig. 2.38*).

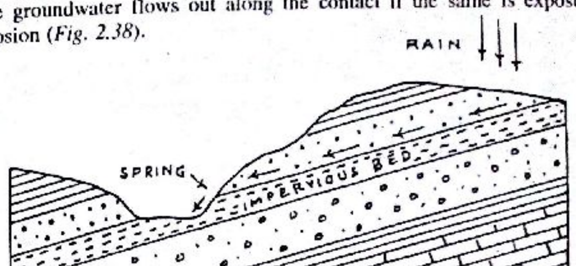


Fig. 2.38. Contact spring.

Karst Spring. Erosion may expose a cavernous rock, such as limestone containing groundwater. The springs formed in this way are called karst spring.

Fault Spring. The flow of groundwater is checked along the fault planes and it may emerge out at the ground surface forming a fault spring.

Mineral Spring. Spring water may contain some dissolved mineral matter in sufficient concentration as to produce some taste or smell. Such springs are called mineral springs.

Thermal Spring. The springs which discharge heated water are called thermal springs.

2.40. EARTHQUAKES

An *"earthquake"* is the sudden vibration of the earth's surface by rapid release of energy. This energy is released when two parts of rock masses move suddenly in relation to each other along a fault.

2.40.1. Effects of Earthquake

1. Buildings are damaged and people get frightened.
2. Roads are fissured, railway lines are twisted and bridges are destroyed.
3. In cities, ground waves disrupt underground services and start fires.
4. Rivers change their courses, Fissures are opened up in the ground which may cause spring.
5. Permanent tilting of the land mass may occur in certain areas. Landslides may occur in hilly regions.

2.40.2. Terminology

Focus. The point of origin of an earthquake within the earth's crust is called the *"focus"* (*Fig. 2.39*). From the focus the earthquake waves radiate in all directions.

Epicentre. The point lying vertically above on the earth's surface, directly above the focus, is called the *"epicentre"* (*Fig. 2.39*). In the epicentre the shaking is most intense. The intensity gradually decreases outwards.

Isoseismal Lines. The lines connecting points of equal intensity on the ground surface are called *"isoseismal lines"*. If the focus is a point, the isoseismal lines will be circles, but as the focus is commonly a line, the isoseismals are generally elliptical. From the distribution of the lines, the epicentre of an earthquake can be determined (*Fig. 2.39*).

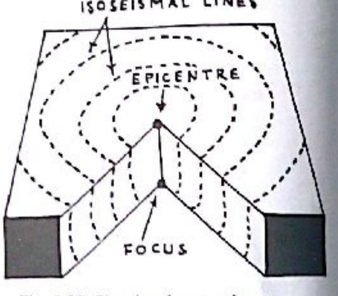


Fig. 2.39. Showing focus, epicentre and isoseismal lines.

Earthquake Intensity. It is a measure of the degree of destruction caused by an earthquake. It is expressed by a number as given in the earthquake intensity scale (*Table 2.4 and 2.5*).

Tsunamis. *"Tsunamis"* are giant sea waves generated by earthquakes on the sea floor. They cause heavy destruction in areas lying near the sea shore. At sea tsunamis have wave lengths as great as 200 kilometers. They can travel at speeds of 800 km per hour. Near the sea shore they slow down and gather height which may be as much as 30 meters. As the tsunami approaches the shore, the sea withdraws and then it rushes back in a series of giant waves that travel far inland and cause destruction.

2.41. SEISMOGRAPHS

"Seismographs" are instruments which detect and record earthquake waves. Most seismographs contain a heavy weight suspended from a support which is attached to bed rock (*Fig. 2.40*). When waves from a distant earthquake reach the instrument, the inertia of the weight keeps it stationary, while the earth and the support vibrate. The movement of the earth in relation to the stationary weight is recorded on a rotating drum.

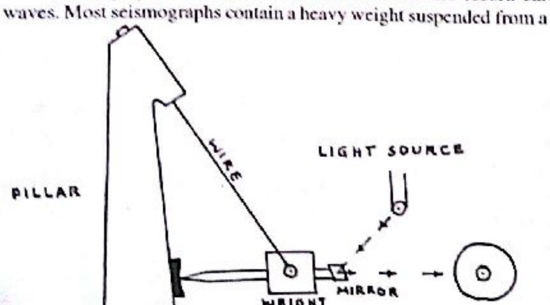


Fig. 2.40. Seismograph.

Some seismographs detect horizontal motion while others detect vertical motion. The trace of the earthquake waves is usually recorded on a travelling photographic paper as a series of zig zag lines (*Fig. 2.41*). These records are called *"seismograms"*. From the seismograms the time interval between the arrival of the P and S waves can be calculated and with the help of the travel-time graph (*Fig. 2.43*), the distance between the recording station and the epicentre is determined.

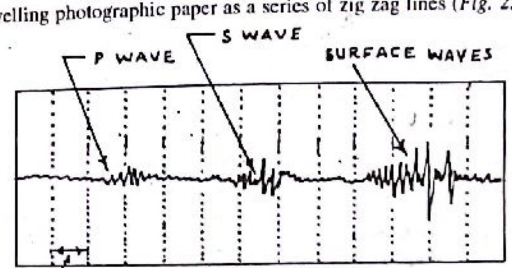


Fig. 2.41. Seismogram.

2.42. EARTHQUAKE WAVES

During an earthquake seismic waves are generated which spread outwards in all directions from the focus. Seismic waves are of three type : (*i*) P waves, (*ii*) S waves, and (*iii*) surface waves or L waves. Surface waves are responsible for causing earthquakes while the main significance of P and S waves is in the study of the earth's interior. P and S waves travel through the interior of the earth and are reflected and refracted as they enter a layer of different material.

P-Waves or Primary Waves. These are compressional waves which cause the particles of rock to vibrate in the longitudinal direction. The P waves travel fastest, therefore they reach a seismic station first. Their velocity is 1.7 times than that of S waves. They pass through solids as well as liquids.

S-Waves or Secondary Waves. These are shear waves which are transverse in nature. Their velocity is less than the P waves. The S waves travel through solids only and do not pass through liquids.

L-Waves or Surface Waves. When P and S waves reach the earth's surface, they are converted into L waves. The L waves travel along the surface and cause earthquake. They are transverse in nature and their velocity is much less than the P and S waves.

2.43. CLASSIFICATION OF EARTHQUAKES

Classification-I. Depending upon their mode of origin, the earthquakes are classified into the following groups.

(*i*) *Earthquakes Due to Surface Causes.* Earthquakes may be generated by landslips and collapse of the roof of underground caverns. Most of these are very minor.

(*ii*) *Earthquakes Due to Volcanic Causes.* Volcanic eruptions may also produce earthquakes but such earthquakes are generally very feeble.

(*iii*) *Earthquakes Due to Tectonic Causes.* Tectonic earthquakes are the most numerous and usually the most disastrous. They are caused by shocks which originate in the earth's crust due to sudden movements along faults.

Calssification-II. On the basis of the depth of focus, the earthquakes are divided into the following groups.

(*i*) *Shallow Focus Earthquakes.* Earthquakes having depth of focus upto 55 km.

(*ii*) *Intermediate Focus Earthquakes.* Earthquakes having depth of focus between 55 to 300 km.

(*iii*) *Deep Focus Earthquakes.* Earthquakes having depth of focus between 300 to 650 km.

The shallow earthquakes are more violent at the surface but affect a smaller area than deep earthquakes.

2.44. ORIGIN OF EARTHQUAKES

Tectonic earthquakes are the most common and therefore the most important. The forces that cause tectonic earthquakes are the same which cause faulting and produce mountains on the earth's surface. The possible mechanism of tectonic earthquakes can be explained by the *"elastic rebound theory"*. This theory was put forward by H.F. Reid.

2.44.1. Elastic Rebound Theory

The main points of the elastic rebound theory are as follows.

1. In certain zones of the earth's crust, the stresses accumulate gradually in rock masses [*Fig. 2.42* (*a*) and (*b*)].
2. When the stresses exceed the elastic limit of rocks, they bend and crack (*Fig. 2.42*). The slippage along the fracture is initially prevented by friction. Under these conditions the rocks will store up energy as elastic strain. Some slight movement along the fracture plane produces *"fore shocks"*.

3. When the strain reaches a critical point, the friction is overcome and slippage takes place. The fractured blocks snap back to its origional shape thereby releasing the stored up energy in the form of earthquake by vibrating back and forth [*Fig. 4.2* (*c*)]. The springing back of the rock is called *"elastic rebound"*. Some adjustments along the fault zone after the main earthquake produce *"after shocks"*.

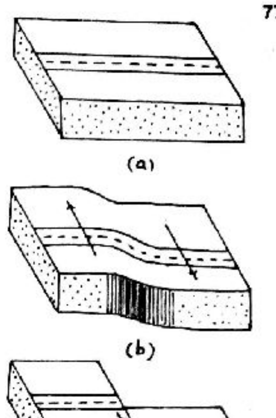


Fig. 2.42. Elastic Rebound Theory. (*a*) No stress condition. (*b*) Elastic strain stored under stress. (*c*) Release of elastic strain.

With the recent developments in the field of plate tectonics, we now know that crustal plates are in constant motion. While moving, the plates may either thrust against one another or may drift away. Where they move apart, oceanic ridges are formed and where they converge and collide, mountain chains are created. Almost all the world's earthquakes occur along the lines joining one crustal plate with another.

2.45. EARTHQUAKE INTENSITY SCALE

Generally the effects of an earthquake are strongest near the epicentre and decrease gradually outwards. To have an idea about the intensity of an earthquake in different areas, intensity scales have been devised. The two commonly used intensity scales are : (*i*) Rossi Forel Scale, and (*ii*) Richter Scale.

2.45.1. Rossi Forel Scale

The earthquake intensity scale devised by Rossi Forel is based on how people behave and react, and howmuch destruction or disturbance is caused to man made structures and natural objects. The Rossi Forel Scale has nine divisions. Intensity I is given to the weakest earthquake which is felt only by very sensitive people at rest. The highest number IX is assigned to the strongest earthquake that cause massive destruction to man made structures and natural objects. Any intensity above IV can cause damage to property.

However the destruction caused by earthquakes is not an adequate means for comparision. Many factors including distance from the epicentre, nature of surface materials and building design cause variations in the amount of damage.

2.45.2. Richter Scale

This earthquake intensity scale was devised by Charles F. Richter, an American seismologist. It is based on the total amount of energy released during an earthquake. This energy is called *"magnitude"*. The magnitude is calculated mathematically using the amount and duration of ground vibrations as recorded by a seismograph.

Table 2.4. Richter Scale

Magnitude	*Effects*
2.5	Generally not felt, but recorded
4.5	Local damage
6.0	Can be destructuve in populous region.
7.0	Major earthquakes. Inflict serious damage.
More than 8.0	Great earthquakes. Cause total destruction.

The Richter Scale (Table 2.4) is widely used to describe the magnitude of an earthquake. This scale is logarithmic, hence an increase in magnitude of one unit corresponds to a tenfold increase in the size of seismic waves and about 30-fold increase in the energy released. Thus an earthquake with a magnitude of 6.5 releases 30 times more energy than one with a magnitude of 5.5. Damage to structures begins at magnitude 5 and increases to nearly total destruction at magnitude greater than 8. Some of the world's major earthquakes are San Francisco 1906, Japan 1923, Chile 1960, and Alaska 1964. All had Richter magnitudes greater than 8.2. An intensity scale modified by Mercali is shown in *table 2.5.*

Table 2.5. Mercali Scale

Intensity		*Acceleration cm/sec/sec*	*Effects*
I	Instrumental	Less than 1 cm.	Recorded by instruments only.
II	Very feeble	Over 1 cm.	Felt on upper floors by a few people.
III	Feeble	Over 2.5 cm	Felt by people at rest.
IV	Moderate	Over 5.0 cm	Felt by people in motion. Dishes and windows rattle.
V	Fairly strong	Over 10.0 cm	Many persons awakened. Dishes broken, plaster cracked, trees and poles disturbed.

Table contd...

Intensity		*Acceleration cm/sec/sec*	*Effects*
VI	Strong	Over 25.0 cm	People run outdoors. Slight damage to buildings. Heavy furniture moved.
VII	Very Strong	Over 50.0 cm	Average homes slightly damaged.
VIII	Destructive	Over 100.0 cm	Well built structures slightly damaged, others badly damaged. Chimneys fall.
IX	Ruinous	Over 250.0 cm	Well designed buildings badly damaged. Cracks open in ground.
X	Disastrous	Over 500.0 cm	Many buildings destroyed, rails bent, ground cracked.
XI	Very disastrous	Over 750.0 cm	Few masonry structures left standing. Bridges destroyed.
XII	Catastrophic	Over 980.0 cm	Total desctruction. Waves seen on the ground surface.

2.46. LOCATION OF EPICENTRE

The focus is the place where the earthquakes originate. The difference in velocities of P and S waves provides a method for determining the epicentre. The position of an epicentre is found by the three point intersection method. The greater the interval between the arrival of the first P wave and the first S-wave, the greater the distance to the earthquake epicentre. By using a travel-time graph (*Fig. 2.43*) the distance from the seismic station to the epicentre can be determined. At three properly located seismic stations, the distance to the epicentre is determined. By using the distance as the radius, a circle is

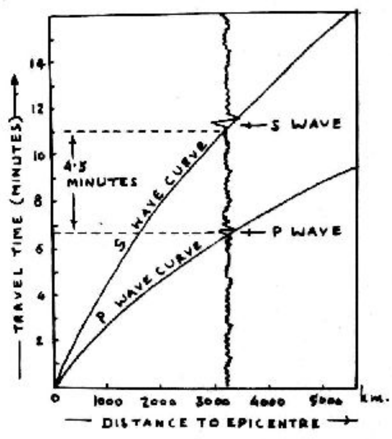


Fig. 2.43. Travel Time curve. The difference in arrival times of *P* and *S* curves is 4.5 minutes. Thus epicentre is nearly 3200 km away.

drawn from each station. The epicentre will be at the point of intersection of the three circles (*Fig. 2.44*).

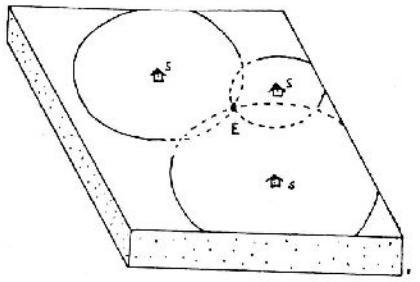


Fig. 2.44. Location of epicentre. S-Recording station, E-Epicentre.

2.47. DISTRIBUTION OF EARTHQUAKES

Earthquakes occur in geologically active areas, such as mid oceanic ridges and mountain building regions. The zones where earthquakes occur frequently are known as *"seismic belts"*. The principal seismic belts on the earth's surface are as follows.

(*i*) **Circum Pacific Belt.** This belt encircles the Pacific ocean and more or less overlaps the belt of young fold mountains and the zone of active volcanoes. About 80% of the world's earthquakes occur in the *"Circum Pacific Belt"*.

(*ii*) **Alpine-Himalayan Belt.** This belt starts from the East Indies and passes through the Himalayan foot-hill region to the Alpine mountain arcs of Europe.

(*iii*) Rift valley region of the east and central Africa.

In India earthquakes frequently occur along the foot-hill zone of Himalayas, starting from Kashmir in the west to Assam in the east. After 1819, 15 very destructive earthquakes have occurred in India. Some of the important earthquakes are as follows.

1. Assam : 1819, 1897, 1935 and 1950
2. Bihar : 1934
3. Indo - Nepal border : 1988.
4. Himachal Pradesh : 1905, 1975 and 1987.
5. Kashmir : 1963, 1972 and 1976
6. Cutch area of Gujrat : 1819, 1956 and 1970.
7. Maharashtra : 1993

2.48. PREDICTION OF EARTHQUAKES

In seismic regions earthquakes occur frequently and cause loss of life and property. This emphasizes the need for reliable methods of earthquake prediction. In order to predict earthquakes it is necessary to detect the fault lines where strains are building up. The following methods are used to locate areas under strains.

1. In Japan, people have concentrated their study on fore-shocks which precede the main earthquake. It is hoped that this study will lead to some pattern which can be used to predict earthquakes.
2. Before an earthquake, the ground on either side of a fault suffers elastic deformation which can be measured by triangulation with a theodolite or leser beam.
3. In California (U.S.A.), uplift or subsidence of the land and changes in movement along a fault zone from a slow creep to a locked position, have been found to precede main earthquakes. Hence it is hoped that the prediction of earthquakes may be done by monitoring ground tilt, fault movement and seismic activity.
4. Now, there are artificial satellites which gather information from instruments placed in the vicinity of major faults. With the help of this information, it is now possible to detect very small movements of the earth's surface and locate areas where strain is building up.
5. Recently a method has been discovered where the amount of water that a rock contains is measured. Under strain, the pores in the rock enlarge which allows more water to enter into it. Thus the knowledge of the water level in wells in the earthquake effected areas is very useful in detecting rocks under strain.

In 1975 an earthquake in northeest China was predicted only hours before it occurred. As a result thousands of lives were saved.

2.48.1. Control of Earthquakes.

In an earthquake prone area if it is known that the strain is accumulating, the threat of earthquakes can be reduced by the following methods.

(*i*) A number of deep holes are drilled along a fault line in which stress has been detected. Then water is pumped down into the holes. This water acts as a lubricant, so the faulted rocks slip smoothly in a series of small nondestructive earthquakes.

(*ii*) Nuclear devices may be exploded along a fault plane which relieves strain by producing small earthquakes.

2.49. EARTHQUAKE RESISTING STRUCTURES

To build earthquake resisting structures, it is necessary to determine the probable intensity and magnitude of earthquake shocks in the area concerned. The history and records of the previous earthquakes and the knowledge of the local geology are of help in this connection. Some precautions are as follows.

(*i*) A study of past earthquakes indicates that the damage is usually much greater in structures founded on soft ground than on hard rocks. It is there-fore advised that in seismic areas the structures should be founded on bed rock. If the same is not possible, reinforced concrete raft foundation should be given. During the passage of seismic waves, the structures built on raft foundation literally floats.

(*ii*) Careful planning can ensure that the streets are wide in relation to the height of buildings. Many of the deaths caused during earthquakes are due to collapse of tall buildings into narrow streets.

(*iii*) It has been found that rigid structures endure seismic shocks better than flexible ones, that is why steel framed or ferro-concrete structures generally survive severe shocks.

(*iv*) Generally taller structures should be avoided.

2.50. VOLCANOES

A *"volcano"* is a vent or fissure in the earth's crust through which hot lava and volcanic gases are thrown out. Volcanic eruptions may be either explosive or quiet.

The earth's upper mantle (asthenosphere), under the crust is nearly molten. Magmas originate at this depth. They migrate upwards, often along faults. In a volcano the magma rises through a chimney-like opening called *"vent"* and reaches the surface as lava. At the surface pressure in the rising magma falls, as a result dissolved gases are separated out. Such a magma is called *"lava"*.

In addition to emission of gases and molten lavas, vast quantities of fragmental materials (pyroclasts) are also produced during volcanic eruptions. This material accumulates around the vent. Conical hill-like masses formed in this way, are called *"volcanic cones"* (*Fig. 2.45*). Volcanoes often have side vents as well. The smaller cones formed around these side vents, are called *"parasitic cones"* (*Fig. 2.45*).

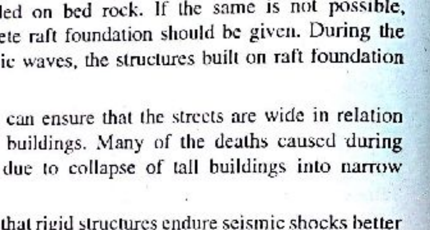


Fig. 2.45. Structure of a volcano.

A circular depression found at the top of volcanic cones is called *"crater"*. A greatly enlarged crater is called *"caldera"*. A caldera is a gigantic depression the diameter of which may be 16

km or more. Most of the calderas may have resulted either due to blowing of the summit of the volcanic cone by explosive action, or it may be due to subsidence. The subsidence is caused when the magma chamber lying below the volcano is partially emptied during eruption and the volcano then sinks into the void.

2.50.1. Types of Volcanoes

Volcanoes commonly do not erupt continuously for long periods. Mostly they show intermittent activity. Depending on the variation in the frequency of their activity, volcanoes are divided into three groups : (*i*) active volcanoes, (*ii*) dormant volcanoes, and (*iii*) extinct volcanoes.

Active Volcanoes. An *"active volcano"* is one which erupts very often. They mostly occur at crustal plate boundaries. The volcanoes that occur along a great arc around the Pacific ocean from Chile to the East Indies, are examples of active volcanoes.

Dormant Volcanoes. The volcanoes which show eruptions after long intervals of time, are called *"dormant volcanoes"*. During dormant period they appear quite inactive.

Extinct Volcanoes. An ancient volcano which has not shown any volcanic activity since a very long time in the geological history, is called *"extinct volcano"*.

2.51. VOLCANIC PRODUCTS

Three types of material are thrown out from a volcano : (*i*) gases, (*ii*) molten lava, and (*iii*) solid rock fragments.

Gaseous Products. The most important constituent of volcanic gases is steam. It forms nearly 90% of the total gas content. The other chief gases, in the order of abundance, are carbon dioxide, nitrogen and sulfur dioxide, and smaller amounts of hydrogen, carbon monoxide, sulfur and chlorine. The density of magma and molten lava is reduced by the presence of dissolved gases.

Liquid Products. Liquid emissions from a volcano are known as *"lavas"*. Lavas of acidic composition are more viscous and less mobile than highly fluid basic lavas. Fluid lava results in calm eruptions as they allow the dissolved gases to escape freely. In viscous lava, the gases do not escape freely. They frequently build up an internal pressure to produce a violent eruption.

Solid Products. Besides gases and liquid lavas, volcanoes eject solid rock fragments of various size. These rock fragments are thrown out by the escaping gases during violent eruptions. When fragments of very viscous lava are blown off into the air, they solidify quickly and fall to the ground as pyroclasts. The solid rock fragments produced during volcanic eruptions are called *"pyroclasts"*. Depending on the size, the pyroclasts are divided into the following groups.

(*i*) **Volcanic Blocks.** Bigger angular fragments of dead lava are called *"volcanic blocks"*. They are formed when large pieces of solidified lava are blown off during an explosion.

(*ii*) **Volcanic Bombs.** Bigger and somewhat rounded or spindle-shaped fragments are called *"volcanic bombs"*. They may be upto the size of the football. Volcanic bombs are clots of live lava which generally solidify before reaching the ground.

(*iii*) **Lapilli or Cinders.** The rock fragments upto the size of gravels or peas, are called *"lapilli"* or *"cinders"*. Normally their size ranges between 4 to 32 millimeters.

(*iv*) **Ash.** Particles that range in size between 0.25 to 4.0 millimeter, are called *"volcanic ash"*.

(*v*) **Dust.** The dust includes very fine particles. Their size is less than 0.25 millimeter.

The volcanic dust and ash on consolidation form a rock which is called *"tuff"*. When hot ash, usually glassy shreds, falls, it sticks together to form a *"welded tuff"*. The larger fragments, such as bombs or blocks of older rocks, commonly accumulate near the volcanic cone. On consolidation they produce a rock called *"agglomerate"* or *"volcanic breccia"*.

In lavas where gases are released during consolidation, small bubbles may be entrapped into the rock. These gas cavities are called *"vesicles"*. In viscous acidic lavas the vesicles may be so abundent that the rock takes the form of a light spongy mass which is called *"pumice"*. The pumice is so light that it floats on water. The term *"scoriae"* is applied to those bombs and lapilli which are spongy like pumice but they are more rugged and have knife sharp edges.

2.51.1. Volcanic Cones

Successive eruptions from a single vent result in the accumulation of volcanic material around it. Conical mountains formed in this way are called *"volcanic cones"*. Volcanic cones are of three types : (*i*) cinder cones, (*ii*) lava cones, and (*iii*) composite cones.

(*i*) **Cinder Cones.** These are steep sided volcanic cones which are built up of fragmentary material, mostly cinders. Such cones are usually very symmetrical and have circular craters. Cinder cones are small in size and their height seldom exceed 300 meters. They often occur as parasitic cones on larger volcanoes.

(*ii*) **Lava Cones.** Lava cones are composed mainly of solidified lava-flows. They are much flatter than cinder cones. They have a slope of a few degrees at their flanks and nearly 10° near their summit. Volcanoes having such type of cones are called *"shield volcanoes"*. They derive their name from the shape of the cones which is more or less like a shield. The Hawaiian volcanoes are the important examples of shield volcanoes. Their cones are formed due to solidification of highly fluid and mobile basic lavas.

(*iii*) **Composite Cones.** These cones are composed of alternate layers of pyroclastic material and solidified lava-flows. Composite cones usually have a steep summit and rather gently sloping flanks. The contributing magma has an andesitic to rhyolitic composition and hence is rather viscous. Volcanoes which possess such well marked stratification are called *"strato-volcanoes"*. The examples of strato-volcanoes are Vesuvius (Italy) and Mount Fuji (Japan).

2.52. VOLCANIC ERUPTIONS

Volcanic eruptions are of two types : (*i*) central eruptions, and (*ii*) fissure eruptions.

Central Eruptions. In central eruptions, the emission of lava takes place through a vent. Such a volcano usually exhibits cone-and-crater arrangement. This volcano may have parasitic cones on the flanks of the main structure. Etna, an European volcano, has more than 200 parasitic cones.

Fissure Eruptions. In fissure eruptions, basic lavas issue relatively quietly from linear fissures in the earth's crust. These lavas cover a very large area before solidifying and considerable thickness of rock is formed from repeated eruptions. These vast accumulations of solidified lava are called *"plateau basalts"*. An example of fissure eruptions is the *"Deccan Traps"* which cover an area of about 1000,000 square kilometers in central India. Ocean floor basalts are also the products of fissure eruptions.

Although volcanic eruptions are sometimes violent, many are very quiet. The factors which determine the nature of eruptions are : (*i*) composition of magma, (*ii*) temperature of magma, and (*iii*) amount of dissolved gases. The first two factors, *i.e.* composition and temperature, mainly affect the magma's vescosity. The vescosity of a magma is directly related to its silica content. The lower the percentage of silica in a magma, the greater the fluidity. Thus basaltic lavas are usually very fluid.

The gases play a major role in causing volcanic eruptions. They provide the force which drives magma out from the cone. Highly viscous magmas often plug the vent thereby trapping the gases below. This results in a build up of pressure which leads to the explosive type eruption. Very fluid magma, on the other hand, allows the gases to escape freely producing rather quiet eruptions. Many gradations exist between these two extremes. Chief types of volcanic eruptions are as follows. They are arranged in the order of their increasing violence.

1. **Hawaiian Type.** In the Hawaiian type eruptions, the mobile lava of basaltic composition is discharged relatively quietly. The lava flows out from lava pools occupying craters or from fissures. Sometimes fountains of lava are formed due to rapid emission of gases. This type of eruption is characterstic of Hawaiian volcanoes perticularly Mauna Loa and Kilauea.

2. **Strombolian Type.** In the Strombolian type eruptions, the viscous lavas erupt with moderate explosion. Clots of incandescent lava are thrown out to form bombs or lumps of scoria. Stromboli volcano in Sicily exhibits such eruptions.

3. **Vulcanian Type.** This type of eruption is more violent than the Strombolian type. The viscous lava solidifies quickly thereby causing severe explosions. This results in the ejection of solid rock fragments of all sizes including cinders, ash and dust. Dark clouds of dust are usually seen.

4. **Vesuvian Type.** In this case the lava highly charged with gases erupts with extreme violence. Large amount of gases and dust are thrown up into the air which form a cauliflower like cloud at great heights.

5. **Plinian Type.** It is the most violent type of volcanic eruption in which a blast of uprushing gases rises to great heights.

6. **Pelean Type.** In this type of eruption, the most viscous lava is thrown out. The blocked vent is cleared due to violent explosions. The hot gases and volcanic ash spread very widely through the air.

2.53. SURFACE OF LAVAFLOWS

The surface texture of a lavaflow depends on : (*i*) temperature of lava, (*ii*) composition of lava, and (*iii*) velocity of the flow during the eruption. The surface textures of newly consolidated lavaflows are of three types.

(*i*) **Blocky Lava.** Rhyolitic lavas, because of their high silica content, are usually very viscous. Their movement is often very slow. Such slow moving lavas generally have a rough and clinker like surface. Such lavas are called *"blocky lavas"*.

(*ii*) **Ropy Lava.** When a lavaflow has a smooth but twisted surface, it is called *"ropy lava"*. Such a surface is commonly formed on fast flowing fluid lava of basaltic composition. When the lava starts solidifying, a plastic skin is formed on its surface. The plastic skin is dragged into wrinkles as the still molten lava continues to advance beneath it.

(*iii*) **Pillow Lava.** When lava of basaltic composition flows over sea floor, it solidifies with a surface which exhibits pillow-like ellipsoids. The diameter of such ellipsoids vary from a few centimeters to a few meters. The lava having such a surface is called *"pillow lava"*. These pillows are commonly glassy outside and finely crystalline inside.

2.54. DISTRIBUTION OF VOLCANOES

There are about 800 active volcanoes on the earth's surface. Besides these, there are many thousands of extinct volcanic cones most of which are under the sea floor. A great majority of volcanoes are found to be concentrated along the following belts.

1. The Circum Pacific belt
2. The Alpine - Indonesian belts
3. The Mid - Oceanic Ridges
4. African rift valleys.

The belt around the Pacific ocean contains the largest number of active volcanoes and therefore it is called the *"ring of fire"*. It seems that the volcanoes are found associated with the boundaries of crustal plates. For example, the Circum Pacific and the Alpine - Indonesian belts are the regions of recent crustal deformation which lie along the collision edges of the crustal plates. Similarly the Mid Oceanic Ridges and the African rift valleys represent the big tensional cracks on the earth surface. A few volcanoes that exist on land away from the plate boundaries are perhaps due to localized heating by radioactivity.

2.55. PHENOMENA ASSOCIATED WITH VOLCANISM

Hot springs, fumaroles and sometimes geysers are found in volcanic regions.

Hot Springs. Hot springs are commonly found associated with volcanic activity of recent date. Surface water which penetrate the ground may be heated either by contact with hot rocks or by gaseous emanations from the volcanic rocks. When it reemerges on the surface, it gives rise to hot springs.

Fumaroles. When jets of steam and hot gases are discharged from a volcanic vent, it is called a *"fumarole"*. *"Solfatars"* are the fumaroles emitting mainly sulfurous gases. Fumaroles often deposit solid minerals (volcanic sublimate) near the vent. Deposits of native sulfur, realgar and orpiment may form in this way.

Geysers. Fountains of hot water ejected periodically are called *"geysers"*. Geysers often rise to heights of 30 - 60 meters. After the jet of water ceases, a column of steam rushes out, usually with a thundering roar. One of the best known geyser areas in the world is Yellowstone National Park (U.S.A.). Geysers are also found in other parts of the world, including New Zealand and Iceland. The siliceous deposits formed around geysers are known as *"geyserite"*.

Mud Volcano. In this case hydrocarbon gases, muddy saline water and some traces of petrolium are discharged from cones of dried mud. Mud volcanoes usually occur near oil fields and they do not appear to show any connection with the actual volcanic activity.

2.56. VOLCANIC ACTIVITY AND PLATE TECTONICS

According to the plate tectonic theory, there are three principal zoues of volcanic activity : (*i*) spreading centres, (*ii*) subduction zones, and (*iii*) regions within the plates themselves. Let us first study the origin of magma and its relation to plate tectonics.

2.56.1. Origin of Magma

(*i*) **Basaltic Magma.** Most basaltic magma is believed to originate in partially molten asthenosphere at depths exceeding 200 kms. Since magma is lighter than the surrounding rock, it has a tendency to rise.

(*ii*) **Andesitic Magma.** Andesitic magma which is of intermediate composition, is believed to originate mainly by the process of differentiation of basaltic magma. However, the close association of andesitic magma with the subduction zone indicates that it may have formed due to melting of the lithosphere. Lithosphere contains layers of sediment over basalt. It can yield a magma of andesitic composition on partial melting. The volcanic Andes Mountains of South America are thought to have formed in this way.

(*iii*) **Rhyolitic Magma.** Rhyolitic lavas erupt only from volcanoes located on continental crust. This magma is believed to have formed due to remelting of the continental crust.

2.56.2. Volcanic Activity at Spreading Centre

Greatest volcanic extrusions occur at mid oceanic ridges where sea floor spreading is active. As the lithosphere moves apart, basaltic magma rises from the asthenosphere and fills the gap. Many successive eruptions, sometimes produce a volcanic cone which may rise above sea level.

2.56.3. Vocanic Activity at Subduction Zone

In convergent zones, oceanic crust is being subducted and melted. The andesitic magma thus generated moves upward and builds a volcanic arc adjacent to the trench. This chain of volcanoes subsequently develops into an island arc.

The present day island arc systems contain igneous rocks of mostly andesitic to granitic composition. Magma of this composition often produces explosive eruptions. Hence some of the most violent volcanic activity has been associated with island arc systems.

The composition of the intermediate igneous rocks that form an island arc, resembles closely with the average composition of continental crust. Thus a developing island arc is a site where new continental crust is being generated from the material of the asthenosphere. This idea can be explained as follows.

(*i*) Partial melting of the asthenosphere produces basaltic magma. On solidification it forms new oceanic crust at the mid oceanic ridges.

(*ii*) The newly formed crust is continually pushed away by the process of sea floor spreading. Ultimately it reaches a trench where it is subducted and partially melted thereby producing the felsic magma.

(*iii*) The felsic magma rises up and forms island arc systems.

Since the continental rocks are less dense than the underlying material, they remain afloat for ever. This means that continental crust appears to be growing larger at the expense of oceanic crust.

2.56.4. Intraplate Volcanic Activity

Volcanism that occurs on continents away from plate boundaries is the most difficult to explain. Some of the volcanic activity that has occurred within a continent may be associated with a spreading centre which is in the most initial stage of growing. The rift zone in Africa is considered to be the beginning stage of such a breakup.

REVIEW QUESTIONS

1. Distinguish between weathering and erosion. Describe the various processes of weathering.
2. What is weathering? Enumerate the various mechanisms of rock weathering. Describe chemical weathering in detail. Discuss the importance of weathering in civil engineering.
3. Discuss the geological work of wind in respect of erosion, transportation and deposition.
4. How do the rivers cause erosion, transportation and deposition? Give the erosional and depositional landforms made by rivers.
5. Give a short account of geological action of streams. Enumerate salient characters of youth, mature and old stages of rivers.
6. Compare the geological work done by a river with that of a glacier. Explain the formation of ox-bow lakes.
7. Discuss briefly the geological work of a mountain glacier. Add a note on the topographic features developed by glacial erosion.

8. Describe the processes involved in glacial erosion. List the important erosional and depositional features of a glacier. Describe briefly the deposional features.
9. Describe the chief characters of Eolian, Alluvial and Glacial deposits. Discuss moraines in detail.
10. How do the sea waves cause erosion and transportation? Describe briefly the erosional and depositional features of the sea.
11. Describe in brief the geological work of sea with a note on the coast protection.
12. Write notes on any four of the following.

    (*i*) Sand dunes, (*ii*) Loess, (*iii*) Ox-bow lakes, (*iv*) River piracy, (*v*) Buried valleys, (*vi*) Moraines, (*vii*) Coral reefs, (viii) Artesian well, (ix) Exfoliation.
13. What is ground water? Describe the various erosional and depositional features of the ground water.
14. Differentiate between unconfined and confined aquifers. Describe the zones of underground water.
15. What is specific yield and specific retention? Write an explainatory note on the pumping of wells?
16. What is an earthquake? Discuss causes of earthquakes. Describe in brief the nature of various earthquake waves.
17. Define the terms *"focus"* and *"epicentre"* in context of earthquakes. How can the epicentre be located if the data at three seismological stations are known?
18. What is meant by intensity and magnitude of an earthquake? How is the magnitude measured? Add a not on the seismic belts of the world.
19. Discuss and describe the causes of earthquakes. What information does the seismic waves provide with regard to the interior of the earth?
20. How does the distribution of earthquake's foci correlate with the three types of plate boundaries? What precautions should generally be taken while doing construction in the earthquake effected areas.
21. What are volcanoes? Explain the nature of fissure and central eruptions. Give the distribution of volcanoes on the earth.
22. What are volcanoes and how are they produced? Describe briefly the products of volcanic eruption.

3 Minerals

3.1. INTRODUCTION

A *"mineral"* is a naturally occurring homogeneous substance which has a more or less definite chemical composition and definite atomic structure. The minerals are usually formed by inorganic processes. They possess a set of constant physical properties. Since the determination of atomic structure and chemical composition requires complex laboratory tests, the more easily recognized physical properties are used in the identification of minerals in the field.

The minerals may be divided into two broad groups : (*i*) rock-forming minerals, and (*ii*) oreforming minerals. *"Rockforming minerals"* are those which are found in abundance in the rocks of the earth's crust. *"Oreforming minerals"* are those which are of economic value and which do not occur in abundance in rocks.

Table 3.1. Mineral Groups

S. No.	*Mineral Groups*	*Examples*
1.	Oxides	Quartz, Magnetite, Hematite, Limonite etc.
2.	Silicates	Felspars, Mica, Hornblende, Augite, Olivines etc.
3.	Carbonates	Calcite, Dolomite, Siderite etc.
4.	Sulfides	Pyrites, Galena, Sphalerite etc.
5.	Sulfates	Gypsum etc.
6.	Chlorites	Rocksalt etc.

Over 2000 minerals are known to exist but most of them are rare. The minerals which occur in common rocks are small in number. They are about 29. It is also interesting to note that only eight elements compose the bulk of these minerals and about 98% of the continental crust. These eight elements are oxygen, silicon, aluminium, iron, calcium, potassium, sodium, and magnesium. Out of these, two most abundant elements are silicon and oxygen which combine to form the mineral group known as the *"silicates"*. The minerals which occur in common rocks can be divided into six groups as shown in Table 3.1.

3.2. PHYSICAL PROPERTIES

The physical properties of minerals can be determined readily by inspection or by simple tests. Because the physical properties are determined in hand specimens, they are important in the recognition of minerals in the field. The chief physical properties are colour, streak, lustre, hardness, habit, cleavage, fracture, odor, feel, tenacity, fluorescence, phosphorescence, magnetism, specific gravity and crystal forms. Crystal forms are described in detail in Chapter 4.

The correct identification of minerals is made with the help of a 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 minerals are identified. Opaque minerals, such as ores, are studied under the ore-microscope in the reflected light. The optical properties of minerals are discussed in the later part of this Chapter.

3.2.1. Colour

Colour of a mineral is due to absorption of certain wave lengths of light by atoms making up the crystal. The remaining wave lengths of white light that are not absorbed give rise to the colour seen by the observer. Thus dark coloured minerals absorb most of the light whereas red minerals reflect or transmit mainly the red light and absorb all others.

Some minerals possess characterstic and fairly constant colour, for example, the lead-grey of galena, brass-yellow of pyrite and green of chlorite. But in other cases, such as quartz, the colour is variable and can not be relied on as a guide to identify minerals.

Presence of small amounts of impurities can give a variety of colours to a white or colourless mineral. For example, the colour of amethyst and rose-quartz is due to the presence of titanium or magnanese in traces. The most common colouring impurity is hematite. It imparts red color to many minerals including some felspar, calcite and jasper.

Some minerals when viewed in different directions show irregular changes in colour tints. This is called *"play of colour"*. The term *"opalescence"* is applied to minerals which show milky appearance, for example, opal.

When bands of prismatic colours are seen on the surface of a mineral, it is said to show *"iridescence"*.

3.2.2. Streak

The colour of the mineral powder is called *"streak"*. It is more consistent and reliable than the body colour of the mineral. The streak is obtained by rubbing a mineral against an unglazed porcelain plate, called the *"streak plate"*. The study of streak is most useful in case of coloured minerals which often give a much lighter streak than their body colour. For example, hematite which appears almost black, gives a red coloured streak. However the streak is less useful for identifying most of the silicates, carbonates, and transparent minerals because they give white streak.

3.2.3. Lustre

Lustre is a very characterstic and useful property of minerals. It is a measure of the reflectivity of the mineral surface. The *"lustre"* may be defined as the general appearance of a mineral surface in reflected light. The various types of lustre are as follows.

1. **Metallic Lustre.** Minerals which have the appearance of a metal, are said to have a *"metallic lustre"*, *e.g.* pyrite and galena.
2. **Submetallic Lustre.** The feebly displayed metallic lustre is called the *"submetallic lustre"*, *e.g.* chromite and hematite.
3. **Adamantine Lustre.** A hard brilliant lustre like that of a diamond, is called *"adamantine lustre"*. It is due to the mineral's high index of refraction, *e.g.* transparent cerussite.
4. **Vitreous Lustre.** It is the lustre exhibited by the broken glass, *e.g.* quartz.
5. **Pearly Lustre.** It is the lustre exhibited by the pearls, *e.g.* muscovite, talc and calcite.
6. **Silky Lustre.** It is the lustre exhibited by the silk fibres. Minerals which crystallize in fibrous habit commonly show silky lustre, *e.g.* asbestos and fibrous gypsum.
7. **Resinous Lustre.** It is the lustre exhibited by the resin, *e.g.* sphalerite.
8. **Greasy Lustre.** It is the lustre exhibited by the grease, *e.g.* talc and nephaline.
9. **Dull or Earthy Lustre.** Minerals showing no lustre are said to possess dull or earthy lustre, *e.g.* kaolin.

3.2.4. Hardness

Hardness is one of the most useful diagnostic properties of a mineral. It is defined as the resistance of a mineral to abrasion or scratching. Hardness is determined by rubbing a mineral of unknown hardness against one of known hardness. A numerical value is obtained by using the *"Mohs scale of hardness"* (Table 3.2). In this scale there are ten minerals which are arranged in the order of their increasing hardness.

Table 3.2. Mohs Scale of Hardness

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

In the absence of hardness testing minerals, the following materials may be used to determine approximate hardness. (*i*) A finger nail will scratch up to about 2.5 (*i.e.* not calcite). (*ii*) A window glass will scratch up to about 5 (*i.e.* not felspar). (*iii*) A penknife will scratch up to about 6.5 (*i.e.* not quartz).

3.2.5. Habit

"Habit" of a mineral may be defined as the size and shape of the crystals, and the structure or form shown by the crystal aggregates and cryptocrystalline masses. The chief habits shown by minerals are as follows.

1. **Accicular.** Minerals showing needle like crystals, for example, natrolite [*Fig. 3.1 (g)*].
2. **Fibrous.** Minerals showing an aggregate of long thin fibres, for example, asbestos and satinspar.
3. **Foliated.** Minerals with platy habit commonly occur as foliated aggregates containing thin separable sheets, for example, muscovite and biotite [*Fig. 3.1 (b)*].
4. **Bladed.** Minerals showing bladed habit occur as small knife blades, for example, kyanite [*Fig. 3.1 (d)*].
5. **Tabular.** Minerals showing broad flat surfaces, for example, felspar [*Fig. 3.1 (a)*].
6. **Columnar.** Minerals showing columnar crystals, for example, tourmaline [*Fig. 3.1 (c)*]. The term *"stalactitic"* refers to columnar forms of minerals, such as calcite and aragonite.

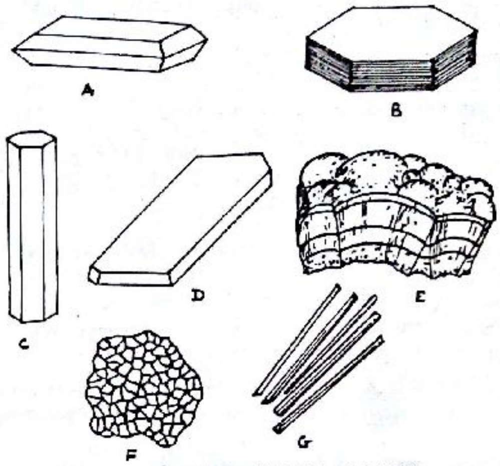


Fig. 3.1. Mineral habits. (*a*) Tabular, (*b*) Foliated, (*c*) Columnar, (*d*) Bladed, (*e*) Botryoidal, (*f*) Granular, (*g*) Accicular.

7. **Botryoidal.** Minerals showing aggregate of rounded masses resembling bunch of grapes, *e.g.* chalcedony [*Fig. 3.1 (e)*].
8. **Reniform.** Minerals showing kidney shaped form, *e.g.* kidney-iron-ore.
9. **Granular.** Minerals which occur as aggregate of equidimensional grains, for example chromite [*Fig. 3.1 (f)*].
10. **Pisolitic.** Minerals which occur as aggregate of rounded grains of a pea size, for example bauxite.
11. **Oolitic.** Minerals showing an aggregate of bodies resembling fish roe. In this case the rounded grains are of the size of a small pinhead.
12. **Massive.** When noncrystalline or cryptocrystalline minerals occur as structureless mass, their habit is described as *"massive"*, for example, flint.

3.2.6 Cleavage

If a mineral breaks along a flat plane, it is said to possess a cleavage, if it breaks with an irregular surface, it is said to show a fracture. Thus the *"cleavage"* may be defined as the tendency of a mineral to break more easily with smooth surfaces along planes of weak bonding. Hence cleavage is the property which is related to the atomic arrangement within the mineral. Because the cleavage always occurs parallel to a possible crystal face, it is designated in terms of the crystal face to which it lies parallel, such as cubic, octahedral, prismatic, basal and so on. For example, galena has cubic cleavage, fluorite has octahedral cleavage, mica has basal cleavage and calcite has rhombohedral cleavage.

Depending on the ease with which a crystal cleaves and the perfection of the surface obtained, the cleavage is classified as *"perfect"*, *"good"*, *"poor"* and *"indistinct"*. Examples of minerals which show perfect cleavage are mica, galena, calcite and fluorite. Quartz has no cleavage at all.

3.2.7. Fracture

Minerals which do not exhibit cleavage, break with an irregular surface. The nature of this broken surface is called *"fracture"*. In case of fracture, the breaking should be in any other direction than the cleavage. Unlike cleavage, the fracture do not produce smooth surfaces. The common types of fracture are as follows.

1. **Conchoidal Fracture.** It is a curved fracture surface showing concentric lines like a shell. Quartz and glass show conchoidal fracture.
2. **Even Fracture.** It is a fracture surface which is almost flat. Flint shows even fracture.
3. **Uneven Fracture.** It is a fracture surface which is irregular and rough. A large number of minerals show uneven fracture.
4. **Hackly Fracture.** It is a fracture surface which is rough with sharp and jagged points. Native metals show hackly fracture.

3.2.8. Odor

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

1. **Arsenical.** The arsenical odor is like the odor of garlic. Orpiment and other arsenic minerals give arsenical odor.
2. **Sulfurous.** This odor is like the odor of burning sulfur. Pyrite gives sulfurous odor.
3. **Argillaceous.** This odor is like the odor of clay. Kaolin gives argillaceous odor.

3.2.9. Feel

Feel is the sensation upon touching or handling minerals. The different types of feel are *"greasy"*, *"soapy"*, *"rough"* and *"harsh"*. The example of greasy feel is talc, that of soapy feel is kaolin and that of rough feel is bauxite.

3.2.10 Tenacity

Tenacity of mineral denotes the degree or character of cohesion. Tenacity is classified as follows.

1. **Sectile.** Minerals which may be cut with knife but slices are not malleable.

2. **Malleable.** Minerals which flatten under the hammer.
3. **Flexible.** Minerals which may be bent.
4. **Elastic.** Minerals which spring back after bending.
5. **Brittle.** Minerals which break easily. Brittle is the opposite of tough.
6. **Friable.** Minerals which crumble easily.
7. **Pulverulent.** Minerals which are powdery and have little or no cohesion, *e.g.* clay or chalk.

3.2.11. Fluorescence

Some minerals when exposed in sunlight or ultraviolet light, produce a colour quite different from their own. Thus green or colourless fluorite shows a blue or purple colour in ultraviolet light. This property of minerals is called *"fluorescence"*. The other minerals which often show fluorescence are calcite and scheelite.

3.2.12. Phosphorescence

Some minerals glow and emit light when they are placed in ultraviolet light or certain other electrical radiation. The glow induced in the mineral may continue for a few seconds or minutes after the removal of the cause. This property of minerals is called *"phosphorescence"*. The examples of minerals which show phosphorescence are diamond and sphalerite.

3.2.13. Magnetism

A few minerals are attracted by a magnet. Of these minerals magnetite and pyrrhotite are the most common examples. The magnetite that possesses attracting power and polarity is called *"lodestone"*.

3.3. SPECIFIC GRAVITY

"Specific gravity" is a number which represents the ratio of the weight of a mineral to the weight of an equal volume of water. Thus a mineral with specific gravity 4.0 is four times as heavy as water. The specific gravity of common silicate minerals is about 2.65 and those of ore minerals varies between 4.5 to 10.0. A rough estimate about the specific gravity of minerals can be made by hefting them in our hand.

3.3.1. Determination of Specific Gravity

The common methods of determining specific gravity of solids are based on the fact that the loss in weight of a body immersed in water, is the weight of an equal volume of water. If W_1 is the weight of the mineral in air and W_2 its weight in water, its specific gravity will be as under.

$$\text{Specific Gravity} = \frac{W_1}{W_1 - W_2}$$

Walker's Steel Yard. Walker's steel yard is an instrument which is mainly used for determining the specific gravity of comparatively large mineral specimens. This instrument consists of a graduated long horizontal beam of steel which is supported near one end on a knife edge as shown in *Fig. 3.2*. At the end of the longer arm, a vertical post is placed. It bears an index mark which helps in aligning the beam in the horizontal position.

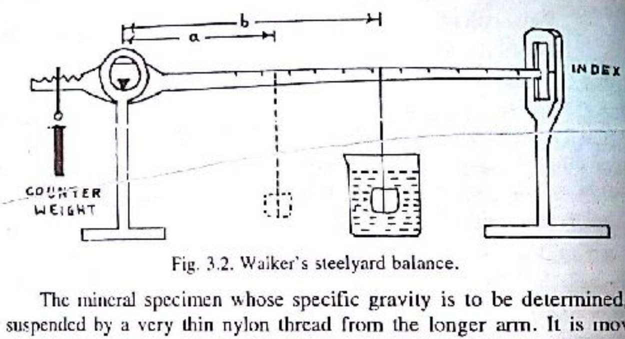


Fig. 3.2. Walker's steelyard balance.

The mineral specimen whose specific gravity is to be determined, is suspended by a very thin nylon thread from the longer arm. It is moved along the graduated arm so as to bring the end of the arm opposite the fixed index mark and the position of the specimen on the arm is noted. Let us assume that the reading is 'a'.

Now the specimen is submerged under water. This is done by placing a beaker filled with water below the specimen. This will disturb the balance. The specimen is then moved away from the fulcrum unitll the beam again comes opposite the index mark. Les us assume that the new reading is now 'b'. The specific gravity of the mineral is calculated as follows.

$$\text{Specific Gravity} = \frac{b}{b-a}$$

It may be noted that there is a "*counter weight*" on the shorter arm. This weight can be shifted from one notch to another on this arm, but it must remain in the same notch during any one experiment.

Jolly's Spring Balance. The specific gravity of small fragments of a mineral is determined by the Jolly's spring balance. The instrument consists of a weak spring suspended vertically against a graduated mirror scale. Two pans, one below the other as shown in *Fig. 3.3*, are attached to the lower end of the spring. The lower pan is always immersed in water. The initial reading "a" of the pointer on the scale is taken without putting anything on the pans. A small piece of mineral whose specific gravity is to be determined, is placed on the upper pan and the second reading "b" is taken. The specimen is then transferred to the lower pan and the third reading "c" is noted. The specific gravity of the mineral is determined as follows.

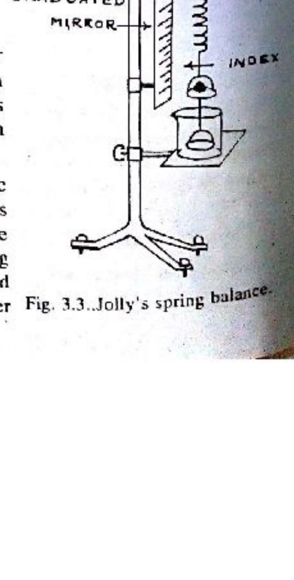


Fig. 3.3. Jolly's spring balance.

$$\text{Specific Gravity} = \frac{(b-a)}{(b-c)}$$

3.4. CHEMICAL PROPERTIES OF MINERALS

Each mineral has a crystalline structure and almost a definite chemical composition. The properties which are related directly to the chemical composition of minerals are isomorphism, polymorphism and pseudomorphism.

3.4.1. Isomorphism

When variations in chemical composition take place in any one mineral structure, the phenomena is called "*isomorphism*". A group of minerals related in this manner form an "*isomorphus series*". These minerals show a continuous variation in their chemical composition but their crystal structure remains almost the same. The plagioclase felspars which are a group of triclinic minerals, provide an example of isomorphism. In these minerals there is the continuous substitution of ($Na + Si^{4+}$) for ($Ca^{2} + Al^{3}$) from anorthite, $CaAl_2Si_2O_8$, to albite, $Na\ Al\ Si_3O_8$.

3.4.2. Polymorphism

The ability of a specific chemical compound to crystallize with more than one type of structure, is known as "*polymorphism*". In this case, each crystal form gives rise to a separate mineral species. Such minerals which have identical chemical composition but different atomic structure are called "*polymorphs*". For example, polymorphs of carbon are graphite and diamond, and of $Ca\ Co_3$ are calcite and aragonite.

3.4.3. Pseudomorphism

If a mineral exists with the outward form of another mineral species, the phenomena is called "*pseudomorphism*". Mineral pseudomorphs are formed when one mineral is replaced by another without any change in the outer form of the original mineral. Thus the chemical composition and structure of a pseudomorph belongs to one mineral species whereas the crystal form corresponds to another. A common example of pseudomorph is a piece of fossil-wood where wood fibres have been replaced by silica. Another example is quartz (SiO_2) after fluorite (CaF_2).

3.5. SILICATE MINERAL STRUCTURES

The silicate mineral group is of great importance because they constitute about 90% of the earth's crust. They are found in all the common rocks except limestones. In order to understand the differences between major silicate mineral groups, it is necessary to study their structure. Every silicate mineral contains oxygen and silicon, and all except quartz, contain one or more additional elements to complete their structure.

The basic unit in all silicate minerals is the *"silicon - oxygen tetrahedron"*. This structure is composed of four oxygen atoms with the silicon atom at its centre (*Fig. 3.4*). These tetrahedra can occur in the silicate structures either as single units or joined into chains, sheets and three dimensional networks by sharing oxygen atoms. Depending upon the type of structure built by these tetrahedra, the silicates are classified into the following groups.

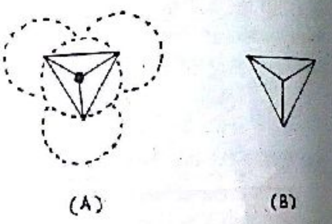


Fig. 3.4. (*a*) The SiO_4 tetrahedron (Four large spheres represent oxygen and dark one represents a silicon atom) (*b*) Diagramatic representation of SiO_4 tetrahedron.

1. **Neosilicates.** Neosilicates include those minerals which are built up from isolated SiO_4 tetrahedra (*Fig. 3.4*). The atomic packing of the neosilicate structure is generally dense which causes the minerals of this group to have relatively high specific gravity and hardness. The crystal habit of these minerals is generally equidimensional and they have poor cleavage. Olivine [$(MgFe)_2SiO_4$], zircon ($ZrSiO_4$) and garnets are the examples of this class.

2. **Sorosilicates.** The sorosilicates are characterized by linked pairs of SiO_4 tetrahedra [*Fig. 3.5 (a)*]. In this structure only one oxygen is shared giving a ratio of Si : O = 2 : 7. Hemimorphite [$Zn_4(Si_2O_7)(OH)_2 \cdot H_2O$] is an example of this class.

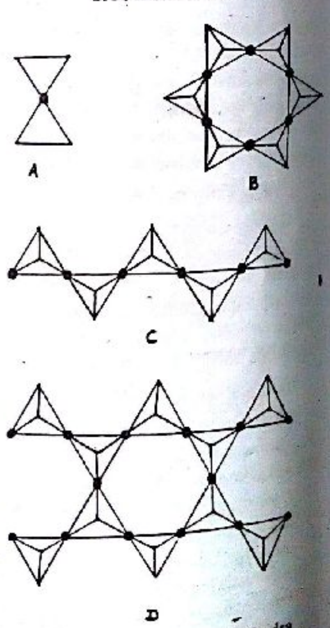


Fig. 3.5. (a) Double tetrahedra structure, (b) Ring structure, (c) Single chain structure, (d) Double chain structure.

3. **Cyclosilicates (Ring Silicates).** The cyclosilicates contain rings of linked SiO_4 tetrahedra having a ratio of Si : O = 1 : 3. These rings may consist of groups of three, four or six linked tetrahedra [*Fig. 3.5 (b)*]. Cyclosilicates form extremely strong minerals, such as beryl and tourmaline.

4. **Inosilicates (Chain Silicates).** In this group SiO_4 tetrahedra are linked by sharing oxygens to form straight chains of indefinite length. These chains may be single chains [*Fig. 3.5 (c)*] or double linked chains [*Fig. 3.5 (d)*]. In the single chain structure two of the four oxygens in each SiO_4 tetrahedron, are shared giving a ratio of Si :O = 1 : 3. In the double chain structure, half of the tetrahedra share three oxygens, while other half share two oxygens yielding a ratio of Si : O = 4 : 11. Inosilicates split easily in one crystal direction because bonds within chains are strong but are weaker between them. These minerals commonly form needle - like crystals, such as asbestos. Pyroxenes are the examples of single chain minerals and amphiboles are the examples of double chain minerals.

5. **Phyllosilicates (Sheet Silicates).** The phyllosilicates form sheet structures in which there is the continuous linking of hexagonal groups of silica tetrahedra (*Fig. 3.6*). In this structure three of the four oxygens in each SiO_4 tetrahedron are shared with neighbouring tetrahedra giving a ratio of Si : O = 2 : 5. As the atomic bonding perpendicular to sheet structure is generally weak, these minerals spilt easily into thin sheets. Flaky minerals, such as micas, chlorite and kaolinite are the examples of this class.

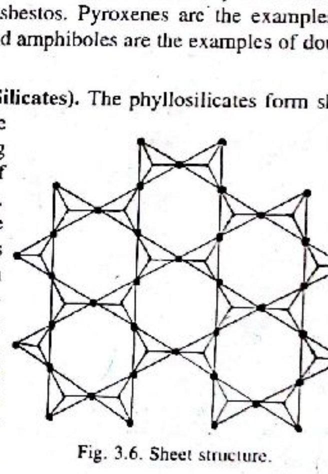


Fig. 3.6. Sheet structure.

6. **Tectosilicates (Framework Silicates).** In tectosilicates SiO_4 tetahedra are linked in three dimensional framework. All oxygens in each SiO_4 tetrahedron are shared with neighbouring tetrahedra. This results in a strongly bonded structure in which the ratio of Si : O is 1 : 2. The minerals belonging to tectosilicate group possess uniform properties throughout. Quartz and felspars are the examples of this class.

3.6. COMMON MINERALS

Silicate minerals are by far the most common rockforming minerals. They constitute about 95% of the earth's crust. The important silicate minerals are felspars, felspathoids, quartz, pyroxenes, amphiboles, micas and olivines. The other minerals which are described here are garnets, chlorite, serpentine, aluminium silicates, calcium minerals and some ore minerals.

3.6.1. Felspar Group

The felspars are the most abundant of all minerals. They fall into two main series : (*i*) K–Na felspars, called the *"alkali felspars"*, and (*ii*) Ca–Na felspars, called the *"plagioclase felspars"*.

All felspars show closely related physical properties. *Cleavage* - **good in two directions at an angle of 90° (approximately).** H – **6.** Sp.gr – **2.55 – 2.63.** *Lustre* – **Vitreous.** *Colour* – **white, grey, pink or green.** *Habit* – **generally tabular.** *Use* – **in the manufacture of porcelain.**

K-Felspars. The important members of this group are *"orthoclase"* and *"microcline"*. Each of these has the composition $KAlSi_3O_8$ but orthoclase crystallizes in the orthorhombic system and microcline in the triclinic system. Potash felspars alter readily into clay minerals, especially *"kaolinite"*.

Plagioclase Felspars. The plagioclase felspars form a complete solution series from pure *"albite"*, $NaAlSi_3O_8$ to pure *"anorthite"*, $CaAl_2Si_2O_8$ (*Fig. 3.7*). The important intermediate members are *"oligoclase"*, *"andesine"*,

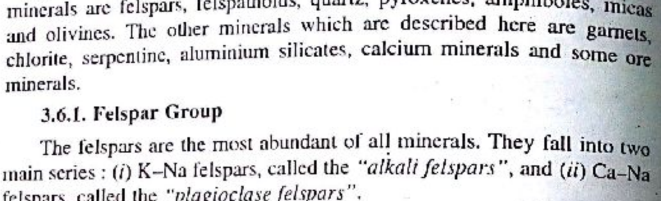


Fig. 3.7. Plagioclase felspar series. Ab–Albite, An–Anorthite.

"labradorite" and *"bytownite"*. The plagioclase felspars crystallize in the triclinic system and are distinguished from K-felspars by the presence of repeated albite twin striations visible on cleavage surfaces. The properties of the various members of the plagioclase series vary in a uniform manner with the change in the chemical composition. The plagioclase felspars usually alter to clay minerals or *"sericite"* (fine grained micaceous material).

Occurrence. (*i*) The alkali felspars which include orthoclase, microcline and albite, have a similar occurrence. They are commonly found in igneous rocks, such as granites, pegmatites, syenites, rhyolites and trachytes. (*ii*) Oligoclase is commonly found in granodiorites and monzonites. (*iii*) Labradorite is a common constituent of gabbros, basalts and anorthosites.

3.6.2. Felspathoid Group

The felspathoids are anhydrous framework silicates. They contain less silica than felspars. The important members of this group are nephaline, leucite and sodalite.

Nephaline : (Na, K) $AlSiO_4$

Crystal system – **hexagonal.** *Cleavage* – **poor.** *H* – **6.** *Sp. gr.* – **2.60 – 2.63.** *Lustre* – **vitreous to greasy.** *Colour* – **colourless, white, gray or yellowish.** *Habit* – **massive.** *Occurrence* – **mostly in nephaline syenites.** *Use* – **in the manufacture of glass and ceramics.**

Leucite : $KAlSi_2O_6$

Crystal system–**cubic (above 625°C) and tetragonal (below 625°C).** *Cleavage*–**very poor.** *H* –**$5\frac{1}{2}$–6.** *Sp. gr.*–**2.47–2.50.** *Lustre*–**vitreous.** *Colour*–**white to grey.** *Habit*–**trapezohedral crystals.** *Occurrence*–**in volcanic rocks only.**

Sodalite : $Na_8(AlSiO_4)_6Cl_2$

Crystal system – **cubic.** *Cleavage* – **poor.** *H* – **$5\frac{1}{2}$–6.** *Sp. gr.* – **2.15 – 2.3.** *Lustre* – **vitreous.** *Colour* – **usually blue, also white, gray, green.** *Habit* – **commonly massive.** *Occurrence* – **with nephaline in nephaline syenites.**

3.6.3. Silica Group

Quartz : SiO_2

Crystal system – **hexagonal.** *Cleavage* – **absent.** *H* – **7.** *Sp. gr.* – **2.65.** *Fracture* – **conchoidal.** *Lustre* – **vitreous.** *Colour* – **colourless, white or with a wide range of tints.** *Habit* – **prismatic crystals or massive.**

The important varieties of quartz are : (*i*) *"Rock crystal"* – Colourless quartz, commonly in distinct crystals. (*ii*) *"Amethyst"* – Transparent quartz with purple colour. (*iii*) *"Smoky quartz"* – Colour in shades of grey or brown. (*iv*) *"Rose quartz"* – Colour a red–rose or pink. (*v*) *"Milky quartz"* – Colour milky white. Cryptocrystalline forms of quartz are : (*a*) *"Chalcedony"* – Waxy lustre and botryoidal from. (*b*) *"Agate"* – A banded variety with layers of chalcedony having different colours. (*c*) *"Jasper"* – Red chalcedony stained by hematite. (*d*) *"Flint"* – Dark gray siliceous nodules. (*e*) *"Chert"* – Light coloured massive quartz. (*f*) *"Opal"* – An amorphous variety of quartz ($SiO_2 \cdot nH_2O$).

Occurrence. Quartz occurs in most igneous, metamorphic and sedimentary rocks. Some sandstones and quartzites are composed almost entirely of quartz. It is also found abundantly as a gangue mineral in mineral veins. Agate occurs in volcanic lavas as cavity filling.

Uses : (*i*) Coloured varieties are used as semiprecious stone.

(*ii*) In the form of sand it is used as construction material.

(*iii*) Quartz is used as a flux or abrasive in industries.

(*iv*) Quartz crystals are used as oscillators in electrical equipments, such as watches.

3.6.4. Pyroxene Group

Pyroxenes form an important group of rockforming minerals. They have a general formula $X_2Si_2O_6$ in which *X* is usually Mg, Fe, Al, Ca, or Na. Some aluminium may partly replace silicon. The common pyroxenes are Ca, Mg and Fe silicates. They are characterized by two cleavages which intersect almost at right angles. Pyroxenes are broadly divided into two groups : (*i*) ortho-pyroxenes, and (*ii*) clino-pyroxenes.

Orthopyroxenes. These pyroxenes crystallize in the orthorhombic system and contain very little calcium. The *"enstatite"* ($MgSiO_3$) and *"hypersthene"* [(Mg, Fe) SiO_3)] belong to this group.

Clinopyroxenes : These pyroxenes crystallize in the monoclinic system and contain either calcium or Na, Al, Fe (ferric) or Li. *"Diopside"*, *"hedenbergite"* and *"augite"* are the important members of this group.

Enstatite : $MgSiO_3$

Hypersthene : (Mg, Fe) SiO_3

Crystal System – **orthorhombic.** *Cleavage* – **good.** *H* – $5\frac{1}{2}$–6, *Sp. gr.* – 3.2–3.6. *Lustre* – **vitreous.** *Colour* – **grayish, yellowish or greenish.** *Habit* – **massive or lamellar.**

Occurrence. Magnesium rich orthopyroxenes are a common constituents of peridotites, gabbros, norites and basalts. They are found associated with augite, olivine and plagioclase. The orthopyroxenes alter to serpentinous products or fibrous amphibole.

Diopside : $CaMgSi_2O_6$

Hedenbergite : $CaFeSi_2O_6$

Augite : (Ca, Na) (Mg, Fe, Al) (Al, Si)$_2$ O_6

Crystal System – **monoclinic.** *Cleavage* – **at 87° and 93°, imperfect.** *H* – **5–6.** *Sp. gr.* – **3.2–3.3.** *Lustre* – **vitreous.** *Colour* – **white to light green in diopside, deepens with increase of iron. Augite is black.** *Habit* – **crystals show square or eight-sided cross-section. Also granular, massive and lamellar.**

Occurrence. Diopside and hedenbergite occur in metamorphic rocks. Augite occurs in gabbros, basalts, diorites and some syenites.

3.6.5. Amphibole Group

The amphibole group includes a number of minerals which have a closely related structure and chemical composition. The amphiboles contain hydroxyl groups in the structure. The angle between two sets of cleavages is 124° and is characterstic of amphiboles. *"Tremolite"* (hydrous silicate of Ca and Mg), *"actinolite"* (hydrous silicate of Ca, Mg and Fe) and *"hornblende"* (hydrous silicate of Na, Ca, Fe and Al) are the important members of amphibole group.

Tremolite : $Ca_2Mg_5Si_8O_{22}(OH)_2$

Actinolite : $Ca_2(Mg, Fe)_5\,Si_8O_{22}(OH)_2$

Crystal System – **monoclinic.** *Cleavage* – **perfect.** *H* – **5–6.** *Sp. gr.* – **3.0–3.3.** *Lustre* – **vitreous or silky.** *Colour* – **white or gray in tremolite and green in actinolite.** *Habit* – **termolite is often bladed and sometimes in silky fibres. Actinolite is often in radiating aggregate. Also fibrous.**

Occurrence. These minerals are commonly found in metamorphic rocks. Tremolite occurs in metamorphosed dolomitic limestones and actinolite is a characterstic mineral of the greenschish facies of metamorphism.

Uses. The fibrous varieties are used as asbestos.

Hornblende : $(Ca, Na)_{2-3}\,(Mg, Fe, Al)_5\,Si_6\,(SiAl)_2\,O_{22}\,(OH)_2$

Crystal System – **monoclinic.** *Cleavage* – **good prismatic.** *H* – **5–6.** *Sp. gr.* **3.0–3.4.** *Lustre* – **vitreous.** *Colour* – **dark green to black.** *Habit* – **crystals with six sided cross–section, also massive or granular.**

Occurrence. Hornblede is an important rockforming mineral. It occurs commonly in syenites and diorites. It is a major mineral of amphibolites.

3.6.6. Mica Group

There are two common varieties of mica : (*i*) *"muscovite"* which is rich in aluminium, and (*ii*) *"biotite"* which is rich in iron and magnesium. The physical properties of both the micas are similar. They crystallize in the monoclinic system and have one perfect basal cleavage. They occur in foliated form and the mineral can be split into thin elastic sheets.

Muscovite : $KAl_2\,(AlSi_3O_{10})\,(OH)_2$

Crystal System – **monoclinic.** *Cleavage* – **perfect basal.** *H* – **2–$2\frac{1}{2}$.** *Sp. gr.* – **2.76 – 2.88.** *Lustre* – **pearly or silky.** *Colour* – **colourless, pale, shade of green and brown. Transparent in thin sheets.** *Habit* – **usually tabular crystals, foliated.**

Occurrence. Muscovite is a characterstic mineral of granites and granite-pegmatite. In pegmatites large crystals of muscovite are found. Muscovite is also common in schists and gneisses.

Uses. Muscovite is widely used for insulation as a dielectric in electrical industry. Ground mica is used as a filler. Muscovite is also used for heat resistant supports and windows.

Biotite : $K(Mg,Fe)_3 (AlSi_3O_{10}) (OH)_2$

Crystal System – monoclinic. *Cleavage* – **perfect basal.** *H* – **2½–3.** *Sp. gr.* – **2.8–3.2.** *Lustre* – pearly or splendent. *Colour* – **dark green, brown to black.** *Habit* – usually in irregular foliated masses.

Occurrence. Biotite is found in granites, syenites, mica-lamprophyres, gneisses and schists.

3.6.7. Olivine Group

This group includes a series of minerals that crystallize in the orthorhombic system. These minerals range in composition from *"forsterite"* Mg_2SiO_4 to *"fayalite"*, Fe_2SiO_4. The composition of common olivine is $(Mg, Fe)_2 SiO_4$.

Olivine : $(Mg, Fe)_2 SiO_4$

Crystal System – **orthorhombic.** *Fracture* – **conchoidal.** *H* – **6½–7.** *Sp. gr.* – **3.27–4.37.** *Lustre* – vitreous. *Colour* – **pale, yellow green or olive green.** *Habit* – **granular.**

Occurrence. Olivine occurs mainly in the dark coloured igneous rocks such as gabbro, peridotite and basalt. The rock, dunite is made up almost wholly of olivine. Olivine alters very readily to serpentine.

3.6.8. Garnet Group

The garnets comprise a group of isomorphus minerals with the general formula $X_3Y_2 (SiO_4)_3$, where *x* may be Ca, Mg, Mn or Fe^{2+} and Y may be Al, Cr^{3+} or Fe^{3+}. The common garnets are : (*i*) *"Pyrope"*, $Mg_3Al_2Si_3O_{12}$ (*ii*) *"Almandite"*, $Fe_3Al_2Si_3O_{12}$, (*iii*) *"Spessartite"*, $Mn_3Al_2Si_3O_{12}$ and (*iv*) *"Grossularite"*, $Ca_3Al_2Si_3O_{12}$.

Crystal System – **cubic.** *Cleavage*–**absent.** *Fracture* – **uneven.** *H* – **6½–7½.** *Sp. gr.* – **3.5–4.3.** *Lustre* – **vitreous to resinous.** *Colour* – **varying with composition. Most commonly red, also brown, yellow or green.** *Streak* – **white.** *Habit* – **dodecahedral crystals common, also granular.**

Occurrence. Garnets occur abundantly in some metamorphic rocks such as mica-schists, hornblende – schists, and gneisses. They also occur as an accessory mineral in some igneous rocks.

Uses. Transparent varieties are used as gem stones. Garnets are also used as an abrasive.

3.6.9. Chlorite Group

The chlorite group includes a number of minerals which have similar physical properties. The important mineral of this group is *"chlorite"*.

Chlorite : $(Mg, Fe,Al)_6 (Al, Si)_4 O_{10} (OH)_8$

Crystal System – **monoclinic.** *Cleavage* – **perfect basal.** *H* – **2–2½.** *Sp. gr.*– **2.6–3.3.** *Lustre* – **vitreous, resinous or dull.** *Colour* – **green of various shades.** *Habit* – **usually foliated masses.**

Occurrence. Chlorite is a common mineral in low grade metamorphic rocks, such as chlorite–schists. In igneous rocks it occurs as an atteration product of pyroxenes, amphiboles and biotite.

3.6.10. Serpentine Group

Serpentine occurs in two distinct forms : (*i*) *"Antigorite"*, a platy variety, and (*ii*) *"Chrysotile"*, a fibrous variety.

Antigorite and Chrysotile : $Mg_3Si_2O_5 (OH)_4$

Crystal System – **monoclinic.** *Cleavage* – **basal in platy variety and none in fibrous crysotile.** *H* – **Variable 3–4.** *Sp. gr.* **2.5–2.6.** *Lustre* – **greasy in the massive varieties, silky in fibrous varieties.** *Colour* – **various shades of green, also brownish.** *Habit* – **lamellar, platy or fibrous (chrysotile).**

Occurrence. Serpentine is usually formed by the alteration of magnesium silicates such as olivine, pyroxene and amphibole. It is found associated with magnesite, chromite and magnetite. Serpentinite is a rock which is made up mostly of the variety antigorite. It is formed by the alteration of olivine bearing rocks.

Uses. Chrysotile variety of serpentine is the chief source of asbestos. Asbestos products are used for fireproofing and as an insulation material against heat and electricity.

3.6.11. Clay Mineral Group

Clays consist mainly of a group of crystalline substances known as the *"clay minerals"*. They are all essentially hydrous aluminum silicates.

Kaolinite : $Al_2Si_2O_5(OH)_4$

Crystal System – **triclinic.** *Cleavage* – **perfect basal.** *H*–**2.** *Sp. gr.* – **2.6.** *Lustre* – **dull earthy.** *Colour* – **white, sometimes brown or gray.** *Streak* – **white.** *Habit* – **clay like masses.**

Occurrence. Kaolinite is a secondary mineral formed by the alteration of alkali felspars. It is the chief constituent of clay.

Uses. (*i*) As a filler in paper. (*ii*) In the manufacture of ceramics.

Talc : $Mg_3Si_4O_{10}(OH)_2$

Crystal System – **monoclinic.** *Cleavage* – **perfect basal.** *H*–**1.** *Sp. gr.* – **2.7–2.8.** *Lustre* – **pearly or greasy.** *Colour* – **white, gray, green or dark brown.** *Streak* – **white.** *Habit* – **usually foliated masses. The compact and massive variety is known as** *"steatite"* **or** *"soapstone"*. *Feel* – **greasy.**

Occurrence. Talc is a secondary mineral formed as a result of the alteration of olivine, pyroxene and amphibole. It is often derived from ultrabasic igneous rocks. It is also found in some schists in association with actinolite.

Uses. (*i*) In talcum powder. (*ii*) As filler in paint, paper and rubber. (*iii*) In ceramics and electrical porcelain.

3.6.12. Al_2SiO_5 Group

The three important members of Al_2SiO_5 group are (*i*) "*Andalusite*", (*ii*) "*Sillimanite*", and (*iii*) "*Kyanite*". These minerals occur in metamorphosed aluminous rocks, such as pelitic schists.

Andalusite : Al_2SiO_5

Crystal System – **orthorhombic.** *Cleavage* – **poor.** *Fracture* – **uneven.** *H*-7½. *Sp. gr.* – **3.16–3.20.** *Lustre* – **vitreous.** *Colour* – **flesh red, reddish brown or olive green.** *Habit* – **prismatic crystals.**

Occurrence. Andalusite occurs typically in thermally metamorphosed argillaceous schists and in regionally metamorphosed rocks formed under low pressure conditions.

Uses. Andalusite is used in the manufacture of porcelains of a high refractory nature.

Sillimanite : Al_2SiO_5

Crystal System – **orthorhombic.** *Cleavage* – **perfect (010).** *H* – **6–7.** *Sp. gr.*– **3.23.** *Lustre* – **vitreous.** *Colour* – **brown, pale, green or white.** *Habit* – **long slender crystals, often in parallel groups, frequently fibrous.**

Occurrence. Sillimanite occurs in schists and gneisses of high grade regional metamorphism.

Kyanite : Al_2SiO_5

Crystal System – **triclinic.** *Cleavage* – **perfect (100).** *HCl*–**5 along length of crystals and 7 at right angles to this direction.** *Sp. gr.* – **3.55 – 3.66.** *Lustre* – **vitreous to pearly.** *Colour* – **usually blue to white, also gray or green.** *Habit* – **crystals usually flat, bladed, also in bladed aggregates.**

Occurrence. Kyanite occurs in regional metamorphic schists and gneisses together with garnet, staurolite, mica and quartz.

Uses. Kyanite is used in the manufacture of refractories.

3.6.13. Miscellaneous Minerals

Beryl : $Be_3Al_2Si_6O_{18}$

Crystal System – **hexagonal.** *Cleavage* – **poor.** *Fracture* – **conchoidal to uneven.** *H* – **8.** *Sp. gr.* – **2.6–2.8.** *Lustre* – **vitreous.** *Colour* – **pale green, bright green, bluish green, yellow or white.** *Habit* – **hexagonal prisms.**

Occurrence. The crystals of beryl occurs in granites, pegmatites, biotite-schists, gneisses and in pneumatolytic hydrothermal veins. Beryl crystals in some pegmatites grow to very large sizes.

Uses. Beryl is the ore of beryllium metal. Transparent varieties are used as gem stones.

Staurolite : $Fe_2Al_9O_6(SiO_4)_4\,(O, OH)_2$

Crystal System – **monoclinic.** *Cleavage* – **distinct.** *Fracture* – **uneven.** *H* – **7–7½.** *Sp. gr.* **3.65–3.75.** *Lustre* – **resinous to vitreous.** *Colour* – **red – brown to brownish black.** *Habit* – **prismatic crystals.**

Occurrence. Staurolite is formed during regional metamorphism of aluminium rich rocks. It occurs commonly as porphyroblasts in schists and gneisses, often in association with garnet, kyanite and mica.

Tourmaline : $Na(Mg, Fe)_3\,Al_6\,(BO_3)_3\,Si_6\,O_{18}\,(OH)_4$

Crystal System – **hexagonal.** *Cleavage* – **very poor.** *Fracture* – **uneven.** *H* – **7–7½.** *Sp. gr.* **3.0–3.25.** *Lustre* – **vitreous to resinous.** *Colour* – **usually black, also brown, dark blue, colourless, pink, green and blue.** *Habit* – **prismatic crystals often with triangular cross-section, parallel or radiating crystal groups common.**

Occurrence. Tourmaline occurs commonly in granite – pegmatites or in some granites which have undergone metasomatism by boron rich fluids.

Uses. The piezoelectric properties of tourmaline are utilized in the manufacture of pressure gauges. The coloured varieties are used as gem stones.

Topaz : $Al_2SiO_4\,(F, OH)_2$

Crystal System – **orthorhombic.** *Cleavage* – **perfect basal.** *H* – **8.** *Sp. gr.* **3.4–3.6.** *Lustre* – **vitreous.** *Colour* – **colourless, yellow, pink, bluish, greenish.** *Habit* – **prismatic crystals, also granular.**

Occurrence. Topaz is found in cavities in granites, granite-pegmatites and high temperature veins, and in a few rhyolites. Topaz is usually associated with cassiterite, tourmaline, fluorite and muscovite.

Uses. Topaz is used as a gemstone.

3.6.14. Calcium Minerals

Calcite : $CaCO_3$

Crystal System – **hexagonal.** *Cleavage* – **perfect.** *H*-**3.** *Sp. gr.* – **2.71.** *Lustre* – **vitreous.** *Colour* – **usually white to colourless. Also gray, red, green, blue, yellow or brown.** *Habit* – **four common forms are tabular, prismatic, rhombohedral and scalenohedral. Besides these fibrous, granular and stalactitic forms are also found.**

Occurrence. The origin of calcite may be igneous as in intrusive carbonatites, sedimentary, such as limestone and metamorphic as in marbles. Calcite is commonly found in metallic ore veins and calcite veins are also found in various rocks.

Uses. The most important use of calcite is for the manufacture of cement and lime. Calcite is also used as a flux in the smelting of ores and as a fertilizer.

Aragonite : $CaCO_3$

Crystal System – **orthorhombic.** *Cleavage* – **distinct.** *Lustre* – **vitreous.** *H*–3½–4. *Sp. gr.* – **2.95.** *Colour* – **colourless, white, pale yellow, gray, rarely green or violet.** *Habit* – **prismatic crystals, also in tabular or stalactitic forms.**

Occurrence. Aragonite is much less common than calcite. It is the main component of shells of may organisms. Aragonite occurs in some sedimentary deposits.

Dolomite : $CaMg(CO_3)_2$

Crystal System – **hexagonal.** *Cleavage* – **perfect rhombohedral.** *H*–3½–4. *Sp. gr.* – **2.85.** *Lustre* – **vitreous to pearly.** *Colour* – **white, yellow, brown, pinkish or colourless.** *Habit* – **crystals show curved faces. Also granular and massive.**

Occurrence. Dolomite occurs as extensive sedimentary beds. It is generally thought to be formed by the replacement of calcium carbonate of limestone by dolomite.

Uses. (*i*) As a building and ornamental stone. (*ii*) In the manufacture of refractory bricks for furnace linings.

Gypsum : $CaSO_4 \cdot 2H_2O$

Crystal System – **monoclinic.** *Cleavage* – **perfect.** *H* – **2.** *Sp. gr.*– **2.32.** *Lustre* – **usually vitreous. Also pearly and silky.** *Colour* – **colourless, white, grey, sometimes yellow, red or brown.** *Habit* – **tabular or prismatic crystals. Also fibrous, foliated granular and massive.** *Varieties*– "*Satinspar*" is a fibrous gypsum with silky lustre. The fine grained massive variety is called "*alabaster*". A variety that yields broad colourless and transparent cleavage folia, is called "*selenite*".

Occurrence. Gypsum occurs as an evaporite deposit. It is also found as a secondary mineral, deposited from percolating groundwater.

Uses. (*i*) For making plaster of Paris, (*ii*) As a fertilizer, and (*iii*) As a filler in various materials.

Anhydrite : $CaSO_4$

Crystal System – **orthorhombic.** *Cleavage* – **perfect.** *H*–3–3½. *Sp. gr.* – **2.89–2.98.** *Lustre* – **vitreous to pearly.** *Colour* – **white, colourless, gray and sometimes bluish or red.** *Habit* – **usually massive, fibrous or granular. Concretionary forms are also found.** *Alteration* – **by hydration anhydrite changes to gypsum with an increases in volume.**

Occurrence. Anhydrite is found in bedded evaporite deposits. Most of the deposits of anhydrite are thought to be secondary after gypsum.

Uses. (*i*) As a fertilizer. (*ii*) For making plaster of Paris and cement. (*iii*) Also in the manufacture of sulfuric acid.

Fluorite : CaF_2

Crystal System – **cubic.** *Cleavage* – **perfect octahedral.** *H* – **4.** *Sp. gr.* – **3.18.** *Lustre* – **vitreous.** *Colour* – **light green, yellow, bluish green or purple. Also colourless white or brown.** *Habit* – **usually cubic crystals. Also massive or granular.**

Occurrence. Commonly found in hydrothermal veins. It is found associated with galena and sphalerite. Fluorite also occurs in pneumatolytic tin veins and in some granites.

Uses : (*i*) As a flux in steel making. (*ii*) For the preparation of hydrofluoric acid.

Apatite : $Ca_5(PO_4)_3(F, Cl, OH)$

Crystal System – **hexagonal.** *Cleavage* – **poor.** *H*–**5.** *Sp. gr.* – **3.15–3.20.** *Lustre* – **vitreous to resinous.** *Colour* – **some shade of green or brown. Also blue, violet or colourless.** *Habit* – **long prismatic crystals, tabular. Also massive or granular.**

Occurrence. Commonly found in all igneous rocks including pegmatites and hydrothermal veins. Apatite is also found in contact and regionally metamorphosed rocks and in sedimentary rocks.

Uses. It is used mainly as a source of phosphate for fertilizer.

3.6.15. Aluminium Minerals

Bauxite : (A mixture of hydrous aluminium oxides)

Crystal System – **bauxite is a mixture of several minerals, such as "gibbsite", "*boehmite*" and "*diaspore*".** *Cleavage* – **none.** *Fracture* – **uneven.** *H* – **2–2.5.** *Lustre* – **dull earthy.** *Colour* – **white, gray, yellow or brown.** *Streak* – **yellow to brown.** *Habit* – **pisolitic. Also massive.**

Occurrence. Bauxite is a secondary product, commonly formed under subtropical to tropical climatic conditions by the leaching away of silica from aluminium – bearing rocks.

Uses. (*i*) As an important ore of aluminium. (*ii*) As a refractory material. (*iii*) As an abrasive material.

Corundum : Al_2O_3

Crystal System – **hexagonal.** *Cleavage* – **absent.** *Fracture* – **uneven.** *H*–**9.** *Sp. gr.* – **4.02.** *Lustre* – **vitreous to adamantine.** *Colour* – **commonly**

bluish gray to brown. Gem varieties are transparent to translucent. "Ruby" is of red colour and *"sapphire"* is of blue of colour. *Habit* – **commonly tabular crystals, also massive or granular (emry).**

Occurrence. Corundum in found in some metamorphic rocks, such as mica-schist and gneiss. It is also found in pegmatites and some nephaline syenites. Gem stones are found in placer deposits.

Uses. Corundum is used as a gem-stone and abrasive.

3.6.16. Iron Minerals

Magnetite : Fe_3O_4

Crystal System – **cubic.** *Cleavage* – **absent.** *H* – **6.** *Sp. gr.* – **5.18.** *Lustre* – **metallic to dull.** *Colour* – **iron–black.** *Streak* – **black.** *Special character* – **strongly magnetic. A natural magnet is called "*lodestone*".** *Habit* – **octahedral crystals, massive or granular.**

Occurrence. Magnetite is a high temperature mineral. It occurs as an accessory mineral in igneous rocks, in contact and regionally metamorphosed rocks, and in high temperature sulfide veins.

Uses. Magnetite is an important ore of iron.

Hematite : Fe_2O_3

Crystal System – **hexagonal.** *Cleavage* – **absent.** *H* – **5–6.** *Sp. gr.* – **5.26.** *Lustre* – **metallic to dull.** *Colour* – **reddish brown to black.** *Streak* – **dark red.** *Habit* – **crystals thin tabular, usually massive. Sometimes in botryoidal forms. It may also be micaceous and foliated.** *Varieties* – red earthy variety is called "*red ocher*". Platy and metallic variety is know as "specularite".

Occurrence. The hematite is found in thick beds of sedimentary origin. It is also found in metamorphosed sediments and contact metamorphic deposits.

Uses. (*i*) Mainly as iron ore. (*ii*) Red ocher is used as pigment.

Goethite : FeO · OH

Crystal System – **orthorhombic.** *Cleavage* – **perfect.** *H* – **5–5½.** *Sp. gr.* **3.3–4.3.** *Lustre* – **adamantine to dull. Silky in fibrous varieties.** *Colour* – **dark brown to yellowish brown.** *Streak* – **yellowish brown.** *Habit* – **elongated prismatic crystals, tabular, massive, stalactitic or radiating fibrous.**

Occurrence. Goethite is a secondary mineral. It is found in the oxidation zone of veins containing iron minerals. It is usually formed by the oxidation of minerals, such a siderite, pyrite and magnetite. Goethite is a principal constituent of limonite.

Uses. Goethite is an important iron ore.

Siderite : $FeCO_3$

Crystal System – **hexagonal.** *Cleavage* – **perfect rhombohedral.** *H*– **3½–4.** *Sp. gr.* – **3.96.** *Lustre* – **vitreous.** *Colour* – **light to dark brown.** *Habit* – **rhombohedral crystals. Also massive, granular, fibrous, botryoidal and earthy.**

Occurrence. Massive siderite occurs as large sedimentary deposits. It also occurs as replacement deposits formed by the action of ferrous solution on limestones, siderite is also found in hydrothermal metallic veins.

Uses. Siderite is used as an ore of iron.

Pyrite : FeS_2

Crystal System – **cubic.** *Fracture* – **conchoidal.** *H* – **6–6½.** *Sp. gr.* – **5.02.** *Lustre* – **metallic.** *Colour* – **brass yellow.** *Streak* – **greenish or brownish black.** *Habit* – **common forms are the cube which often show striations. Also massive, granular and stalactitic.**

Occurrence. Pyrite is the most common sulfide mineral. It is found in hydrothermal veins, contact metamorphic deposits and as an acessory mineral in sedimentary rocks. It is often associated with chalcopyrite.

Uses. It is used for the manufacture of sulfuric acid.

Pyrrhotite : FeS

Crystal System – **hexagonal.** *Cleavage* – **absent.** *Fracture* – **uneven.** *H*–**4.** *Sp. gr.* – **4.58 – 4.65.** *Lustre* – **metallic.** *Colour* – **bronze yellow tarnishing to brown.** *Streak* – **black.** *Special Character* – **magnetic.** *Habit* – **tabular crystals. Also massive or granular.**

Occurrence. Pyrrhotite is formed by magmatic segregation in basic rocks. It is also found in high temperature sulfide veins and replacement bodies.

Uses. Pyrrhotite is important as it contains nickel in minor amount.

Marcasite : FeS_2

Crystal System – **orthorhombic.** *Cleavage* – **present.** *H* – **6 – 6½.** *Sp. gr.* – **4.89.** *Lustre* – **metallic.** *Colour* – **pale bronze – yellow.** *Streak* – **grayish black.** *Habit* – **tabular crystals common. Also in stalactitic and radiating forms.**

Occurrence. It occurs as concretions in sedimentary rocks.

3.6.17. Manganese Minerals

Braunite : $(Mn, Si)_2 O_3$

Crystal System – **tetragonal.** *Cleavage* – **perfect.** *Fracture* – **uneven.** *H* –**6–6½.** *Sp. gr.* – **4.75–4.82.** *Lustre* – **submetallic.** *Colour* – **brownish** black to steel gray. *Streak* – **brownish black to steel gray.** *Habit* – **massive, granular.**

Occurrence. Braunite occurs in hydrothermal veins with other manganese oxides. It also occurs with pyrolucite and psilomelane as a secondary mineral.

Uses. As an ore of manganese.

Pyrolusite : MnO_2

Crystal System – tetragonal. *Cleavage* – **perfect.** *H* – **1–2.** *Sp. gr.* – **4.75.** *Lustre* – **metallic to dull.** *Colour and Streak* – **iron black.** *Habit* – **as reniform sooty masses which soil the fingers. Rarely as elongated crystals.**

Occurrence. Pyrolusite appears similar to psilomelane. It is a secondary mineral formed by the alteration of manganite or other primary manganese minerals. It is commonly found associated with braunite, goethite and limonite.

Uses. As an ore of manganese.

Psilomelane : $(Ba^{2+}, Mn^{2+})_3 (O, OH)_6 Mn_8^{4+} O_{16}$

Crystal System – **orthorhombic.** *Fracture* – **uneven.** *H*–**5–6.** *Sp. gr.* – **4.4 – 4.7.** *Lustre* – **submetallic.** *Colour* – **black.** *Streak* – **brownish black, shining.** *Habit* – **massive, botryoidal and stalactitic.**

Occurrence. Psilomelane is a secondary mineral which is formed by the weathering of manganese carbonates or silicates. It occurs usually with pyrolusite.

Uses. An ore of manganese.

Manganite : MnO(OH)

Crystal System – **monoclinic.** *Cleavage* – **perfect.** *H*–**4.** *Sp. gr.* – **4.3.** *Lustre* – **submetallic to dull.** *Colour* – **steel gray to iron black.** *Streak* – **dark brown.** *Habit* – **prismatic crystals, often grouped in bundles. Also columnar.**

Occurrence. Manganite is a low temperature mineral found in hydrothermal veins. It is often associated with pyrolusite, goethite and baryte.

Uses. An ore of manganese.

3.6.18. Copper Minerals

Azurite : $Cu_3 (CO_3)_2 (OH)_2$

Crystal System – **monoclinic.** *Cleavage* – **perfect prismatic.** *H*–**3½–4.** *Sp. gr.* – **3.77.** *Lustre* – **vitreous.** *Colour* – **azure-blue.** *Streak* – **pale-blue.** *Habit* – **crystalline. Also in radiating groups or massive.**

Occurrence. It occurs as a secondary mineral. It frequently alters to malachite.

Malachite : $Cu_2CO_3 (OH)_2$

Crystal System – **monoclinic.** *Cleavage* – **perfect but rarely seen.** *H* – **3½ – 4.** *Sp. gr.* – **3.9 – 4.03.** *Lustre* – **vitreous in crystals, silky in fibrous varieties and dull in massive varieties.** *Colour* – **bright green.** *Streak* – **pale green.** *Habit* – **usually in radiating fibres forming botryoidal or stalactitic masses. Also granular or earthy.**

Occurrence. Malachite is a secondary copper mineral found in the zone of oxidation of copper veins.

Uses. An ore of copper.

Cuprite : Cu_2O

Crystal System – **cubic.** *Cleavage* – **poor.** *Fracture* – **uneven.** *H*–**3½–4.** *Sp. gr.*– **6.14.** *Lustre* – **submetallic.** *Colour* – **dark red.** *Streak* – **brownish red.** *Habit* – **often massive, granular or crystalline.**

Occurrence. Cuprite is found in the upper oxidized portions of copper veins. It is often associated with native copper, malachite and azurite.

Uses. A valuable ore of copper.

Bornite : Cu_5FeS_4

Crystal System – **cubic.** *Cleavage* – **absent.** *Fracture* – **uneven.** *H*–**3.** *Sp. gr.* – **5.06–5.08.** *Lustre* – **metallic.** *Colour* – **copper red, tarnishing to purple iridescent.** *Streak* – **grayish black.** *Habit* – **usually massive.**

Occurrence. Bornite is commonly found in hydrothermal ore deposits.

Uses. An important ore of copper.

Chalcopyrite : $CuFeS_2$

Crystal System – **tetragonal.** *Cleavage* – **poor.** *Fracture* – **uneven.** *H*–**3½–4.** *Sp. gr.* – **4.28.** *Lustre* – **metallic.** *Colour* – **brass yellow.** *Streak* – **greenish black.** *Habit* – **crystals show tetrahedral shape. Also massive and compact.**

Occurrence. Chalcopyrite is the commonest copper mineral. It is found in hydrothermal veins. It is associated with pyrite and other sulfides.

Uses. An important ore of copper.

Chalcocite : Cu_2S

Crystal System – **orthorhombic.** *Cleavage* – **poor.** *Fracture* – **conchoidal.** *H*–**2½–3** *Sp. gr.* – **5.77.** *Lustre* – **metallic.** *Colour and Streak* – **dark gray.** *Habit* – **short prismatic crystals. Also massive.**

Occurrence. Chalcocite is formed by the alteration of primary copper sulfides in zones of secondary enrichment.

Uses. It is an important ore of copper.

Covellite : CuS

Crystal System – **hexagonal.** *Cleavage* – **perfect giving flexible plates.** *H*–1½–2. *Sp. gr.* – 4.6–4.76. *Lustre* – **metallic, massive varieties dull.** *Colour* – **indigo blue.** *Streak*—**dark gray, shining.** *Habit* – **platy crystals, usually massive.**

Occurrence. Covellite is found in the zone of sulfide eurichment. It is associated with other copper minerals, such as chalcocite, chalcopyrite, bornite, etc.

Uses. An important ore of copper.

3.6.19. Lead and Zinc Minerals

Galena : PbS

Crystal System – **cubic.** *Cleavage* – **perfect cubic.** *Fracture* – **stepped fracture.** *H*– 2½. *Sp. gr.* – 7.4 – 7.6. *Lustre* – **bright metallic.** *Colour and Streak* – **lead grey.** *Habit* – **often cubic crystals. Also massive.**

Occurrence. Galena is commonly found in hydrothermal sulfide veins associated with sphalerite, pyrite, chalcopyrite, etc. It is also associated with silver minerals.

Uses. An important ore of lead and silver.

Sphalerite : ZnS

Crystal System – **cubic.** *Cleavage* – **perfect.** *Fracture* – **conchoidal.** *H* – 3½ – 4. *Sp. gr.* – 3.9 – 4.1. *Lustre* – **resinous.** *Colour* – **yellow, brown to black.** *Streak* – **brown to yellow.** *Habit* – **crystals occur as tetrahedra. Also massive or fibrous.**

Occurrence. Sphalerite occurs in hydrothermal veins. It is often associated with galena and other sulfides.

Uses. Principal ore of zinc.

3.6.20. Miscellaneous Ores

Chromite : $FeCr_2O_4$

Crystal System – **cubic.** *Cleavage* – **absent.** *Fracture* – **uneven.** *H*–5½. *Sp. gr.* – 4.6. *Lustre* – **metallic to submetallic.** *Colour* – **black.** *Streak* – **dark brown.** *Habit* – **commonly massive or granular.**

Occurrence. Chromite occurs in igneous rocks such as peridotites and other ultrabasic rocks and in serpentines derived from them. It is also found in alluvial deposits.

Uses. (*i*) As an ore of chromium. (*ii*) As refractory material.

Ilmenite : $FeTiO_3$

Crystal System – **hexagonal.** *Cleavage* – **absent.** *Fracture* – **conchoidal.** *H*–5½–6. *Sp. gr.* – 4.7. *Lustre* – **metallic to dull.** *Colour* – **iron-black.** *Streak* – **black.** *Habit* – **thick tabular crystals, often massive or as sand grains.**

Occurrence. Ilmenite occurs as an accessory mineral in igneous rocks such as gabbros, diorites and anorthosites. It is also found in ore veins and pegmatites. Beach sands may also contain ilmenite.

Uses. As an ore of titanium.

Monazite : (Ce, La, Th) PO_4

Crystal System – **monoclinic.** *Cleavage* – **poor.** *Fracture* – **uneven.** *H*–5–5½. *Sp. gr.* – **4.6–5.4.** *Lustre* – **resinous.** *Colour* – **yellowish brown or reddish brown.** *Streak* – **white.** *Habit* – **as granular masses and as sand.**

Occurrence. Monazite occurs as an accessory mineral in granites and gneisses. It gets concentrated in alluvial sands which are the chief source.

Uses. A principal source of thorium, cerium and other rare earths.

Barytes : $BaSO_4$

Crystal System – **orthorhombic.** *Cleavage* – **perfect.** *H*–3–3½. *Sp. gr.* – 4.5. *Lustre* – **vitreous.** *Colour* – **colourless, white, yellowish, gray, pale-green, red and brown.** *Streak* – **white.** *Habit* – **usually tabular crystal. Also fibrous, lamellar and granular.**

Occurrence. Barytes commonly occurs as a gangue mineral in metalliferous hydrothermal veins. In sedimentary rocks, it occurs as veins and concretions.

Uses. Barytes is mainly used as a drilling mud for oil and gas wells. It is also used for making paints.

Magnesite : $MgCO_3$

Crystal System – **hexagonal.** *Cleavage* – **perfect.** *Fracture* – **conchoidal or uneven.** *H*–3½–4. *Sp. gr.* – **3.0–3.2.** *Lustre* – **vitreous or earthy.** *Colour* – **white, colourless, gray, brown or yellow.** *Streak* – **white.** *Habit* – **usually massive, fibrous or granular.**

Occurrence. Magnesite is formed by the replacement of limestones by solutions containing magnesium. It is also formed by the action of carbonate rich solutions on rocks containing magnesium minerals.

Uses. For making cement, refractory bricks and crucibles.

Molybdenite : MoS_2

Crystal System – **hexagonal.** *Cleavage* – **perfect.** *H*–1–1½. *Sp. gr.* – 4.7. **Lustre** – **metallic.** *Colour* – **lead gray.** *Streak* – **greenish gray.** *Habit* – **tabular crystals, foliated, massive or scaly.**

Occurrence. In small amounts it occurs in granites and pegmatites. It also occurs in deep-seated hydrothermal veins where it is associated with scheelite, wolframite, topaz and fluorite.

Uses. An ore of molybdenum which is widely used as an alloy in steels.

Cinnabar : HgS

Crystal System – **hexagonal.** *Cleavage* – **perfect.** H–2–2½. *Sp. gr.* – **8.09.** *Lustre* – **crystals adamantine, massive varieties dull.** *Colour* – **scarlet, brownish red.** *Streak* – **red.** *Habit* – **crystals rhombohedral or tabular. Also granular and massive.**

Occurrence. Cinnabar is a low temperature mineral which is found in hydrothermal deposits in volcanic regions. It is also deposited in hot springs. Cinnabar is found associated with pyrite, chalcopyrite, realgar and stibnite.

Uses. Cinnabar is the chief ore of mercury.

Arsenopyrite : FeAsS

Crystal System – **monoclinic.** *Cleavage* – **poor.** *Fracture* – **uneven.** *H*–5½–6. *Sp. gr.* – **5.9–6.2.** *Lustre* – **metallic.** *Colour* – **silver white to gray white.** *Streak* – **grayish black.** *Habit* – **prismatic crystals with striations. Also massive or granular.**

Occurrence. Arsenopyrite is the most abundant arsenic mineral. It occurs with tin and tungsten ores in high temperature hydrothermal deposits.

Uses. Arsenopyrite is the principal source of arsenic.

Realgar : AsS

Crystal System – **monoclinic.** *Cleavage* – **good.** *Fracture* – *uneven.* *H*–1½–2. *Sp. gr.* – **3.48.** *Lustre* – **resinous.** *Colour and Streak* –**red – orrange.** *Habit* – **short prismatic crystals, granular or massive.**

Occurrence. Realgar is found in low temperature, hydrothermal deposits. It is found associated with orpiment, stibnite and other arsenic minerals.

Uses. An ore of arsenic.

Orpiment : As_2S_3

Crystal System – **monoclinic.** Cleavage – **perfect.** *H*–1½–2. *Sp. gr.* – **3.49.** *Lustre* – **resinous to pearly.** *Colour* – **lemon-yellow.** *Streak* – **pale yellow.** *Habit* – **usually foliated or granular.**

Occurrence. Orpiment is a rare mineral. It is found associated usually with realgur.

Uses. It is used in dyeing.

Stibnite : Sb_2S_3

Crystal System – **orthorhombic.** *Cleavage* – **perfect.** *H*–2. *Sp. gr.* – **4.52–4.62.** *Lustre* – **metallic.** *Colour and Streak* – **lead gray.** *Habit* – **often in radiating crystal groups.**

Occurrence. Stibnite is found in low temperature hydrothermal veins or replacement deposits and in hot spring deposits. It is usually associated with realgar, orpiment, galena, pyrite and cinnabar.

Uses. As an ore of antimony.

Wolframite : (Fe, Mn) WO_4

Crystal System – **monoclinic.** *Cleavage* – **perfect.** *Fracture* – **uneven.** *H*– 4–4½. *Sp. gr.* – **7.25–7.6.** *Lustre* – **resinous, metallic or submetallic.** *Colour and Streak* – **reddish-brown to brownish-black.** *Habit* – **short prismatic crystals, often massive.**

Occurrence. Wolframite occurs in quartz veins and pegmatites. In granites it is found associated with cassiterite, scheelite, etc. It also occurs in some alluvial deposits where it has been concentrated by water action.

Uses. It is the chief ore of tungsten.

3.7. OPTICAL PROPERTIES

Optical properties of minerals are important for their identification. Optical properties are determined with the help of *"polarising microscope"*.

Ordinary Light. Ordinary light travels in straight lines with a transverse motion. It vibrates in all directions at right angles to the direction of propogation.

Polarized Light. When the vibrations of the wave motion is confined to a single plane only, the light is called *"polarized light"* (*Fig. 3.8*). The plane along which such vibrations take place is called *"plane of polarization"*.

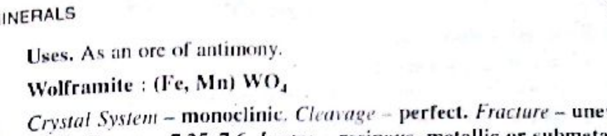


Fig. 3.8. Polarization of light.

There are three ways by which the polarized light can be obtained : (*i*) by double refraction, (*ii*) by absorption, and (*iii*) by reflection. Nicol prisms and Polaroids are used in the microscopes to produce polarized light.

3.8. REFRACTIVE INDEX

When a ray of light passes from air into a denser medium such as glass, it gets refracted. In the glass the light travels with a lesser velocity than in air and deviates from its previous path. The amount of deviation depends on the angle of incidence and the relative velocity of light in the two media.

The refractive index (n) of a mineral can be expressed as a ratio of the velocity of light in the air (V_1) and its velocity in the mineral (V_2).

$$n = \frac{V_1}{V_2}$$

The velocity of light in air is generally considered equal to 1, therefore, n becomes equal to $1/V_2$. This shows that the refractive index of a mineral varies inversely with the velocity of light in it.

For a perticular mineral, the relationship between the angle of incidence (i) and the angle of refraction (r) is given by Snell's law. This law states that the ratio of sine of incident angle to the sine of the refracted angle is a constant. This constant is called the refractive index (n) of the mineral. (*Fig. 3.9*).

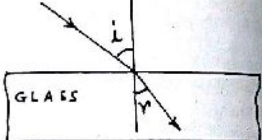


Fig. 3.9. Refracted light.

$$n = \frac{\sin i}{\sin r}$$

3.9. ISOTROPIC AND ANISOTROPIC MINERALS

Depending upon the optical properties, the minerals can be divided into two groups : (*i*) isotropic minerals, and (*ii*) anisotropic minerals.

Isotropic Minerals. In crystals belonging to cubic system, the light travels with the same velocity in all directions and therefore each mineral has only one refractive index. Such minerals are called *"isotropic minerals"*. Noncrystalline substances, such as opal and glass, are also isotropic.

Anisotropic Minerals. The anisotropic group includes all crystals except those of the cubic system. In these crystals the velocity of light and consequently the refractive index varies with the crystallographic direction. Anisotropic minerals generally show double refraction.

3.10. DOUBLE REFRACTION

When a ray of light passes through an anisotropic crystal, it breaks into two polarized rays vibrating in mutually perpendicular planes. One ray which obeys laws of refraction is called *"ordinary ray"* or *"O-ray"*, and the second ray which does not obey these laws, is called *"extraordinary ray"* or *"E-ray"*.

Ordinary Ray. The ordinary ray travels with the same velocity in all directions through the crystal. This ray will, therefore, have a constant refractive index.

Extraordinary Ray. The velocity of this ray changes with the variation of its path through the crystal and therefore, its refractive index also changes.

Birefringence. The difference between the refractive indices of the O-ray and E-ray is called *"birefringence"*. For biaxial crystals, the numerical difference between the greatest and least refractive indices is the birefringence.

Optic Axis. A direction in an anisotropic mineral, along which there is no double refraction, is called *"optic axis"*. The minerals crystallizing in the tetragonal and hexagonal systems have one optic axis and therefore, they are called *"uniaxial"*. The minerals belonging to the orthorhombic, monoclinic and triclinic systems are called *"biaxial"* because they have two optic axes.

3.11. UNIAXIAL MINERALS

The crystals of the tetragonal and hexagonal systems possess only one optic axis which is parallel to the c-axis. For this reason they are called *"uniaxial"*. The optical characters of the uniaxial minerals may be summarized as follows.

1. When a ray of light passes through an uniaxial crystal in any direction other than the optic axis, two polarized rays are produced due to double refraction. These are O-ray and E-ray which vibrate in mutually perpendicular planes and travel with different velocities. The O-ray vibrates in the basal plane and E-ray vibrates in the plane that includes c-axis.
2. The O-ray has a single and constant refractive index ω (omega) whereas refractive index of the E-ray varies with the direction of the crystal section. The refractive index of E-ray becomes maximum in crystal sections parallel to the c-axis and this maximum value is denoted by the symbol γ (gamma). In sections making oblique angles with the c-axis, the refractive index of E-ray varies between limits ω and γ. The difference between the refractive indices of the O-ray and E-ray is called *"birefringence"*.
3. In a section normal to the optic axis, there is no double refraction and the light has only one value of refractive index which is ω. In this direction the crystal behaves as an isotropic substance.

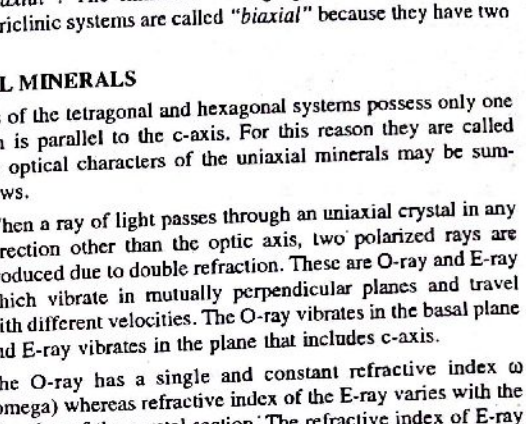


Fig. 3.10. Ray velocity surfaces of uniaxial crystals.

Positive and Negative Crystals. As the O-ray travels with the same velocity in all directions, its surface can be represented by a sphere as shown in *Fig. 3.10*. The surface of E-ray is an ellipsoid of revolution because its velocity varies with the direction. Uniaxial crystals are said to be *"positive"* if velocity of O-ray is greater then E-ray, and *"negative"* if velocity of E-ray is greater (*Fig. 3.10*).

3.12. BIAXIAL MINERALS

Crystals belonging to the orthorhombic, monoclinic and triclinic systems have two optic axes and therefore they are called *"biaxial"*. These optic axes intersect each other to form acute and obtuse angles. The acute angle between the two optic axes is called *"optic axial angle"* and is commonly designated as 2v. The plane containing the two optic axes is called *"optic axial plane"*. The important optical characters of the biaxial crystals are as follows.

1. When light passes through a biaxial crystal in a direction other than an optic axis, it splits into two rays with mutually perpendicular vibrations. The velocities of the rays differ from each other and change with the change in the crystallographic direction. Thus in biaxial crystals, there are three vibration directions : (*i*) *X*, the vibration direction of the fastest ray, (*ii*) *Z*, the vibration direction of the slowest ray, and (*iii*) *Y*, the vibration direction of the ray of intermediate velocity. These *X*, *Y* and *Z* directions are at right angles to one another.
2. There are three refractive indices, α (alpha), β (beta) and γ (gamma), corresponding to the fast, medium and slow rays in the *X*, *Y* and *Z* vibration directions respectively. The value of α is lowest, γ is highest, and β is intermediate between the two. The difference between the greatest and least refractive indices is called *"birefringence"*.
3. The *X* and *Z* vibration directions lie in the optic axial plane. The *Y* direction that lies at right angles to this plane, is called the *"optic normal"*.
4. The *X* and *Z* vibration directions bisect the acute and obtuse angles between the two optic axes. The direction which bisects the acute angle, is called *"acute bisectrix"* and the one which bisects the obtuse angle, is called *"obtuse bisectrix"*.
5. A biaxial mineral is said to be *"positive"* when Z is the acute bisectrix and *"negative"* when *X* is the acute bisectrix.

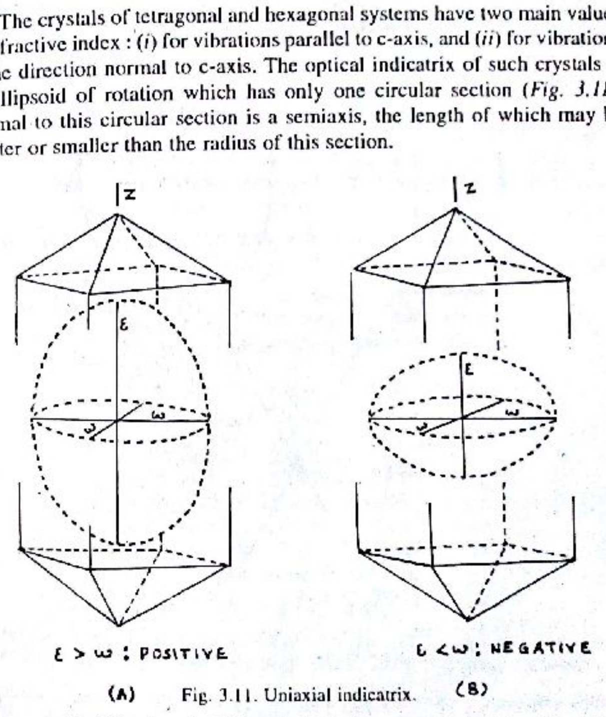
3.13. OPTICAL INDICATRIX

In an anisotropic mineral, the refractive index varies with the crystal direction. This relationship can be illustrated with the help of a geometrical

figure called the *"optical indicatrix"*. The optical indicatrix of an anisotropic crystal is an ellipsoid whose semiaxes are proportional to the refractive indices in the respective directions. In the crystals of cubic system as the refractive index is the same in all directions, the indicatrix will have the form of a sphere.

3.13.1. Uniaxial Indicatrix

The crystals of tetragonal and hexagonal systems have two main values of refractive index : (*i*) for vibrations parallel to c-axis, and (*ii*) for vibrations in the direction normal to c-axis. The optical indicatrix of such crystals is an ellipsoid of rotation which has only one circular section (*Fig. 3.11*). Normal to this circular section is a semiaxis, the length of which may be greater or smaller than the radius of this section.



ε > ω : POSITIVE ε < ω : NEGATIVE

(A) Fig. 3.11. Uniaxial indicatrix. (B)

1. If the length of the semiaxis is greater than the radius of the circular section, the ellipsoid will be prolate (*i.e.* extended along the optic axis) and the crystal is said to be optically *"positive"* [*Fig. 3.11* (*a*)].
2. If the length of the semiaxis is less than the radius of the circular section, the ellipsoid is oblate (*i.e.* flattened along the optic axis) and the crystal is said to be optically *"negative"* [*Fig. 3.11* (*b*)].

The direction normal to the circular section is called *"optic axis"*. The light moving parallel to this axis is not doubly refracted. In all other directions the light is doubly refracted and gives rise to ordinary and extraordinary rays.

3.13.2. Biaxial Indicatrix

In crystals belonging to orthorhombic, monoclinic and triclinic systems, the optical indicatrix is a triaxial ellipsoid. The lengths of its three semiaxes

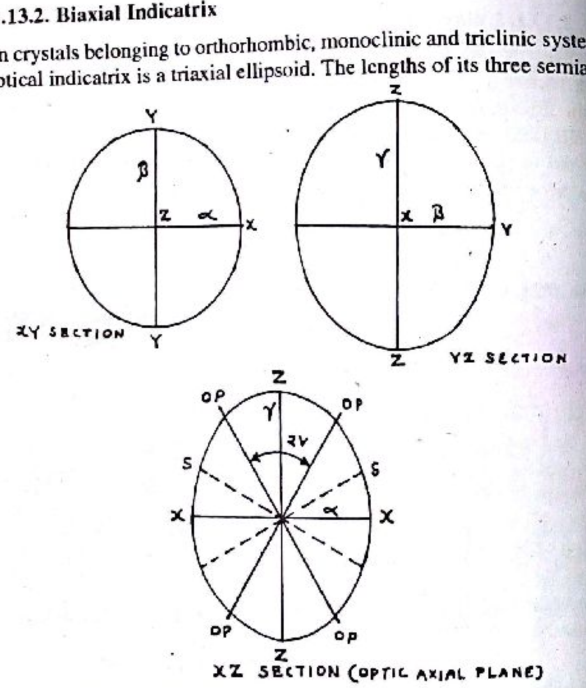


Fig. 3.12. Principal sections through the biaxial indicatrix of a positive crystal. [*OP*–Optic axis, *S*–Circular section, Z–Acute bisectrix, *X*–Obtuse bisectrix]

are proportional to the refractive indices α, β and γ : (*i*) α along *X* direction, (*ii*) β along *Y* direction, and (*iii*) γ along Z direction (*Fig. 3.12*). This triaxial ellipsoid has two circular sections having diameter equal to its intermediate axis. The directions normal to these circular sections are *"optic axes"*. As there are two optic axes, the crystals of this group are called *"biaxial"*.

Three principal sections through the indicatrix along planes *XY*, *YZ* and *XZ* are shown in *Fig. 3.12*. They are all ellipses. The lengths of semimajor and semiminor axes of each represent the refractive indices in the corresponding direction. Of these three sections, the *XZ* section is most important and its main characters are as follows.

1. The lengths of semimajor and semiminor axes of the *XZ* section are proportional to γ and α respectively. Between these two extreme values, it is possible to locate points on the ellipse where the radius is proportional to the intermediate refractive index β. This radius is shown by *S* in *Fig. 3.12*.
2. There are two circular sections of radius *S*. The directions perpendicular to these sections are the *"optic axes"*. The *XZ* plane that contains them is the *"optic axial plane"*.
3. The intermediate axis *Y* which is perpendicular to the *XZ* plane, is called the *"optic normal"*.
4. The acute angle between the two optic axes is called the *"optic axial angle"*. It is designated by 2V.
5. As the Z direction is the acute bisectrix, the crystal shown in *Fig. 3.12* is optically positive.

3.14. POLARIZING MICROSCOPE

Polarizing microscope is used for determining the optical properties of minerals. To study minerals under the microscope, their thin sections (about 0.035 mm thick) are prepared. These thin sections are then placed on the rotating stage of the microscope and examined.

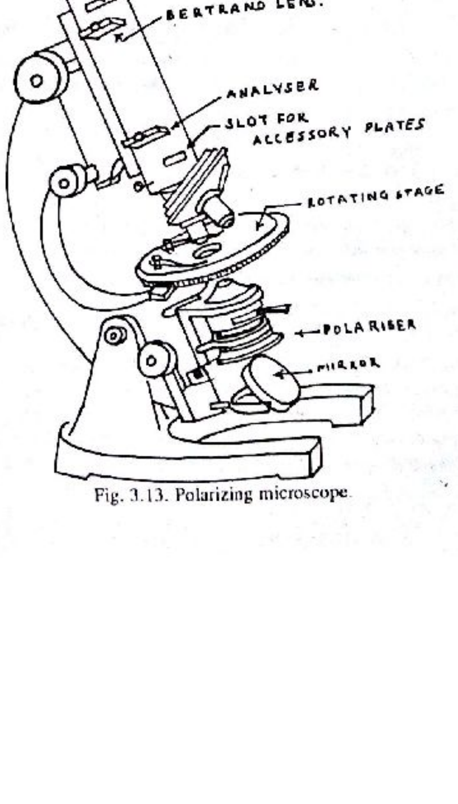


Fig. 3.13. Polarizing microscope.

The main parts of the polarizing microscope (*Fig. 3.13*) are as follows.

(*i*) **Rotating Stage.** The thin section of a mineral to be examined is placed on this stage. The axis of rotation of the stage coincides with the microscope axis.

(*ii*) **Polarizer.** The ploarizer is fitted below the stage. It transmits polarized light vibrating in the E-W direction.

(*iii*) **Analyser.** The analyser is placed in the microscope tube above the stage and is removable. The analyser transmits light vibrating in the N-S direction. When both the polarizer and analyser are in position, they are said to be crossed.

(*iv*) **Eyepiece.** The eyepiece of the microscope carries cross-hairs, one in the N-S direction and the other in the E-W direction. These cross-hairs help in locating a perticular mineral grain for detailed examination. They are also useful in aligning cleavage fragments for making angular measurements.

(*v*) **Objective.** For mineralogical work, generally three objectives are required : (*a*) low power (2*x*). (*b*) medium (10*x*), and (*iii*) high power (50*x*).

(*vi*) **Iris Diaphragm.** This diaphragm is located below the stage. It regulates the intensity of light.

(*vii*) **Condenser.** The condensing lenses are located below the stage. They are used with high power objective and produce converging light rays when required.

(*viii*) **Bertrand Lens.** This lens is used to observe interference figures.

(*ix*) **Slot for Assessories.** The microscope tube carries a slot at 45° to the cross-hairs. It is used for the insertion of accessory plates.

3.15. PREPARATION OF THIN SECTION

A thin section of a mineral (or rock) is made by grinding and polishing on one side of a piece of it. This side is then cemented to a slip of glass with Canada balsam ($n = 1.54$). The mineral chip is then ground down on the other side with successively finer grades of carborundum powder. When a suitable thickness is left (about 0.030 mm) a cover slip is cemented on it.

3.16. EXAMINATION OF MINERALS IN POLARIZED LIGHT

In the microscope, polarizer is set with its plane of polarization parallel to one of the two cross-hairs (usually E-W cross-hair) of the eyepiece. The vibration direction of the analyser will be normal to that of the polarizer. To examine minerals in the polarized light, the analyser is removed from the microscope tube. The properties that are commonly examined in polarized light are colour, relief, refractive index, form, cleavage and pleochroism. The description of some of the important properties are as follows.

3.16.1. Relief

When a mineral grain is brought into focus in the polarized light, it stands out in relief. To study relief of a grain, the sharpness of its outline and the roughness of its surface is observed. The relief of a crystal is a function of its refractive index and that of the cement.

(*i*) If the difference between the refractive index of the mineral and the cement is less, the crystal will appear flat and featureless with faint outline. It is then said to have a *"low relief"*.

(*ii*) If the difference in the refractive index of the mineral and the cement is high, the grain outline will appear bold and cracks on its surface will become conspicuous. In this case the mineral is said to have a *"high relief"*.

3.16.2. Refractive Index

The relief indicates the difference in the refractive index between the mineral grain and the cement. The refractive index of the grain may be above or below that of the cement. To determine whether the grain is of higher or lower refractive index than the cement, *"Becke Line"* test is carried out.

Backe Line Test. In the Becke test, a high power objective is used and the iris diaphragm of the microscope below the stage is partly closed. A tapering edge of a mineral grain is selected and brought into focus. If now the microscope tube is raised, a narrow line of light, called *"Backe line"*, will appear at the grain boundary. The Backe line moves towards the medium of higher refractive index when the tube is raised. This test is very useful for isotropic minerals which have only one value of refractive index.

In order to determine the accurate value of refractive index of a mineral, a set of suitable liquids of known refractive index is required. These liquids are called *"immersion media"*. A mineral grain under examination is immersed in a drop of liquid of known refractive index. Then by the use of Becke line, the refractive index of the mineral and liquid is compared. Thus if the Becke line moves into the mineral grain, a new mount is made by using a liquid of higher refractive index. This procedure is repeated till an exact match between the liquid and mineral grain is obtained. In such a case, the refractive index of the mineral will be equal to that of the liquid.

3.16.3. Pleochroism

A crystal is said to be *"pleochroic"* when on rotating in polarized light it shows change in quality or quantity of colour. This change in colour is due to the change in absorption of light vibrating in different directions of the crystal.

(*i*) Uniaxial crystals have two vibration directions. Such a crystal shows two different colours for these vibration directions. This property is called *"dichroism"*. For example, in tourmaline the rays vibrating parallel to the length of crystal are much less absorbed than those vibrating at right angles to the length.

(*ii*) In biaxial crystals there are three principal vibration directions, *X*, *Y* and *Z*. Along these directions, three distinct colours are observed. This phenomenon is called *"pleochroism"*.

Pleochroism or dichroism is described by noting the colour of light transmitted when each principal vibration direction of a mineral coincides with the plane of polarizer. For example, in hornblende the pleochroism is described as follows : *X*–pale yellow, *Y*– yellow green, and *Z*–green ($X < Y < Z$).

3.17. EXAMINATION OF MINERALS IN CROSSED POLARS

When the analyser is placed in the position with its plane of polarization at right angles to that of the polarizer, the polars are said to be *"crossed"*. If a section of a doubly refracting mineral is placed between crossed polars, the light is doubly refracted and polarized three times as discussed below.

1. The light that enters the polarizer, is doubly refracted and polarized. The E-ray vibrates in the vibration direction of the polarizer and O-ray at right angles to it. Here O-ray is eliminated and only E-ray passes through the polarizer.
2. When this ray strikes an anisotropic mineral section, it is divided into two rays : (*i*) E′-ray, and (*ii*) O′-ray. They vibrate at right angles to each other in the vibration directions of the mineral. These two rays move upward to the analyser.
3. At the analyser, the third double refraction takes place and the two rays are divided into four rays : (*i*) E″-ray, (*ii*) O″-ray, (*iii*) E‴-ray, and (*iv*) O‴-ray. Here the two ordinary rays are eliminated and the two extraordinary rays (E″ and E‴) pass through the analyser. Since they vibrate in the same plane (plane of analyser) and have a fixed phase difference, they interfere. If the phase difference of the two rays is zero or integral multiple of wave lengths, darkness results, and if this phase difference is one-half wave length or any uneven multiple thereof, maximum brightness is produced.

3.17.1. Isotropic Minerals

Isotropic minerals do not show double refraction. If a thin section of an isotropic mineral is viewed in crossed polars, it will appear totally dark. The reason is that the light coming from the polarizer passes through the isotropic mineral unchanged. The analyer cuts out this light completely and darkness results. If the position of the mineral grain is changed by rotating the stage, it will remain dark through the complete rotation.

3.17.2. Interference Colour

When a thin section of an anisotropic mineral is examined in crossed polars, it generally appears bright. If the stage of the microscope is rotated, the mineral will become dark and bright four times in a complete rotation. This phenomenon can be explained with the help of *Fig. 3.14* as follows

1. Suppose the vibration directions of the anisotropic crystal under examination, are at oblique angles to those of polarizer and analyser.
2. When light from the polarizer strikes the anisotropic crystal section, it is broken up into two rays. These rays vibrate in mutually perpendicular planes in the vibration directions of the crystal.
3. During the passage through the crystal, the two rays have travelled with different velocities. Thus on emerging, one ray is retarded relative to the other. These rays pass upward to the analyser.
4. On entering the analyser, each of these rays is broken up into two components (O-ray and E-ray). Only those components of the two rays are transmitted which vibrate parallel to the plane of the analyser.
5. The two rays which emerge from the analyser, vibrate in the same plane. As there is

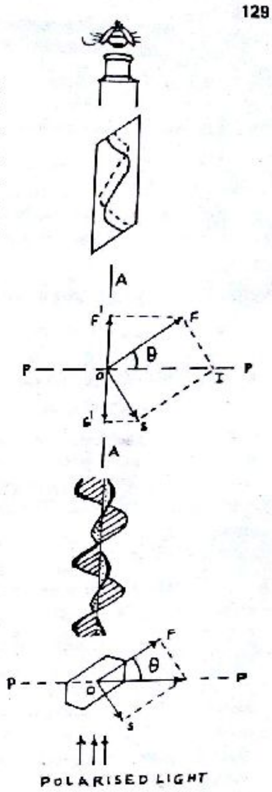


Fig. 3.14. Anisotropic crystal in crossed polars. [(*i*) *P*–*P* and *A*–*A* are the vibration planes of polarizer and analyser respectively. (*ii*) *OF* and *OS* are the fast and slow rays vibrating in the vibration plane of the crystal, (*iii*) these rays do not interfere with each other, but one wave is retarded relative to the other, (*iv*) *OF*′ and *OS*′ are the components of the two rays transmitted through the analyzer. Phase difference in them causes interference and produces interference colours.]

phase difference in them, they interfere with one another. The amount of phase difference depends both on the difference in velocities and on the thickness of the crystal section traversed.

6. The conditions of interference which cause darkness vary for rays of different wave lengths. Hence when white light is used, the intensity of some wave lengths are reduced to zero whereas the intensity of others are increased to maximum. The colours of the spectrum thus produced are called *"interference colours"*.
7. There are different *"orders of interference"* depending on whether the colours result from a path difference of 1λ, 2λ, 3λ, etc. These colours are called first order, second order, third order, etc. colours respectively.

3.18. EXTINCTION DIRECTIONS

When vibration directions of an anisotropic mineral coincide with those of the polarizer and analyser, the mineral appears dark. This position of an anisotropic mineral is called *"position of extinction"*. During a complete rotation of the microscope stage, the position of extinction occurs four times at 90° intervals. In extinction positions, the light from the polarzier passes through the crystal vibrating parallel to the plane of the polarizer and is eliminated in the analyser.

The extinction position helps in locating the vibration directions of the crystal section under study. In this position the vibration directions of the crystal coincide with the cross-hairs of the microscope eyepiece which are set parallel to the planes of polarizer and analyser.

Extinction Angle. The *"extinction angle"* is the angle between the extinction position and some crystallographic direction of a crystal. Since extinction positions are always 90° apart, usually the angle between the cleavage planes or crystal boundary and the nearest extinction position is measured.

3.18.1. Types of Extinction

Parallel Extinction. When the direction of extinction of a crystal is parallel to its crystallographic axis or to the trace of an axial plane, it is said to show *"parallel extinction"*. Generally the physical directions of a crystal, such as straight edges, cleavage cracks and length of the crystal, represent crystallographic directions. In uniaxial minerals, since vibration directions always lie in some crystallographic axial plane, all sections show parallel extinction. Orthorhombic crystals also show parallel extinction.

Symmetrical Extinction. When the direction of extinction bisects the angle between two sets of cleavages, the crystal is said to show *"symmetrical extinction"*. For example, diamond shaped sections of hornblende and

augite, cut normal to c-axis, show symmetrical extinction. Symmetrical extinction is characterstic of orthorhombic crystals.

Inclined Extinction. When the direction of extinction is not parallel to the crystallographic directions, the crystal is said to show *"inclined extinction"*. Minerals belonging to monoclinic and triclinic systems show inclined extinction.

3.19. ACCESSORY PLATES

The standard accessory plates which are used with the polarizing microscope are : (*i*) quartz wedge, (*ii*) gypsum plate, and (*iii*) mica plate. These plates are made in such a way that the fast vibration direction (*X*–direction) of each is parallel to their length. The function of these plates is to produce a given interference colour.

(*i*) **Quartz Wedge.** The quartz wedge is a very thin wedge-shpaed plate of quartz in which the fast vibration direction is parallel to its length. When the quartz wedge is moved forward in the microscope slot, the first order, second order, third order, etc. interference colours are produced successively.

(*ii*) **Gypsum Plate.** This plate is made by cutting a gypsum crystal to such a thickness that it produces a first order red interference colour between cross polars. Gypsum plate has fast vibration direction along its length. This plate is also called *"sensitive tint plate"* because with a slight increase in double refraction, it gives a blue colour and with a corresponding decrease, its colour changes to yellow.

(*iii*) **Mica Plate.** The mica plate is also called *"quarter wave plate"*. This plate consists of a thin cleavage flake of muscovite which produces a path difference of a quarter of a wave length of yellow light.

3.20. SIGN OF ELONGATION

An anisotropic mineral in a thin section contains two vibration directions, one *"fast"* and the other *"slow"*. To identify these directions, the mineral section is turned from a position of extinction through 45°. Then through the slot in the microscope tube, the gypsum plate is inserted.

1. If the *X*-direction of the gypsum plate and the mineral coincide, the interference colour will rise in its order.
2. If the optical directions of the two are opposed to each other, the interference colour will fall.

Hexagonal and tetragonal crystals are frequently elongated on the c-axis. If such an orientation is known, the optical sign of the elongated grain can be determined. The sign of elongation is said to be *"positive"* when the slow vibration direction is parallel to the direction of elongation of a mineral grain. It is said to be *"negative"* when the fast direction coincides with the length of the grain.

3.21. OBSERVATIONS IN CONVERGENT LIGHT

When sections of an anisotropic crystal are examined in convergent polarized light, *"interference figures"* are seen. In order to see interference figures, the following adjustment are made in the polarizing microscope.

(*i*) Polars are crossed.

(*ii*) Condenser lens is used below the stage to produce a converging beam.

(*iii*) A high power objective is used.

(*iv*) A Bertrand lens is introduced between the eyepiece and the analyser. In case when Bertrand lens is not used, interference figures are seen by removing the eyepiece.

Interference figures are observed in those sections of anisotropic minerals which are : (*i*) normal to an optic axis of uniaxial or biaxial minerals, and (*ii*) normal to a bisectrix in biaxial minerals.

3.21.1. Uniaxial Interference Figure

Uniaxial interference figures consist of a black cross with its arm parallel to the cross hairs and a series of concentric coloured rings. The colours of these concentric rings correspond to that of the spectrum. The black cross is formed where the vibration directions of the E-ray and O-ray coincide with the vibration directions of the polarizer and analyser. Thus the two arms of this cross indicate the vibration directions of the E-ray and O-ray (*Fig. 3.15*).

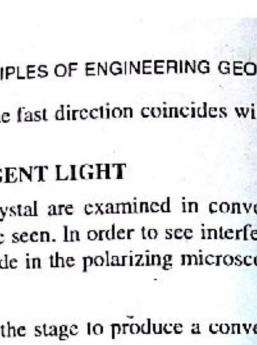


Fig. 3.15. Uniaxial interference figure. E-ray vibrates radially and O-ray vibrate tengentially.

Determination of Optic Sign. In an optic axis interference figure, the E-ray vibrates radially and the o-ray tangentially. With the help of an accessory plate, the optic sign of a crystal can easily be determined.

Let mica plate be inserted at 45° to the cross hairs over an optic axis figure. Here two possibilities arise.

(*i*) In negative minerals, in which the O-ray is slow, the mica plate will reinforce the interference colours in the SE and NW quadrants causing them to shift towards the centre. In the other pair of quadrants, subtraction takes place and the colours move away from the centre. Two black spots are also formed in these quadrants near the centre of the black cross.

(*ii*) In positive minerals, the above effect is reversed as shown in *Fig. 3.16*.

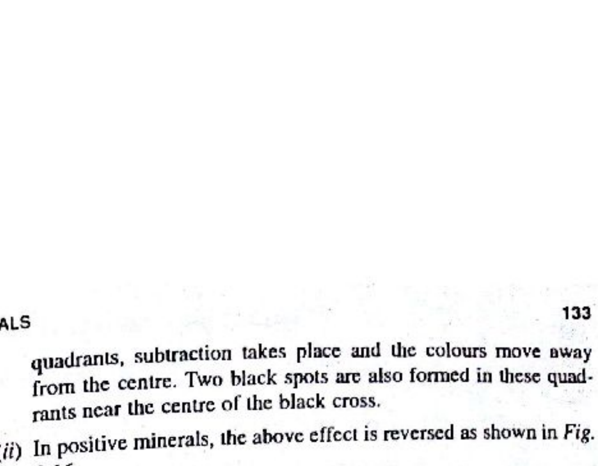


Fig. 3.16. Optic sign determination of a positive crystal (*a*) with mica plate, (*b*) with gypsum plate.

In the optic axis figures which show low order interference colours, the gypsum plates is used and in those which show high order interference colours, the quartz wedge is used.

3.12.2. Biaxial Interference Figure

Although interference figures can be observed on any section of biaxial crystals, the most important are those obtained on sections normal to the acute bisectrix.

Acute Bisectrix Figure. This figure is observed on a crystal section cut normal to the acute bisectrix of a biaxial mineral. If the optic axial angle is

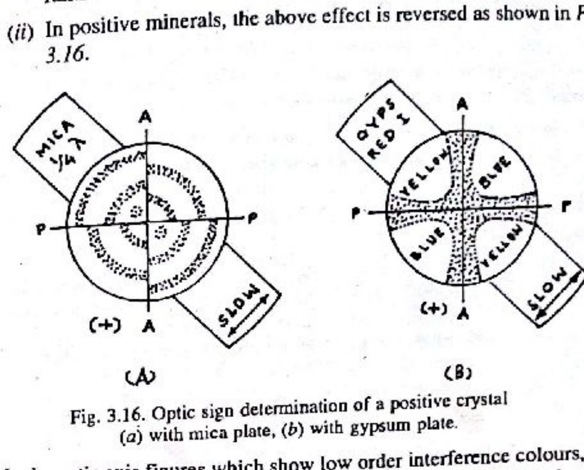


Fig. 3.17. Acute bisectrix interference figure of a biaxial crystal. (*a*) Parallel position, (*b*) 45° position.

moderate, say less than 45°, both the optic axes emerge within the field of view of the microscope.

The typical acute bisectrix figures are shown in *Fig. 3.17.* When the optic axial plane lies parallel to the E-W cross-hair (plane of vibration of the polarizer), a figure similar to that of *Fig. 3.17* (*a*) is observed and when the optic axial plane makes 45° angle with the cross-hair, the figure like that shown in *Fig. 3.17* (*b*) is observed.

When the plane of optic axes is parallel to the vibration direction of the polarizer, the biaxial interference figure shows a black cross. The horizontal bar of this cross is thinner and better defined than the vertical one. At two points on the horizontal bar, there are concentric dark elliptical curves. The outer curves fuse to form a double curve.

On rotating the microscope stage, the black cross breaks into two hyperbolas. These hyperbolas are called *"isogyres"*. They show maximum separation at 45° position and each becomes narrowest at the point of emergence of optic axes. The isogyres are always convex towards the acute bisectrix.

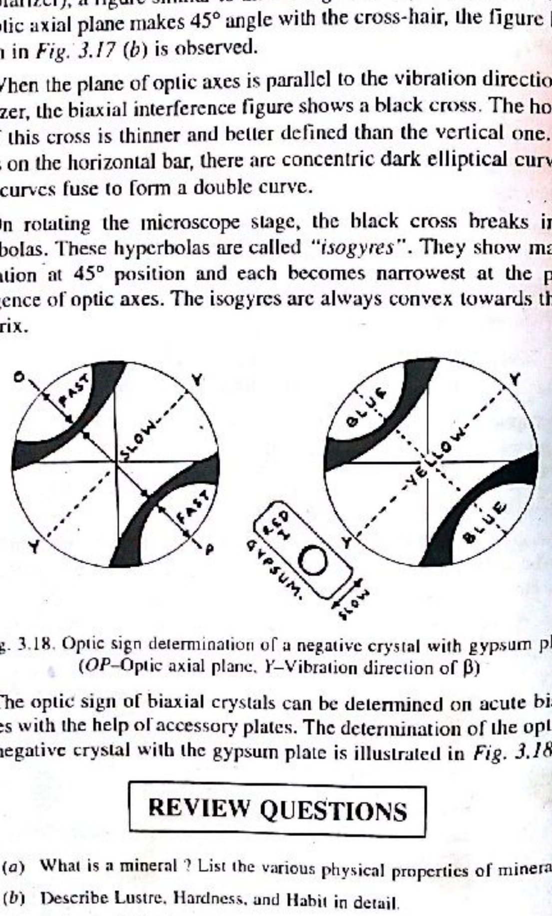


Fig. 3.18. Optic sign determination of a negative crystal with gypsum plate. (*OP*–Optic axial plane, *Y*–Vibration direction of β)

The optic sign of biaxial crystals can be determined on acute bisectrix figures with the help of accessory plates. The determination of the optic sign of a negative crystal with the gypsum plate is illustrated in *Fig. 3.18.*

REVIEW QUESTIONS

1. (*a*) What is a mineral ? List the various physical properties of minerals.
   (*b*) Describe Lustre, Hardness, and Habit in detail.
2. On the basis of silicate structure classify silicate minerals into various groups. Explain the structure of each group in detail.

3. Give the chemical composition and important physical properties of the following minerals.
   Talc, Kyanite, Beryl, Gypsum, Calcite, Garnet, Muscovite, Hornblende, Orthoclase and Quartz.
4. (*a*) How is the specific gravity of a mineral determined by Walker's steel yard.
   (*b*) Explain the terms Isomorphism, Polymorphism and Pseudomorphism with reference to minerals.
5. Give the physical properties, occurrence and uses of the following ore minerals.
   Arsenopyrite, wolframite, Barytes, Chromite, Galena, Bauxite, Chalcopyrite, Sphalerite, Pyrolusite, Hematite.
6. What are rockforming minerals ? Give a brief account of the physical properties of the Felspar, Pyroxene, Amphibole and Mica group of minerals.
7. Differentiate between the following.
   (*i*) Isotropic and Anisotropic minerals.
   (*ii*) Uniaxial and Biaxial minerals.
   (*iii*) Positive and Negative crystals.
   (*iv*) Dichroism and Pleochroism.
   (*v*) Parallel extinction and Symmetrical extinction.
8. What is double refraction ? Describe the optical properties of minerals that are observed in the polarized light.
9. (*a*) What is a polarising microscope ? Explain the function of its principal parts.
   (*b*) Describe the optical properties of the uniaxial and biaxial minerals.
10. (*a*) What is an extinction angle ? Describe the various types of extinctions found in minerals.
    (*b*) How is the optical sign of elongation of a mineral grain determined by the gypsum plate.
11. What is an optical indicatrix ? Explain in brief the chief characters of the uniaxial and biaxial indicatrix.
12. Write short notes on the following.
    Interference colour, Interference figure, Accessory plates, Optical indicatrix, Refractive index.

4 Crystallography

4.1. INTRODUCTION

"*Crystallography*" is a branch of mineralogy which deals with the study of crystals and the laws that govern their growth, external shape and internal structure. Most minerals are crystalline while a few are amorphus (noncrystalline). When minerals crystallize under favourable conditions, they take the form of crystals. Thus the crystal form of a mineral reflects its orderly internal arrangement of atoms.

Crystal. A solid which possesses a regular geometrical shape, is called a "*crystal*". A crystal is bounded by faces which lie parallel to the planes of atoms in the crystal structure. In addition to faces, crystals contain edges and solid angles arranged in a regular order. "*Edges*" are formed where two adjacent faces meet and a "*solid angle*" is formed where three or more edges meet.

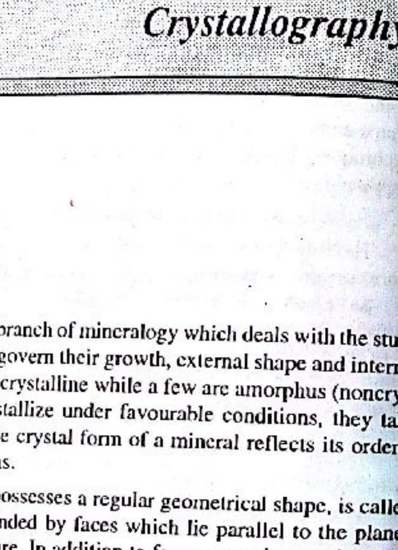


Fig. 4.1. Crystal zones and zone axis.

Zone. In many crystals a group of faces are arranged in such a manner that their intersection edges are parallel to each other. Such faces constitute a "*zone*". A line which passes through the centre of the crystal and lie parallel to the line of the face intersections is called the "*zone axis*". In *Fig. 4.1* the faces *m'*, *a*, *m* and *b* are in one zone, and *b*, *r*, *c* and *r'* in another. The lines [001] and [100] are the zone axes.

4.2. UNIT CELL

Faces of a crystal bear a definite relation to the internal structural pattern of atoms. This structural pattern consists of units. In each unit there is a group of atoms linked in a fixed spatial relationship to one another. Crystals are formed by the repetition of a unit in three dimensions. The "*unit cell*", therefore, is a tiny building block of crystals. It represents the smallest volume which possesses all the chemical, physical and geometrical properties of the crystal. Different mineral species have different types of unit cell. The shape and size of unit cells of minerals are determined by *x*-ray diffraction techniques.

4.3. INTERFACIAL ANGLE

In a crystal, the angle between adjacent faces is called "*interfacial angle*". Because crystal faces have a direct relationship to the internal structure, it follows that the faces have a definite relationship to each other. This relationship is expressed by "*law of the constancy of interfacial angles*" which states that "*the interfacial angles between corresponding faces are constant for all crystals of a given mineral*".

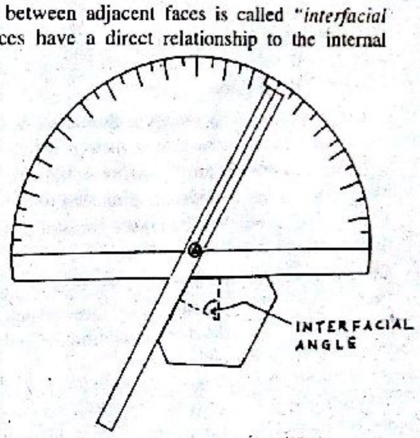


Fig. 4.2. Contact geniometer.

Interfacial angles are measured either with a contact goniometer or a reflecting goniometer. Contact goniometer is a simple device which consists of a pivoted metal arm, called pointer. This arm slides over a semicircular scale and measures the interfacial angle between two adjacent faces of a crystal as shown in *Fig. 4.2.*

4.4. CRYSTALLOGRAPHIC AXES

In order to describe the faces and symmetry of crystals, a set of three or four reference axes are established. These imaginary reference lines are called "*crystallographic axes*" and are generally taken parallel to the intersection edges of major crystal faces. In fact, crystallographic axes are the reference lines which run parallel to the edges of the unit cell and their lengths are proportional to the lengths of the unit cell edges. Thus when we say that the three axes of the cubic system are equal and mutually perpendicular, it means that the three edges of the cubic unit cell are equal and mutually perpendicular. The lengths of the unit cell edges measured in the direction of crystallographic axes, are called *"unit lengths"* and are generally expressed as *a*, *b* and *c*.

4.4.1. Lettering of Crystallographic Axes

Normally the vertical crystallographic axis is labeled as '*c*', the left to right axis as '*b*' and front to back axis as '*a*'. If the axes are of equal length, they are all labeled as '*a*'. For example, in cubic system the three equal axes are referred to as a_1, a_2 and a_3.

One end of each axis is designated as plus and the other end as minus. The front end of a-axis, the right hand end of b-axis and the upper end of c-axis are positive while the opposite ends are negative (*Fig. 4.3*).

When the crystallographic axes are not at right angles, the angle between the positive ends of b and c is referred to as α (alpha), between + *a* and + *c* as β (beta) and between + *a* and + *b* as γ (gamma) (*Fig. 421*).

4.4.2. Axial Ratio

The *"unit lengths"* of crystallographic axes are length of the unit cell edges. These are expressed as *a*, *b* and *c*. For example, for the orthorhombic mineral sulfur, the unit cell dimensions are : a = 10.47 A°, b = 12.87 A°, and c = 24.29 A°. Taking *b* as a unit of measure, we can determine the lengths *a* and *c* in terms of *b*. The ratio determined in this way is $a : b : c$ = 0.813 : 1 : 1.903. This ratio which expresses the relative lengths of the unit cell edges along crystallographic axes is called *"axial ratio"*.

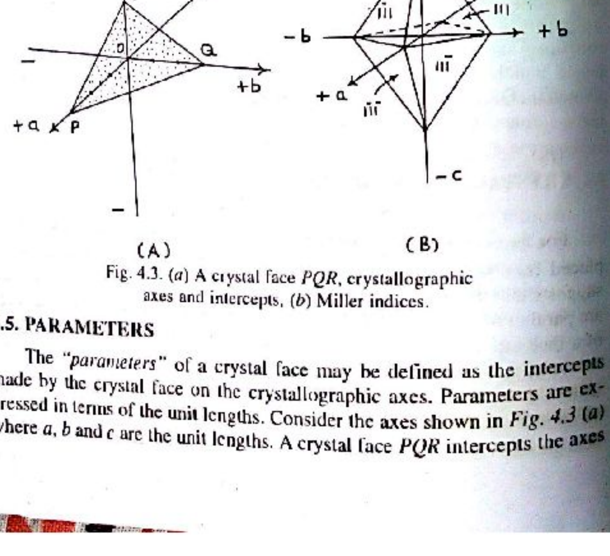


Fig. 4.3. (*a*) A crystal face *PQR*, crystallographic axes and intercepts, (*b*) Miller indices.

4.5. PARAMETERS

The *"parameters"* of a crystal face may be defined as the intercepts made by the crystal face on the crystallographic axes. Parameters are expressed in terms of the unit lengths. Consider the axes shown in *Fig. 4.3 (a)* where *a*, *b* and *c* are the unit lengths. A crystal face *PQR* intercepts the axes

at distances of $3a$, $3b$, and $2c$ respectively from the origin, so its parameters will be $3a : 3b : 2c$. The form whose face is taken to be making unit parameters is called a *"unit form"*.

4.6. CRYSTALLOGRAPHIC NOTATION

The slopes of crystal faces can be described with reference to the intercepts they make on the crystallographic axes. The methods that are commonly used for expressing the intercepts of crystal faces are : (*i*) parameter system of Weiss, and (*ii*) index system of Miller.

4.6.1. Parameter System of Weiss

In this system the parameters of a crystal face are written along with the notation of the crystallographic axes. For example, a face that cuts the a-axis at unit distance, b-axis at a distance of 2 units and lies parallel to the c-axis, its Weiss symbol is written as follows.

$$a, 2b, \infty c$$

4.6.2. Index System of Miller

In the index system of Miller, the notations of crystal faces are called *"Miller indices"*. The Miller indices of a face consists of a series of whole numbers that have been derived from the parameters by taking their reciprocals and then by clearing of fractions. The numbers of the Miller indices are always written in the axial order a, b and c. For example, let us consider the crystal face PQR shown in *Fig. 4.3* (*a*). Its Miller indices are determined as follows.

(*i*) For the face *PQR* which cuts the positive ends of the crystallographic axes, the parameters are $3a$, $3b$ and $2c$ respectively. Since the intercepts are always written the axial order *a*, *b* and *c*, the letters themselves are omitted and the parameters are written as : 3, 3 and 2.

(*ii*) The reciprocal of the parameters are taken which leads to 1/3, 1/3 and 1/2 respectively.

(*iii*) The fractions are cleared by multiplying all by 6 and the Miller symbol for the face PQR is obtained, which is "223". The Miller indices of the octahedron is shown in *Fig. 4.3* (*b*).

For faces that intersect negative ends of crystallographic axes, a bar is placed over the corresponding index figure. For example, the index $22\bar{3}$ suggests that this face intercepts the c-axis on the negative end. Faces which are parallel to an axis, cut that axis at infinity. For example, if the intercepts of a face are 1, ∞, ∞, its Miller symbol will be 100.

A Miller symbol which is not bracketted, strictly denotes a single face, while the bracketted symbol represents all the faces of a form. The general symbol for a face that cuts all the axes at different lengths, is *"hkl"* and for hexagonal system it is *"hkil"*.

It may be noted that for given faces of a crystal, the Miller indices could always be expressed by simple whole numbers or zero. This is known as the *"law of rational indices"*.

4.7. FORMS

a *"form"* consists of a group of crystal faces all of which have the same relation to the elements of symmetry. The number of faces in a form is determined by the symmetry of the crystal class. Miller indices may be used to represent forms and they are then enclosed in brackets.

4.7.1. Closed and Open Forms

A *"closed form"* is that whose faces enclose space and can exist alone. The cube and the octahedron in the cubic system are both closed forms. Faces of an *"open form"* do not enclose space. In a crystal an open form always occurs in combination with other forms. An expample of open form is prism.

4.7.2. Holohedral and Hemihedral Forms

In a crystal system, each form of the normal class is called *"holohedral form"*. This form contains all the possible faces that have similar relation to the elements of symmetry. However in the lower symmetry classes there are some forms which contain half the number of faces found in the corresponding holohedral form. Such a form is called the *"hemihedral form"*. It may be noted that to account for all the faces of the holohedral form, two similar hemihedral forms exist. They are called *"positive"* and *"negative"* respectively. For example, in the cubic system, the tetrahedron is the hemihedral form of octahedron. The positive and negative tetrahedron are shown in *Fig. 4.8.*

4.7.3. Hemimorphic Forms

In the lower symmetry classes of some systems, there are some crystal forms in which faces occur only on one end of the vertical crystallographic axis. Such forms are called *"hemimorphic forms"*. Obviously crystals with

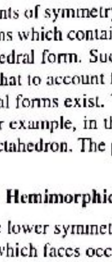


Fig. 4.4. Tourmaline crystal showing hemimorphism.

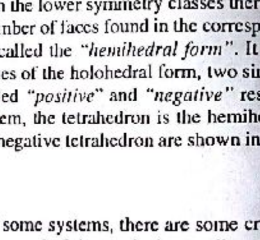


Fig. 4.5. Enantiomorphism.
(*a*) Left hand crystal of quartz.
(*b*) Right hand crystal of quartz.

hemimorphic forms, such as tourmaline, have no centre of symmetry (*Fig. 4.4*).

4.7.4. Enantiomorphous Forms

Crystals which do not possess plane and centre of symmetry, contain a form that occurs in two positions and which are mirror images of each other. These two positions are related in the same way as right and left hand and are not interchangeable. Such a form in called *"enantiomorphous form: (Fig. 4.5).*

4.8. SYMMETRY ELEMENTS

Every crystal possesses a certain symmetry. Symmetry elements are used to describe this symmetry. Three elements of symmetry can be recognized in a crystal. These are : (*i*) plane of symmetry, (*ii*) axis of symmetry, and (*iii*) centre of symmetry.

Plane of Symmetry. A plane of symmetry is an imaginary plane which divides a crystal into two halves, each of which is the mirror image of the other [*Fig. 4.6* (*a*) and (*b*)]. A cube has nine planes of symmetry.

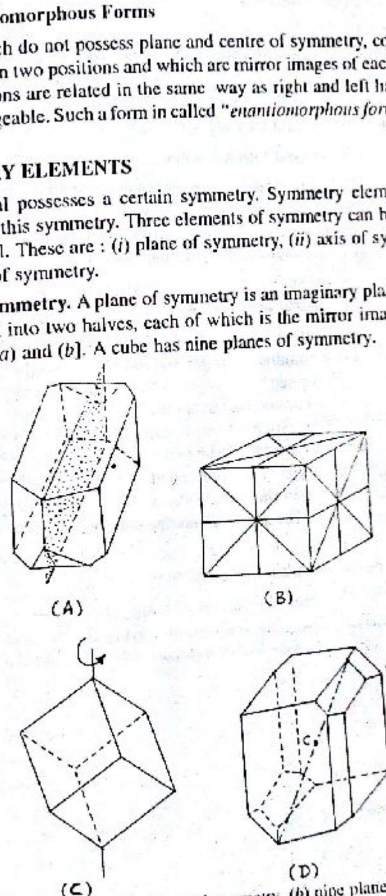


Fig. 4.6. Symmetry elements. (*a*) Plane of symmetry, (*b*) nine planes of symmetry in a cube, (c) Axis of 3-fold symmetry (*d*) A centre of symmetry.

Axis of Symmetry. It is an imaginary line through the crystal about which if the crystal is rotated, it gives the observer exactly the same view more than once in a single rotation. If the same view is repeated 2, 3, 4 or 6 times, the axis of symmetry is referred to as two-fold, three-fold, four-fold or six-fold respectively. *Fig. 4.6* (*c*) shows an axis of three-fold symmetry.

Centre of Symmetry. If each face in a crystal is duplicated by a similar parallel face on the opposite side, it is said to have a centre of symmetry [*Fig. 4.6* (*d*)]. The cube and octahedron possess a centre of symmetry whereas a tetrahedron does not.

4.9. SIX CRYSTAL SYSTEMS

All crystals that occur in nature can be grouped into six major crystal systems. These crystal systems are as follows. Their symmetry elements are given in Table 4.1.

(*i*) **Cubic or Isometric System.** The crystals belonging to this system have three mutually perpendicular axes of equal lengths. These axes are designated as a_1, a_2 and a_3 [*Fig. 4.7* (*a*)].

(*ii*) **Tetragonal System.** The crystals of this system are referred to three mutually perpendicular axes. The two horizontal axes are equal (a_1 and a_2) and the vertical axis is longer or shorter than the other two (*Fig. 4.10*).

(*iii*) **Hexagonal System.** In the crystals of the hexagonal system, there are, four crystallographic axes. Three of these are of equal length and lie at angles of 120° to each other in the horizontal plane. These are designated as a_1, a_2 and a_3. The fourth axis is vertical and is either longer or shorter than the other axes [*Fig. 4.13* (*a*)].

(*iv*) **Orthorhombic System.** The crystals of this system have three mutually perpendicular axes of different lengths. They are designated as *a*, *b* and *c*. (*Fig. 4.17*).

Table 4.1. Symmetry Elements of Major Crystal Systems

S. No.	*Systems*	*Plane of Symmetry*	*Axis of Symmetry*	*Centre of Symmetry*
1.	Cubic	9P	$3^{iv}, 4^{iii}, 6^{ii}$	A centre
2.	Tetragonal	5P	$1^{iv}, 4^{ii}$	A centre
3.	Hexagonal	7P	$1^{vi}, 6^{ii}$	A centre
4.	Orthorhombic	3P	3^{ii}	A centre
5.	Monoclinic	1P	1^{ii}	A centre
6.	Triclinic	None	None	A centre

(*v*) **Monoclinic System.** In the crystals of this system, there are three unequal crystallographic axes. The '*a*' and '*c*' axes are inclined to each other at an oblique angle and the '*b*' axis is perpendicular to the plane of the two [*Fig. 4.19* (*a*)].

(*vi*) **Triclinic System.** There are three unequal axes all intersecting at oblique angles [*Fig. 4.21* (*a*)].

4.10. CUBIC OR ISOMETRIC SYSTEM

Some of the most common minerals that crystallize in the cubic system are galena, garnet, fluorite and magnetite.

Crystallographic Axes. Crystals of the cubic system are referred to three mutually perpendicular equal axes [*Fig. 4.7* (*a*)]. These axes are interchangeable and are designated as a_1, a_2 and a_3.

Classes. There are five classes in the cubic system of these the most important classes are : (*i*) *"Galena type"*, (*ii*) *"Pyrite type"*, and (*iii*) *"Tetrahedrite type"*.

4.10.1. Galena Type

It is the normal class of the cubic system which possesses the highest degree of symmetry.

Symmetry. The symmetry elements of this class are as follows.

Planes 9 { 3 axial; 6 diagonal

Axes 13 { 3 crystallographic axes of 4-fold symmetry; 4 diagonal axes of 3-fold symmetry; 6 diagonal axes of 2-fold symmetry

A centre of symmetry.

Forms. The are seven basic forms in this class.

(1) **Cube (100).** This form is composed of six square faces that make 90° angles with each other. Each face intersects one of the crystallographic axes and is parallel to the other two [*Fig. 4.7* (*b*)].

(2) **Octahedron (111).** Octahedron is composed of eight equilateral triangular faces. Each face intersects the three crystallographic axes at equal lengths [*Fig. 4.7* (*c*)].

(3) **Dodecahedron (110).** This form is composed of 12 rhomb shaped faces. Each face intersects the two crystallographic axes equally and is parallel to the third [*Fig. 4.7* (*d*)].

(4) **Trapezohedron (hll).** This form is composed of 24 trapezium shaped faces. Each face intersects one crystallographic axis at unit distance and the other two at equal multiples. The most common trapezohedron is (211) [*Fig. 4.7* (*e*)].

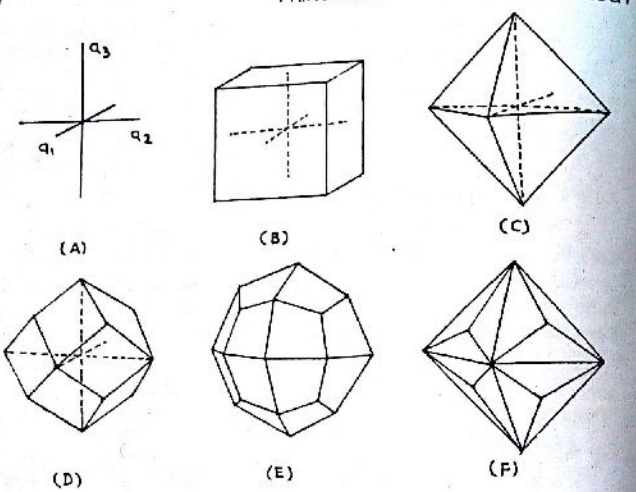


Fig. 4.7. (*a*) Axes of cubic system, (*b*) Cube, (*c*) Octahedron, (*d*) Dodecahedron, (*e*) Trapezohedron, (*f*) Trisoctahedron.

(5) **Tetrahexahedon (hko).** The tetrahexahedron is made up of 24 faces, each of which is an isosceles triangle. Each face intersects one axis at unity, the second axis at some multiple of unity and is parallel to the third. The most common tetrahexahedron is (210).

(6) **Trisoctahedron (hhl).** This form is composed of 24 triangular faces. Each face intersects two crystallographic axes at unity and the third at some multiple of it. The most common trisoctahedron is (221) [*Fig. 4.7 (f)*].

(7) **Hexoctahedron (hkl).** This form is made up of 48 triangular faces. Each face intersects all the three crystallographic axes at unequal distances. A common hexoctahedron is (321).

4.10.2. Pyrite Type

Symmetry. The symmetry elements of this class are as follows.

Plane 3, axial

Axes 7 {3 crystallographic axes of 2-fold symmetry; 4 diagonal axes of 3-fold symmetry}

A centre of symmetry.

Forms. The important forms of the pyrite type are the *"pyritohedron"* and the *"diploid"*.

1. **Pyritohedron (hko).** This form is composed of 12 pentagonal faces. Each face intersects one axis at unity, the second axis at

some multiple of unity and is parallel to the third. The most common pyritohedron is (210) [*Fig. 4.8 (a)*].

There are two pyritohedrons : (*i*) positive (210) and (*ii*) negative (120). A rotation of 90° about one of the crystallographic axes brings the positive pyritohedron into the negative position. the positive and negative pyritohedrons together forms 24 faces of the tetrahexahedron of the normal class.

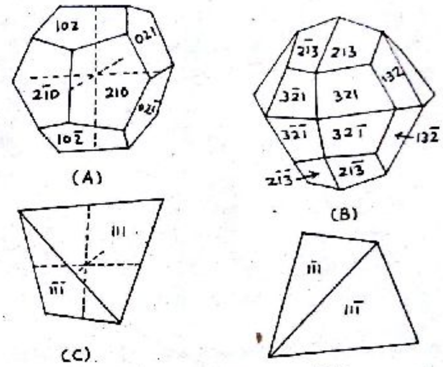


Fig. 4.8. (*a*) Pyritohedron, (*b*) Diploid, (*c*) Positive tetrahedron, (*d*) Negative tetrahedron.

2. **Diploid (hkl).** The diploid is composed of 24 faces that correspond to one-half of the faces of the hexoctahedron of the normal class. Each face intersects the axes at unequal distances. A common diploid is (321) [*Fig. 4.8 (b)*]. There are two diploids: (*i*) positive (321), and (*ii*) negative (312). The positive and negative forms together comprise all the faces of the hexoctahedron of the normal class.

In addition to the pyritohedron and diploid, the other forms such as cube, octahedron, dodecahedron, trisoctahedron and trapezohedron, are also found in the pyrite type class. These forms are geometrically similar to the normal class but they show a lower symmetry due to the presence of striations and etch marks.

4.10.3. Tetrahedrite Type

Symmetry. The symmetry elements of this class are as follows.

Plane 6, diagonal

Axes 7 {3 crystallographic axes of 2-fold symmetry; 4 diagonal axes of 3-fold symmetry}

No centre of symmetry.

Forms. The typical forms of this class are as follows.

1. **Tetrahedron (111).** It is a solid bounded by four faces each of which is an equilateral triangle. Each face intersects the crystallographic axes at equal lengths. There are two tetrahedrons : (*i*) positive (111) and (*ii*) negative ($1\bar{1}1$) [*Fig. 4.8* (*c*) and (*d*)].
2. **Tristetrahedron (hll).** This form has 12 faces. Its faces correspond to one-half of those of the trapezohedron of normal class. Each face intersects one axis at unity and the other two at equal multiples. The most common tristetrahedron is (211) [*Fig. 4.9* (*b*)]. There are two tristetrahedrons : (*i*) positive (*hll*) and (*ii*) negative ($h\bar{l}\bar{l}$).

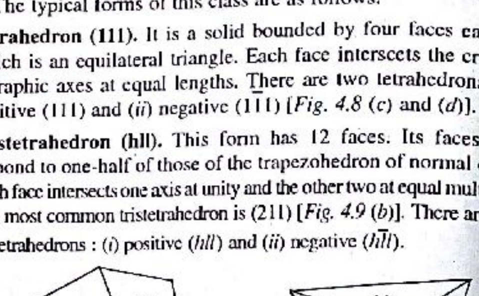


Fig. 4.9. (*a*) Deltoid dodecahedron, (*b*) Tristetrahedron.

3. **Deltoid–dodecahedron (hhl).** There are two deltoid – dodecahedrons : (*i*) positive (*hhl*), and (*ii*) negative ($h\bar{h}l$). This form has 12 faces which correspond to one-half of those of the trisoctahedron of the normal class. Each face intersects the two axes at equal lengths and the third at a greater length. The common deltoid-dodecahedron is (221) [*Fig. 4.9* (*a*)].
4. **Hextetrahedron (hkl).** There are two hextetrahedrons (*i*) positive (*hkl*), and (*ii*) negative ($h\bar{k}l$). This form has 24 triangular faces which correspond to one-half of the faces of the hexoctahedron of the normal class. Each face intersects all the three crystallographic axes at different lengths. The most common hextetrahedron is (321).

The other forms found in the tetrahedrite type class are cube, dodecahedron and tetrahexahedron. These are geometrically similar to the normal class but have a lower symmetry due to difference in their molecular structure.

4.11. TETRAGONAL SYSTEM

The most common minerals that crystallize in the tetragonal system are zircon, cassiterite and rutile.

Crystallographic Axes. All the crystals in the tetragonal system are referred to three mutually perpendicular axes. The two horizontal axes (a_1 and a_2) are equal but the vertical axis is of different length (*Fig. 4.10*).

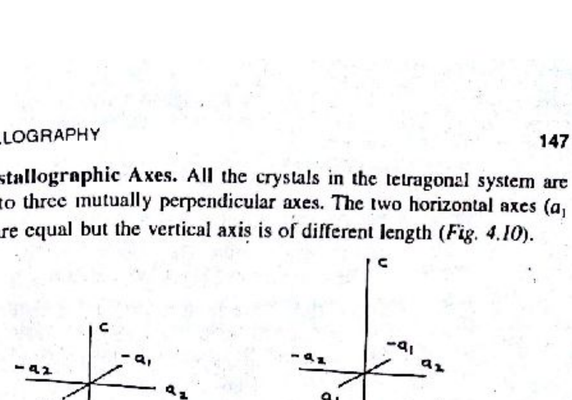


Fig. 4.10. Tetragonal crystal axes. (*a*) *c*-axis less than *a*, (*b*) *c*-axis greater than *a*.

Class. "*Zircon type*" is the normal symmetry class of the tetragonal system.

4.11.1. Zircon Type

Symmetry. The symmetry elements of this class are as follows.

Planes 5 { 1 horizontal; 4 vertical

Axes 5 { 1 vertical axis (crystallographic) of 4-fold symmetry; 4 horizontal axes (2 crystallographic and 2 diagonal) of 2-fold symmetry

A centre of symmetry.

Forms. The typical forms of this class are as follows.

1. **Basal Pinacoid (001).** This form is composed of two horizontal faces which are parallel to the plane of horizontal axes (*Fig. 4.11*).
2. **Prism of First Order (110).** This form four rectangular vertical faces. Each face intersects the two horizontal crystallographic

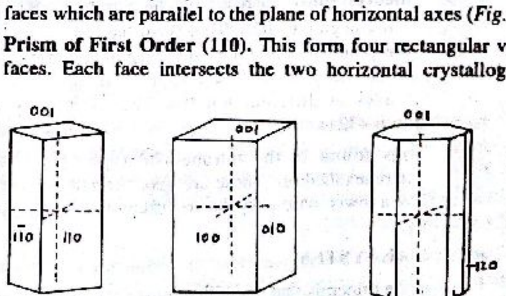


Fig. 4.11. Tetragonal prisms. (*a*) First order, (*b*) Second order, (*c*) Ditetragonal.

axes at equal lengths and lies parallel to the vertical axis [*Fig. 4.11 (a)*].

3. **Prism of Second Order (100).** This form has four rectangular vertical faces. Each face intersects one horizontal crystallographic axis and is parallel to the other two [*Fig. 4.11 (b)*].
4. **Ditetragonal Prism (hko).** This form has eight rectangular vertical faces. Each face intersects the two horizontal crystallographic axes at unequal distances and is parallel to the vertical axis. The common ditetragonal prism is (210) [*Fig. 4.11 (c)*].
5. **Dipyramid of First Order (hhl).** This form is composed of eight isosceles triangular faces. Each face intersects the two horizontal crystallographic axes at equal distances and the vertical axis at a different length. The unit dipyramid of first order is shown in *Fig. 4.12 (a)*. The other dipyramids of first order are (221, (331), etc.
6. **Dipyramid of Second Order (hol).** This form is composed of eight isosceles triangular faces. Each face intersects one horizontal axis and the vertical axis, and is parallel to the remaining axis [*Fig. 4.12 (b)*]. The various dipyramids of second order are (101), (201), (301), (102), etc.

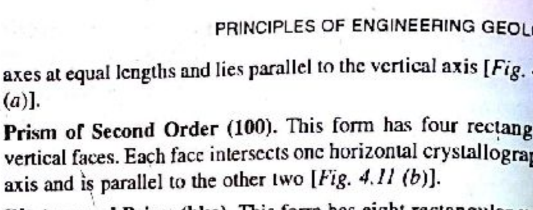


Fig. 4.12. Tetragonal dipyramids
(*a*) First order, (*b*) Second order, (c) Ditetragonal.

7. **Ditetragonal Dipyramid (hkl).** This form has 16 triangular faces. Each face intersects all the three crystallographic axes, the intercepts on the horizontal axes being unequal. A common ditetragonal dipyramid is (311) [*Fig. 4.12 (c)*].

4.12. HEXAGONAL SYSTEM

The common minerals that crystallize in the hexagonal system are beryl, apatite, quartz, calcite, dolomite and tourmaline.

Crystallographic Axes. All the crystals in the hexagonal system are referred to four axes. Of these three (a_1, a_2 and a_3) are of equal length. They

lie in the horizontal plane with angle of 120° between the positive ends. The fourth axis is vertical and is either longer or shorter than the other axes [*Fig. 4.13 (a)*].

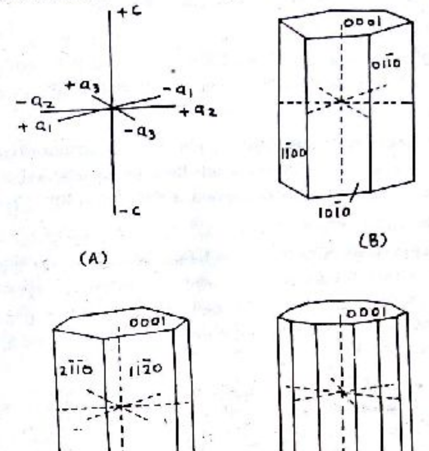


Fig. 4.13. (*a*) Hexagonal crystal axes, (*b*) First order hexagonal prisms, (*c*) Second order hexagonal prisms, (*d*) Dihexagonal prisms.

Classes. The two important symmetry classes of the hexagonal system are : (*i*) *"Beryl type"* and (*ii*) *"Calcite type"*.

4.12.1. Beryl Type

Beryl type is the normal class of the hexagonal system. It shows the highest degree of symmetry.

Symmetry. The symmetry elements of the Beryl type class are as follows.

Planes 7 { 6 vertical; 1 horizontal

Axes 7 { 1 vertical axis of 6-fold symmetry; 6 horizontal axes of 2-fold symmetry

A centre of symmetry.

Forms. The typical forms of this class are as follows.

1. **Basal Pinacoid (0001).** This form is composed of two horizontal faces which are parallel to the plane of horizontal axes (*Fig. 4.13*).

2. **Prism of First Order (10$\bar{1}$0).** This form has six vertical faces. Each face intersects two of the horizontal crystallographic axes equally and is parallel to the third [*Fig. 4.13* (*b*)].
3. **Prism of Second Order (11$\bar{2}$0).** This form has six vertical faces. Each face intersects two of the horizontal axes equally and the intermediate horizontal axis at one-half this distance (*Fig. 4.13* (*c*)].
4. **Dihexagonal Prism** (*hk$\bar{i}$o*).. This form is composed of 12 vertical faces. Each face intersects all three horizontal axes at different lengths. A common dihexagonal prism is (21$\bar{3}$0) [*Fig. 4.13* (*d*)].
5. **Dipyramid of First Order** (*ho$\bar{h}$l*). This form is composed of 12 isosceles triangular faces. Each face intersects two of the horizontal crystallographic axes equally, is parallel to the third and cuts the vertical axis. There are various dipyramids depending on the inclination of the faces to the c-axis. The symbol of the unit form is (10$\bar{1}$1) [*Fig. 4.14* (*a*)].
6. **Dipyramid of Second Order** (*hh2$\bar{h}$l*). This form is composed of 12 isosceles triangular faces. Each face intersects two horizontal axes equally, the intermediate horizontal axis at one-half this distance and also intersects the vertical axis. A common dipyramid of second order is (11$\bar{2}$2) [*Fig. 4.14* (*b*)].

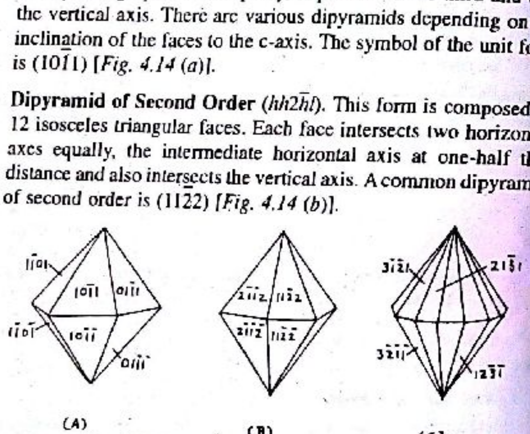


Fig. 4.14. Hexagonal dipyramids
(*a*) First order, (*b*) Second order, (*c*) Dihexagonal.

7. **Dihexagonal Dipyramid** (*hk$\bar{i}$l*).. This form is composed of 24 triangular faces. Each face intersects all three horizontal axes at different lengths and also intersects the vertical axis. A common dihexagonal dipyramid is (21$\bar{3}$1) [*Fig. 4.14* (*c*)].

4.12.2. Calcite Type

Symmetry. The symmetry elements of this class are as follows.

Planes 3 vertical

Axes 4 { 1 vertical axis of 3-fold symmetry
3 horizontal axes of 2-fold symmetry

A centre of symmetry.

Forms. The typical forms of this class are the rhombohedron and the scalenohedron.

1. **Rhombohedron (ho$\bar{h}$l).** There are two rhombohedrons : (*i*) positive (*ho$\bar{h}$l*), and (*ii*) negative (*oh$\bar{h}$l*). This form is composed of six rhomb-shaped faces, of which three faces at the top alternate with three faces at the bottom. Each face intersects two of the horizontal axes equally, is parallel to the third and also intersects the vertical axis. Various rhombohedrons are possible depending on the inclination of the faces to the c-axis. The unit form of the positive rhombohedron is (10$\bar{1}$1) while that of negative rhombohedron is (01$\bar{1}$1) [*Fig. 4.15* (*a*) and (*b*)].

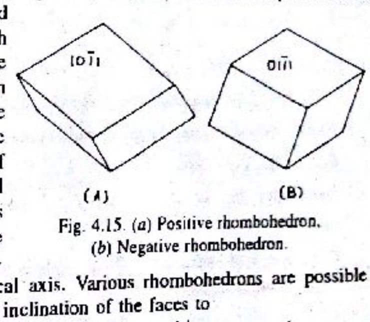


Fig. 4.15. (*a*) Positive rhombohedron. (*b*) Negative rhombohedron.

2. **Scalenohedron** (*hk$\bar{i}$l*). There are two scalenohedrons : (*i*) positive (*hk$\bar{i}$l*), and (*ii*) negative (*kh$\bar{i}$l*). This form is composed of 12 triangular faces. Each face is a scalene triangle. Each face intersects all there horizontal axes at different lengths and also meets the vertical axis. A common positive scalenohedron is (21$\bar{3}$1) (*Fig. 4.16*) and its complementary negative scalenohedron is (1$\bar{2}$31)

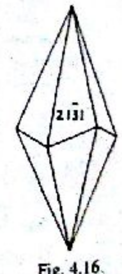


Fig. 4.16. Scalenohedron.

The basal pinacoid, prism of first order, prism of second order, dihexagonal prism and dipyramid of second order which are present in the beryl type are also found in this class, but these have a lower symmetry.

4.13. ORTHORHOMBIC SYSTEM

The common minerals that crystallize in the orthorhombic system are Baryte, olivine, andalusite and topaz.

Crystallographic Axes. Crystals belonging to the orthorhombic system are referred to three unequal, mutually perpendicular axes. The 'a' axis being shorter is called "*brachy axis*" and the 'b' axis being longer is called "*macro axis*" [*Fig. 4.17* (*a*)].

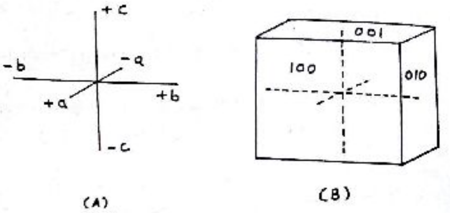


Fig. 4.17. (*a*) Orthorhombic crystal axes, (*b*) Orthorhombic pinacoids.

Class. *"Barytes type"* is the normal class of the orthorhombic system.

4.13.1. Barytes Type

Symmetry. The symmetry elements of this class are as follows.

Planes 3, axial

Axes 3, crystallographic of 2-fold symmetry.

A centre of symmetry.

Forms. The typical forms of this class are as follows.

1. **Pinacoids.** A pinacoid is composed of two parallel faces each of which intersects one crystallographic axis and is parallel to the other two. Pinacoids are of three type.
   (*i*) *Basal Pinacoid (001).* Its faces intersect c-axis and lie parallel to '*a*' and '*b*' [*Fig. 4.17* (*b*)].
   (*ii*) *Macro Pinacoid (100).* It is also called ***"a-pinacoid"*** as its faces intersect 'a' axis and lie parallel to '*b*' and '*c*' [*Fig. 4.17* (*b*)].
   (*iii*) *Brachy Pinacoid (010).* It is also called ***"b-pinacoid"*** as its faces intersect b-axis and lie parallel to '*a*' and '*c*' [*Fig. 4.17* (*b*)].
2. **Prisms (hko).** A prism is composed of four vertical faces. Each face intersects both the horizontal axes and is parallel to the vertical axis. Unit prism has the symbol (110) [*Fig. 4.18* (*c*)]. Various other prisms are possible depending on the variation in the axial intercepts, *e.g.*, (210), (120), etc.
3. **Macrodomes (hol).** This form is composed of four faces. Each face is parallel to the 'b' axis (macro axis) and intersects '*a*' and '*c*'. The symbol of the unit macrodome is (101) [*Fig. 4.18* (*b*)]. Other macrodomes are (103, (102), (203), etc.
4. **Brachydomes (okl).** This form is composed of four faces. Each face is parallel to the 'a' axis (brachy axis) and intersects '*b*' and

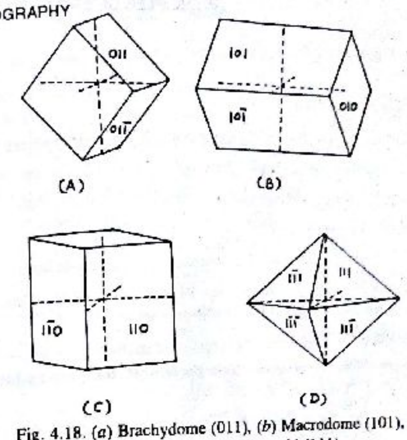


Fig. 4.18. (*a*) Brachydome (011), (*b*) Macrodome (101), (*c*) Prism (110), (*d*) Dipyramid (111).

'*c*'. The symbol of the unit brachydome is (011) [*Fig. 4.18* (*a*)]. Other brachydomes are (013), (012), (023), etc.

5. **Dipyramids (hkl).** An orthorhombic dipyramid has eight triangular faces, each of which intersects all three crystallographic axes. The symbol of the unit dipyramid is (111) [*Fig. 4.18* (*d*)].

4.14. MONOCLINIC SYSTEM

Many minerals crystallize in the monolinic system. Some of the most common are gypsum, micas, orthoclase and diopside.

Crystallographic Axes. Crystals in the monoclinic system are referred to three unequal crystallographic axes. The '*c*' and '*b*' axes are at right angles to each other but the '*a*' axis is inclined to the plane containing the other two axes. The 'a' axis is called *"clino-axis"* and the 'b' axis *"ortho-axis"*. The angle between $+a$ and $+c$ is greater than 90° and is designated as β [*Fig. 4.19* (*a*)].

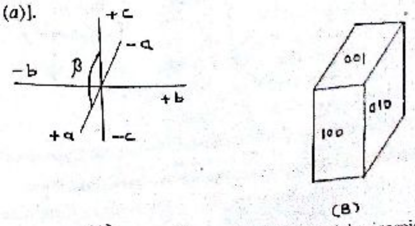


Fig. 4.19. (*a*) Monoclinic crystal axes; (*b*) Monoclinic pinacoids.

Class. *"Gypsum type"* is the normal symmetry class of the monoclinic system.

4.14.1. Gypsum Type

Symmetry. The symmetry elements of the gypsum type are as follows.

Planes 1, containing '*a*' and '*c*' axes.

Axis 1, b-axis of 2-fold symmetry.

A centre of symmetry.

Forms. The chief forms of the gypsum type are as follows.

1. **Pinacoids.** The pinacoids are of three types : (*i*) basal pinacoid, (*ii*) orthopinacoid and (*iii*) clinopinacoid.
   (*i*) *Basal Pinacoid (001).* This form includes two faces. Each face intersects c-axis and lies parallel to the plane containing '*a*' and '*b*' axes [*Fig. 4.19* (*b*)].
   (*ii*) *Orthopinacoid (100).* The orthopinacoid is also called *"a-pinacoid"*. It is composed of two faces. Each face intersects 'a' axis and lies parallel to the plane containing '*b*' and '*c*' axes [*Fig. 4.19 (b)*].
   (*iii*) *Clinopinacoid (010).* This form is also called *"b-pinacoid"*. It is composed of two faces. Each face intersects 'b' axis and lies parallel to the plane containing '*a*' and '*c*' axes [*Fig. 4.19* (*b*)].
2. **Prisms (hko).** A monoclinic prism consists of four faces. Each face is parallel to the vertical axis and intersects both the horizontal axes. The symbol of the unit prism is (110) (*Fig. 4.20*).

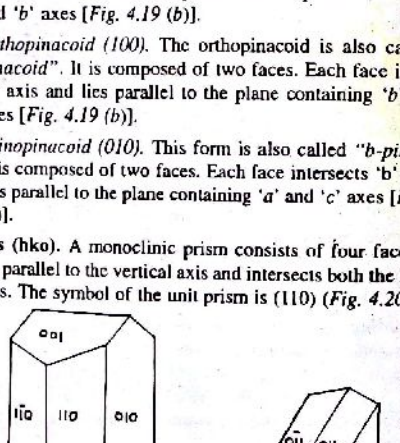


Fig. 4.20. Monoclinic forms in (*a*) Orthoclase crystal, (*b*) Gypsum crystal.

3. **Hemiorthodomes (hol).** There are two hemiorthodomes : (*i*) positive (*hol*) and (*ii*) negative ($\bar{h}ol$). This form is composed of two faces. Each face lies parallel to the b-axis and intersects '*a*' and '*c*' axes. The positive unit hemiorthodome (101) has the faces 101 and $\bar{1}0\bar{1}$, and the negative unit hemiorthodome ($\bar{1}01$) has the faces $\bar{1}01$ and $10\bar{1}$ [*Fig. 4.20* (*a*)].
4. **Clinodomes (okl).** A clinodome has four faces. Each face is parallel to the 'a' axis and intersects the '*b*' and '*c*' axes. The symbol of the unit clinodome is (011) [*Fig. 4.20* (*b*)].
5. **Hemipyramids (hkl).** There are two hemipyramids (*i*) positive (*hkl*) and (*ii*) negative ($\bar{h}kl$). This form has four faces only. Each face intersects all three crystallographic axes. Examples of positive and negative hemipyramids are (321) and ($\bar{3}21$) respectively with the faces 321, $3\bar{2}1$, $3\,\bar{2}\,\bar{1}$ and $\bar{3}\,21$, $\bar{3}\,\bar{2}1$, $32\,\bar{1}$, $3\bar{2}\,\bar{1}$.

4.15. TRICLINIC SYSTEM

The common minerals that crystallize in the triclinic system are axinite, albite, anorthite, microcline and kyanite.

Crystallographic Axes. In the triclinic system the crystal forms are referred to three unequal axes that make oblique angles with each other. The angles between the positive ends of '*b*' and '*c*', '*c*' and '*a*', and '*a*' and '*b*' are designated as α (alpha), β (beta) and γ (gamma) respectively [*Fig. 4.21* (*a*)]. The 'b' axis is longer than the 'a' axis and these are called *"macro-axis"* and *"brachy-axis"* respectively.

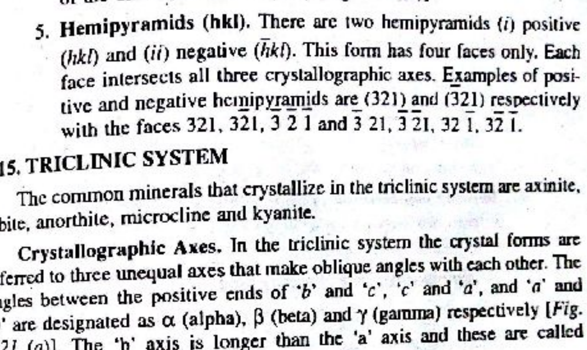


Fig. 4.21. (*a*) Triclinic crystal axes, (*b*) Axinite crystal showing triclinic forms.

Class. *"Axinite type"* is the normal symmetry class of the triclinic system.

4.15.1. Axinite Type

Symmetry. The symmetry elements of the axinite type are as follows.

Planes, none

Axes, none

A centre of symmetry.

Forms. Each form of this class is made up of two faces which are parallel to one another and are symmetrical with reference to the centre of symmetry.

1. **Pinacoids.** The pinacoids are of three types : (*i*) basal pinacoid, (*ii*) brachy-pinacoid, and (*iii*) macro-pinacoid.

   (*i*) *Basal Pinacoid (001).* The basal pinacoid is also called *"c-pinacoid"*. This form has two faces. Each face intersects c-axis and is parallel to the other two.

   (*ii*) *Brachypinacoid (010).* This form is also called *"b-pinacoid"*. It is composed of two faces. Each face intersects 'b' axis and is parallel to the other two.

   (*iii*) *Macropinacoid (100).* This form is also called *"a-pinacoid"*. It is composed of two faces. Each face intersects 'a' axis and is parallel to the other two [*Fig. 4.21 (b)*].

2. **Hemiprisms, Hemimacrodomes and Hemibrachydomes.** Each of these forms include two faces. For each form there is a positive and a negative form.

   (*i*) **Hemiprism.** Positive (*hko*), Negative ($h\bar{k}o$).

   (*ii*) **Hemimacrodome.** Positive (*hol*), Negative ($\bar{h}ol$).

   (*iii*) **Hemibrachydome.** Positive (*okl*), Negative ($o\bar{k}l$).

3. **Quarter Pyramids.** Quarter-pyramids are composed of two faces. Each face intersects all three crystallographic axes. The various quarter-pyramids are : (*i*) positive right (*hkl*), (*ii*) positive left ($h\bar{k}l$), (*iii*) negative right ($\bar{h}kl$) and (*iv*) negative left ($\bar{h}\bar{k}l$).

4.16. CRYSTAL GROUPS

In many instances crystals occur in groups. Crystal groups are of three types : (*i*) crystal aggregates, (*ii*) parallel growths, and (*iii*) twin crystals.

Crystal Aggregates

Groups of associated crystals are known as *"crystal aggregates"*. If the crystals forming the aggregate are made of one mineral only, the aggregate is said to be *"homogeneous"* and if different minerals occur in the aggregate, it is termed as *"heterogeneous"*.

Parallel Growths

When two or more crystals are grown in such a way that the crystallographic axes of the one individual are parallel to those of the other, the grouping is called *"parallel growth"*.

Twin Crystals

When a crystal shows two separate portions joined at a common crystallographic plane, it is called *"twinned crystal"*. Geniculate twin of rutile [*Fig. 4.22 (a)*] is a good example of twinned crystal.

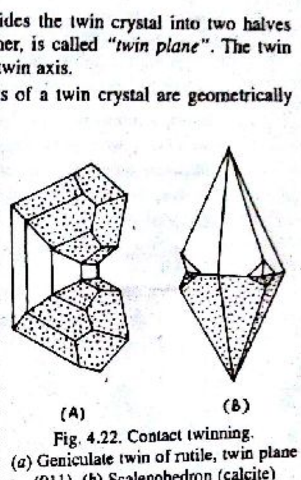
4.17. TWINNING

The *"twin crystals"* may be defined as the symmetrical intergrowth of two or more individual crystals. In a twin crystal the lattice directions of one unit exhibit a definite crystallographic relation to the lattice directions of the other.

Twin Plane. The plane that divides the twin crystal into two halves which are mirror images of each other, is called *"twin plane"*. The twin plane is always perpendicular to the twin axis.

Twin Axis. The component parts of a twin crystal are geometrically related to each other as if one part is derived from the other by an angular rotation of 180° about some crystal line common to both. The *"twin axis"* therefore may be defined as the axis about which a 180° rotation of one-half of the twinned crystal would convert it into a single crystal.

Composition Plane. The plane on which the two halves of a twin meet is called *"composition plane"*. The composition plane commonly but not always coincides with the twin plane. In the twin crystal of rutile [*Fig. 4.22 (a)*] the twin plane and composition plane is (011). If the composition plane is irregular, it is called the *"composition surface"*.

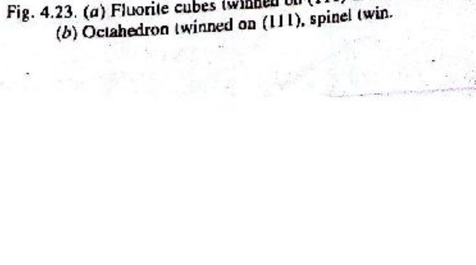


(A) (B)

Fig. 4.22. Contact twinning.
(*a*) Geniculate twin of rutile, twin plane (011), (*b*) Scalenohedron (calcite) twinned on (0001)

Twin Law. The description of the relation between the parts of a twin, is called *"twin law"*. It states whether there is an axis or a twin plane and gives the crystallographic orientation for this axis or plane.

Reentrant Angles. Twinned crystals usually possess reentrant angles. *"Reentrant angles"* are the V-shaped depressions found at the junctions



(A) (B)

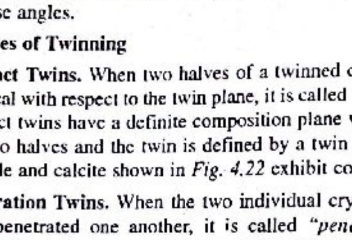
Fig. 4.23. (*a*) Fluorite cubes twinned on (111) as twin axis, (*b*) Octahedron twinned on (111), spinel twin.

between crystal pairs [*Fig. 4.23 (b)*]. Twinning is commonly detected by the presence of these angles.

4.17.1. Types of Twinning

(*i*) **Contact Twins.** When two halves of a twinned crystal are symmetrical with respect to the twin plane, it is called *"contact twin"*. Contact twins have a definite composition plane which separates the two halves and the twin is defined by a twin plane. Crystals of rutile and calcite shown in *Fig. 4.22* exhibit contact twins.

(*ii*) **Penetration Twins.** When the two individual crystals appear to have penetrated one another, it is called *"penetration twin"*. Penetration twins have an irregular composition surface and the twin law is usually defined by a twin axis (*Fig. 4.24*). The main

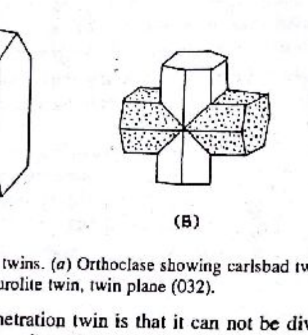


(A) (B)

Fig. 4.24. Penetration twins. (*a*) Orthoclase showing carlsbad twin (*b*) Saturolite twin, twin plane (032).

feature of the penetration twin is that it can not be divided into two separate halves. Crystals of staurolite and fluorite commonly show penetration twin.

(*iii*) **Repeated Twins.** When a twin crystal is composed of three or more parts which are related to one another by the same twinning law, the twin is called *"repeated"* or *"multiple twins"*. The



(A) (B)

Fig. 4.25. Repeated twin. (*a*) Plagioclase, (*b*) Chrysoberyl.

repeated twins are of two types : (*i*) polysynthetic twins and (*ii*) cyclic twins.

(*a*) *Polysynthetic Twins.* A polysynthetic twin is a repeated twin in which all the successive composition surfaces are parallel. It is common in plagioclase felspars [*Fig. 4.25 (a)*].

(*b*) *Cyclic Twins.* A cyclic twin is a repeated twin in which the successive composition planes are not parallel [*Fig. 4.25 (b)*].

4.17.2. Common Twin Laws

Cubic System. In the *"galena type"* class of the cubic system, the most common twin has (111) as the twin plane. As this type of twin is very common is crystals of spinel, it is called *"spinel twin"* [*Fig. 4.23 (b)*].

In the *"pyrite type"* class of the cubic system the two pyritohedrons may form a penetration twin with a 90° rotation about the twin axis. The twin plane is (011). This twin is called *"iron cross twin"*.

Tetragonal System. In this system the twinning on (011) is most common. A crystal of rutile, twinned according to this law is shown in *Fig. 4.22 (a)*.

Hexagonal System. In this system important twins are found in the class *"calcite type"*. Calcite crystals commonly show twinning on three twin laws. The twin plane may be (0001), $(10\bar{1}1)$ or $(01\bar{1}2)$. *Fig. 4.22 (b)* shows calcite scalenohedron twinned on (0001).

Orthorhombic System. In the orthorhombic system the twinning on (110) is most common. For example, contact twin of aragonite and cyclic twin of cerussite are all twinned on (110).

Monoclinic System. In the monoclinic system twinning on (100) and (001) is most common. Gypsum frequently shows twinning on (100) and the *"Manebach twin"* of orthoclase is on (001). Orthoclase also forms penetration twins according to the *"Carlsbad law"* in which the twin axis is the 'c' crystallographic axis, and the composition surface is roughly parallel to (010) [*Fig. 4.24 (a)*]. Orthoclase also shows the *"Baveno twin"* in which the twin plane is (021).

Triclinic System. In the triclinic system the twinning exhibited by the plagioclase felspars is most important. They are twinned according to the *"Albite law"* in which the twin plane is (010) [*Fig. 4.25 (a)*].

REVIEW QUESTIONS

1. (*a*) What is symmetry of a crystal ? Describe in brief the various criteria of symmetry.

(b) Describe in brief the symmetry and forms of the *"galena type"* class of the isometric system.

2. (a) What is *"parameter"* of a crystal face ? Describe how is crystallographic notation done by *"Index System of Miller"*.

(b) Describe in brief the symmetry and forms of the *"zircon type"* class of the tetragonal system.

3. (a) Define a crystal. Explain what do you mean by *"interfacial angle"*, *"axial ratio"* and *"hemihedral forms"*.

(b) Describe how is crystallographic notation done by *"Parameter System of Weiss"*.

4. Discuss in brief about the symmetry and forms of the *"orthorhombic system"* and *"monoclinic systems"*.

5. What are twin crystals ? Explain different types of twinning. Discuss common twin laws.

6. (a) Write about the characteristic features of the crystallographic axes of all the six major crystal systems.

(b) Describe the symmetry and forms of the *"axinite type"* class of the triclinic system.

7. (a) Write a summary of the symmetry elements of all major crystal systems.

(b) Describe the *"pyrite type"* or *"tetrahedrite type"* class of the cubic system.

8. Differentiate between the *"tetragonal"* and *"hexagonal systems"*. Describe the symmetry and forms of the *"calcite type"* class of the hexagonal system.

5 Rocks I : Igneous Rocks

5.1. ROCKS

Rocks form a major part of the earth's crust. They may be defined as aggregates of minerals. Some rocks, such as quartzite (quartz) and marble (calcite), contain grains of one mineral only but most are composed of a variety of different minerals. The rocks are broadly classified into three groups : (*i*) igneous, (*ii*) sedimentary, and (*iii*) metamorphic.

Igneous Rocks. Igneous rocks are formed by cooling and solidification of magma. Typical igneous rocks are granite and basalt.

Sedimentary Rocks. Sedimentary rocks are formed by consolidation and cementation of the sediments deposited under water. Typical sedimentary rocks are sandstone, limestone and shale.

Metamorphic Rocks. Metamorphic rocks are formed when the pre-existing rocks have been changed in texture and composition by increased temperature and pressure. Typical rocks of this kind are schist and gneiss.

5.2. ROCK CYCLE

The rock cycle shows the relationship between the three types of rocks, that is the igneous, sedimentary and metamorphic rocks. One type of rock changes slowly to another type. Erosion produces sediment which is transported and deposited into deep basins under the sea. Then it hardens to form *"sedimentary rocks"*. If these rocks are deeply buried, the temperature and pressure turn them into *"metamorphic rocks"*. Intense heat at great depths melts metamorphic rocks and produces magma. The magma may rise up and reach the earth's surface where it cools to form *"igneous rocks"*. At the surface, igneous rocks are exposed to weathering and erosion, and the cycle begins again.

5.3. IGNEOUS ROCKS

Approximately 90% of the earth's crust is composed of igneous rocks but their great abundance is hidden on the earth's surface by a relatively thin layer of sedimentary and metamorphic rocks. *"Igneous rocks"* are formed by cooling and solidification of magma. *'Magma'* is a hot viscous, siliceous melt containing water vapour and gases. It comes from great depth below the earth's surface. It is composed mainly of O, Si, Al, Fe, Ca, Mg, Na and K. When a magma comes out upon the earth's surface, it looses its gases. Such a magma is called *"lava"*.

5.3.1. Chemical Composition

The chemical composition of igneous rocks exhibit a fairly limited range. The largest oxide component is SiO_2 which in common igneous rocks ranges from 40 to 75 percent by weight. The percentage of Al_2O_3 generally ranges from about 10–20% and each of the other major components (*e.g.* oxides of Ca, Mg and Fe) seldom exceed 10%.

Acid and Basic Rocks. The composition of igneous rocks depends upon the composition of the magma from which they are originated. Magmas are divided into two broad groups : (*i*) acid magma, and (*ii*) basic magma. The *"acid magma"* is rich in Si, Na and K, and poor in Ca, Mg and Fe. The *"basic magma"* on the other hand, is rich in Ca, Mg and Fe, and poor in Si, Na and K.

On the basis of the silica percentage present, igneous rocks are classified into the following groups.

(*i*) *Ultrabasic Rocks.* These contain less than 45% silica, *e.g.* peridotite.

(*ii*) *Basic Rocks.* These contain silica between 45% and 55%, *e.g.* gabbro and basalt.

(*iii*) *Intermediate Rocks.* These contain silica between 55% and 65%, *e.g.* diorite.

(*iv*) *Acid Rocks.* These contain more than 65% silica, e.g. granite.

In general, acid igneous rocks are light in colour, low in specific gravity (about 2.7) and have high proportion of minerals like quartz and alkali felspars. Acid rocks are also called the *"felsic rocks"*. An example of acid rock is granite. Basic rocks, on the other hand, are usually dark in colour (often black), relatively high in specific gravity (about 3.2) and contain mainly silica poor minerals, such as olivine, pyroxene, hornblende or biotite and little or no quartz. Basic rocks are also called *"mafic rocks"* as they contain a high percentage of ferromagnesian minerals. An example of basic rock is basalt.

Igneous rocks can also be classified as : (*i*) oversaturated rocks, (*ii*) saturated rocks, and (*iii*) undersaturated rocks.

(*i*) **Oversaturated Rocks .** These rocks crystallize from melts containing higher amount of silica. They contain abundant quartz and alkali felspars.

(*ii*) **Saturated Rocks.** These rocks are formed when the amount of silica present in the melt is just sufficient to form silicate minerals. Saturated igneous rocks do not contain quartz.

(*iii*) **Undersaturated Rocks.** These rocks crystallize from a melt which is deficient in silica and high in alkalies and aluminium oxide. Such rocks contain silica poor minerals, such as felspathoids, and lack quartz.

5.4. OCCURRENCE OF IGNROUS ROCKS

Magma is produced deep in the earth's crust where temperatures are of the order of 900°-1600°C. It being lighter than the surrounding rocks, works its way towards the surface. On consolidation it produces two major types of igneous rocks : (*i*) extrusive, and (*ii*) intrusive.

5.4.1. Extrusive Rocks

When magma reaches the earth's surface, it causes a volcanic eruption. This eruption generates extensive lavaflows. The rocks formed due to solidification of lava are called *"extrusive rocks"*. The extrusive rocks are also called the *"volcanic rocks"*. As the lava tend to cool and crystallize rapidly, the texture of volcanic rocks are generally fine grained or glassy. During cooling of lava, the volatiles present in it escape into the atmosphere. Volcanic rocks often contain gas cavities, called the *"vesicles"*. These rocks sometimes show *"flow structure"* which is the result of movement in a viscous lava. It is seen as lines or streaks of different colour in a rock.

5.4.2. Intrusive Rocks

"Intrusive rocks" are formed when magma crystallizes beneath the earth's surface. Depending on the depth of formation, intrusive rocks are divided into two groups : (*i*) plutonic rocks, and (*ii*) hypabyssal rocks.

Plutonic Rocks. Rocks crystallized at great depths are called *"plutonic rocks"*. A magma which is deeply buried in the earth's crust, cools slowly with the retention of the volatiles. As a result the mineral constituents crystallizing from it have time to grow to considerable size giving the rock a coarse grained texture.

Hypabyssal Rocks. *"Hypabyssal rocks"* are formed when magma solidifies close to the earth's surface. These rocks occur as injections within the country rocks. Their textures are usually finer grained than those of plutonic rocks but coarser than those of volcanic rocks. The hypabyssal rocks commonly show porphyritic texture.

5.5. CLASSIFICATION

Because magmas vary considerably in chemical composition and conditions of crystallization, igneous rocks show a wide variation in mineral composition and texture. There is a complete gradation from one rock type into another. Many schemes have been proposed for the classification of igneous rocks but the most useful for the beginners is based on mineralogy and texture. In this scheme the various criteria that are considered in classifying igneous rocks are as follows.

(i) **Relative Silica Content.** Presence of quartz in an igneous rock indicates excess of silica whereas felspathoids indicate deficiency of it.

(ii) **Kinds of Felspar.** Determination of relative amount of alkali felspar and plagioclase helps greatly in classifying igneous rocks.

(iii) **Mafic Minerals.** The relative amount and type of mafic minerals present in an igneous rock are determined. This information is valuable from the point of view of classification of igneous rocks.

(iv) **Texture.** Texture of an igneous rock is an important criterion of classification.

The classification of igneous rocks based on their mineral composition and texture is given in Table 5.1.

Table 5.1. Classification of Igneous Rocks
(PLUTONIC rocks in capitals, Volcanic rocks in small letters)

Composition	*Mainly Alkali flespar*	*Alkali flespar ≡ Plagioclase*	*Mainly Plagioclase*
ACID (Light Minerals > 60%)	GRANITE Rhyolite	ADAMELLITE Rhyodacite	GRANODIORITE Dacite
INTERMEDIATE (Light minerals 60–30%, Quartz < 10%)	SYENITE Trachyte	MONZONITE Trachyandesite	DIORITE Andesite
BASIC (Dark minerals > 60%, Calcic-plagioclase)	ALKALI-GABBRO Alkali-basalt	SYENO-GABBRO Trachybasalt	GABBRO Basalt, Dolerite
ULTRABASIC (No felspar)			DUNITE PERIDOTITE PYROXENITE

Quartz is an essential mineral in acid rocks. It occurs as an accessory mineral in intermediate and basic rocks while it remains absent in ultrabasic rocks. Potash felspars together with sodium rich plagioclases are know as the *"alkali felspars"*. Alkali felspars occur as essentialminerals in acid rocks but they are either absent or found in only in minor amounts in intermediate, basic and ultrabasic rocks. Calcium rich plagioclases are found mostly in basic rocks and andesine in intermediate rocks. Ultrabasic rocks normally do not contain felspars.

Olivine occurs as an essential mineral only in basic and ultrabasic rocks. Pyroxenes and amphiboles are the important constituents of basic and ultrabasic rocks but they occur as accessory minerals in acid and intermediate rocks.

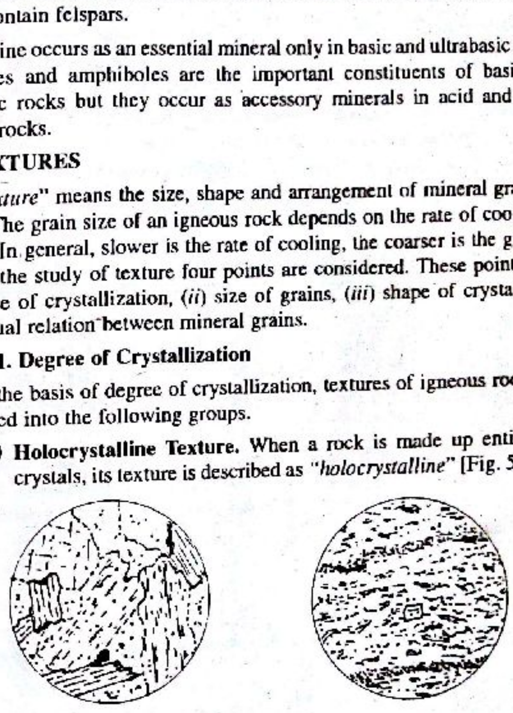
5.6. TEXTURES

"Texture" means the size, shape and arrangement of mineral grains in a rock. The grain size of an igneous rock depends on the rate of cooling of magma. In general, slower is the rate of cooling, the coarser is the grain of rock. In the study of texture four points are considered. These points are : (*i*) degree of crystallization, (*ii*) size of grains, (*iii*) shape of crystals, and (*iv*) mutual relation between mineral grains.

5.6.1. Degree of Crystallization

On the basis of degree of crystallization, textures of igneous rocks can be divided into the following groups.

(i) **Holocrystalline Texture.** When a rock is made up entirely of crystals, its texture is described as *"holocrystalline"* [Fig. 5.1 (*a*)].



(A) (B)

Fig. 5.1. (*a*) Holocrystalline texture (Biotite granite), (*b*) Holohyaline texture (Obsidian).

(ii) **Holohyaline Texture.** When a rock is composed entirely of glassy material, its texture is called *"holohyaline"* [Fig. 5.1 (*b*)].

(iii) **Merocrystalline Texture.** When a rock is composed partly of crystals and partly of glass, the texture is called *"merocrystalline"*.

5.6.2. Size of Grains

The size of grains in an igneous rock varies considerably. The slow cooling gives crystals time to grow to sizes greater than 5 mm. In rapid cooling, the mineral grains crystallize quickly as a mass of tiny crystals which are generally less than one millimeter in size. In some lavas, the cooling is so rapid that they fail to crystallize and *"glassy texture"* results.

Igneous rocks whose constituent mineral grains can be seen with the naked eyes, are described as *"phaneric"*, while those whose mineral grains are too small to be seen with the naked eyes, are called *"aphanitic"*.

The texture of phaneric igneous rocks can be further subdivided as : *(i)* coarse grained, *(ii)* medium grained, and *(iii)* fine grained, and that of aphanitic rocks as : *(i)* microcrystalline, and *(ii)* cryptocrystalline.

(i) **Coarse Grained Texture.** If the grains of a rock are more than 5 mm in diameter, its texture is said to be *"coarse grained"*. Most intrusive igneous rocks have corase grained texture.

(ii) **Medium Grained Texture.** If the size of grains are between 1 mm and 5 mm, the rock is described as *"medium grained"*.

(iii) **Fine Grained Texture.** If the grains are like granulated sugar where their diameter is less than one millimeter, the texture of the rock is called *"fine grained"*. Most extrusive igneous rocks are fine grained.

(iv) **Microcrystalline Texture.** In an aphanitic rick if the mineral grains can be distinguished under a microscope, the rock is said to be *"microcrystalline"*.

(v) **Cryptocrystalline Texture.** In a cryptocrystalline texture, the individual crystals are very small. They are not visible under the microscope but their presence can be felt as they react to the polarized light.

5.6.3. Shape of Crystals

The grains of an igneous rock are called *"euhedral"* if they show well developed crystal faces, and if the crystal faces are partly developed, they are described as *"subhedral"*. The term *"anhedral"* is used for those grains in which crystal faces are absent.

5.6.4. Mutual Relations of Grains

Depending on mutual relations of grains, the textures of igneous rocks may be classified into four major groups : *(i)* equigranular texture, *(ii)* inequigranular texture, *(iii)* directive texture, and *(iv)* intergrowth texture.

Equigranular Textures. Igneous rocks containing mineral grains of more or less equal size are said to have an *"equigranular texture"*. Equigranular textures are of the following types.

(i) **Panidiomorphic Texture.** When most of the grains are euhedral, the texture of rock is called *"panidiomorphic"*. This texture is usually found in lamprophyres.

(ii) **Hypidiomorphic Texture.** When most of the crystals are subhedral, the texture is called *"hypidiomorphic"*. This texture is characterstic of many plutonic rocks such as granites and syenites.

(iii) **Allotriomorphic Texture.** When most of the crystals are anhedral, the texture is called *"allotriomorphic"*. This texture is found in some aplites.

(iv) **Microgranular Texture.** Microcrystalline igneous rocks may also have an equigranular texture. The crystals of these fine grained rocks are commonly anhedral or subhedral. Such a texture is called *"mircrogranular texture"*.

(v) **Orthophyric Texture.** Some highly felspathic rocks such as orthophyres and plagiophyers, possess a fine grained panidiomorphic texture. This texture is called *"orthophyric texture"*.

(vi) **Felsitic Texture.** An igneous rock containing a uniform mass of cryptocrystalline matter is said to have a *"felsitic texture"*.

Inequigranular Textures. Igneous rocks showing variations in the size of mineral grains are said to have the *"inequigranular texture"*. Inequigranular textures are of the following types.

(i) **Porphyritic Texture.** When an igneous rock contains large crystals of some minerals set in a matrix which is much finer grained or even glassy, the texture is called *"porphyritic: [Fig. 5.2 (a)]*. The large crystals are called *"phenocrysts"* and the finer grained material is called *"groundmass"*. Igneous rocks showing porphyritic texture are known as *"porphyries"* such as granite porphyry, diorite porphyry and rhyolite porphyry. This texture develops when some of the crystals grow to a considerable size before the main mass of the magma consolidates into finer and uniform grade material. Porphyritic texture is found largely in volcanic and hypabyssal rocks.

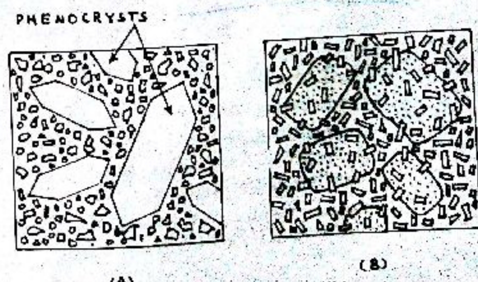


Fig. 5.2. *(a)* Porphyritic texture, *(b)* Poikilitic texture.

(ii) **Poikilitic Texture.** When in a rock smaller crystals are enclosed within larger crystals without common orientation, the texture is called "*poikilitic texture*". This texture is commonly found in syenites and monzonites where orthoclase forms the host mineral [Fig. 5.2 (*b*)].

(iii) **Ophitic Texture.** "*Ophitic texture*" is a special type of poikilitic texture in which bigger crystals of augite enclose smaller laths of plagioclase. If the plagioclase laths are only partly enclosed in the larger grains of augite, the texture is called "*sub-ophitic*". Ophitic texture is characterstic of dolerites.

(iv) **Intergranular and Instersertal Textures.** In many basalts plagioclase laths occur in such a way that they form a network with triangular or polygonal interspaces. These interspaces are filled with minute grains of augite, olivine and iron oxide. Such a texture is called "*intergranular texture*". When glassy or fine grained chloritic or serpentinous materials occur in the interspaces, the texture is called "*intersertal*".

Directive Textures. The textures produced as a result of flow of lavas during their consolidation, are called "*directive textures*". The chief directive textures are as follows.

(i) *Trachytic Texture.* Certain volcanic rocks, such as trachyte, contain felspar laths arranged in lines parallel to the direction of flow of lava. Such a texture is called the "*trachytic texture*", (Fig. 5.3).

(ii) *Hyalopilitic Texture.* In a volcanic rock if felspar laths are found intermixed with glass, the texture is called "*hyalopilitic*".

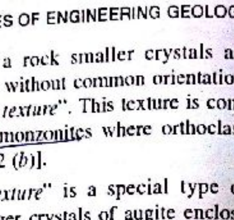


Fig. 5.3. Trachytic texture showing phenocrysts of felspar in fluidal groundmass.

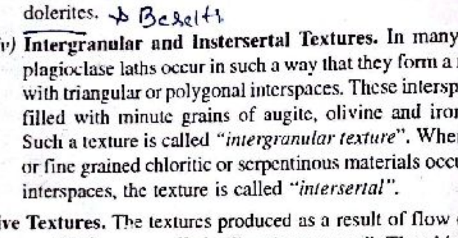


Fig. 5.4. (*a*) Reaction structure. The rim around olivine is made up of pyroxene (*b*) Graphic granite.

Intergrowth Texture. The intergrowth of quartz and orthoclase may take place when they crystallize simultaneously. This intergrowth frequently produces "*graphic texture*" in which skeletons of quartz crystals are embedded in the orthoclase.The two intergrown minerals have the same optical orientation over large areas. A variety of granite, called the "*graphic granite*" shows the graphic texture [Fig. 5.4 (*b*)].

5.7. STRUCTURES OF IGNEOUS ROCKS

Flow Structures. Sometimes an igneous rock shows parallel or sub parallel bands or streaks which are caused by the flow of magma or lava during cooling and crystallization. Such structures are called the "*flow structures*".

Reaction Rims. During formation of igneous rocks, reaction often takes place between early formed minerals and the magma. If this reaction is complete, the early formed minerals disappear altogether. On the other hand, if the reaction is incomplete, reaction products frequently occur around the corroded mineral grains. This zone of reaction products which occurs near the boundary of the mineral grains, is called the "*reaction rim*" [Fig. 5.4 (*a*)]. Reaction rims are of two types : (*i*) coronas, and (*ii*) kelyphitic borders. "*Coronas*" are the reaction rims formed by primary magmatic reactions while "*kelyphitic borders*" are those which develop during secondary processes such as metamorphism.

Xenolithic Structures. Foreign rock fragments are included into the magma when it rises up towards the earth's surface. If they are not digested, they remain entrapped within the mass of the igneous rock and produce heterogeneity in the texture. Such entrapped fragments of foreign rocks are called the "*xenoliths*" and the structure is called the "*xenolithic structure*".

Vesicular Structure. Most lavas contain large amounts of gas and volatiles. These gas and volatiles escape into the atmosphere when they solidify on the earth's surface. As a result of this, numerous gas cavities are formed near tops of lavaflows. These gas cavities are called the "*vesicles*" and the volcanic rock which contains vesicles is said to have a "*vesicular structure*".

Amygdaloidal Structure. The vesicles of volcanic rocks may subsequently be filled by the secondary minerals such as calcite and zeolites. Such filled vesicles are called the "*amygdales*" and the rock is said to have an "*amygdaloidal structure*".

Pegmatitic Structure. If the constituent mineral grains exceed several centimeter in size, the rock is said to have a "*pegmatitic structure*". The pegmatitic structure shows a coarse and very irregular type of crystallization.

In summary, it may be said that the texture and structure of an igneous rock provide numerous clues that suggest the circumstances of formation of the rocks.

5.8. FORMS OF IGNEOUS BODIES

The igneous rock bodies are of two types : *(i)* extrusive, and *(ii)* intrusive.

Extrusive Igneous Bodies. Extrusive igneous rock bodies are formed from magma poured out at the earth's surface. Examples of these are lavaflows.

Intrusive Igneous Bodies. Intrusive igneous bodies are formed by the consolidation of magma at some depth below the earth's surface. Such rock bodies show considerable variations in their size and shape. Examples of intrusive bodies are batholith, stock, dyke, sill, etc. The intrusive bodies are divided into two groups : *(i)* discordant bodies, and *(ii)* concordant bodies.

(i) **Discordant Bodies.** The discordant igneous bodies are those which cut through the overlying strata. Examples of these are batholiths, stocks and dykes.

(ii) **Concordant Bodies.** The concordant igneous bodies are those which lie between rock beds. Such bodies do not show transgressive relation to the rocks they invade. Examples of concordant bodies are sills, lopoliths and laccoliths.

5.8.1 Description of Igneous Bodies

Batholith. Batholiths are large intrusive igneous bodies which have transgressive relation with the adjacent country rocks. Their diameter is usually 100 km or more and their outcrop at the surface is roughly circular or oval. In cross-section batholiths possess steep outwardly dipping contacts and they are thought to be bottomless (*Fig. 5.5*). The composition of batholiths is usually granitic or granodioritic.

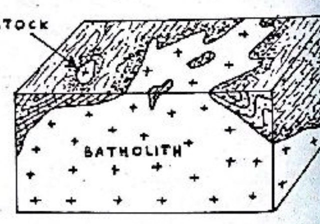


Fig. 5.5. Batholith.

Stock and Boss. Irregular igneous masses of batholithic habit are called *"stocks"*. They are of smaller size and their diameter is usually between 10 to 20 kilometers (Fig. 5.5). The term *"boss"* is applied to those stocks which have an approximately circular outcrop.

Lopolith. A *"lopolith"* is a saucer shaped concordant igneous body which is bent downward into a basin like shape (Fig. 5.6). Its diameter is usually 10 to 20 times its thickness. Thus lopoliths are very much larger than laccoliths. The composition of lopoliths is commonly basic.

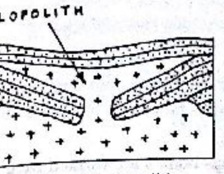


Fig. 5.6. Lopolith.

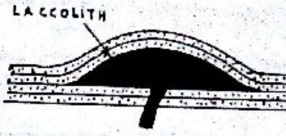


Fig. 5.7. Lacolith.

Laccolith. A *"laccolith"* is a lens shaped intrusive igneous body which causes the overlying beds to arch in the form of a dome (Fig. 5.7). It has a flat base and a domed top. A laccolith may be 2 to 3 kilometers in diameter and several hundred meters in thickness. It differs from a batholith in being much smaller and having a known floor.

Phacolith. *"Phacoliths"* are crescent shaped bodies of igneous rocks. They occupy crests and troughs of folded strata (Fig. 5.8). Phacoliths are formed when igneous material invades the folded region. The igneous material accumulates at the crests and troughs of folds because these are the zones of minimum stress.

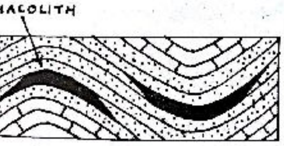


Fig. 5.8. Phacolith.

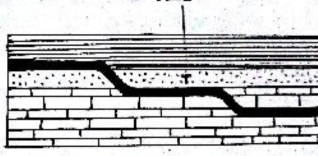


Fig. 5.9. Sill.

Sill. A *"sill"* is a sheet like igneous body which runs parallel to the bedding planes of the pre-existing strata (Fig. 5.9). They may be horizontal, inclined or vertical depending upon the attitude of strata in which they are intruded. Sills vary in thickness from a few centimeters to several hundred meters but they are always thin as compared to their length along beds. Sills are commonly made up of dolerites and basalts.

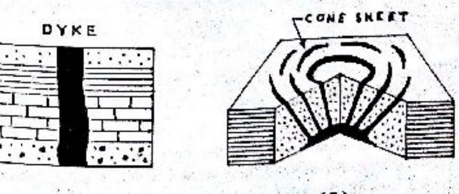


Fig. 5.10. *(a)* Dyke. *(b)* Cone sheets.

Dyke. A *"dyke"* is a wall like igneous body that cuts across the strata of the pre-exsiting rocks [Fig. 5.10 (*a*)]. Dykes are often vertical or steeply inclined. Their thickness varies from a few centimeters to a hundred meter or more. Dykes tend to occur in groups where they run parallel to one direction or are radial to a centre. A dyke having a circular outcrop and a conical form is called a *"ring dyke"* [Fig. 5.10 (*b*)]. Those which have inverted conical form and circular outcrops are described as *"cone-sheets"*. Dykes probably represent a crustal fracture into which the magma was injected.

Volcanic Plug. A volcanic plug is a vertical cylindrically shaped igneous body which has a roughly oval or circular cross-section (*Fig. 5.11*). It represents the vent of an extinct volcano. Volcanic plugs range in diameter from a few hundred meters to a kilometer or more.

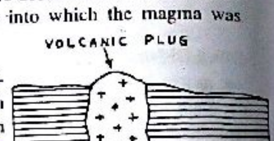


Fig. 5.11. Volcanic plug.

Lavaflows. The volcanic igneous rocks occur as lavaflows. The lavaflows are tabular in shape and may range in thickness from a few meters to several hundred meters. They are formed when lava erupts on the earth's surface from fissures. The lavas cover a very large area before solidifying and considerable thickness of rock is formed from repeated eruptions. The Deccan Traps which cover a vast area in Central India, is a famous example of lavaflows.

5.9. MECHANICS OF INTRUSION

Origin of Magma. The earth's upper mantle, under the crust, is nearly molten. A slight drop in pressure caused by deep faulting etc. completes the melting process. The *"basaltic magma"* originates in this manner.

The *"granitic magma"* can be produced in two ways : (*i*) from melting of continental crustal rocks, and (*ii*) from differentiation of primary basaltic magma. The continental crust is much thicker than the oceanic crust. At considerable depths, the temperature is high enough to melt the continental rocks. It is also believed that pockets of radioactive elements generate enough heat to melt the rocks in the earth's crust. In this way the granitic magma may be produced.

Intrusion of Magma. The magma being lighter than the surrounding rocks, rises slowly to the surface and makes room for itself in the following manner.

(*i*) The magma may melt or react and dissolve the overlying rocks and create a room for itself. This process is called *"magmatic assimilation"*. The magmatic assimilation can not explain the emplacement of large igneous bodies which have quite sharp contact with the country rocks.

(*ii*) The magma may push aside the overlying country rocks and make a place for itself. This process is called the *"intrusion"*. Laccoliths, sills and dykes are believed to have been emplaced by this method.

(*iii*) The magma forces its way into cracks present in the overlying rocks and breaks off blocks of various sizes. In this way a room is created by quarrying the overlying rocks. This process is called *"magmatic stoping"*. Major intrusive bodies, such as batholiths, have been emplaced by this method.

5.10. FORMATION OF IGNEOUS ROCKS

Experimental studies of crystallization sequence of minerals from a melt have helped greatly in understanding the origin of igneous rocks. The temperature-composition diagrams involving a liquid phase are called *"liquidus diagrams"*.

Most igneous rocks are multicomponent. They consist of two, three, four or five principal mineral constituents. To study solidification of magma, they are taken in the order of increasing complexity.

5.10.1. Crystallization of Binary Magmas

Nonmixing Constituents. The crystallization of a magma consisting of two non-mixing constituents may be illustrated by the use of the temperature-composition diagram (*Fig. 5.12*). The two end members of the bicomponent system are *A* and *B* which lack solid solution between them. The melting temperatures of pure *A* and *B* are T_A and T_B respectively. The addition of some amount of *B* to a melt of *A* lowers the melting temperature of the liquid that can coexist with A along the curve between T_A and *E*. Here *E* is the *"eutectic point"*. Similarly the melting temperatures of the liquid that can coexist with *B* is lowered by the addition of some amount of substance *A* as shown by the curve between T_B and *E*. The lowest temperature at which crystals and the melt are in equilibrium is T_E.

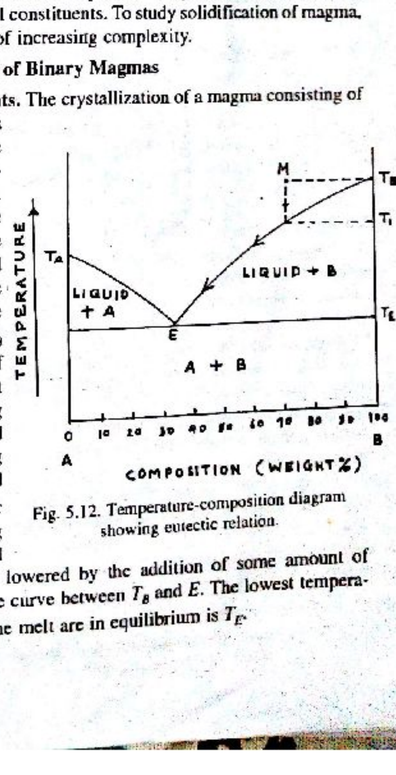


Fig. 5.12. Temperature-composition diagram showing eutectic relation.

Let us now study the crystallization sequence of a melt of composition *M* in *Fig. 5.12*.

(*i*) The melt *M* cools and its temperature drops from T_a without any crystallization.

(*ii*) At temperature T_1 substance *B* begins to crystallize. The crystallization of *B* from the melt continues along the curve from T_B to *E*. As a result of this the content of *A* in the melt increases continuously.

(*iii*) At the eutectic point *E* both *A* and *B* crystallize simultaneously at constant temperature T_E untill the melt is exhausted. At this point no further change in composition of the melt occurs. "*Eutectic*" is the constant proportion in which the two constituents crystallize simultaneously.

Mixed Crystals. When the two components are isomorphus and miscible in all proportions in solid state, they form "*mixed crystals*". The plagioclases are good examples of these types of crystals. The crystallization of mixed crystals from a melt can be represented by a temperature-composition diagram shown in Fig. 5.13. Complete solid solution exists between the two end members *A* and *B*. The

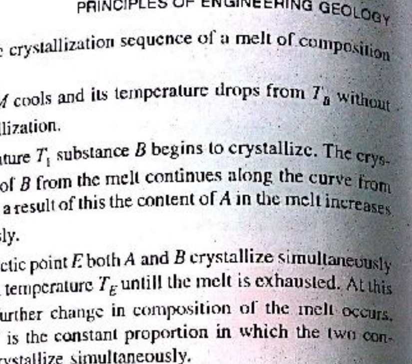


Fig. 5.13. Temperature-composition diagram of a binary system showing solid solution relation.

melting point of pure *A* is T_A and that of pure *B* is T_B. A mixed-crystal does not melt at a definite temperature, but melting is spread over an interval the lower limit of which is fixed by the "*solidus*" and the upper limit by the "*liquidus*". In Fig. 5.13 the upper curve is "*liquidus*". It represents the locus of melt compositions in equilibrium with crystals. The lower curve is known as "*solidus*". It is the locus for the composition of the crystalline phases in equilibrium with the melt. Let us study the crystallization of a melt of composition *M* and temperature T_B.

(*i*) The crystallization of the melt *M* starts at temperature T_1 and crystals of composition *D*(*A*–14%, *B*–86%) begin to form. As

these crystals contain greater amount of *B*, the melt becomes enriched in *A* and its composition moves along the liquidus curve towards *A*.

(*ii*) Due to continual lowering of temperature, the crystals of original composition *D* react with the melt and their composition changes in the direction of the arrow on the solidus curve. As a result content of *A* will increase in both the crystalline product and the melt with falling temperature.

(*iii*) The crystallization stops at temperature T_2 when the crystals have the same composition as that of the original melt *M*. If the temperature is lowered further the composition of the crystals will remain constant at composition *M*.

5.10.2. Crystallization of Ternary Magmas

The crystallization of three component magma can be represented by a triangular diagram. An example of such a diagram is shown in *Fig. 5.14* in terms of three components : (*i*) albite, (*ii*) anorthite, and (*iii*) diopside. The contours in this diagram represent melting temperatures and are known as

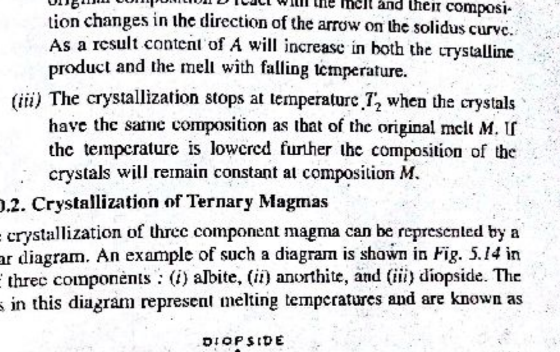


Fig. 5.14. Crystallization of ternary system diopside, albite, anorthite.

"*isotherms*". The surface defined by these isotherms is called "*liquidus surface*". Let us study the crystallization of a magma of composition *F*. The composition *F* represents 50% diopside, 25% albite and 25% anorthite. In Fig. 5.14 there is one boundary curve which separates the field of plagioclase from field of diopside. The point *F* is in the diopside field and represents a temperature 1275°C.

(*i*) As the temperature falls, diopside begins to crystallize. With the separation of diopside the liquid is enriched in albite and anorthite, and the point *F* moves downwards in the direction of the arrow. Ultimately it reaches the boundary of the plagioclase field at G (temperature 1235°C).

(ii) Point G represents 17% diopside crystals and 83% liquid. Here anorthite-rich-plagioclase (Ab_1An_4) starts crystallizing. With the separation of crystals of both diopside and An-rich-plagioclase, the composition of the melt moves along the boundary curve in the direction of the arrow. It means that the melt progressively becomes rich in albite.

(iii) With falling temperature the earlier formed crystals of plagioclase react with the melt and their composition changes continuously. For example, at *K* plagioclase of composition *L* (Ab_1An_2) separates out and all earlier crystals of plagioclase will also change over to this composition.

(iv) All the liquid disappears at *M* and the plagioclase arrives at the composition Ab_1An_1. The composition of diopside, however, remains unchanged.

In the above discussion perfect equilibrium is assumed throughout the crystallization. If however the equilibrium between crystals and liquid is not maintained due to rapid cooling, new plagioclase will coat the early ones thereby forming zoned crystals. Magmas that give rise to igneous rocks, are made up of several components and their crystallization is rather a complex process.

5.11. ORIGIN OF IGNEOUS ROCKS

The mineral composition of an igneous rock is determined by the chemical composition of the magma from which it crystallized. Because a large variety of igneous rocks exists, it was originally thought that an equally large variety of magmas also existed. Later on geologists found that only two types of magma existed and all types of igneous rocks were derived from them. These magmas are *(i)* acid magma, and *(ii)* basic magma.

Acid Magma. The magma which is rich in Si, Na and K, and poor in Ca, Mg and Fe is called *"acid magma"*. It results from melting of the earth's crust itself as a part of the rock cycle. Acid magma produces *"acid rocks"* such as granites and rhyolites.

Basic Magma. The magma which is rich in CA, Mg and Fe, and poor in Si, Na and K, is called *"basic magma"*. It originates due to partial melting of rocks lying beneath the earth's crust. Basic magma gives rise to *"basic rocks"* such as gabbro and basalt.

The two magma theory was also discarded soon and it was suggested that a single magma of basaltic composition could produce rocks of varying mineral composition. The process by which the primary basaltic magma splits up into fractions that give rise to rocks of various types, is called *"differentiation"*.

5.11.1. Differentiation

The process by which a magma splits into parts having different composition, is called *"differentiation"*. These parts on cooling and solidification produces rocks of different types. Differentiation frequently takes place during cooling of magma. The various processes that operate during differentiation are : *(i)* liquid immiscibility, *(ii)* fractional crystallization, *(iii)* gravity settling, *(iv)* gaseous transfer, and *(v)* filterpressing.

Liquid Immiscibility. A magma may split up into two immiscible liquid fractions of different composition like oil and water, as a result of cooling. Subsequent crystallization of these immiscible parts gives rise to different types of rocks. Liquid immiscibility, however, does not occur between fluid rockforming silicates and therefore its role in causing differentiation of magma is insignificant. The only well-known case of liquid immiscibility is between sulfides and silicates.

Fractional Crystallization. As soon as a magma starts crystallizing, differentiation begins. Differentiation is brought about in two ways : *(i)* through localization of crystallization, and *(ii)* through relative movement of crystals and liquids.

Crystallization may be localized at a cooling margin. As crystallization proceeds, the peripheral parts of the mass get impoverised in the crystallizing substance. The supply of this substance is believed to be maintained by ionic diffusion or convection currents from all parts of the magma. Thus in an igneous mass concentration of basic minerals may occur near the margins and acidic minerals may segregate in the central part.

It was, however, found that ionic diffusion or convection currents play very little role in causing fractional crystallization.

Gravity Settling. Heavy crystals formed during the early phase of crystallization of a magma have a tendency to sink down. This process of sinking is controlled by the vescosity of the magma and by the size, shape and density of the crystals. Settling of crystals under gravity is an effective process of differentiation. This process acts simultaneously with fractional crystallization. Many cases are known where segregation of olivine, pyroxene, magnetite and other heavy minerals are found near the base of an intrusive body.

Gaseous Transfer. With release of pressure, the magmatic gases and volatile compounds tend to migrate upward in the direction of lessened pressure. Their movement generates a sort of convection which causes separation of some of the magmatic constituents. Deposits of sulfide metallic ores that occur near the apices of some igneous bodies are believed to have formed in this way.

Filter Pressing. In mountain building regions lateral pressure prevails. When the lateral pressure acts on a crystallizing magma, it drives out the residual fluid from the crystalline mesh. This results in the separation of the residual fluid from the solid phase. In the new location the residual fluid crystallizes and forms a rock much different from the first. This process of differentiation is called *"filter pressing"*.

5.11.2. Assimilation

A magma while rising up towards the earth's surface can engulf fragments of country rocks through which it passes. If these fragments are digested by the magma, the process is called *"assimilation"*. If they are not digested, they remain entrapped within the mass of the crystallized magma. Such entrapped fragments of country rocks are called *"xenoliths"*.

As assimilation involves remixing of rocks in the magma, it may be regarded as the reverse of differentiation. Assimilation also produces variation in the composition of igneous rocks. Igneous rocks containing partly digested xenoliths are called *"hybrid rocks"*. In hybrid rocks mutual reactions take place between xenoliths and the invading magma. As a result the acid magma is basified and the basic xenoliths are acidified.

Because magmas usually have a limited amount of super heat, their capacity to digest xenoliths is not much. They can assimilate xenoliths only upto 10% of their own mass. Thus the process of assimilation is not of much importance in causing variation in igneous rocks.

5.12. BOWEN'S REACTION SERIES

The cooling and crystallization of magma is a complex chemical process in which various silicate minerals crystallize in a definite order. The sequence of separation of minerals from a silicate melt is now well established. If a mineral remained in the melt after it crystallized, is would react with the remaining melt and produce the next mineral in the sequence. While studying the crystallization of cooling silicate melts, N.L. Bowen discovered two reaction series : (*i*) continuous reaction series, and (*ii*) discontinuous reaction series.

Continuous Reaction Series. Minerals of a solid solution series generally form a continuous reaction series. The plagioclase felspars with end members anorthite and albite, exhibit such a reaction. In a cooling melt An-rich plagioclases crystallize before the Ab-rich members. With falling temperature there is a continuous reaction between the melt and precipitated crystals and thus the composition of crystals is continuously being changed. Such a solid solution series in which the variation in composition is perfectly continuous, is called *"continuous reaction series"*. If chemical equilibrium is not maintained between melt and crystals during cooling, the resulting crystals may show compositional zoning.

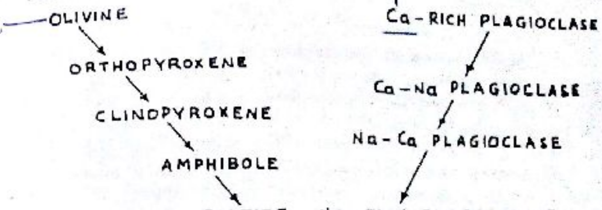


Fig. 5.15. Bowen's reaction series.
(*a*) Discontinuous series, (*b*) Continuous series.

Discontinuous Reaction Series. Discontinuous reactions are those which occur at fairly definite temperatures. Such a reaction takes place in a cooling magma at a certain lower temperature when an early crystallized mineral reacts with the magma to form a new mineral of different composition. A series of Mg-Fe rich minerals that crystallize from a basaltic magma, are found to be related to each other by the discontinuous reaction. Such minerals when arranged in a proper order constitute a *"discontinuous reaction series"*. For example, early formed olivine may react with the melt at a lower temperature to form the pyroxene, then the pyroxene may transform into the amphibole, and biotite may form as a reaction product of earlier crystallized amphibole (Fig. 5.15). The two adjacent minerals of a discontinuous reaction series are said to form a *"reaction pair"*. For example, olivine and pyroxene together form a reaction pair. Minerals of the discontinuous series often exhibit incongruent melting.

A criterion which is common to both the continuous and discontinuous reaction series, is the tendency of one mineral to grow around another. In case of the continuous series, this results in the zoning of mix-crystals and in the discontinuous series this commonly forms reaction rims, coronas, etc.

Bowen's reaction series is illustrated in *Fig. 5.15*. At the upper end where mixtures are more basic, there are two distinct reaction series : (i) the continuous series of the plagioclases, and (*ii*) the discontinuous series, olivines–pyroxenes–amphiboles, etc. Towards the lower end they become less distinct and finally merge into a single series.

The reaction series suggests that as a magma of basaltic composition cools, olivine and An-rich plagioclase may crystallize first. If these minerals remain in contact with the magma, they will tend to change into pyroxene and more Ab-rich plagioclase, and the resulting rock will be a gabbro or a basalt. If, however, most of the early olivine and An-rich plagioclase is removed, as by gravity settling, the composition of the remaining melt will tend to become enriched in Si, Al, Fe^{2+}, K, Na and H_2O and CO_2. Such melt would produce a mineral assemblage consisting mainly of amphiboles, some mica, alkali felspar and quartz. It should be noted that these minerals are relatively low temperature, late stage crystallization products.

5.13. IGNEOUS ROCK TYPES

Granite

Nature. Plutonic rock, Acidic. Light coloured.

Mineral Composition. Essential minerals are K-felspar and quartz. Usually both K-felspar and oligoclase are present. Common accessory minerals are mica or hornblende. Mica is commonly biotite but muscovite may also be present.

Texture. Textures vary from fine to very coarse. Equigranular texture is common. Some varieties may show porphyritic texture.

Varieties. Granites are named according to the main accessory mineral, such as biotite-granite, hornblende-granite, etc. There is a complete series grading from granite to granodiorite. "*Granodiorites*" are those in which plagioclases exceed K-felspar. In these rocks percentage of dark minerals also increases.

Occurrence. Granites commonly occur as major intrusive bodies, such as batholiths and stocks. Many granites are considered to be the result of crystallization from melts at relatively low temperatures.

Syenite

Nature. Coarse grained rock. Light coloured. Composition intermediate between acid and basic.

Mineral Composition. Essential minerals are K-felspar and oligoclase. The average syenite contains from 80 - 85% felspar. Chief accessory minerals are hornblende, biotite and pyroxene.

Texture. Generally equigranular coarse grained. Some varieties may show porphyritic texture.

Varieties. (*i*) **Monzonite.** A syenite with alkali felspar and plagioclase (andesine) in almost equal amounts is called monzonite. It usually contains greater amount of dark minerals. (*ii*) **Nepheline syenite.** A syenite with alkali felspar and more than 5% nepheline is called nepheline-syenite.

Occurrence. Syenites form marginal facies about granite intrusions. They may also occur as stocks and laccoliths.

Diorite

Nature. Plutonic rock. Composition intermediate between acid and basic.

Mineral Composition. Principal mineral is plagioclase felspar (oligoclase to andesine). Hornblende is the chief dark mineral. Usually biotite is also present. Pyroxenes are rare. Mafic minerals are present in sufficient amount to give the rock a dark appearance.

Texture. Equigranualr. Coarse to medium grained.

Occurrence. Diorites occur as marginal facies of granite. They also occur as stocks and bosses.

Gabbro

Nature. Plutonic rock. Basic. Dark coloured.

Mineral Composition. Plagioclase felspar and mafic minerals are present in almost equal amount. Essential minerals are calcic-plagioclase (labradorite to anorthite), pyroxene (augite) and magnetite. Olivine is also present in most gabbros. Accessory minerals are biotite, hornblende and ilmenite.

Texture. Equigranular. Coarse to medium grained.

Varieties. (*i*) **Norite.** Rock containing enstatite and hypersthene (orthorhombic pyroxenes) along with plagioclases is called norite. (*ii*) **Anorthosite.** Rock composed almost entirely of plagioclase is called anorthosite.

Occurrence. Gabbro occurs in the form of intrusive igneous bodies.

Lamprophyre

Nature. Medium grained alkali-rich rocks of basic to intermediate composition are called lamprophyres.

Mineral Composition. Chief mineral constituents are felspars (both orthoclase and plagioclase) and mafic minerals (biotite, pyroxenes or amphiboles).

Texture. Medium grained rock having abundant euhedral crystals. Such a texture is called penidiomorphic texture.

Occurrence. Lamprophyres occur as dykes and sills.

Peridotite

Nature. Plutonic rock. Ultrabasic. Dark coloured.

Mineral Composition. Peridotite is composed almost entirely of ferromagnesian minerals. The mafic minerals are chiefly pyroxenes and olivine in varying proportions. Felspars are negligible. Accessory minerals are hornblende, biotite and spinel. Magnetite, chromite, ilmenite and garnet are frequently associated with peridotites.

remain in contact with the magma, they will tend to change into pyroxene and more Ab-rich plagioclase, and the resulting rock will be a gabbro or a basalt. If, however, most of the early olivine and An-rich plagioclase is removed, as by gravity settling, the composition of the remaining melt will tend to become enriched in Si, Al, Fe^{2+}, K, Na and H_2O and CO_2. Such melt would produce a mineral assemblage consisting mainly of amphiboles, some mica, alkali felspar and quartz. It should be noted that these minerals are relatively low temperature, late stage crystallization products.

5.13. IGNEOUS ROCK TYPES

Granite

Nature. Plutonic rock, Acidic. Light coloured.

Mineral Composition. Essential minerals are K-felspar and quartz. Usually both K-felspar and oligoclase are present. Common accessory minerals are mica or hornblende. Mica is commonly biotite but muscovite may also be present.

Texture. Textures vary from fine to very coarse. Equigranular texture is common. Some varieties may show porphyritic texture.

Varieties. Granites are named according to the main accessory mineral, such as biotite-granite, hornblende-granite, etc. There is a complete series grading from granite to granodiorite. "*Granodiorites*" are those in which plagioclases exceed K-felspar. In these rocks percentage of dark minerals also increases.

Occurrence. Granites commonly occur as major intrusive bodies, such as batholiths and stocks. Many granites are considered to be the result of crystallization from melts at relatively low temperatures.

Syenite

Nature. Coarse grained rock. Light coloured. Composition intermediate between acid and basic.

Mineral Composition. Essential minerals are K-felspar and oligoclase. The average syenite contains from 80 - 85% felspar. Chief accessory minerals are hornblende, biotite and pyroxene.

Texture. Generally equigranular coarse grained. Some varieties may show porphyritic texture.

Varieties. (*i*) **Monzonite.** A syenite with alkali felspar and plagioclase (andesine) in almost equal amounts is called monzonite. It usually contains greater amount of dark minerals. (*ii*) **Nepheline syenite.** A syenite with alkali felspar and more than 5% nepheline is called nepheline-syenite.

Occurrence. Syenites form marginal facies about granite intrusions. They may also occur as stocks and laccoliths.

Diorite

Nature. Plutonic rock. Composition intermediate between acid and basic.

Mineral Composition. Principal mineral is plagioclase felspar (oligoclase to andesine). Hornblende is the chief dark mineral. Usually biotite is also present. Pyroxenes are rare. Mafic minerals are present in sufficient amount to give the rock a dark appearance.

Texture. Equigranualr. Coarse to medium grained.

Occurrence. Diorites occur as marginal facies of granite. They also occur as stocks and bosses.

Gabbro

Nature. Plutonic rock. Basic. Dark coloured.

Mineral Composition. Plagioclase felspar and mafic minerals are present in almost equal amount. Essential minerals are calcic-plagioclase (labradorite to anorthite), pyroxene (augite) and magnetite. Olivine is also present in most gabbros. Accessory minerals are biotite, hornblende and ilmenite.

Texture. Equigranular. Coarse to medium grained.

Varieties. (*i*) **Norite.** Rock containing enstatite and hypersthene (orthorhombic pyroxenes) along with plagioclases is called norite. (*ii*) **Anorthosite.** Rock composed almost entirely of plagioclase is called anorthosite.

Occurrence. Gabbro occurs in the form of intrusive igneous bodies.

Lamprophyre

Nature. Medium grained alkali-rich rocks of basic to intermediate composition are called lamprophyres.

Mineral Composition. Chief mineral constituents are felspars (both orthoclase and plagioclase) and mafic minerals (biotite, pyroxenes or amphiboles).

Texture. Medium grained rock having abundant euhedral crystals. Such a texture is called penidiomorphic texture.

Occurrence. Lamprophyres occur as dykes and sills.

Peridotite

Nature. Plutonic rock. Ultrabasic. Dark coloured.

Mineral Composition. Peridotite is composed almost entirely of ferromagnesian minerals. The mafic minerals are chiefly pyroxenes and olivine in varying proportions. Felspars are negligible. Accessory minerals are hornblende, biotite and spinel. Magnetite, chromite, ilmenite and garnet are frequently associated with peridotites.

Texture. Equigranular. Usually coarse grained.

Varieties. (i) **Dunite.** The rock composed almost wholly of olivine is called dunite. (ii) **Pyroxenite**. The rock composed essentially of pyroxenes is called pyroxenite. (iii) **Kimberlite.** A variety of altered peridotite in which diamonds are found, is called kimberlite.

Rhyolite

Nature. Dense fine grained rock. Volcanic equivalent of granite. Acidic. Light coloured (commonly white, grey or pink).

Mineral Composition. Mineral composition of rhyolite is similar to that of granite. Essential minerals are alkali felspars and quartz.

Texture. Fine grained. Porphyritic texture is often found where phenocrysts of felspar are set in a finely crystalline or glassy groundmass. Rhyolites may show a flow structure giving a banded or streaked appearance to the rock.

Varieties : (i) **Obsidian.** Completely glassy rock of acidic composition is called obsidian. It shows vitreous lustre. Colour of the rock is brown, black or green. (ii) **Pitchstone.** A black coloured glassy rock having a pitch like lustre is called pitchstone. (iii) **Pumice.** It is a glassy rock of acidic composition. It contains abundant vesicles due to which the rock takes the form of a light spongy mass. Pumice is formed on the surface of acid lavas.

Occurrence. Rhyolites commonly occur in lavaflows.

Trachyte

Nature. Volcanic equivalent of syenite. Acidic. Light coloured.

Mineral Composition. Mineral composition is similar to syenite. It is thus composed chiefly of alkali felspars with some mafic minerals.

Texture. Fine grained. Porphyritic texture. Phenocrysts of sanidine or felspars are embedded in the groundmass of minute felspar crystals. Banding or streaking due to flow is common in the trachytes. As a result of flow the tabular felspar crystals frequently show a subparallel orientation which is so common in trachytes that it is called *"trachytic texture"*. Unlike the rhyolites, glass is seldom found in the groundmass.

Andesite

Nature. Volcanic equivalent of quartz-diorite. Composition intermediate between acid and basic.

Mineral Composition. The rock is mainly composed of plagioclase (oilgoclase or andesine). Hornblende, biotite, augite or hypersthene may be present frequently as phenocrysts. K-felspar and quartz are absent or present in amounts of less than 10%.

Texture. The rock is fine grained with porphyritic texture. Felspars and mafic minerals occur as phenocrysts.

Varieties. Andesites are named according to the prominent ferromagnesian mineral present, such as hornblende-andesite or biotite-andesite.

Occurrence. Andesites occur as volcanic lavaflows.

Dolerite

Nature. Dark coloured rock of fine grained texture.

Mineral Composition. Dolerite is mainly composed of calcic-plagioclase and augite. Augite forms nearly 50% of the rock.

Texture. Medium to fine grained. Inequigranular porphyritic.

Varieties. An altered form of dolerite that has a dull green colour is called **"diabase"**.

Occurrence. Dolerites occur mainly as dykes and sills.

Basalt

Nature. Volcanic equivalent of gabbro. Composition basic to ultrabasic. Dark coloured.

Mineral Composition. Essential minerals are augite, calcic-plagioclase and iron oxide. Usually olivine is also present. Labradorite felspar is the chief constituent of the groundmass whereas more calcic-plagioclase (bytownite or anorthite) may occur as phenocrysts. Augite is frequently found both as phenocrysts and in the groundmass, but olivine as a rule occurs only as phenocrysts.

Texture. Fine grained to glassy. Porphyritic texture common. Abundant gas cavities may occur near the top of basalt flows to make the rock vesicular.

Varieties. (i) **Olivine - basalt**. When olivine is present in notable amount. (ii) **Quartz-basalt.** When quartz is present. (iii) **Trachylyte.** Basaltic glass is called trachylyte. (iv) **Ankaramite.** Ultrabasic basalt rich in augite is called ankaramite. (v) **Oceanite.** Ultrabasic basic basalt rich in olivine is called oceanite.

Occurrence. Basalts are the most abundant of the volcanic rocks and form extensive lavaflows. In addition to this, basalt is widely found forming many small dykes.

Pegmatites

Nature. Extremely coarse grained. Commonly associated with granites. Their composition is usually granitic.

Mineral Composition. Most pegmatites contain the common minerals found in granites but they are of externely large size. These minerals are quartz, felspar and mica. Crystals of the minerals measuring 25 centimeters across are common. Tourmaline, beryl, topaz, apatite, monazite and fluorite may be found associated with pegmatites.

Texture. Extremely coarse grained and irregular. The constituent minerals are 3 cm or more in size.

Varieties. A peculiar textural variety known as **"graphic granite"** is commonly found in pegmatites. This rock contains crystals showing intergrowth of quartz and felspar.

Occurrence. Pegmatites are closely related genetically to large masses of plutonic rocks. They may be found as veins or dykes traversing the plutonic igneous rock. More commonly they extend out from it into the surrounding country rocks. The coarse grains of pegmatites are largely the result of the presence of volatiles during crystallization rather than the result of slow cooling.

REVIEW QUESTIONS

1. What is texture of an igneous rock. Discuss briefly the types of textures found in igneous rocks.
2. Enumerate the important igneous rocks and give their distinguishing characters.
3. What is magmatic differentiation ? Describe the processes that brings about differentiation of magma.
4. Classify igneous rocks into various groups. Give the tabular classification of igneous rocks.
5. Discuss magmatic differentiation. Explain the reaction series of Bowen.
6. Describe the various textures and structures found in igneous rocks.
7. What is eutectic ? Describe the crystallization of magma consisting largely of two constituents.
8. Discuss how the knowledge of the crystallization of silicate melts helps us in understanding the origin of igneous rocks.
9. (*a*) Describe the various structures found in igneous rocks.
   (*b*) Write a short account of the fractional crystallization of basaltic magmas.
10. Write short notes on the following.
    Reaction rim, Batholith, Dyke and sill, Xenolithic structure, Rock cycle, Assimilation, Extrusive rocks, Porphyritic texture.

6 Rocks-II : Sedimentary and Metamorphic Rocks

6.1. SEDIMENATARY ROCKS

The total amount of sedimentary rocks that exists in the upper 16 kilometers of the earth's crust is estimated to be only about 5%. These rocks are found chiefly as an extensive cover over the continents. *"Sedimentary rocks"* are formed by consolidation and cementation of sediments deposited under water. Sedimentary rocks also include the rocks formed by accumulation of chemically precipitated or organically derived material. Sedimentary rocks occur in layers and frequently contain fossils.

6.2. FORMATION OF SEDIMENTARY ROCKS

The formation of sedimentary rocks takes place in three stages: (*i*) weathering and erosion of preexisting rocks, (*ii*) sedimentation, and (*iii*) lithification and diagenesis.

Weathering and Erosion. During weathering and erosion, the preexisting rocks and their constituent minerals are broken down. The material thus produced is called the *"sediment"*. The sediments are usually transported and deposited in areas of accumulation by the action of water or less frequently by glacial or wind action. During transportation, the sediments are roughly sorted and deposited according to size. Bigger rocks fragments, such as gravel, settle first, sands are next in order and clays are deposited in the last. The minerals which are dissolved by the water, travel in solution.

Sedimentation. The process of accumulation of sediments at a site of deposition is called the *"sedimentation"*. The material carried in solution precipitates and accumulates. Sedimentation is the intermediate stage in the formation of sedimentary rocks.

Lithification and Diagenesis. *"Lithification"* is a process by which soft and loose sediments are converted into hard and firm rocks. This process is also called "*consolidation*". During this process many physical and chemical changes take place within the sediment. Such changes are called the diagenetic changes and the process is described as "*diagenesis*". The diagenesis includes three processes : (*i*) compaction, (*ii*) cementation, and (*iii*) recrystallization.

(*i*) **Compaction.** Compaction occurs when the weight of overlying layers compresses the sediments below. As the grains of sediments are pressed closer and closer together, there is considerable reduction in pore space and volume. Fine grained sediments, such as clays are consolidated more effectively by this process.

(*ii*) **Cementation.** When water circulates through the pores of coarse grained sediment, dissolved mineral matter is precipitated between the grains which causes cementation. The most common cementing materials are silica, calcium carbonate, iron oxides and clay minerals. The identification of the cementing material is a relatively simple matter. Calcite cement will effervesce with dilute hydrochloric acid, while iron oxide gives the rock a characterstic red, orrange or yellow colour. Silica, the hardest of the cements, produces the hardest sedimentary rocks.

(*iii*) **Recrystallization.** Although most sedimentary rocks are lithified by compaction, cementation or a combination of both, some are consolidated chiefly by the recrystallization of their constituents. Chemically formed rocks, such as limestones, dolomites, salt and gypsum are the examples of the rocks consolidated by recrystallization.

6.3. CLASSIFICATION

The sediments from which sedimentary rocks are formed, may be divided into two major groups : (*i*) clastic sediments, and (*ii*) non-clastic sediments.

6.3.1. Clastic Sediments

"*Clastic sediments*" are broken fragments of preexisting rocks ranging in size from minute clay particles to very large boulders. Clastic rocks are formed by the mechanical accumulation of grains of clastic sediments. Depending upon the size of constituent grains, the clastic rocks are classified into three groups : (*i*) rudaceous rocks, (*ii*) arenaceous rocks, and (*iii*) argillaceous rocks.

Rudaceous Rocks. These rocks are formed by accumulation of bigger rocks fragments such as gravels, pebbles and boulders. If the grains are rounded, the rock is called "*conglomerate*" and if they are angular, the rock is termed as "*breccia*".

Arenaceous Rocks. These rocks are composed almost entirely of sand grains. When individual grains are rounded, the rock is called "*sandstone*", and "*grit*" if the grains are angular.

Argillaceous Rocks. These rocks are made up of very fine grained sediments. "*Shale*" and "*mudstone*" are typical argillaceous rocks which are composed of clay-sized sediment.

There are some clastic rocks which do not fit into the above said classification. They require consideration of mineral composition also. For example, when appreciable quantities of felspars are present in a sandstone, the rock is called "*arkose*". When the sandstone contains an appreciable quantity of clay as well as angular quartz grains, the rock is called "*graywacke*". In addition there are many clastic rocks which contain grains of more than one size. For example, a rock containing a mixture of sand and silt may be classified as "*sandy siltstone*" or "*silty sandstone*" depending on which particle size dominates.

6.3.2. Nonclastic Sediments

Nonclastic rocks include those sedimentary rocks which are formed by chemical precipitation of minerals from water or by accumulation of remains of animals and plants. They are classified into two groups : (*i*) chemically formed rocks, and (*ii*) organically formed rocks.

Chemically Formed Rocks. These rocks are formed when mineral matter in solution is precipitated from water, usually because of changes in water temperature or in the chemical content of water. Such chemical sediments are derived from the dissolution of materials from older rocks and subsequent transportation of dissolved chemical substances into a sea or lake. On the basis of composition, the chemically formed rocks are classified as follows.

(*i*) **Carbonate Rocks.** "*Limestones*" and "*dolomites*" are the most abundant carbonate rocks. They are formed by the chemical precipitation of calcium carbonate from sea water.

(*ii*) **Salt Rocks.** Evaporation is the major process involved in the deposition of chemical precipitates. The salt deposits formed by the evaporation of saline lakes are called the "*evaporites*". The principal minerals of these deposits are chlorides and sulfates of Na, K, Mg and Ca. Rock-salt, gypsum and anhydrite are by far the most abundant minerals of evaporites. They commonly form massive beds.

(*iii*) **Ferruginous Rocks.** This group includes those rocks which are formed by the chemical precipitation of iron oxides. Such rocks contain a high proportion of iron-bearing minerals such as siderite, hematite, chamosite and pyrite. "*Iron-stone*" is an example of ferruginous rocks.

(*iv*) **Siliceous Deposits.** Siliceous rocks are formed when silica is precipitated from water. Examples of such deposits are flint, chert, jasper and agate.

Organically Formed Rocks. These rocks are composed mainly of remains of animals or plants. Organically formed rocks are subdivided into two groups : (*i*) biochemical rocks,and (*ii*) organic rocks.

(*i*) **Biochemical Rocks.** The biochemical sediment is produced when plants and animals living under water, extract from it dissolved mineral matter, usually calcite, to form shells or other hard parts. These shells accumulate on the ocean floor in great quantities to form sedimentary rocks. An example of the biochemical rock is "*shell - limestone*".

(*ii*) **Organic Rocks.** Rocks containing organic matter belong to this group. An example of such rocks is "*coal*". These are also called the "*carbonaceous rocks*".

6.4. TEXTURE

"*Texture*" means the size, shape and arrangement of grains in a rock. As sediments contain particles of various size, grain size is an important factor for the description of sedimentary rocks. Depending upon the size, particles of sediments are classified into pebbles, gravels, sand, silt and clay, and each of these gives rise to a perticular type of rock. This classification is shown in Table 6.1.

Table 6.1. Particle Size in Sediments

Grade	*Grain Size*	*Rock Type*
Pebble Gravel	10 mm and above 2 mm to 10 mm	Conglomerate
Sand	0.1 mm to 2 mm	Sandstone
Silt	0.01 mm to 0.1 mm	Siltstone
Clay	Less than 0.01 mm	Shale

The grain size of sands varies from 2 mm to 0.1 mm. They are subdivided into four groups : (*i*) "*very coarse sand*" (grain size more than 1.0 mm), (*ii*) "*coarse sand*" (grain size 1 to 0.5 mm), (*iii*) "*medium sand*" (grain size 0.5 to 0.25 mm) , and (*iv*) "*fine sand*" (grain size 0.25 to 0.1 mm).

Sediments which contain grains of various grades in nearly equal amount are said to be "*unassorted*". On the other hand, sediments containing mainly grains of one grade only, are said to be "*well assorted*" or "*graded*". The degree of assortment may be high in many wind deposits and in sediments deposited on gently sloping sea floors. Stream deposits are commonly less well graded. Glacial deposits are generally unassorted.

The shapes of the constituent grains of sedimentary rocks are of considerable significance in the study of texture. The grains of a rock may be

rounded, partially rounded or angular. Grains which have been transported to considerable distances commonly show a high degree of rounding whereas grains that have resulted from disintegration, volcanic explosion or glacial action are commonly angular. In breccias the rock fragments are angular while in conglomerates, they are rounded.

The chemically formed rocks may contain rounded concretions. If they are of the size of a pin head (size 1mm), the texture of the rock is said to be "*oolitic*", and if they are of the size of a pea, the texture is described as "*pisolitic*".

The texture and mineral composition of sedimentary rocks are of great value in determining the nature of the environment at the time when the sediment was deposited. A conglomerate, for example, indicates a high energy environment,such as a swiftly flowing stream where only the coarse material can be deposited. The arkose suggests a dry climate where little chemical alteration of felspar is possible. Carbonaceous shale indicates a low energy, organic rich environment, such as swamp or lagoon.

6.5. STRUCTURAL FEATURES

The important structural features of sedimentary rocks are stratification, lamination, graded bedding, current bedding and ripple marks. Besides these, there are some minor structures such as mud cracks, rain prints, tracks of terrestrial animals, etc. These structures give clues to the past environment.

Stratification. All sedimentary rocks are, in general, characterized by stratification. Deposition of sediments into layers or beds is called the "*stratification*". The planes dividing different beds are called the "*bedding planes*" (*Fig. 6.1*). The thickness of a bed may vary from a few centimeters to many meters. Different beds are distinguished from each other by (*i*) difference in mineral composition, (*ii*) variation in grain size or texture, (*iii*) difference in colour, and (*iv*) variation in thickness.

Lamination. Thin bedding, less than one centimeter in thickness, are called "*lamination*" (*Fig. 6.1*). Lamination is usually found in very fine grained rocks like shale and gives them the characterstic property of fissility. In laminated rocks, the clay and other flaky minerals tend to lie with their flat surfaces parallel to the plane of lamination. It should be noted that lamination refers to parallel arrangements of minerals within a bed whereas stratification refers to a succession of beds separated by bedding planes.

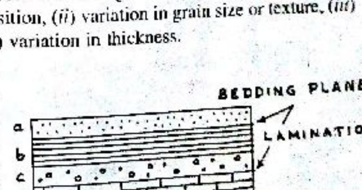


Fig. 6.1. Stratification. Bed '*b*' shows lamination.

Graded Bedding. In *"graded bedding"* each bed shows a gradation in grain size from coarse below to fine above (*Fig. 6.2*). The graded bedding results from rapid sedimentation in water. This structure is commonly found in graywackes. The bottom of a graded bed generally lies on shale and may consist of a coarse grit. It than shows an upward transition towards finer material. At the top it commonly ends in shale.

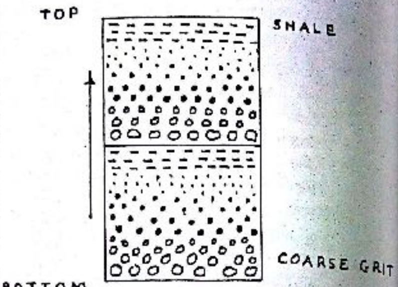


Fig. 6.2. Graded bedding.

Current Bedding. Current bedding is also called the *"cross bedding"*. In this structure minor beds or laminations lie at an angle to the planes of

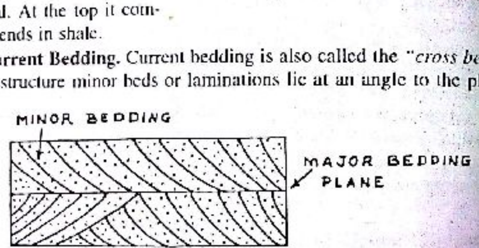


Fig. 6.3. Current bedding.

general stratification (*Fig. 6.3*). These minor beds commonly terminate abruptly at the top where they are overlain by the next current bedded deposit. Current bedding is commonly found in shallow water and wind formed deposits. This structure indicates rapid changes in the velocity and direction of flow of streams or wind carrying sediment. In current bedding, the minor beds are inclined and stacked up in the form a wedge in the direction of water currents or prevailing wind.

Ripple Marks. *"Ripple marks"* are the wavy undulations seen on the surface of bedding planes (*Fig. 6.4*). They are produced by the action of waves and currents in shallow water. This structure may also be formed on the surface of deposits formed by wind. Ripple marks are of two types : (*i*) asymmetrical or current ripple marks, and (*ii*) symmetrical or oscillation ripple marks. The oscillation ripple marks are useful in determining top and bottom of deformed beds.

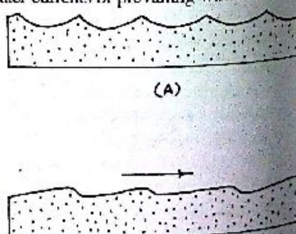


Fig. 6.4. (*a*) Symmetrical ripple marks (*b*) Assymetrical ripple marks.

Minor Structures. The surface of bedding planes may show some minor structures such as mud cracks, rain prints, and tracks and trails of animals. These structures are commonly preserved as casts. *"Mud cracks"* are often found in the fine grained sedimentary rocks that have been exposed to drying under sub-aerial conditions. They form a network of fissures enclosing polygonal areas. Mud cracks are charactersitc of the flood plains of large rivers. A *"rain print"* is a slight shallow depression rimmed by a low ridge which is raised by the impact of the rain drop. It is formed when a brief rain shower falls on a smooth surface of fine grained sediment. *"Tracks and trails"* are the markings indicating the passage of some animal over soft sediment. All these minor structures if found in formations that have been disturbed by severe folding, are of great help in determining the top and bottom of beds.

Concretions. *"Concretions"* are variously shaped masses or nodules of mineral matter found within a sedimentary rock. Their shape may be spherical, ellipsoidal, lenticular or irregular. Concretions generally consist of calcium carbonate or silica and often possess an internal radiating or concentric structure. They are formed by the deposition of mineral matter from percolating solutions about a nucleus. Their chemical composition is generally different from the enclosing rock. They often represent a concentration of one of the minor constituents of the host rock. For example, in limestones there are concretions of chert or flint, in clays concretions are of calcium carbonate or iron sulfide, and in sandstones the concretions are commonly of iron oxide or calcium carbonate.

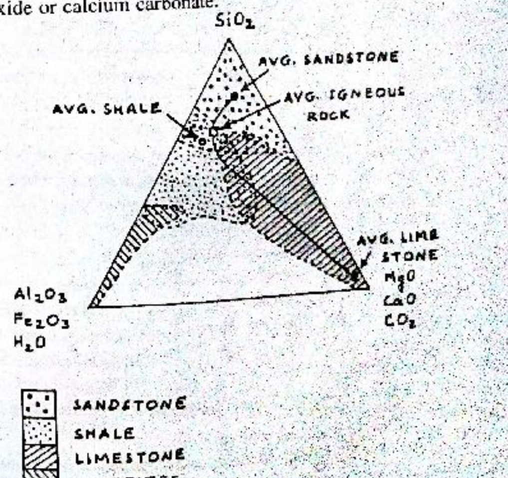


Fig. 6.5. Showing range in composition of common sediments.

6.6. CHEMCIAL COMPOSITION

The range in chemical composition of sedimentary rocks is quite large and in this respect they differ from igneous rocks. For example, a sandstone may contain as much as 99% silica, in banded iron formations the iron oxide content may be as high as 58%, in pure limestones the CaO content may reach 55%. This large range in composition which is illustrated in *Fig. 6.5* (page 191), is caused by weathering cycle. This cycle has a tendency to produce mechanical sediments which are compositionally very different from chemical sediments.

6.7. MINERALOGICAL COMPOSITION

The minerals of sedimentary rocks can be divided into two major groups : (*i*) minerals which are resistant to weathering and (*ii*) minerals which are products of chemical weathering. The relative stabilities of minerals to weathering are shown in Table 6.2. This table shows that quartz is one of the most resistant minerals whereas olivine is easily altered by chemical weathering. The position of minerals shown between quartz and olivine have intermediate stabilities.

Table 6.2. Relative Stabilities of Rockforming Minerals During Weathering

Low stability		Olivine
	Anorthite	
Increasing Stability ↓	Intermediate Plagioclases	Augite, Hornblende
	Albite	
		Biotite, K-felspar, Muscovite
High stability		Quartz

Detrital sedimentary rocks consist mainly of the most resistant rock-forming minerals such as quartz, K-felspar, mica and sometimes plagioclase. Small amounts of garnet, zircon and spinel may also occur. Sedimentary rocks which are formed from the inorganic or organic precipitation of minerals frequently contain calcite, argonite, gypsum, halite, hematite, siderite and chert.

In addition to the detrital minerals and chemical precipitates, sedimentary rocks may contain clay minerals (Kaolinite, Montmorillonite, Illite) and chlorite. These minerals result from the weathering of earlier primary silicates, such as felspars, olivines and pyroxenes.

6.8. SEDIMENTARY ROCK TYPES

Conglomerate

Nature. Consolidated gravels. Colour variable.

Mineral Composition. Rounded pebbles are set in a fine grained matrix. The matrix commonly consists of sand or silt and it is cemented by silica, calcium carbonate or iron oxide. The individual pebbles may be entirely composed of quartz or may be rock fragments that have not been decomposed.

Texture. Very coarse grained.

Varieties. Fine conglomerates grade into coarse sandstones. If the rock contains angular or subangular fragments, it is called **"breccia"**. The angularity of rock fragments in breccia suggests that this material could not have travelled very far from its source.

Sandstone

Nature. Arenaceous. Colour variable according to the type of cementing material. Rocks having silica or calcite as their cementing material are light in colour, those that contain iron oxide are red to reddish brown.

Mineral Composition. Quartz is the chief mineral constituent. Small amounts of felspar, mica, garnet, etc. may also occur. Cementing material may be silica, calcite, iron oxide, clay or chlorite.

Texture. Sandstones are composed almost entirely of well sorted, subangular to rounded sand grains. The texture of sandstone is : (*i*) *"coarse grained"* when the size of grains is between 2 to 0.5 mm, (*ii*) *"medium grained"*, when the size of grains is between 0.5 to 0.25 mm, and (*iii*) *"fine grained"*, when the size of grains is between 0.25 to 0.1mm.

Structure. The common structures seen in the sandstones are stratification, current bedding, ripple marks and rain prints.

Varieties. (*i*) **Orthoquartzite.** White siliceous sandstones in which most of the grains as well as cement consist of quartz, are called orthoquartzite. (*ii*) **Grit.** It is a sandstone containing sharply angular grains. (*iii*) **Arkose.** A coarse grained sandstone containing notable amounts of felspar is called arkose. (*iv*) **Graywackes.** It is a grey coloured rock containing poorly sorted angular fragments of quartz and basic igneous rocks, and fine grained chlorite or clay material. Graywackes may contain as much as 30% fine grained clay or chlorite or both. The finer grained grawackes grade into the shales. (*v*) **Glauconite sandstone.** It is a green coloured sandstone containing a mineral called glauconite.

Shale

Nature. Argillaceous. Colour variable. Shales are often soft and can be scratched by a knife.

Mineral Composition. Shales are composed mainly of clay minerals like kaolinite, montmorillonite and illite. Small amounts of other minerals such as quartz, mica and chlorite are also present.

Texture. Very fine grained with grain size less than 0.01 mm.

Structure. Lamination, ripple marks and some organic structures may be present.

Varieties. (*i*) **Calcarious shale.** When considerable amount of calcium carbonate is present. (*ii*) **Ferruginous shale.** When considerable amount of iron oxide is present. (*iii*) **Carbonaceous shale.** When considerable amount of carbonaceous (organic) matter is present. (*iv*) **Siltstone.** It is a rock containing compact silt (grain size 0.01 to 0.1 mm). (*v*) **Mudstone.** It is a structureless rock containing compacted mud.

Limestone

Nature. Calcarious rock. Formed chemically or organically. Commonly white, grey or cream coloured. Often contains fossils. Limestones are identified by their softness, fossil content and effervescence in dilute hydrochloric acid.

Mineral Composition. Calcium carbonate in the chief constituent. Magensium carbonate is also present is variable amounts. Chalcedony, silt and clays are present as impurities. Some limestones may also contain calcarious shells of marine animals.

Texture. Limestone is a fine grained rock. It is commonly compact and massive. Some limestones may have oolitic structure. Organic structures are also common.

Varieties. The important varieties of limestones are as follows. (*i*) **Chalk.** The porous fine grained and generally friable limestone composed mainly of foraminiferal shells, is know as chalk. (*ii*) **Oolitic limestone.** This limestone is mainly composed of rounded grains resembling fish roe. It is believed to have been formed by chemical precipitation. Under the microscope each grain (Oolith) is seen to be made up of concentric layers of $CaCO_3$, often with a bit of shell at the centre. (*iii*) **Marl.** Impure limestones in which the percentage of clay and calcium carbonate is almost equal, are known a "*marl*".

Dolomite

Nature. Dolomites resemble limestones.

Mineral Composition. The chief constituent of dolomite rock is dolomite mineral [$CaMg(CO_3)_2$]. It may also contain some calcite. Dolomites are generally not formed by original chemical precipitation. They are formed when calcium carbonate of limestone is replaced by dolomite. This process is called "*dolomitization*". Depending upon the relative proportion of calcite and dolomite present, the limestones and dolomites are classified as follows.

(*i*) *Limestones.* Those rocks which contain more than 90% calcite and less than 10% dolomite.

(*ii*) *Dolomitic limestones.* Those rocks which contain 90 - 50% calcite and 10—50% dolomite.

(*iii*) *Calcitic dolomites.* The rocks which contain 50 - 10% calcite and 50—90% dolomite.

(*iv*) *Dolomites.* Those rocks which contain less than 10% calcite and more than 90% dolomite.

Texture. Dolomite is a fine grained rock. It is commonly compact and massive.

Iron Formation

Nature. Iron-formation is a banded iron rock. It is formed due to chemical precipitation of iron oxide and chert.

Mineral Composition. The iron-formation consists mainly of chert-magnetite, chert-hematite, and chert-hematite-magnetite. Other minerals that are commonly present are siderite, ankerite and chamosite.

Texture and Structure. In these rocks the sedimentary banding is generally well preserved.

Laterite

Nature. Colour is often red, brown or yellow. Laterite is a residual product of weathering in hot humid climate. It occurs as mantle over bed rocks.

Minerals Composition. Laterites are essentially clays rich in aluminium and iron hydroxides with minor amounts of silica.

Texture. Porous and concretionary.

Varieties. Laterites rich in aluminium hydroxides are called **"bauxites".** Bauxites commonly show "*pisolitic*" structure.

6.9. METAMORPHIC ROCKS

"*Metamorphic rocks*" are formed from the older rocks when they are subjected to increased temperature, pressure and shearing stresses at considerable depth in the earth's crust. The older rocks may be either sedimentary, igneous or other metamorphic rocks. During metamorphism recrystallization takes place essentially in the solid state and new minerals and new textures are produced.

6.9.1. Agents of Metamorphism

The agents which bring about metamorphic changes in the rocks are: (*i*) heat, (*ii*) uniform pressure, (*iii*) directed pressure or stress, and (*iv*) chemically active fluids and gases.

Heat. Within the earth, temperature increases with depth and as a result appreciably high temperature exists at great depths. In the outer parts of the earth, the common cause for elevated temperature is the intrusion of hot igneous bodies.

Uniform Pressure. The static pressure on rocks is caused by deep burial. This pressure is due to the weight of the overlying rocks. As temperature gradient exists within the earth, the static pressure is usually associated with higher temperatures.

Directed Pressure. Directed pressure or stress operates during folding movements that accompany mountain building. Generally directed pressure plays an important role near the earth's surface. As the depth increases, the effect of directed pressure decreases and that of uniform pressure increases.

Chemically Active Fluids and Gases. Chemically active fluids and gases when pass through the pores of rocks, they bring about changes in their original composition. The source of these chemical agents is generally the intrusive igneous body within the country rocks.

6.9.2. Processes of Metamorphism

The processes which operate together in the effected rock to bring about metamorphism are : (*i*) granulation, (*ii*) plastic deformation, (*iii*) recrystallization, and (*iv*) metasomatism.

Granulation. Pressure shatters rocks and the friction is so great that the rock are partially melted. This process where crushing of rocks takes place without loss of coherence, is called the *"granulation"*.

Plastic Deformation. When a solid is subjected to stresses, its shape changes. On the removal of stresses if the solid does not regain its original shape, its is said to be plastically deformed.

Recrystallization. "Recrystallization" means either the formation of new minerals or formation of new crystals of the pre-existing minerals. The pore fluid of rocks is thought to facilitate this process. Recrystallization causes mineralogical and textural changes in rocks during metamorphism.

Metasomatism. "Metasomatism" is the process in which the original composition of rocks are changed primarily by the addition or removal of material. This change is caused by the movement of hydrothermal fluids through rocks usually under high temperatures and pressures.

All the above said processes usually operate in combination to produce metamorphic rocks. During granulation individual crystals are plastically deformed. This deformation initiates recrystallization. During recrystallization the structures of original minerals are changed. They are elongated or flattened in the direction of minimum stress. Thus new textures are produced in the rocks. New minerals are formed as a result of exchange of elements and compounds.

6.10. TYPES OF METAMORPHISM

The main types of metamorphism are : (*i*) cataclastic metamorphism, (*ii*) dynamic metamorphism, (*iii*) contact metamorphism, (*iv*) plutonic metamorphism, (*v*) regional metamorphism, (*vi*) metasomatism, and (*vii*) retrogressive metamorphism.

6.10.1. Cataclastic Metamorphism.

The metamorphism in which only the directed pressure or lateral stress plays dominant role, is called the *"cataclastic metamorphism"*. These stresses are caused by earth movements such as folding and faulting. They operate mainly in the upper part of the earth's crust where the temperatures are moderately low. Due to these stresses rocks are crushed, ground and deformed. New rocks thus formed are called *"cataclastic rocks"*. They show mainly mechanical crushing with little new mineral formation. Examples of cataclastic rocks are *"mylonites"* and *"fault breccias"*.

6.10.2. Dynamic Metamorphism

A metamorphism which is associated with high pressure with little increase in temperature, is called the *"dynamic metamorphism"*. In this case a new rock is formed partly by the mechanical effects of flow and partly by the growth of new minerals that develop in the direction of flow. Slates which possess flow cleavage, are perhaps the best example of a dynamically metamorphosed rock.

6.10.3. Contact Metamorphism

Contact metamorphism is also called the *"thermal metamorphism"*. This metamorphism is caused due to local heating of rocks by the intrusion of hot igneous bodies nearby. The zone of contact metamorphic rocks which occurs surrounding the intrusion is called *"aureole"* (*Fig. 6.6*). As temperature decreases away from the intrusive, the outer rocks in the aureole are less intensely metamorphosed than that of the innermost rocks. Thus depending upon the degree of alteration, the rocks in the aureole can be divided into concentric zones which may differ greatly in mineral assemblages.

In the contact metamorphism heat plays dominant role and its general effect is to promote recrystallization. In this process, minerals grow haphazardly in all directions and the metamorphic rock acquires a granular fabric which is called the *"hornfels texture"*. Contact metamorphic rocks do not show schistosity.

During contact metamorphism transfer of magmatic vapours and gases from an igneous body into the country rocks often takes place. These emanations react with the country rocks and form new minerals. Such a process is called the *"pneumatolytic metamorphism"*. A localized burning or baking effect may be produced at the contact of an igneous body and the country rocks. This effect is described as the *"pyrometamorphism"*.

Contact Metamorphism of Shales. Where argillaceous rocks such as shales, come into contact with an igneous intrusion, a metamorphic aureole is formed. Within this aureole metamorphic zones of increasing intensity can be traced as the contact is approached. These zones are as follows.

(i) *Outermost Zone of Spotted Slate.* The spots in the spotted slates may be composed either of a single mineral or a fine grained mass of different minerals.

(ii) *Intermediate Zone of Spotted Hornfels.* Nearer the igneous intrusion, the cleavage of the slate disappears and the rock becomes harder. The spots in this rock are now due to small crystals of andalusite and the groundmass recrystallizes to form mica and quartz.

(iii) *Innermost Zone of Hornfels.* Close to the contact of intrusion thorough recrystallization takes place and hornfels, a fine grained hard rock is formed (*Fig. 6.6*).

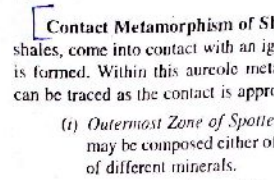


Fig. 6.6. Contact metamorphic aureole.

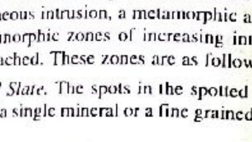


Fig. 6.7. Prophyroblast distorting groundmass.

In the hornfels porphyroblasts may be present. "*Porphyroblasts*" are the large, well shaped crystals which are set in a fine grained matrix (*Fig. 6.7*). These may reach 4 or 5 centimeters in size. Porphyroblasts crystallize late in the solid rock during metamorphism. The minerals which commonly occur as porphyroblasts in the contact metamorphic hornfelses are cordierite, andalusite and sillimanite. Hornfels may form from any type of parent rock. Metacrysts or porphyroblasts are not limited to contact metamorphic rocks. They also occur in regionally metamorphosed rocks.

Contact Metamorphism of Other Rocks. The contact metamorphism of sandstones, graywackes, impure limestones and basic igneous rocks may be summarized as follows.

1. Pure sandstones recrystallize to quartzites composed of quartz with perhaps a little biotite and magnetite derived from the impurities of clays and iron oxide respectively. Pure limestones yield calcite marbles.

2. When medium to coarse grained sedimentary rocks such as graywackes and impure sandstones, are subjected to contact metamorphism, aluminium bearing minerals (*e.g.* felspars) are converted into micas and garnets. When carbonate minerals, such as calcite, are present as impurities in the parent rocks, hornblende, epidote and diopside are formed.
3. Impure limestones containing sand, chert or clayey material during contact metamorphism produce calc-silicate rocks. These rocks contain mostly calcite, lime-garnets, olivine, serpentine, wollastonite, termolite and diopside.
4. On contact metamorphism basic igneous rocks, such as basalt and gabbro, give rise to hornfels containing generally pyroxene and plagioclase.

6.10.4. Plutonic Metamorphism

At great depths below the earth's surface, static pressures and high temperatures operate together. The metamorphism caused by these factors is called the "*plutonic metamorphism*". High static pressure favours reduction in volume. Hence during recrystallization mainly denser minerals are formed. The metamorphic rocks produced in this way commonly have an even grained texture. Such rocks are called "*granulites*".

6.10.5. Regional Metamorphism

When directed pressure and heat act together in the presence of migrating hydrothermal fluids, the rocks are metamorphosed over wider areas. This kind of metamorphism is called the "*regional*" or "*dynamothermal metamorphism*". Regional metamorphism takes place at great depths, such as in root regions of fold mountains, where temperatures and stresses are high.

Heat promotes recrystallization and the stresses cause shearing and flow movements which produce new structures in rocks. The new minerals that grow under directed pressure are usually flat, elongated, bladed or flaky in nature. Examples of such minerals are muscovite, biotite, chlorite, talc and amphiboles. These minerals arrange themselves in parallel layers and produce a banded or laminated structure, called "*foliation*". The most common foliated metamorphic rocks are slates, phyllites, schists and gneisses. Foliated rocks split easily into flaky sheets.

When shales are subjected to regional metamorphism, the characterstic minerals that develop in succession with the rise in temperature and stress are chlorite, biotite, garnet, staurolite, kyanite and sillimanite. Thus shale changes to "*slate*" in early stages, to "*schist*" in the middle stage and finally to "*gneiss*" at the highest temperatures of regional metamorphism. The schist commonly contains staurolite, garnet, biotite, muscovite and quartz and the gneiss contains sillimanite, garnet, cordierite, potash felspar and quartz.

During regional metamorphism sandstones and limestones do not form foliated rocks. They recrystallize into *"quartzite"* and *"marble"* respectively. Both of these rocks show granular structure.

Basic igneous rocks, such as basalt, dolerite or diabase during different grades of regional metamorphism, change into green-schists, amphibolites, granulites or eclogites as follows.

(*i*) During low grades of regional metamorphism, basic igneous rocks change into *"green-schists"* containing mainly chlorite, albite and epidote.

(*ii*) At medium to high grades of metamorphism, greenschists are converted into *"amphibolites"*. Amphibolites are coarse grained rocks containing garnet, hornblende or diopside and plagioclase. Schistosity or bands of dark coloured minerals may be present.

(*iii*) At the highest metamorphic grades, *"granulites"* are formed. Granulites possess a granular texture and contain plagioclase, hypersthene and diopside. *"Charnockites"* are the most common granulite-type rocks which are formed from basic igneous rocks. Hypersthene is the characterstic mineral of charnockites.

(*iv*) In the most deep seated conditions where very high pressures prevail, a red and green rock called *"eclogite"* is formed. Eclogite is a coarse grained granulose rock consisting of pyrope garnet and omphacite (pyroxene). Though eclogites are often classified as metamorphic rocks, their origin is rather obscure. They are also believed to be of igneous origin.

6.10.6. Metasomatism

Many metamorphic reactions are generally considered to be essentially isochemical. This implies that during recrystallization and other metamorphic reactions, the bulk chemistry of the rocks has remained nearly constant. If other elements are introduced into the rock by circulating fluids derived from igneous magma, the resulting metamorphism is called the *"metasomatism"*. In other words, the metasomatism is a type of contact metamorphism in which much material is added to the rock by the hydrothermal fluids. During metasomatism the composition of the parent rock is changed substantially but its volume remains unchanged. As this alteration occurs without any deformation, the textures and structures of the original rock are usually preserved.

Scarns. During contact metamorphism, metasomatism is perticularly effective. *"Scarns"* are the product of metasomatism formed at the contact of granites with limestones. When granitic magma rich in water and other

volatile components comes in contact with limestones, a variety of minerals including magnetite, garnet, diopside, enstatite and forsterite are formed. Metalliferous ore deposits containing sulfides of lead, zinc, copper and iron are commonly found in association with scarns.

Granitization. Some granites show evidences of former sedimentary bedding. If they are traced towards the margin, they gradually grade into gneiss (migmatite), felspethized schists, mica schists, and finally to shale. Such granites appear to have formed by the metasomatism of schists where new mineral matter is added and the old is carried away. This process of transformation of country rocks into granite is called *"granitization"*. The material which is displaced during grantization, commonly contains Mg, Fe and Ca. This results in the concentration of ferromagesian minerals, such as biotite, garnet, pyroxene or amphibole in the peripheral zone. Thus with the formation of granites, a frontal zone of Fe - Mg enrichment is formed. This zone is called the *"basic front"*. It must be remembered that all fronts are not basic. Silica fronts of various kinds are developed when quartz rich rocks are granitized. Granites and granitic rocks are known to have formed from various types of igneous, sedimentary and metamorphic rocks. During granitization the transfer of material is caused by the infiltration of gaseous or liquid emanations (granitizing solutions) into country rocks or by diffusion of ions in a solid medium.

Lit-Par-Lit Injection. Near the contact of the intrusive body, emanations from the invading magma are often injected into the metamorphosed country rocks along the foliation and other planes of weakness. When an appreciably large quantity of magmatic fluid is introduced in the country rocks, numerous thin sills are formed between layers of bedding or foliation. This phenomenon is called *"lit-par lit injection"*. When there is a large scale transfer of igneous material in the surrounding country rocks, a mixed type of rock having gneissose structure is formed. Such mixed rocks are called the *"migmatites"*. Most migmaties have a somewhat granitic composition.

6.10.7. Retrogressive Metamorphism

When high temperature metamorphic mineral assemblages are changed to a low temperature mineral assemblages, the process is called the *"retrogressive"* or *"retrograde"* metamorphism. Such changes take place when an intensely metamorphosed rock is subjected either to strong differential movement or to hydrothermal activity. In zones of displacement an amphibolite may be converted to a green-schist and due to hydrothermal alteration a serpentine rock may change to talc-magnesite-schist.

6.11. METAMORPHIC MINERALS

The minerals which form in metamorphic rocks are largely controlled by the conditions of temperature, pressure or stress. These minerals can be divided into three groups : (*i*) stress minerals, (*ii*) antistress minerals, and (*iii*) relict minerals. "*Stress minerals*" are formed under conditions of stress or directed pressure during regional metamorphism. They are usually flat, tabular, elongated or flaky in nature and grow parallel to the direction of least pressure. Stress minerals play a major role in producing parallel structures and textures which are characterstic of many metamorphic rocks. Examples of stress minerals are micas, chlorite, talc, albite, amphiboles, kyanite and staurolite.

The "*antistress minerals*" develop mainly under conditions of uniform pressure, such as in plutonic metamorphism. These minerals are often equidimensional in form. Examples of antistress minerals are pyroxenes, olivine, andalusite, sillimanite, cordierite and spinel.

During metamorphism recrystallization of minerals takes place essentially in the solid state. Complete recrystallization is not always possible and therefore certain original minerals continue to survive in the metamorphic rocks. These original minerals which have failed to react to the changed conditions of temperature and pressure, are called the "*relict minerals*".

6.12. METAMORPHIC ZONES

Below the earth's surface temperature and pressure both increases with increasing depth. The degree or grade of metamorphism exhibited by a rock, therefore, varies with depth. On the basis of this concept three depth zones of metamorphism have been recognized : (*i*) epizone, (*ii*) mesozone, and (*iii*) katazone.

(*i*) **Epizone.** This zone of metamorphism occurs near the earth's surface. In this zone generally the conditions of cataclastic metamorphism prevail.

(*ii*) **Mesozone.** This is the intermediate zone of metamorphism which lies below the epizone. In the mesozone, the conditions of temperatures and pressures are such as to promote regional metamorphism.

(*iii*) **Katazone.** The bottommost zone of metamorphism is called the katazone. In this zone plutonic metamorphism takes place.

6.12.1. Grade of Metamorphism

The degree or intensity of metamorphism that has affected a rock, is called the "*grade of metamorphism*". It varies directly with the amount of heat and pressure to which the rocks have been subjected. Parent rocks of the same composition form different mineral assemblages in different grades of metamorphism. The grade of metamorphism is expressed as very low, low, medium and high grade (*Fig. 6.8*). For example, slate and phyllite which are formed away from the intrusive igneous body, show a low grade of metamorphism while a high grade metamorphic rock like gneiss is formed close to its margin. The increase in the grade of metamorphism is also

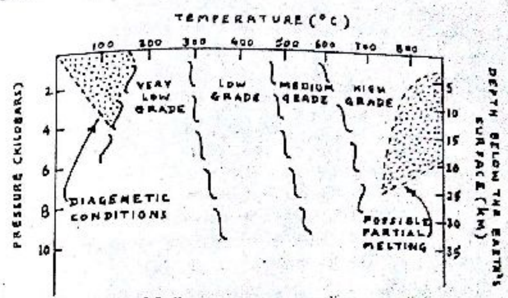


Fig. 6.8. Pressure-temperature diagram outlining approximate fields of various metamorphic grades.

accompanied by an increase in the grain size of rocks. For example, slates and phyllites are fine grained rocks while schists and gneisses are coarse grained.

6.12.2. Zones of Progressive Regional Metamorphism

In an area where argillaceous sedimentary rocks have been subjected to regional metamorphism, five metamorphic zones have been recognized on the basis of the occurrence of index minerals. The "*index minerals*" are those minerals which indicate the grade of metamorphism. At successively higher grades of metamorphism, the index minerals that develop in the argillaceous rocks are, first chlorite, then biotite, next almandite, afterwards staurolite, then kyanite and at the highest temperatures sillimanite. The various metamorphic zones are named after the index minerals present in them. These zones in the order of increasing grade of metamorphism are as follows.

(*i*) **Chlorite Zone.** In this zone the clayey material recrystallizes as muscovite and chlorite. Phyllites and slates are the typical rocks of this zone.

(*ii*) **Biotite Zone.** In this zone brown biotite appears in place of muscovite and chlorite. The typical rock of this zone is biotite-schist.

(*iii*) **Garnet Zone.** The characterstic mineral of this zone is porphyroblastic almandite garnet. The important rock of this zone is garnetiferous mica-schist.

(*iv*) **Staurolite-Kyanite Zone.** Staurolite is formed only in iron rich argillaceous rocks, while kyanite is formed in normal argillaceous rocks.

(*v*) **Sillimanite Zone.** Gneisses containig biotite, garnet and sillimanite along with potash felspar occur in this zone.

When the various metamorphic zones are demarcated on a geological map, the boundaries between different zones are called the *"isograds"*. The isograds reflect positions of similar metamorphic grade in terms of temperature and pressure.

6.13. METAMORPHIC FACIES

Metamorphic rocks are often classified on the basis of metamorphic facies. Parent rocks of different compositions, if metamorphosed under the same pressure-temperature conditions, will characterstically contain the same set of definite minerals. They are said to belong to the same metamorphic facies. A *"metamorphic facies"* therefore, may be defined as a group of metamorphic rocks that have formed under the same set of physico-chemical conditions and is characterized by a definite set of minerals. The various metamorphic facies are as follows.

(*i*) **Zeolite Facies.** This facies represents the lowest grade of metamorphism. The mineral assemblages include zeolites, chlorite, muscovite and quartz.

(*ii*) **Green Schist Facies.** This facies represents low grade of metamorphism found in many regionally metamorphosed areas. The mineral assemblages of green-schist facies include chlorite, epidote, muscovite, albite and quartz.

(*iii*) **Amphibolite Facies.** This facies is found in medium to high grade metamorphic terrains. The mineral assemblages include hornblende, plagioclase and almandite. Amphibolite facies represents those metamorphic conditions which occur in staurolite and sillimanite grade of metamorphism.

(*iv*) **Glaucophane Lawsonite Schist Facies.** This facies represents the metamorphism that takes place in conditions of relatively low temperatures but high pressures. Such conditions commonly occur in young orogenic zones, such as California (U.S.A.) and Japan. The mineral assemblages include lawsonite, jadeite, albite, glaucophane, muscovite and garnet.

(*v*) **Granulite Facies.** This facies represents the maximum temperature conditions of regional metamorphism, such as those found in Archaean terrains. The characterstic minerals of this facies are plagioclase, hypersthene, garnet and diopside.

(*vi*) **Eclogite Facies.** This facies represents the most deep seated conditions of metamorphism. The characterstic minerals are pyrope garnet and omphacite. Such mineral assamblages are commonly found in kimberlite pipes, many of which contain diamonds.

6.14. TEXTURES OF METAMORPHIC ROCKS

Crystalloblastic Texture. The holocrystalline texture of metamorphic rocks is called the *"crystalloblastic texture"*. This texture develops due to recrystallization of mineral grains in the solid medium. The crystals showing perfect crystal outline, are called the *"idioblasts"* while those which do not have any definite shape, are described as *"xenoblasts"*.

Porphyroblastic Texture. When idioblasts occur as large crystals embedded in a fine grained groundmass, the texture is called *"porphyroblastic"*. The large well-shpaed crystals of this texture are referred to as *"porphyroblasts"* or *"metacrysts"*.

Granoblastic Texture. In a metamorphic rock if the major constituents are granular or equidimensional, the texture is called *"granoblastic"*.

Palimpest Texture. The remnant texture of the parent rock found preserved in the metamorphic rock, is called *"palimpest texture"*.

6.15. STRUCTURES OF METAMORPHIC ROCKS

Cataclastic Structure. Cataclastic structure is found in rocks such as crush breccias and mylonites. These rocks are formed mainly under the influence of shearing stresses in the upper zones of the earth's crust. Harder constituents of rocks are broken into pieces while softer ones are crushed to powder.

Maculose Structure. When argillaceous rocks are subjected to contact metamorphism, a spotted rock is formed in areas where incomplete recrystallization takes place. The spots in the spotted rock are due to the development of bigger crystals of some minerals (*e.g.* andalusite) within the fine grained groundmass. This structure is called the *"maculose structure"*.

Slaty Structure. Slaty structure is also called the *"slaty cleavage"*. This structure commonly develops in shales thathaveundergone slight metamorphism. Rocks showing a slaty structure are very fine grained composed primarily of microscopic flaks of mica. The slaty structure is caused due to the parallel orientation of flaky minerals, mainly micas and chlorite. Slaty rocks split readily into thin sheets. The slaty cleavage may form at any angle to the old bedding planes of the shale from which the slaty rock has been derived [*Fig. 6.9* (*c*)].

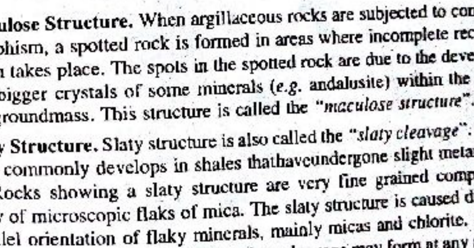


Fig. 6.9. Structures of metamorphic rocks.
(*a*) Schistose structure, (*b*) Gneissose structure, (*c*) Slaty structure, (*d*) Granulose structure.

Schistose Structure. The most obvious structural feature of most metamorphic rocks is the alignment of minerals in parallel layers. The parallel arrangement of platy or flaky minerals brought about by recrystallization during regional metamorphism, is called "*foliation*". A foliated rock which is coarse grained and is largely composed of flaky and platy minerals, is called "*schist*". The foliation of schists is called "*schistosity*" [*Fig. 6.9 (a)*].

Gneissose Structure. In rocks that have been thoroughly recrystallized under conditions of high grade metamorphism, the light and dark minerals may segregate into alternate bands parallel to the schistosity. Such a coarse grained metamorphic rock showing banded or streaked appearance, is called "*gneiss*" and its structure is called the "*gneissose structure*". The light coloured bands are composed of quartz and felspars while dark coloured bands contain ferromagnesian minerals. In gneissose rocks the planes of schistosity are poorly defined [*Fig. 6.9 (b)*].

Granulose Structure. Granulose structure is produced due to predominance of equidimensional minerals such as quartz, felspar, pyroxenes, and calcite [*Fig. 6.9 (d)*]. The flaky minerals are either absent or present only in small amounts. Granulose structure is characterstic of rocks such as marbles and quartzites. Because granulose rocks have even grained structure, they break with a rough fracture surface.

Hornfelsic Structure. Hornfelsic texture is characterstic of the contact metamorphic rock called the "*hornfels*". A hornfels is a dark, compact, fine grained rock having granoblastic texture. Hornfelsic structure is formed due to the predominance of equidimensional minerals such as felspars, andalusite, cordierite, and quartz.

6.16. METAMORPHIC ROCK TYPES

Slate

Nature. Slates are dark coloured exceedingly fine grained low grade metamorphic rocks. They have a remarkable property called slaty cleavage which permits them to be split into thin broad sheets. Their colour is commonly gray to black but may be green, yellow, brown and red.

Mineral Composition. Slates are composed of a very fine grained mixture of micas and chlorite with some quartz and felspar.

Texture and Structure. Slates are very fine grained rocks which show slaty cleavage.

Origin. Majority of slates are formed by the dynamic metamorphism of shales. Their characterstic slaty cleavage may or may not be parallel to the bedding planes of the original shales.

Phyllite

Nature. A phyllite is a fine grained, foliated lustrous rock.

Mineral Composition. It consists of chlorite, muscovite and quartz. The grains of this rocks are so fine that individual minerals can not be recognized by unaided eye.

Texture and Structure. It is a fine grained rock showing foliated structure. It splits along foliation planes with an uneven surface.

Origin. Phyllites are formed due to dynamothermal metamorphism of shales. They represent an intermediate stage of metamorphism between slate and schist.

Schist

Nature. Schists are coarse grained metamorphic rocks which show well developed foliation or schistosity along which the rock may be easily broken. Their colour varies according to mineral composition. Mica-schists are the most common metamorphic rocks.

Mineral Composition. Mica-schists consist essentially of quartz and mica, usually muscovite or biotite. Mica is the major mineral which occurs in irregular leaves and foliated masses. Mica-schists frequently carry characterstic accessory minerals such as garnet, staurolite, kyanite, sillimanite, andalusite, epidote and hornblende.

Varieties. Besides mica-schists, there are various other kinds of schists which are chiefly derived by the metamorphism of the basic igneous rocks. The most important types are **"talc-schist"**, **"chlorite-schist"**, **"hornblende-schist"** and **"amphibolite"**. These are characterized, as their names indicate, by the abundance of some metamorphic ferromagnesian mineral.

Texture and Structure. Schists are coarse grained rocks having a prominent schistose structure. They split easily into thin sheets along the planes of schistosity.

Origin. Schists are generally the product of regional metamorphism.

Gneiss

Nature. A gneiss is a coarse grained, irregularly banded metamorphic rock having poor schistosity. A gneiss has usually a light colour, although this is not necessarily so.

Mineral Composition. Quartz and felspar occur together in light coloured bands which alternate with dark bands of flaky ferromagnesian minerals, such as biotite or hornblende. Generally quartz and felspars predominate over micaceous minerals.

Varieties. There are many varieties of gneiss having varied mineral associations. They are named generally according to the dominent ferromagnesian mineral present, such as **"biotite-gneiss"** and **"hornblende-gneiss"**. When it is certain that a gneiss is the result of metamorphism of an earlier formed igneous rock, the igneous rock name is used in the terminology, such as the "**granite-gneiss**" or "**syenite-gneiss**".

Texture and Structure. Gneisses are coarse grained rocks having gneissose structure.

Origin. Gneisses are more commonly derived by the high grade regional metamorphism of igneous rocks, mostly granites. They may also be formed from sedimentary rocks.

Quartzite

Nature. A quartzite is a hard, dense, siliceous metamorphic rock having granular texture. It is distinguished from a sandstone by noting the fracture which in a quartzite passes through the grains but in a sandstone passes around them.

Mineral Composition. Quartzites are composed essentially of quartz with small amounts of mica, tourmaline, graphite or iron minerals. They are usually light in colour.

Texture and Structure. A quartzite is a compact rock of interlocking quartz grains. Its structure is granulose. This rocks breaks with a rough fracture surface.

Origin. Quartzites are derived from sandstones by high grade metamorphism.

Marble

Nature. A marble is a crystalline calcarious metamorphic rock having granular texture. Marbles are generally white but various impurities may create a wide range of colour such as pink, yellow, grey, green and black.

Mineral Composition. A marble is composed of grains of calcite or more rarely dolomite.

Texture and Structure. The marbles show granulose texture. The individual grains may be so small that they can not be distinguished by the eye or they may be quite coarse and show clearly the characterstic calcite cleavage.

Origin. Marbles are formed as a result of metamorphism of limestones.

Hornfels

Nature. A hornfels is a fine grained, dense, nonschistose rock composed mostly of equidimensional grains. It is commonly found in the contact zones of igneous intrusions.

Mineral Composition. Mineral composition of hornfelses varies because they may be produced from any type of rock. The minerals which commonly occur in these rocks are felspar, andalusite, cordierite, magnetite, biotite and quartz.

Texture and Structure. Hornfelses commonly show granoblastic texture. The fine grained granoblstic texture of these rocks is also called the "*hornfelsic texture*".

Origin. Hornfelses are formed in the contact aureoles of igneous intrusions.

REVIEW QUESTIONS

1. Explain how are the sedimentary rocks formed. Describe the various structures present in these rocks.
2. What is a sedimentary rock ? Classify sedimentary rocks into various classes and give a brief description of each class.
3. Describe in detail the textures and structures of either sedimentary or metamorphic rocks.
4. Give the distinguishing characters of the following rocks. Sandstones. Conglomerate, Shale, Limestone, Slate, Gneiss, Schist, Hornfels.
5. (*a*) What is a metamorphic rock ? Discuss the various agents of metamorphism.

   (*b*) Describe in brief the processes involved in the metamorphism.
6. Enumerate the various types of metamorphism. Explain in brief either contact metamorphism or regional metamorphism.
7. Discuss the facies concept in metamorphism with suitable examples.
8. What is meant by zones of progressive regional metamorphism ? Describe briefly the stages of advancing regional metamorphism of argillaceous sediments.
9. Write short notes on the following.

   Greywackes, Concretions, Stratification, Metamorphic facies, Granitization, Migmatite, Metasomatism.

தலைசிறந்த சொல், "செயல்".

7 Geological Structures

7.1. DIP AND STRIKE

The beds of undisturbed sedimentary rockformations generally occur in horizontal disposition. During earth movements, the strata may be tilted out of the horizontal. Such inclined rock beds are said to have a *"dip"*. The object of measuring dip and strike of rocks is to obtain information on their three dimension position.

Dip. The angle of inclination of a rock bed with the horizontal plane is called the *"dip"*. It is measured in a plane perpendicular to the strike (*Fig. 7.1*). In addition to the amount of dip, its direction must also be stated. The dip angle is measured with a clinometer and its direction is measured with a compass. An example of recording dip is 60°, N45°E. This means that the beds dip at an angle of 60° in a northeasterly direction.

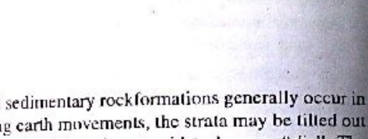


Fig. 7.1. Strike and dip of an inclined bed.

7.1.1. Apparent Dip and True Dip

The *"true dip"* is defined as the maximum angle of dip on a rock bed. It is measured in the direction at right angles to the strike (cd in *Fig. 7.2*).

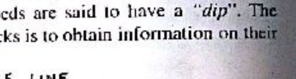


Fig. 7.2. True dip and apparent dip.

A dip measured in any other direction than the true dip, is called the *"apparent dip"*. An apparent dip will always have a value less than the true dip. The amount of dip decreases as the direction of dip moves round towards the strike direction. Along the strike direction, however, the dip will be zero. In *Fig. 7.2* the dip measured in cd_1, and cd_2 directions are the apparent dips.

Strike. The trend of a rock bed on the ground surface is called the strike. The *"strike"* may be defined as the direction of a line formed by the intersection of a bedding plane and a horizontal plane. The strike is always at right angles to the true dip direction. Thus the strike is a horizontal line on a surface of rock beds (ab in *Fig. 7.1 and 7.2*). The direction of the strike is measured by compass with reference to the true north and south. For example, if the strike direction of a perticular bed is 30° east of north, the strike will be recorded as N30°E–S30°W.

7.2. FOLDS

When the compressional stress is applied slowly under high confining pressure, rock beds tend to yield by folding. During mountain building, flat lying sedimentary rocks are bent into folds. The result of folding is a shortening and thickening of the earth's crust.

Folds. *"Folds"* may be defined as a curved or zig-zag structure shown by rock beds. In other words wavy undulations in the rock beds are called *"folds"*. They consist of arches and troughs in alternate manner. They are best displayed by the sedimentary rocks. The size of folds vary greatly. Width of some folds are measured in kilometers while those of others in meters or centimeters.

7.2.1. Elements of Folds

Anticline and Syncline. An *"anticline"* is an up-fold where the limbs dip away from the axis of fold on either side (*Fig. 7.3*). A *"syncline"* is a down-fold where the limbs dip towards the axis of fold on either side (*Fig. 7.3*). The highest point on the arch of an anticline is called the *"crest"* of the fold and the lowest point on the syncline is called the *"trough"* (*Fig. 7.4*). A single anticline or syncline may range in size from a few centimeters to several kilometers across.

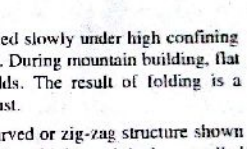


Fig. 7.3. Anticline and syncline.

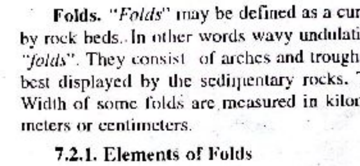


Fig. 7.4. Anticline showing axial plane and axis.

Limbs. The sloping sides of a fold from crest to trough are called the *"limbs"* (*Fig. 7.4*).

Axial Plane. It is an imaginary plane or surface which divides a fold into two equal halves (Fig. 7.4).

Axis of Fold. An *"axis of fold"* is defined as the line of intersection between the axial plane and the surface of any of the constituent rock bed (Fig. 7.4).

Plunge of Fold. Folds having inclined axes are called *"plunging folds"*. The angle of inclination of a fold axis with the horizontal, is called the *"angle of plunge"* (Fig. 7.8). The direction in which this axis is inclined is called the direction of plunge.

7.3. TYPES OF FOLD

Symmetrical Fold. A *"symmetrical fold"* is one where the two limbs dip at the same angle but in opposite directions. In this case the axial plane is vertical and it passes through the crest or trough [Fig. 7.5 (*a*)].

Asymmetrical Fold. An *"asymmetrical fold"* is one where the limbs dip at unequal angles in opposite directions. In this case the axial plane is inclined and it not necessarily passes through the crest line [*Fig. 7.5* (*b*)].

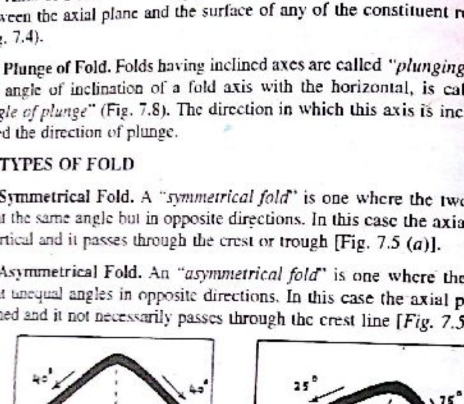


Fig. 7.5. (*a*) Symmetrical fold. (*b*) Asymmetrical fold. (*c*) Overturned fold. (*d*) Recumbent fold.

Overturned Fold. It is an asymmetrical fold whose one limb is turned past the vertical. In this case the axial plane is inclined and both the limbs dip in the same direction. In the overturned fold the lower limb is turned upside down [*Fig. 7.5* (*c*)].

Recumbent Fold. In *"recumbent folds"*, the folding is so intense that both the limbs become almost horizontal. In this case the axial plane also becomes nearly horizontal and the lower limb gets overturned [*Fig. 7.5* (*d*)].

In recumbent folds fractures usually develop across bends to produce overthrusts (*Fig. 7.6*).

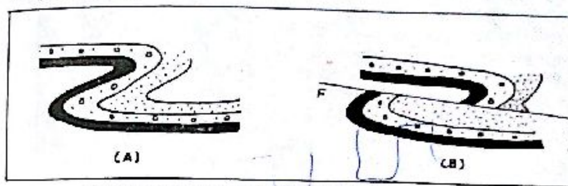


Fig. 7.6. (*a*) Recumbent fold, (*b*) Passing into an overthrust.

Isoclinal Fold. Folds that have parallel limbs are called *"isoclinal folds"*. In this case limbs dip at the same angle and in the same direction. Isoclinal folds are of three types : (*i*) *"inclined isoclinal folds"*, where the axial plane is inclined [*Fig. 7.7* (*b*)], (*ii*) *"vertical isoclinal folds"*, where

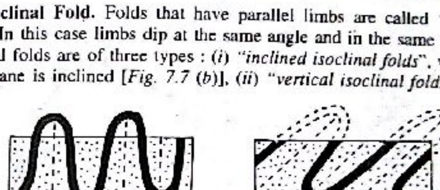


Fig. 7.7. Isoclinal folds (*a*) Vertical isoclinal folds, (*b*) Inclined isoclinal folds.

the axial plane is vertical [*Fig. 7.7* (*a*)], and (*iii*) *"recumbent isoclinal folds"*, where the axial plane is horizontal.

Nonplunging and Plunging Folds. The axis of a fold may be horizontal or inclined. Anticlines and synclines whose axes are horizontal, are said to be *"nonplunging"*. Folds having inclined axes are called the *"plunging folds"* (*Fig. 7.8*). The angle of inclination of the axis measured from the horizontal, is called the *"angle of plunge"* and the direction in which this axis is inclined is called the *"direction of plunge"*.

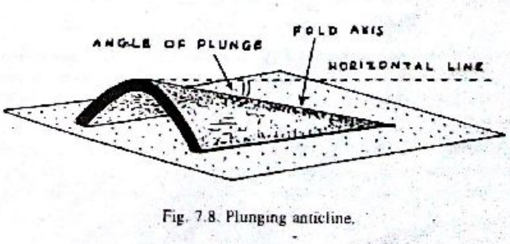


Fig. 7.8. Plunging anticline.

An outcrop of a plunging anticline and syncline is shown in *Fig. 7.9.* The plunge causes the outcrop to turn and double back producing a *"nose"*. The nose is important as it indicates the direction of plunge. In case of an anticline, the plunge is always in the direction of nose whereas in a syncline, it is away from the nose.

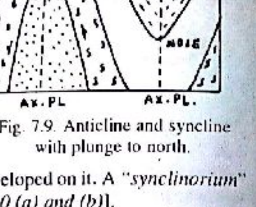


Fig. 7.9. Anticline and syncline with plunge to north.

Anticlinorium and Synclinorium. These are the complex large folds of general anticlinal and synclinal form. An *"anticlinorium"* is a large anticline with a number of secondary folds of smaller size developed on it. A *"synclinorium"* is a large syncline of similar nature [*Fig. 7.10 (a) and (b)*].

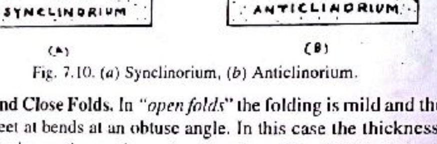


Fig. 7.10. (*a*) Synclinorium, (*b*) Anticlinorium.

Open and Close Folds. In *"open folds"* the folding is mild and therefore the limbs meet at bends at an obtuse angle. In this case the thickness of the constituent beds remains unchanged everywhere [*Fig. 7.11 (a)*].

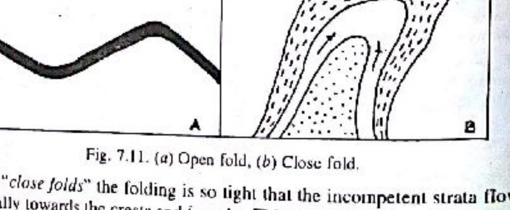


Fig. 7.11. (*a*) Open fold, (*b*) Close fold.

In *"close folds"* the folding is so tight that the incompetent strata flow plastically towards the crests and troughs. This causes thinning at the flanks and thickening at the crests [*Fig. 7.11 (b)*]. The close folds develop under great stresses.

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 into a basin. These folds are about as wide as they are long

Thus a *"dome"* may be defined as an up-fold where the beds dip radially outward in all directions from the centre [*Fig. 7.12 (a)*]. In such a case the

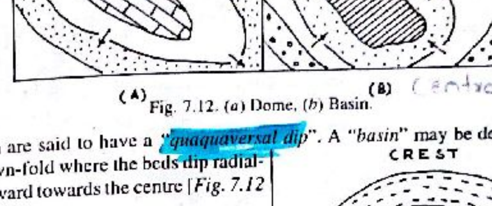


Fig. 7.12. (*a*) Dome, (*b*) Basin.

strata are said to have a *"quaquaversal dip"*. A *"basin"* may be defined as a down-fold where the beds dip radially inward towards the centre [*Fig. 7.12 (b)*].

Fan Folds. A *"fan fold"* is an upright fold in which both the limbs are overturned. In anticlines limbs dip towards the axial plane and in synclines they dip away from it. The beds within the anticline are much compressed below while they open out above (*Fig. 7.13*). The crests and troughs of fan folds are generally sufficiently rounded.

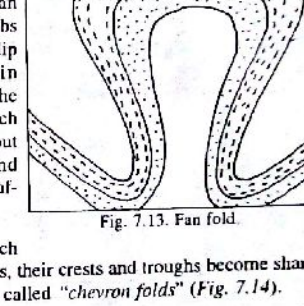


Fig. 7.13. Fan fold.

Chevron Folds. The folds which have straight or nearly straight limbs, their crests and troughs become sharp and angular. Such zig zag folds are called *"chevron folds"* (*Fig. 7.14*).

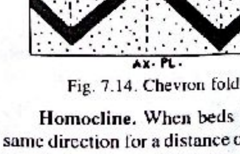


Fig. 7.14. Chevron fold.

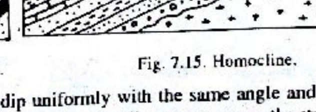


Fig. 7.15. Homocline.

Homocline. When beds dip uniformly with the same angle and in the same direction for a distance of the order of a kilometer or more, the structure is called a *"homocline"* (*Fig. 7.15*).

Monocline. A local warping in the horizontal strata is called the *"monocline"*. In this case the rock beds lying at two levels are separated by a limb which shows steep inclination [*Fig. 7.16 (a)*]. A monocline is formed by the vertical movement. A fault is generally found below most monoclines. The width of monoclines are often several kilometers.

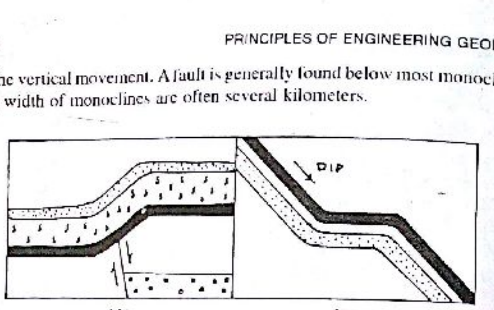


Fig. 7.16. (*a*) Monocline, (*b*) Structural terrace.

Structural Terrace. A local flattening in an otherwise uniformly dipping beds is called the *"structural terrace"*. In this case the dipping strata become horizontal at a perticular spot and then they continue to follow their original dip [*Fig. 7.16 (b)*].

Drag Folds. The *"drag folds"* may be defined as minor folds developed within the body of incompetent beds during the process of major folding (*Fig. 7.17*). When a sequence where incompetent beds are interbedded between competent beds, is subjected to folding, drag folds develop in the

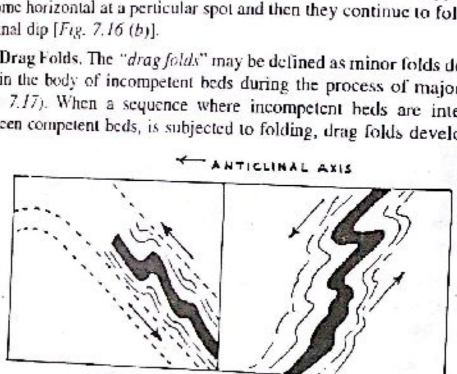


Fig. 7.17. Drag fold (*a*) In normally dipping beds, (*b*) In overturned beds.

incompetent layer. During folding the competent beds slip over one another without deformation while the weak and incompetent layer is contorted into small secondary folds. Drag folds are important because their shape indicates the direction of relative movement. These folds may be used to determine the top and bottom of highly inclined strata as their transverse axes are approximately parallel to that of the major fold.

The *"incompetent rock beds"* are those which become mobile and flow plastically during folding. Such beds show variations in thickness from place to place. An example of incompetent rock is shale. The *"competent beds"*,

on the other hand, show greater rigidity and their thickness remains unchanged during folding. An example of competent rock is sandstone.

7.4. MECHANICS OF FOLDING

All rocks do not respond in the same way to the same forces. Depending on their reaction to folding, the rocks are classified into two groups: (*i*) competent rocks, and (*ii*) incompetent rocks. Competent rocks are the resistant rocks which bend and crack without much flowage and incompetent rocks are the weaker rocks which deform due to plastic flow. The folds that develop in these rocks are of three types: (*i*) flexure folds, (*ii*) flow folds and (*iii*) shear folds.

Flexure Folds. The true folds that are formed by the compression of competent rock beds are called the *"flexure folds"*. These folds are frequently larger and their outlines are relatively simple.

Flow Folds. The incompetent rocks behave like a thick paste and therefore they can not transmit pressure easily. The *"flow folds"* that are formed in the incompetent rocks, are accompanied by rock flowage. In flow folds the rock material flows into the crest and trough thereby causing thinning and thickening of beds. Many minor folds frequently develop in the incompetent strata (*Fig. 7.17*).

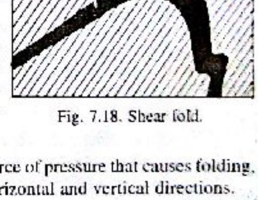


Fig. 7.18. Shear fold.

Shear Folds. The *"shear folds"* are produced in brittle rocks by the movement on minute closely spaced fractures called the *"shear planes"*. These shear planes develop across beds and thin slices of the rock move in relation to each other thereby forming a fold (*Fig. 7.18*).

With increasing distance from the source of pressure that causes folding, the folds gradually die out both in the horizontal and vertical directions.

7.5. RECOGNITION OF FOLDS

Recognition of folds in the field is not always easy. All the limbs of the fold are seldom visible and therefore a systematic study is required for identifying folds. The features which help in recognizing folded strata are as follows.

1. In some areas folds are easily inferred by the topography. Aerial photographs are used for this purpose.
2. The repetition of outcrops of rocks suggests the presence of a fold (*Fig. 7.19*). In such cases care should be taken to eliminate the possibility of a fault.
3. If fold is of open type, the reversal of dip direction is enough to identify folds (*Fig. 7.19*). In anticlines the oldest rock bed will

occupy an axial position and in synclines the youngest bed will occur there.

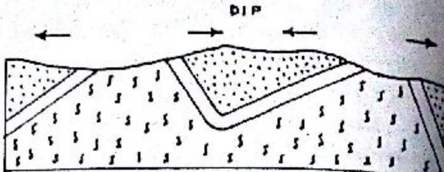


Fig. 7.19. Repetition of outcrop.

4. Plunging folds as a rule, give rise to curved outcrops the apex of which is called a *"closure"* or *"nose"* (*Fig. 7.9*).

5. In case of the overturned and isoclinal folds where all the limbs dip in the same direction, detailed observations are necessary to identify synclines and anticlines. The features which aid in finding out the top and bottom of a rock bed and hence the synclines and anticlines are drag folds, rock cleavage, cross-bedding, oscillation ripple marks, graded bedding and mud cracks.

(*i*) **Drag Folds.** These folds show characteristics which are similar to major folds. As a rule the axial plane of a drag fold is roughly parallel to that of the major fold of which it is a part. This provides a very useful means of knowing the general symmetry of the major fold (*Fig. 7.17*).

(*ii*) **Rock Cleavage.** The flow cleavage or slaty cleavage is formed due to parallel orientation of platy and flaky minerals. This cleavage develops parallel to the fold axis and therefore it can be used in the study of major folds (*Fig. 7.20*).

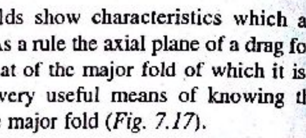


Fig. 7.20. Slaty cleavage.

(*iii*) **Cross-Bedding.** In cross-bedding the laminae of the rock are tengential to the true bedding at the bottom but form sharp angles at the top (Fig. 6.3).

(*iv*) **Graded Bedding.** In a graded sedimentary bed, the coarser grains are always at the bottom (*Fig. 6.2*).

(*v*) **Mud Cracks.** In mud cracks the tapering end indicates the bottom.

7.6. FAULTS

A *"fault"* may be defined as a fracture along which blocks of rock have been displaced relative to each other. This planar discontinuity originates by tectonic forces acting regionally. The displacement along a fault may be less

than a meter, several hundred meters or many kilometers. Faults result from tensional as well as compressional forces.

7.6.1. Fault Terminology

Fault Plane. The fracture surface along which relative movement has taken place, is called a *"fault plane"* (*Fig. 7.21*). The word fault includes both the fault plane and the displacement that has occurred along it. A fault plane may be markedly curved or in some cases undulating. In stead of one clearly defined fault plane there may be a number of parallel shear fractures along which the fault movement is distributed. Such a fracture zone is called a *"shear zone"*.

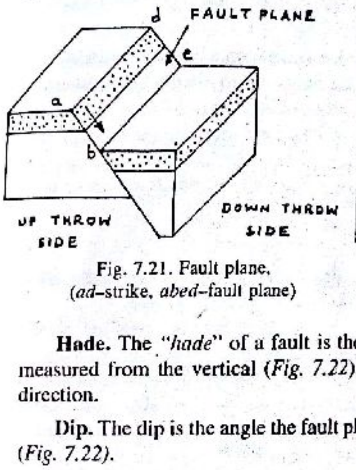


Fig. 7.21. Fault plane, (*ad*–strike, *abed*–fault plane)

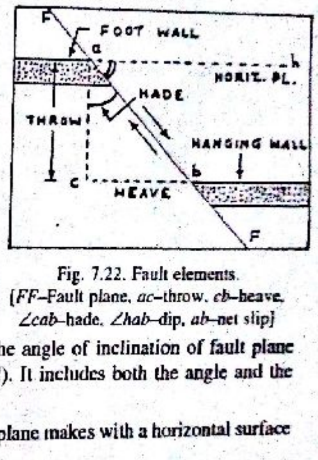


Fig. 7.22. Fault elements. [*FF*–Fault plane, *ac*–throw, *cb*–heave, ∠*cab*–hade, ∠*hab*–dip, *ab*–net slip]

Hade. The *"hade"* of a fault is the angle of inclination of fault plane measured from the vertical (*Fig. 7.22*). It includes both the angle and the direction.

Dip. The dip is the angle the fault plane makes with a horizontal surface (*Fig. 7.22*).

Strike. The *"strike"* of a fault is the direction of its continuity on the ground surface. It may be defined as the trend of the line formed by intersection of a fault plane and a horizontal plane (*Fig. 7.21*), such as the ground surface or a map surface.

Throw. The vertical component of the displacement of fractured rock blocks, is called the throw of fault (*Fig. 7.22*). The side on which the strata appear to have thrown down is called the *"down throw side"* while the other side on which they appear to have gone up is called the *"up throw side"* (*Fig. 7.21*).

Heave. The horizontal component of the displacement of a fault is called the *"heave"*. It is the horizontal shift of strata as seen in a section of a fault (*Fig. 7.22*).

Net Slip. The total displacement measured along the fault plane is called the *"net slip"*. It is measured between the two points which were originally in contact (*Fig. 7.27*). The movement along the fault plane can be resolved into two component directions, dip slip and strike slip.

Strike Slip and Dip Slip. "*Dip slip*" is movement parallel to the direction of dip of the fault plane. The movement which is parallel to the strike of the fault plane is called "*strike slip*" [*Fig. 7.27 (a) and (b)*].

Fault Scarp. A "*fault scarp*" is the cliff formed initially along the up-throw side of a fault.

Hanging Wall and Foot Wall. If the fault plane is not vertical, the block of rock lying above it is known as the "*hanging wall*", and the block blow the fault plane is known as the "*foot wall*" (*Fig. 7.22 and 7.23*). Vertical faults have neither hanging wall nor foot wall.

Fault Zone. Most fault planes are associated with a zone of crushed or altered rocks. This zone is called the "*fault zone*". When several parallel faults occur close together, the resulting zone of broken and crushed rock is called the "*shear zone*". A shear zone differs from a fault zone in that no distinct fault planes can be detected because here the local deformation is ductile. The fault zones and shear zones vary greatly in width and in some cases they are measured in hundreds of meters.

7.7. CLASSIFICATION OF FAULTS

Classification-I. On the basis of apparent movement the faults are classified into two groups: (*i*) normal fault, and (*ii*) reverse fault.

Normal Fault. A "*normal fault*" is one in which the hanging wall appears to have moved downward relative to the foot wall [*Fig. 7.23 (a)*]. In this case the fault plane dips toward the down-throw side. Generally normal faults are produced by tensional forces and they are also called the "*gravity faults*". These faults indicate lengthening of the earth's crust. The subdivision of the crust into blocks by normal faults is called the "*block faulting*". Normal faults usually have a high angle dip.

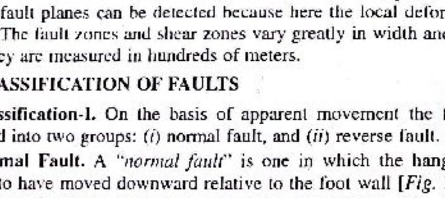


Fig. 7.23. (*a*) Normal fault, (*b*) Reverse fault.

Reverse Fault. A "*reverse fault*" is one in which the hanging wall appears to have moved upward relative to the foot wall [*Fig. 7.23 (b)*]. In this case the fault plane dips toward the up-throw side. The reverse faults are usually high angle faults. They are produced by compressional forces. These faults indicate shortening of the earth's crust.

Normally reverse faults have dips of the order of 45° or more. Intense compression produces low angle reverse faults called the "*thrusts*" (*Fig. 7.6*). Thrust faults may curve at the bottom to merge with a bedding plane. A horizontal or low angle thrust fault in which the displacement is large, is called the "*overthrust*". The displacement of overthrusts may be measured in kilometers. The sheet of rock that has moved forward along the thrust plane is called the "*nappe*". Isolated parts of overthrust rock mass resting on the underlying strata are known as the "*nappe outlier*" or "*klippe*" (*Fig. 7.50*).

Classification-II. On the basis of relationship between the strike of a fault and the attitude of strata, the faults are classified into five groups: (*i*) dip fault, (*ii*) strike fault, (*iii*) bedding fault, (*iv*) oblique fault, and (*v*) tear or wrench fault.

Dip Fault. A fault which strikes approximately parallel to the dip direction of beds, is called the "*dip fault*" [*Fig. 7.24 (a)*].

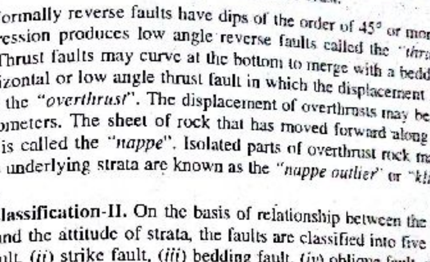


Fig. 7.24. (*a*) Dip fault, (*b*) Strike fault

Strike Fault. A fault which runs parallel to the strike of strata, is called the "*strike fault*" [*Fig. 7.24 (b)*]. A strike fault is termed as a "*longitudinal fault*" when it runs along the strike of the regional structure such as major fold axes, etc.

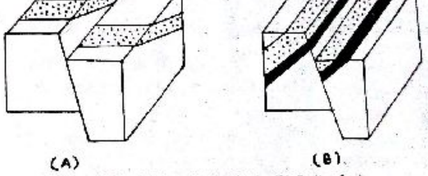


Fig. 7.25. (*a*) Bedding fault, (*b*) Oblique fault

Bedding Fault. A bedding fault is one which occurs along a contact between beds of different or same lithology [*Fig. 7.25 (a)*]. The bedding faults are difficult to recognize.

Oblique Fault. A fault which runs oblique to the strike and dip directions of strata is called the *"oblique fault"* [*Fig. 7.25 (b)*]. When a fault strikes diagonal to the dip of the regional structure, it is known as the *"transverse fault"*.

Tear Fault or Wrench Fault. In strike-slip faulting the relative displacement of the blocks is horizontal. The fault plane of a strike-slip fault is more or less vertical and often extends for long distances. Because these faults frequently strike across the trend of folds, they are called *"transcurrent"*, *"tear"* or *"wrench"* faults (*Fig. 7.26*).

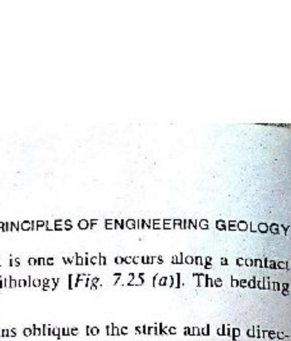


Fig. 7.26. Tear or wrench fault.

Classification-III. On the basis of the degree of dip, the faults are classified into two groups : (*i*) high angle faults and (*ii*) low angle faults.

High Angle Faults. The *"high angle faults"* are those which have a dip greater than 45°. Normal faults are commonly high angle faults.

Low Angle Faults. The *"low angle faults"* are those which have a dip less than 45°. Thrust faults are commonly low angle faults.

Classification-IV. On the basis of the relationship between the direction of slip and the attitude of the fault plane, the faults have been classified into three groups : (*i*) strike-slip fault, (*ii*) dip-slip fault, and (*iii*) oblique-slip fault.

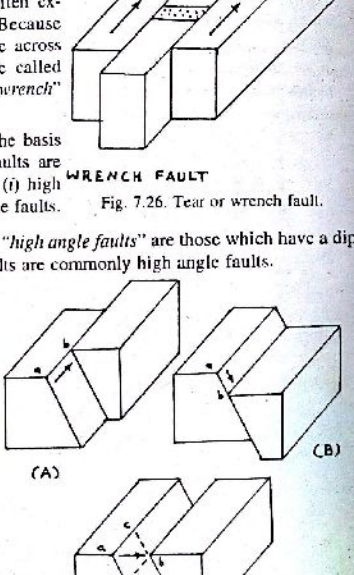


Fig. 7.27. (*a*) Strike slip fault (ab = strike slip = net slip). (*b*) Dip slip fault (ab = dip slip = net slip). (*c*) Oblique slip fault (ac = strike fault, cb = dip slip, ab = net slip)

Strike Slip Fault. In *"strike-slip faults"* the movement is essentially horizontal along the strike of fault [*Fig. 7.27 (a)*]. These faults usually have very steep to vertical dips.

Dip Slip Fault. A fault in which movement is essentially downward along the dip of fault, is called the *"dip-slip fault"* [*Fig. 7.27 (b)*].

Oblique Slip Fault. A fault in which the direction of movement is diagonal to both the dip and strike of fault, is called the *"oblique slip fault"* [*Fig. 7.27 (c)*].

Classification-V. On the basis of the forces responsible for the formation of faults, the faults have been classified into four groups : (*i*) gravity or tension faults, (*ii*) compressional faults, (*iii*) transcurrent faults and (*iv*) pivotal faults.

Gravity or Tension Faults. These faults are formed by tensional forces which pull the earth's crust apart. Normal faults are the examples of this group.

Compressional Faults. These faults are caused by the compressional forces which produce folds as well as faults. Reverse faults and thrusts belong to this group and they are commonly associated with folding.

Transcurrent Faults. These faults are caused by the lateral thrust. Tear or wrench faults belong to this group. Transcurrent faults exhibit mainly horizontal movement.

Pivotal Faults. These faults are caused by the rotational stresses and the movement involved is mainly rotational.

Classification-VI. Faults usually occur in groups. When a number of faults occur together, they form a *"fault system"*. On the basis of their pattern, the faults are classified into seven groups : (i) parallel faults, (*ii*) step faults, (*iii*) graben, (*iv*) horst, (*v*) enechelon faults, (*vi*) peripheral faults, and (*vii*) radial faults.

Parallel Faults. A series of faults that have the same strike and dip are called the *"parallel faults"*. Such faults run parallel to one another and all hade in the same direction with the same angle (*Fig. 7.28*).

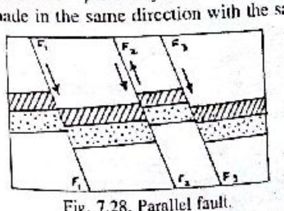


Fig. 7.28. Parallel fault.

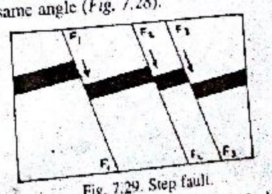


Fig. 7.29. Step fault.

Step Faults. The term *"step faults"* is applied to those parallel faults where the down-throw of all are in the same direction. In these faults the down-thrown blocks produce a step-like structure (*Fig. 7.29*).

Graben or Rift Fault. "*Grabens*" are long and relatively narrow fault troughs bounded by parallel high angle faults. This structure is produced when the two parallel normal faults hade towards each other and the rock beds between them are thrown down under the influence of gravity forming a topographic low (*Fig. 7.30*). Tensional crustal forces which pulls the crust apart are responsible for the formation of rift faults. Grabens typically occur along crests of upwarps.

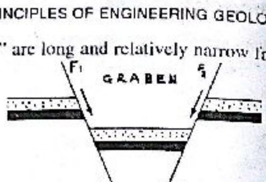


Fig. 7.30. Graben.

Horst. When two parallel normal faults hade away from one another and the rock block between them is uplifted to form a ridge, the structure is called a "*horst*" (*Fig. 7.31*).

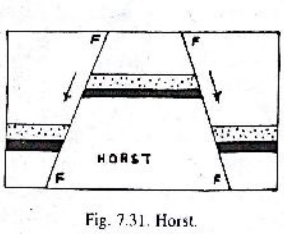


Fig. 7.31. Horst.

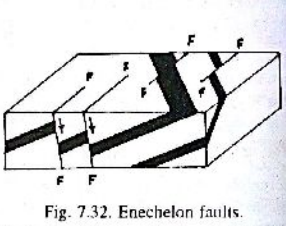


Fig. 7.32. Enechelon faults.

Enechelon Faults. These are relatively short faults which overlap each other (*Fig. 7.32*).

Peripheral Faults. The curved faults which have nearly circular or arc-like outcrops on level surface, are called "*peripheral faults*" (*Fig. 7.33*).

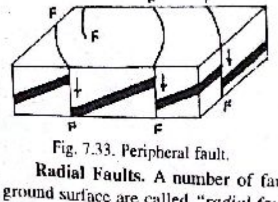


Fig. 7.33. Peripheral fault.

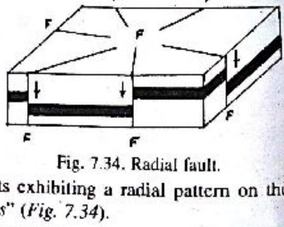


Fig. 7.34. Radial fault.

Radial Faults. A number of faults exhibiting a radial pattern on the ground surface are called "*radial faults*" (*Fig. 7.34*).

7.8. EFFECTS OF FAULTS ON OUTCROP

Effects of Dip Faults. The effect of the dip faults is to cause a lateral displacement in the outcrops of the disrupted strata (*Fig. 7.35*). The amount

of displacement becomes less with the increase in the dip of rock beds and in the vertical strata the displacement of outcrop will be nil.

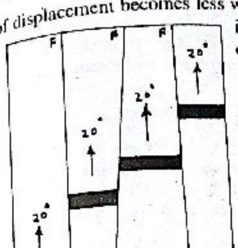


Fig. 7.35. Plan showing displacement of outcrops by dip faults.

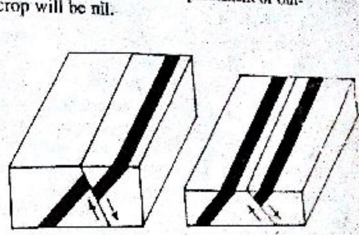


Fig. 7.36. Repetition of outcrop. (*a*) Strike-faulting, (*b*) After denudation.

Effects of Strike Faults. The effect of strike faults is either to cause the repetition of the outcrops of the disrupted strata or to eliminate the outcrops of some of the beds altogether. Repetition of outcrop occurs when a strike fault hades in the direction opposite to that of the dip of strata (*Fig. 7.36*). Omission or concealment of outcrop occurs when a strike fault hades in the same direction as the dip of strata (*Fig. 7.37*).

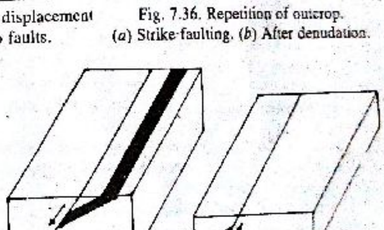


Fig. 7.37. Omission of outcrop. (*a*) Strike faulting, (*b*) After denudation.

Effects of Faults on Folded Strata. In a syncline the outcrop of the limbs come closer on the up-throw side (Fig. 7.38) while the reverse applies in case of an anticline.

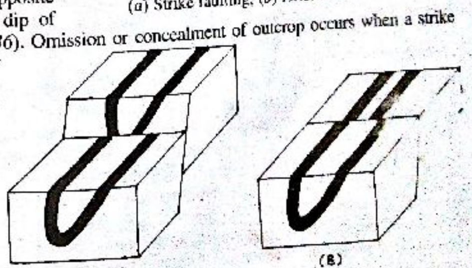


Fig. 7.38. Effect of faulting on a syncline. (*a*) Faulting, (*b*) After denudation.

7.9. EVIDENCES OF FAULTING

The criteria for the recognition of faults in the field can be divided into three groups : (*i*) geological evidences, (*ii*) fault plane evidences, and (*iii*) physiographic evidences.

7.9.1. Geological Evidences

The geological evidences are seen very clearly on the geological maps. The most important geological evidences of faulting are : (*i*) offsets of rock units, (*ii*) repetition or omission of strata, (*iii*) abrupt termination of structures along their trend, (*iv*) strata out of stratigraphic sequence and (*v*) abrupt change in the attitude of strata.

Offsets of Rock Units. Displacement of rock beds, dykes, veins, etc. occurs on opposite sides of a fault.

Repetition or Omission of Strata. In a traverse line, the outcrop of a bed may be repeated in cyclic order or it may disappear altogether. Such a repetition or omission of beds often establishes a fault.

Abrupt Termination of Structures. The strata, dykes, veins, folds or other structures may end abruptly against a fault line. Such termination of structures along their trend is usually caused by the dip and diagonal faulting. The lost portion of the structure may be concealed under water, alluvium, lava or younger series of beds.

Strata Out of Stratigraphic Sequence. The normal stratigraphic sequence of a region may be disturbed by faulting. When older strata occur above younger strata, faulting is indicated.

Abrupt Change in Attitude of Strata. When the strike and dip of strata changes suddenly, faulting is indicated.

7.9.2. Fault Plane Evidences

The fault plane evidences include the minor structures which are found associated with faults. They are observed in the immediate vicinity of fault planes. The most important fault plane evidences are : (*i*) slickensides, (*ii*) drag, (*iii*) fault breccia and gauge, (*iv*) silicification and mineralization, and (*v*) feather joints.

Slickensides. The movement of one wall against another results in polishing and grooving of fault surfaces. These grooves and striations are called the "*slickensides*". Slickensides are useful in knowing the direction of the latest movement on a fault surface. Slickensides are commonly associated with faults and are formed along the fault planes. In addition to striations slickensides may also contain small steps-like features facing in the same direction and oriented more or less normal to striations. More pronounced parallel furrows along the fault planes are "*mullions*". Mullions are larger than slickensides and are not easily erased by subsequent movements.

Drag. In the immediate vicinity of a fault, the ends of strata may bend up and down (Fig. 7.39). This local bending which is caused by the fault displacement, is called the "*drag*". It indicates the direction of movement along a fault.

Fault Breccia and Gouge. Along some faults the rocks are found highly fractured or even crushed to angular fragments. Angular fragments embedded in a matrix of finely grounded rock are called "*fault breccia*". Fragment size of fault breccia may range from microscopic to serval centimeters. Secondary minerals such as quartz, calcite or sometimes pyrite may fill open spaces within the fault breccia. When the dislocating forces are very severe as is frequently the case in thrusting, the rocks may be ground to fine clay like powder called the "*gouge*". The gouge is frequently polished and striated by the fault movements. A microbreccia that fills faults in wider zones of intense deformation is called the "*mylonite*".

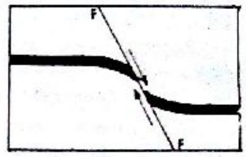


Fig. 7.39. Drag on faults.

Silicification and Mineralization. Circulating water while percolating through a fault zone may deposit fine grained quartz causing silicification. Fault planes also act as passages for mineralizing solutions and many mineral deposits are formed in the fault plane itself.

Feather Joints. Feather joints are the tension fractures formed due to fault displacements. They commonly develop adjacent to major faults. The feather joints indicate the direction of movement along the fault (*Fig. 7.40*).

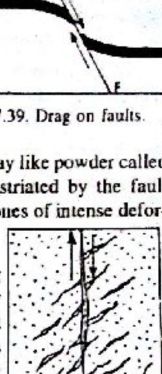


Fig. 7.40. Feather joints on faults.

7.9.3. Physiographic Evidences

The physiographic evidences are seen clearly from a distance or on an aerial photograph. It may be noted that physiographic evidences are not conclusive. The chief physiographic evidences are : (*i*) fault scarp, (*ii*) fault line scarp, (*iii*) offset ridges, (*iv*) fault control of streams, and (*v*) lines of pond, springs or water seeking plants.

Fault Scrap. A steep straight slope of a ridge is called the "*scarp*". Fault scarps are the scarps formed as a result of faulting. They are found only in those areas where faulting has been geologically very recent. Fault scarps face in the direction of the down-throw side.

Fault Line Scarp. Faults frequently bring together resistant and non-resistant rock beds. A ridge may be formed along a fault due to the process of unequal erosion. Such ridges are called the "*fault line scarps*". They may face either in the same direction as the original scarp or in the opposite direction. In the later case the scarp is called the "*obsequent fault line scarp*".

Offset Ridges. In regions where resistant rock beds are displaced along a fault, *"offset ridges"* are formed.

Fault Control of Streams. Streams may be guided in the direction and course of their flow by faulting. Such a stream may follow a nearly straight line or make approximately right angle turns.

Lines of Ponds, Springs or Water Seeking Plants. Linear arrangement of ponds, springs or water seeking plants may concide with the alignment of faults.

The various criteria discussed above, are mostly indicative of faulting. Individually they do not give any conclusive evidence. Besides some of these criteria also suggest other structures, such as unconformities and folds. Usually a combination of several criteria is required for the establishment of a fault.

7.10. SIGNIFICANCE OF FOLDS AND FAULTS

Folds and faults are of major significance to industrial geologists because they often form structural traps for valuable mineral deposits. Faults that develop above an intrusive granite allow mineralizing fluids to pass into the overlying rocks. The deposits of minerals such as lead, tin, zinc and copper ores are formed in this way. Faults that do not reach the surface may form channels through which oil and gas can rise. In synclines where porous sand beds overlie impermeable clays and shale, collection of water form reservoirs which produce artesian springs.

Correct interpretation of folds and faults is essential in mining. For example, recumbent folding and reverse faulting can cause coal seams to be repeated vertically, while normal faulting can cause a horizontal gap. A coal seam may thus be passed through several times in drilling or alternatively missed altogether.

Along a fault zone, highly crushed and sheared rocks are met with. These zones being weak, unstable and highly permeable, pose expensive problems in civil engineering constructions, such as dams, reservoirs, tunnels and highways.

7.11. UNCONFORMITIES

When the sedimentary rock beds are found to have been deposited without interruption, they are said to be *"conformable"*. Unconformities are formed when there is break in sedimentation. This creates a gap in the geological record.

Unconformity. Major breaks in sedimentation are called *"unconformities"*. Thus an unconformity may be defined as an old erosion surface which separates younger series of rocks from the older series. Unconformities represent an interval of time of unknown length which is spent in the erosion of the underlying strata before the deposition of the overlying rocks.

Fig. 7.41 shows a group of horizontal beds 'A' resting unconformably on the inclined and eroded beds 'B'. The unconformity at X-Y represents a long period of time during which the older beds 'B' were uplifted, tilted (possibly folded and faulted), eroded and submerged beneath the sea again, before the upper group of beds 'A' were deposited.

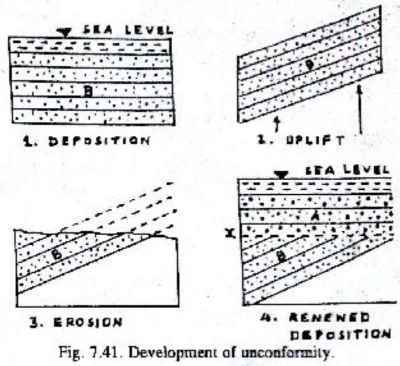


Fig. 7.41. Development of unconformity.

7.11.1. Types of Unconformity

Unconformities are of three types : (*i*) angular unconformity, (*ii*) disconformity and (*iii*) nonconformity.

Angular Unconformity. The rock beds on opposite sides of an *"angular unconformity"* are not parallel [*Fig. 7.42* (*a*)]. The angular unconformities occur where the older series of beds have been tilted, deformed and eroded before the deposition of younger beds.

Disconformity. The rock beds on opposite sides of a *"disconformity"* are parallel [*Fig. 7.42* (*b*)]. Disconformities occur where the strata of the older series have not been tilted or deformed in any way before the younger rock beds were deposited above them. They represent either a period of non-deposition or a period of erosion.

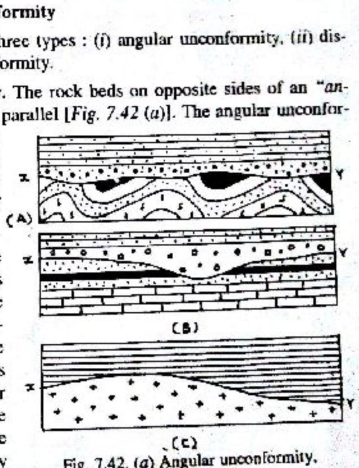


Fig. 7.42. (*a*) Angular unconformity. (*b*) Disconformity, (*c*) Nonconformity.

Nonconformity. When bedded sedimentary rocks overlie the non-bedded igneous mass, the structure is called the *"nonconformity"* [*Fig. 7.42* (*c*)].

7.11.2. Recognition of Unconformities

The factors which aid in recognizing the unconformities in the field, are as follows.

(*i*) **Difference in Structure.** The group of rocks on either side of an unconformity may show structural discordance.

(*ii*) **Difference in Fossil Record.** Rock beds lying below an unconformity surface commonly contain faunas which do not occur in the rocks above. Moreover fossils in the younger series may be of higher evolutionary rank. This suggests that a gap exists in the succession of rock beds.

(*iii*) **Presence of Conglomerate.** At an unconformity a bed of conglomerate is commonly found at the base of the upper series of rocks. Such conglomerates contain fragments of the underlying rocks.

(*iv*) **Fossil Soil.** Subaerial weathering profiles may be preserved at an unconformity as clay rich reddened or ocherous horizons.

(*v*) **Difference in Environment of Deposition.** Association of such rock beds which were formed under contrasting conditions, indicates the presence of an unconformity. For example, nonmarine beds overlain by marine beds, or cross-bedded strata overlain by strata showing graded-bedding.

(*vi*) **Relation to Intrusives.** Unconformities may be recognized by truncation of volcanic necks or other volcanic intrusions.

(*vii*) **Difference in Grade of Metamorphism.** The younger series of rocks are likely to be less metamorphosed than the rocks of older series.

7.12. OVERLAP

In some cases the junction between two series of beds is smooth and represents a gently sloping old land surface which slowly sank below sea level. As a result when the younger series of rocks were deposited on the older beds, each new bed in turn, as c, b, and a in *Fig. 7.43*, encroached more and more on the old land surface. Unconformities of this type are known as the *"overlap"*.

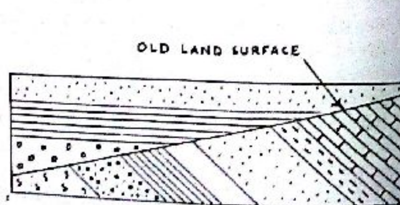


Fig. 7.43. Overlap.

7.13. JOINTS

When rock masses are subjected to tensional or compressional forces, regular or irregular fractures develop in them. Such fractures along which there has been no relative displacement are called *"joints"*. Joints occur in almost every type of rock. They may be vertical, inclined or even horizontal.

Commonly rocks contain a large number of joints which lie parallel to one another. These parallel joints together form a *"joint set"*. Very often two or more sets of joints occur in rocks which break them into large nearly rectangular blocks. Two or more sets together constitute a *"joint system"*.

Since joints have well defined fracture surfaces, their position in space is recorded in terms of dip and strike. The dip and strike of joints are measured in the same way as that of sedimentary strata.

7.13.1. Classification of Joints

Classification-I. Depending on the mode of formation, the joints are 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 lavaflows (*Fig. 7.45*) and the longitudinal joints in anticlines that run parallel to the fold axis (*Fig 7.44*) are the examples of tension joints.

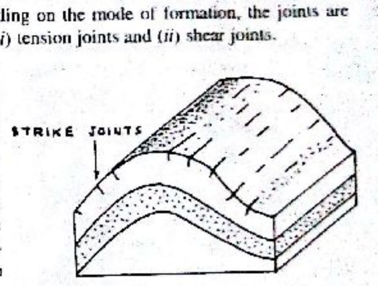


Fig. 7.44. Anticline showing strike joints formed due to tension

Shear Joints. *"Shear joints"* are those which are formed due to compressional forces 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"*.

Classification-II. Depending on their attitude and geometry, the joints are classified into three groups : (*i*) strike joints, (*ii*) dip joints and (*iii*) oblique joints.

Strike Joints. The joints which run parallel to the strike of country rocks, are called the *"strike joints"* (*Fig. 7.44*).

Dip Joints. The joints which run parallel to the direction of dip of the country rocks are calledthe *"dip joints"*.

Oblique Joints. The joints which run oblique to the dip and strike directions of the country rocks, are called the *"oblique joints"*.

7.13.2. Description of Common Joints

Bedding Joints. The joints which are oriented parallel to the bedding planes in sedimentary rocks, are called the *"bedding joints"*.

Master Joints. In sedimentary rocks, the joints usually run in two directions at nearly right angles. One set of joints run parallel to the dip direction and the other parallel to the strike direction. Of these, one set of joints is commonly more strongly developed and extends for long distances. Such well developed joints are called the *"master joints"*.

Primary Joints. In igneous rocks, joints are formed during cooling and contraction of magma. Such joints are called the *"primary joints"*. The primary joints are of following types.

(*i*) **Mural Joints.** Granites commonly show three sets of joints mutually at right angles which divide the rock mass into more or less cubical blocks. Such joints are called the *"mural joints"*.

(*ii*) **Sheet Joints.** Sheet Joints are often seen in the exposures of granites. These joints run in the horizontal direction and are formed as tension cracks. They are believed to have developed by unloading through removal of overlying rocks by erosion. The sheet joints are some what curved and are essentially parallel to the topographic surface. They are more conspicuous and close together near the ground surface.

(*iii*) **Columnar Joints.** Columnar joints are formed in tabular igneous masses such as dykes, sills and lavaflows. These joints divide the rock masses into hexagonal, square, rhombic or triangular columns (*Fig. 7.45*). Such columns develop at right angles to the chief cooling surface. In lavas and sills, the columns are vertical while in dykes they are nearly horizontal.

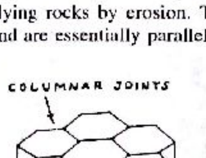


Fig. 7.45. Columnar joints.

7.14. CONCEPTS OF STRESS AND STRAIN

All stresses which are applied to a rock mass can be resolved into three mutually perpendicular directions. These directions are called *"axes of stress"* and their magnitude is expressed as greatest, intermediate, and least. When the magnitude of stresses for each axis is equal, the stresses are said to be hydrostatic. Under such stresses only the volume of the rock changes while its shape remains the same. When the stresses are unbalanced, a deformational force operates which changes the shape of the rock.

Application of stresses produces a *"strain"*. The distribution of strain along the principal stress axes gives rise to strain axes. These strain axes are as follows.

(*i*) **Axis of Least Strain.** The axis of greatest stress is the axis of greatest compression. Hence it is regarded as the *"axis of least strain"*.

(*ii*) **Axis of Greatest Strain.** The axis of least stress is the axis of least compression. Hence it becomes the *"axis of greatest strain"*.

(*iii*) **Axis of Intermediate Strain.** The axis of intermediate stress becomes the *"axis of intermediate strain"*.

7.14.1. Strain Ellipsoid

The strain ellipsoid in an imaginary figure. It is produced when a sphere of homogeneous rock is subjected to a deforming stress. In this ellipsoid the orientation of strain axes is show in *Fig. 7.46*.

Most sections through the ellipsoid are ellipse. Two of the sections, however, are circles whose diameters are '*ac*' and '*bd*' (*Fig. 7.46*). Along

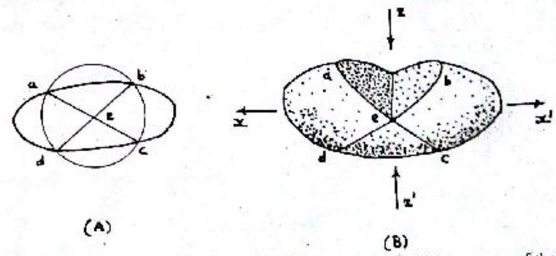


Fig. 7.46. Strain ellipsoid. (*a*) Longitudinal section. ac and bd are traces of the circular sections. (*b*) Ellipsoid showing planes of shear. xx' is the greatest strain axis. zz' is the least strain axis.

the circular sections the surface of the ellipsoid and the sphere coincides. It means that along these sections no change in shape has taken place. Along all other sections, however, the shape has been distorted.

In the segment '*bec*' of the ellipsoid the strain has produced elongation while in the segment '*aeb*', the strain has caused shortening. The plane of circular cross-section '*bd*' lies between these two segments. This is a surface of shear because the distribution of stress on either side of it is in opposite directions. Thus there are two shear planes which pass through the strain ellipsoid. These shear planes become surfaces of rupture when the compressional strength of the rock has been exceeded.

In the strain ellipsoid, the axis of greatest strain indicates the direction of elongation. If the tension fractures form, they develop parallel to the plane that contains the least and intermediate strain axes. It means tension fractures form at right angles to the greatest axis of the strain ellipsoid.

7.15. LANDFORMS

Some rock types give rise to very distinctive landforms, for example, limestones on weathering produces *"karst topography"*. The landscape produced by the processes of weathering and erosion is closely related to climate and rock types.

1. The angle of surface slope is controlled directly by the strength of the rock. Hard rocks like limestones and sandstones stand out as convex curves in contrast to the concave curves formed on soft rocks like clay or shale (*Fig. 7.47*).

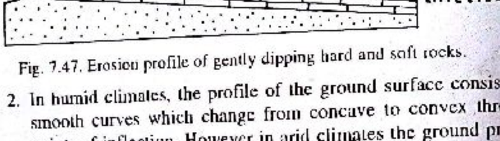


Fig. 7.47. Erosion profile of gently dipping hard and soft rocks.

2. In humid climates, the profile of the ground surface consists of smooth curves which change from concave to convex through points of inflection. However in arid climates the ground profile is usually much sharper. There are angular intersections between different slope angles.

7.15.1. Stages of Landform Development

The whole period of history of a land mass can be described in terms of *"youth"*, *"maturity"* and *"old"* age.

Youthful Landscape. A *"youthful landscape"* is one in which the agents of erosion have been acting for a relatively short period on a recently uplifted

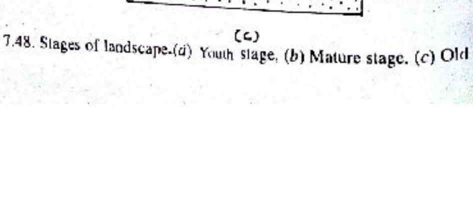


Fig. 7.48. Stages of landscape. (*a*) Youth stage, (*b*) Mature stage, (*c*) Old stage.

land mass. This type of landscape has wide flat surfaces dissected by rivers which have narrow valleys with steep sides [*Fig. 7.48 (a)*]. Here the erosion is chiefly downwards.

Mature Landscape. In *"mature landscape"* the river valleys become wide and they meet adjacent ones. As a result only a small parts of the original flat uplifted land area are left [Fig. 7.48 (*b*)].

Old Landscape. In *"old landscape"*, the landscape becomes almost flat with isolated hills standing up above a plain which is almost at sea level. Such a plain is called the *"peneplain"* [*Fig. 7.48 (c)*]. In the old stage the erosive power of rivers is greatly reduced and their gradient becomes low. After the old stage, the land mass would either sink below sea or is uplifted again and the above cycle is repeated.

7.16. STRUCTURES DUE TO DENUDATION

Outcrop. An *"outcrop"* is the area where the bed rock is exposed on the ground surface.

Outlier and Inlier. An *"outlier"* is a patch of younger rocks surrounded by older rocks on all sides (*Fig. 7.49*). It is formed when a part of a bed or a series of beds gets separated from the main mass by erosion. An *"inlier"* may be defined as a patch of older strata which is surrounded on all sides by younger strata (*Fig. 7.49*).

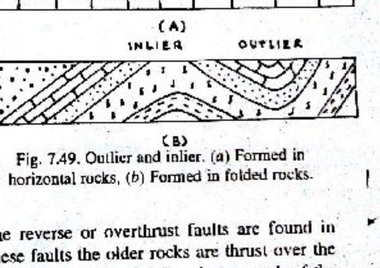


Fig. 7.49. Outlier and inlier. (*a*) Formed in horizontal rocks, (*b*) Formed in folded rocks.

Klippe and Window. The reverse or overthrust faults are found in complex fold mountains. In these faults the older rocks are thrust over the younger ones. In such a case if erosion works and detaches a patch of the

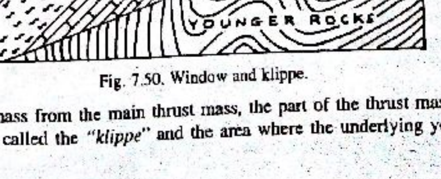


Fig. 7.50. Window and klippe.

travelled mass from the main thrust mass, the part of the thrust mass thus isolated is called the *"klippe"* and the area where the underlying younger rocks are exposed, is called the "*window*" (*Fig. 7.50*). In other words, klippe is a nappe outlier and the window is a nappe inlier.

Plateau, Mesa and Butte. The plateaus, mesas and buttes are erosional landforms that develop in the horizontal sedimentary strata with alternate resistant and nonresistant beds. The resistant beds support the elevated flat areas and the softer beds erode to form the gentler slope.

A "*plateau*" is a board flat area that rises to a height of over 300 meters above its surroundings. Few plateaus have elevations much higher than 3000 meters. The Tibetan plateau has an average height of about 5000 meters. Smaller plateaus are called "*mesas*". A mesa may be defined as a low flat-topped upland having steep sides. The "*butte*" is a term used for an isolated hill with steep sides and a small crest. With continued erosion mesas may become butte (*Fig. 7.51*).

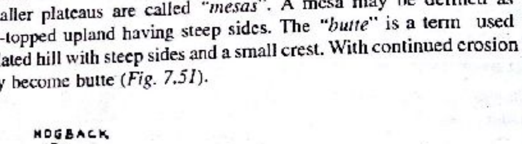


Fig. 7.51. Hogback, Cuesta, Mesa and Butte.

Cuesta and Escarpment. A "*cuesta*" is an asymmetric ridge formed in regions where rock beds are gently inclined and hard and soft rocks alternate. One side of a cuesta has a long gentle slope determined by the dip of the resistant bed while the other side has the steep slope formed at the erosional edge of the resistant bed where it is undercut by the erosion of the softer bed underneath. The side having steep slope is called the "*escarpment*" (*Fig. 7.51*).

Hogback. A "*hogback*" is the narrow steep ridge formed by erosion of the nearly vertical or steeply inclined resistant rock beds (*Fig. 7.51*).

7.17. MOUNTAIN BUILIDNG

Mountain. Mountains are high lands which rise several hundred meters or more above the surrounding terrain. Large mountain systems generally show evidence of enormus forces which have folded, faulted and deformed large sections of the earth's crust.

Orogenic Movements. The crustal movement which result in the formation of a mountain system, are called the "*orogenic movements*". During these movements extensive folding and faulting of sedimentary strata take place.

Epeirogenic Movements. The sedimentary rocks which were originally deposited in the ancient sea, are now present on the land surface, several hundred meters above sea level. Although these rocks have been uplifted to hundreds of meters, the individual rock layers are still in a horizontal position. Such vertical movements by which continental blocks are raised or lowered slowly and continuously, are called the "*epeirogenic movements*". In such cases, generally folding of strata does not take place.

The theory of isostatic balance can account for some uplifting. The earth's crust is believed to be floating on the partially molten asthenosphere. As erosion removes the tops of mountains, the mountains themselves will rise up. The processes of uplifting and erosion will continue till the root of the mountain has reached the same height as the surrounding land. Similarly if weight is added to the crust, as by the accumulation of sediments on the ocean basins, it will respond by subsiding.

7.17.1. Types of Mountain

The mountains are of five types : (*i*) volcanic mountains, (*ii*) relict mountains, (*iii*) fault-block mountains, (*iv*) upwarped mountains and (*v*) fold mountains. Since fold mountains represent the world's major mountain systems, the process of mountain building is usually described in terms of their formation.

Volcanic Mountains. The volcanic mountains are formed due to accumulation of laves and pyroclastic materials. Many of the mountain peaks in the western Andes of South America are of volcanic origin.

Relict Mountains. The relict mountains are also called the "*erosional mountains*". They are formed due to differential erosion of rock masses. Plateaus are the examples of relict mountains. "*Plateaus*" may be defined as flat topped areas that rise to a height of over 300 meters above their surroundings.

Fault Block Mountains. These mountains are commonly known as "*block mountains*". They are bounded by high angle normal faults. They are usually associated with rift valleys. The block mountains, found in the Basin and Range Province of the southwestern United States, are notable examples of this class.

Upwarped Mountains. These mountains are also called "*domed mountains*". They are formed by the intrusion of an igneous body, such as a batholith or laccolith. When the igneous body is intruded, upwarping of the overlying strata may occur thereby forming a mountain.

Fold Mountains. The largest and most complex mountain systems of the world belong of this category. In fold mountains, folding is always dominent but faulting and igneous activity are also present in varying degrees. The Himalayas, Alps, Urals and Rockies are the examples of this type.

7.17.2. Formation of Mountains

Since world's major mountain systems belong to the class of fold mountains, their process of formation is of great importance. While discussing the formation of fold mountains, the following points may be noted.

(*i*) The great mountain ranges are built of thick sequences of sedimentary rocks which are usually highly metamorphosed in the deeper levels.

(*ii*) The sedimentary strata forming mountain ranges are usually folded, faulted and intruded by igneous bodies.

(*iii*) The mountain ranges occur in relatively narrow belts of great length on the earth's surface.

It is generally believed that the mountains are originated from geosynclines. A *"geosyncline"* may be defined as a long, relatively narrow mobile trough in which vast quantities of sediments, having thickness of the order of 10 kilometers or more, are deposited. A geosyncline is formed at the margin of a continental mass and its bottom sinks gradually with the deposition of sediment. The width of a geosyncline varies from a few tens of kilometers to hundreds of kilometers and its length is usually more than 1000 kilometers. A geosyncline can be subdivided into two parts : (*i*) miogeosyncline, and (*ii*) eugeosyncline. An inner belt closer to the continental platform is called the *"miogeosyncline"*. It contains lesser thickness of sediments. The *"eugeosyncline"* on the other hand, is the outer belt which lie closer to an ocean basin. It contains greater thickness of sediments.

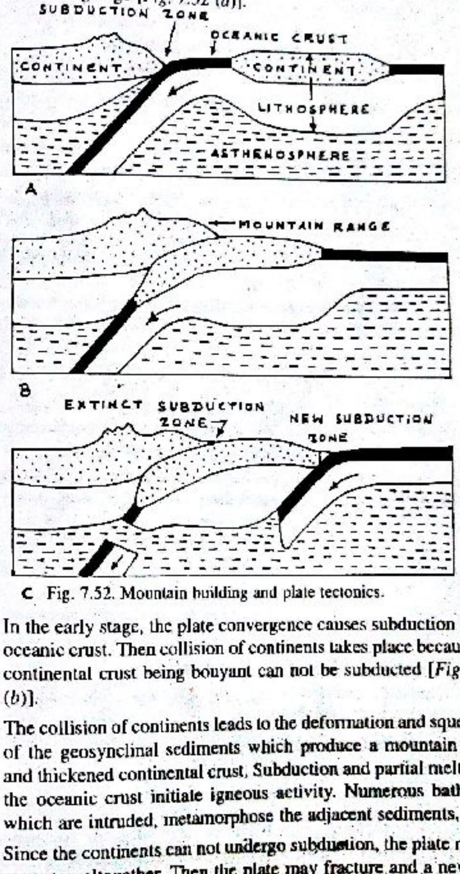
After the accumulation of great thickness of sediments, horizontal forces from the seaward side of the geosyncline begin to compress the sediments. As a result, the sediments are folded and deformed, and a mountain system with complex structure is formed. In this process of mountain building which involves thickening and shortening of the earth's crust, much of the sediments is also pushed deeper into the earth. Roots of mountains are formed in this way. The deeply buried sediments melt and produce magma. This magma moves upward and intrude the overlying sediments. The batholiths thus formed metamorphose the sediments intruded. In this way a complex mountain system containing folded and faulted sedimentary rocks surrounding a core of igneous intrusions and metamorphic rocks, is formed.

Although the geosynclinal concept of mountain building has many merits, it fails to answer the two vital questions : (*i*) what produced the subsidence in the geosyncline and (*ii*) why did the force come from the sea to squeeze the sediments. The mechanism of mountain building has nicely been explained by the *"plate tectonics theory"*.

7.18. MOUNTAIN BUILDING AND PLATE TECTONICS

According to the plate tectonics theory, fold mountains are formed by the movements and collisions of large plates that make up the earth's crust. These plates are usually very large in size and carry whole continents. The process of formation of fold mountains may be summarized as follows.

(*i*) A plate with a continent at the leading edge converge toward another plate carrying a continent but having a oceanic crust at the leading edge [*Fig.* 7.52 (*a*)].



C Fig. 7.52. Mountain building and plate tectonics.

(*ii*) In the early stage, the plate convergence causes subduction of the oceanic crust. Then collision of continents takes place because the continental crust being bouyant can not be subducted [*Fig.* 7.52 (*b*)].

(*iii*) The collision of continents leads to the deformation and squeezing of the geosynclinal sediments which produce a mountain range and thickened continental crust. Subduction and partial melting of the oceanic crust initiate igneous activity. Numerous batholiths which are intruded, metamorphose the adjacent sediments.

(*iv*) Since the continents can not undergo subduction, the plate motion may stop altogether. Then the plate may fracture and a new subduction zone be started at another place [*Fig.* 7.52 (*c*)].

(*v*) An extinct subduction zone may now appear as a mountain belt within a continent. The Himalayas and the Ural mountains are examples of such extinct subduction zones.

REVIEW QUESTIONS

1. Classify and describe the different types of fold and describe the criteria for their recognition in the field.
2. What are folds ? Sketch the different geometric elements of folds. Explain how are they recognized in the field ?
3. Distinguish between joints and faults. Give the classification of faults and illustrate your answer with neat sketches. Give field evidences of faulting.
4. Define faults. Describe the various parts of faults. Explain the effects of the different types of fault on the outcrops of strata.
5. Classify and describe the different types of fault. Give the various minor structures found in the fault zones. Discuss the effects of faulting on various engineering projects.
6. How are faults recognized in the field ? Describe the effects of the various types of fault on outcrops of strata.
7. Describe the different types of unconformities and discuss the criteria for their recognition.
8. Define unconformities. How are they formed ? Classify and describe the different types of unconformity. Explain how are they recognized in the field.
9. What are joints ? Classify and describe various types of joints ?
10. Explain the concept of stress and strain ellipsoid. How does this concept help in understanding the nature of rock deformation.
11. What is a fold mountain ? Describe the formation of fold mountains in context with the theory of plate tectonics.
12. Write short notes on any four of the following.

Shear fold, Geosynclines, Overlap, Window, Inlier, Tension joints, Drag fold, Hogback.

8 Indian Stratigraphy

8.1. INTRODUCTION

"*Stratigraphy*" is the science of description,correlation and classification of strata in sedimentary rocks. It also includes the interpretation of the despositional environments of the strata.

Facies. A set of lithological and palaeontological charactersties of a sedimentary rock which indicate its perticular environment of deposition, are called "*facies*". A lateral variation in lithology and fossil assemblage in a formation which result from change in the environment of deposition, is called "*facies variation*". For example, a formation may be composed of shale in one locality and limestone in another or fresh water fossils at one place and marine fossils at another. For a metamorphic rock the term facies means the perticular range of pressure and temperature under which the rock crystallized.

Index Fossils. Those fossil forms which have short time ranges of their existence and wide geographical distribution, are called "*index fossils*". In Fig.8.1 the fossils 'A' have wide distribution and short duration, and there-

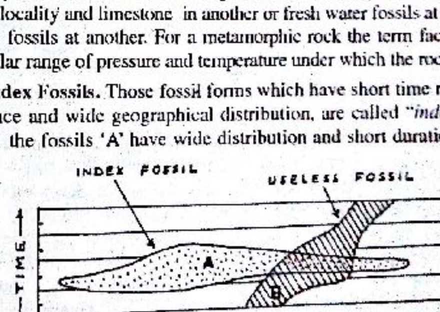


Fig. 8.1. Showing Index Fossil.

fore they are the index fossils. The fossils 'B' are not index fossils because they have long time ranges and limited distribution. The index fossils are an excellent tool for correlating the fossiliferous rockformations of the same age.

8.2. PRINCIPLES OF STRATIGRAPHY

There are three major principles which are used to determine the relative ages of strata. These principles are as follows.

Law of Superposition. In a series of undisturbed beds, a bed that overlies another bed is always the younger. The youngest bed will be at the top of the sequence.

Fossil Content. William Smith in 1799 noticed that each of the sedimentary beds contain a perticular set of fossils by which it can be identified. Because the lower forms of life existed long before the higher organism appeared, it is possible to assign relative ages to the strata containing fossils.

Lithological Character. A sedimentary bed may be indentified by its distinct lithological character. But as similar rock beds are known to occur in formations of widely different geological ages, the lithology is not of much use for determining relative ages.

8.3.PRINCIPLES OF CORRELATION

The rock formations of widely separated areas are correlated with the help of the following criteria.

Lithology. Correlation by means of lithology is not reliable because a rock bed when traced laterally may change its character. Further similar rock beds are known to occur in formations of widely different geological ages.

Fossil Content. Fossiliferous rocks are characterized by the presence of distinct and definite set of fossils in them. However, just as the beds show lateral variation in the lithology,they may also show lateral variation in the fossil assemblage. Hence only index fossils are used for correlation purposes.

Unconformities. The unconformities are of great significance in classifying and correlating rock formations. The unconformities represent breaks in depositional sequence hence they are significant in the interpretation of the geological history. For example, an angular unconformity is a surface of erosion that separates two sets of beds whose bedding planes are not parallel.It suggests that first the lower set of beds was formed in the horizontal disposition. This set was deformed and then eroded to a more or less even surface before the upper set was deposited horizontally upon it.

Metamorphism. In a perticular area,the older rocks may show higher grade of metamorphism as compared to the younger rocks.

Igneous Intrusion. The igneous history of a perticular region may be identical to another region. In such cases rocks can be correlated.

Radiometric Dating. The age of intrusive igneous bodies may be determined by the radiometric methods and then the correlation may be done.

8.4. FOSSILS

"*Fossils*" are remains or impressions of ancient animals and plants which have been preserved within the sedimentary rocks.

8.4.1. Conditions of Preservation

All the animals and plants are not preserved as fossils. The two most important conditions which favour the preservation of fossils are : (*i*) possession of hard parts, and (*ii*) immediate burial.

Possession of Hard Parts. After the death of the organisms, the soft parts are generally easily decomposed. Therefore animals like jelly fish and insects which are totally composed of soft parts, are not ordinarily preserved as fossils. The animals which possess hard skeleton have a better chance of being converted into fossils.

Immediate Burial. If the animals and plants are not buried quickly after their death, they are likely to be destroyed by chemical decay and other agencies of erosion.

8.4.2. Forms of Fossils

The fossils are preserved in rocks in a number of different forms which are as follows.

Entire Organism Preserved. The whole body of the organism including its soft parts, may be preserved. For example, the bodies of mammoth elephants of pleistocene age are found preserved in the ice in northern Siberia. These types of fossils are, however, extremely rare.

Skeleton of Organism Preserved. In rocks of Tertiary age, the bony skeletons of animals having original composition and structure are found.

Petrifaction of Hard Parts. Mineral matter like silica, calcium carbonate and iron sulfide may replace the remains of organism particle by particle thereby preserving the structure faithfully. An example of this type of fossil is the silicified wood.

Molds. After burial the hard parts of the organisms may be totally dissolved and removed in solution. As a result hollows having the shape of the outside of the body are left within the rock beds. Such hollows are called "*molds*".

Casts. Molds may be filled with mineral matter producing natural "*casts*". A cast shows all the external markings of the body of organism but not its internal structure.

Carbonization. When plants decompose slowly, their organic tissues are transformed into carbon. Such carbonized remains commonly preserve the structure of the original material. Seams of coal are the best examples of carbonized remains of plants.

Imprints. Plants and animals which do not have hard parts may be preserved as imprints in soft sediments such as shales. Distinct impressions of plant leaves are often found preserved in the shales above coal seams.

8.4.3. Uses of Fossils

1. The fossils are commonly used for correlating the strata and determining their relative ages.
2. Fossils indicate whether the rock is a fresh water deposit or a marine deposit.
3. Fossils give information about the climate of the times in which they lived.
4. The fossils have helped in understanding the evolution of plants and animals.

8.5. GEOLOGICAL TIME SCALE

The time span of earth's history is about 3000 million years. It is roughly represented by the column of sedimentary rocks now present on the earth. In this record the time elasped during the formation of unconformities is missing. The unconformities are however, important because they subdivide the geological time into smaller units. On this basis a standard Geological Time Scale (Table 8.1) has been prepared which is used universally for the correlation of rockformations.

Eras. The major units of the geological time are called "*eras*". In the geological time scale, there are four eras : (*i*) Precambrian, (*ii*) Palaeozoic, (*iii*) Mesozoic, and (*iv*) Cenozoic.

Periods. Each era has been subdivided into smaller time units called "*periods*". The stratigraphic breaks which subdivide eras are relatively of lesser significance. For example, in the Palaeozoic era, there are six periods: (*i*) Cambrian, (*ii*) Ordovician, (*iii*) Silurian, (*iv*) Devonian, (*v*) Carboniferous, and (*vi*) Permian. A succession of rocks deposited during a period constitutes a "*system*".

Epochs. The periods are further divided into smaller parts called "*epochs*". The rock units corresponding to epochs are called "*series*". For example, in the Triassic period, there are three epochs : (*i*) Lower Triassic, (*ii*) Middle Triassic, and (*iii*) Upper Triassic.

Stage. A part of the series is called "*stage*". It is characterized by a typical assemblage of fossils.

Zone. The basic unit of a stage is called "*zone*". It is recognised mainly on the basis of the most characterstic fossil form.

On the basis of palaeontology, the Precambrian era has been divided into two groups : (*i*) Archaeozoic, and (*ii*) Proterozoic.

Table 8.1. Subdivisions of Geological Time Scale

Age Million Years	*Era*	*Period*	*Epoch*
	CENOZOIC	Quaternary	Recent
2 –			Pleistocene
12 –		Tertiary	Pliocene
26 –			Miocene
37 –			Oligocene
53 –			Eocene
65 –			Paleocene
136 –	MESOZOIC	Cretaceous	
190 –		Jurassic	
230 –		Triassic	
280 –	PALAEOZOIC	Permian	
345 –		Carboniferous	
395 –		Devonian	
430 –		Silurian	
500 –		Ordovician	
570 –		Cambrian	
2500 –	PRECAMBRIAN	Proterozoic	
		Archaeozoic	

The rockformations belonging to the "*Archaeozoic group*" are generally unfossiliferous whereas those belonging to the "*Proterozoic group*" show traces of the most primitive life. The rocks of the Palaeozoic, Mesozoic, and Cenozoic eras contain abundant remains of past life (Table 8.2).

8.6. LITHOSTRATIGRAPHIC CLASSIFICATION

In regions having different kinds of geological history, the boundaries of the Geological Time Scale do not coincide with the actual stratigraphic boundaries. In many areas, though the major straligraphic divisions are identified, the demarcation of smaller divisions, such as series and stages become very difficult. In case of unfossiliferous strata, it is not possible to identify the divisions corresponding to those of the standard time scale. In order to avoid these difficulties the "*Lithostratigraphic classification*" has been devised. In this classification the rockformations are divided chiefly on the basis of lithological criteria.

Table 8.2. Geological Time Scale

Eras	*Periods*	*Life*
Quaternary	Recent Pleistocene	Man. Modern plants, and animals. Many mammals die.
Tertiary	Pliocene Miocene Oligocene Eocene Paleocene	Mammals, Birds, Mollusca and Flowering plants.
Mesozoic	Cretaceous Jurassic Triassic	Dinosaurs, Flowering plants. Ammonites, Dinosaurs. Ammonites, Reptiles, Amphibians.
Palaeozoic	Permian Carboniferous Devonian Silurian Ordovician Cambrian	Reptiles, Nonflowering plants. Amphibians, Non-flowering plants. Corals, Brachiopods, Early land plants. Freshwater fishes, Graptolites. Trilobites, Graptolites. Trilobites.
Precambrian	Proterozoic Archaeozoic	Soft bodied animals and plants. Lifeless.

Group. The major divisions of rockformations are called *"Groups"*. Each Group includes a thick succession of rocks which extends over a large area. The bigger unconformities separate one Group from another. A *"Supergroup"* is formed when two or more Groups join together.

Formation. It is the basic unit used for naming the rocks in stratigraphy. It may be defined as a set of rocks which have some distinctive feature of lithology and are large enough to be mapped.

Bed. A bed is the smallest lithological unit. It may be defined as a single sedimentary rock unit which has a distinct set of mineralogical or fossil characterstics which help to distinguish it from beds above and below.

8.7. STRATIGRAPHIC UNITS OF INDIA

The general outline of the broad stratigraphic units of India together with their relationship to the Geological Time Scale has been shown in Table 8.3. More than half of the Peninsular India is covered with the Archaean rocks, the rest is occupied by the Cuddapahs, Vindhyans, Gondwanas, and Deccan Traps. In the Extra-Peninsular India, mainly the marine sedimentary rocks ranging in age from the Cambrian to Eocene are exposed.

Table 8.3. Major Stratigraphic Units of India

Era	*Periods*	*Stratigraphic Units of India*
Quaternary	Recent	Recent alluvium
	Pleistocene	Karewas of Kashmir, Older alluvium.
Tertiary	Mio-Pliocene	Siwalik Group
	Oligocene	Murre Group
	Eocene	Ranikot, Laki formations.
Mesozoic	Cretaceous	Cretaceous of Trichinopoly, Deccan traps.
	Jurasic Triassic	Gondwana Supergroup Spiti shales, Lilang Group, Kioto limestone Kuling group
Palaeozoic	Permian Carboniferous	
	Devonian Silurian Ordovician Cambrian	Missing in Peninsular India and present in Himalayan region.
Precambrian	Proterozoic	Cuddapah and Vindhyan Supergroups.
	Archaeozoic	Archaean, Dharwar and Aravali Groups.

8.8. PHYSIOGRAPHIC DIVISIONS OF INDIA

India can be divided into three main divisions which differ from one another in physiography, structure and stratigraphy (Fig. 8.2.). These divisions are as follows.

1. Peninsular India.
2. Indo-Gangetic Plain.
3. Extra-Peninsular India.

8.8.1. Peninsular India

The Peninsular India lies to the south of the plains of Indus and Ganga river system.

Physiography. The Peninsular India has an extremely variable physiography. There are plateaus, peneplained ancient fold mountains, massifs, elongated graben like valleys, and coastal plains. The Western Ghats which forms a prominent physiographic feature exists at the western margin of the

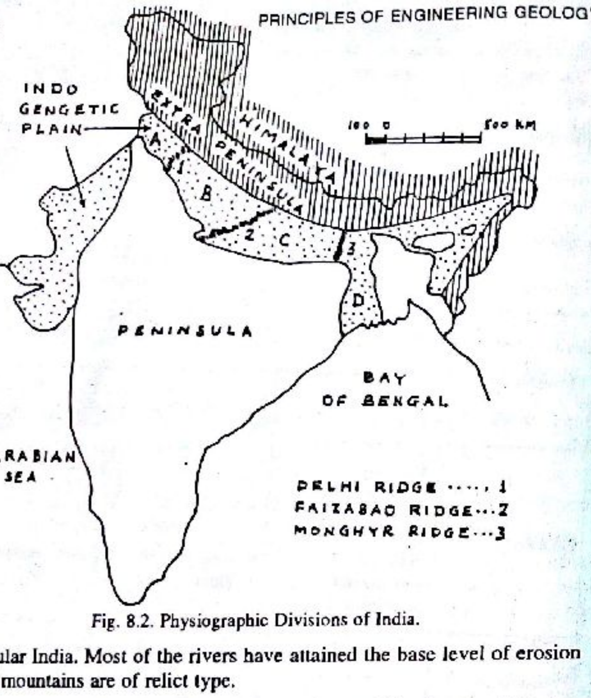


Fig. 8.2. Physiographic Divisions of India.

Peninsular India. Most of the rivers have attained the base level of erosion and its mountains are of relict type.

Structure. The Peninsular India is nearly a stable plateau which has remained unaffected by the orogenic movements of post Cambrian age. The normal and block faulting is however common.

The Narmada, Son and Damodar rivers flow in the graben-like valleys which trend in the E–W direction. The trend of the Mahanadi and Godavari valleys is in the NW–SE direction. The four distinct geomorphic and structural trends which have been recognised in the Peninsular India are :

(*i*) NNW-SSE, trend of the southern parts of Western Ghats, (*ii*) NE–SW, trend of Eastern Ghats, (*iii*) E–W, trend of Satpura in central India, and (*iv*) NE–SW, trend of Aravallis in Rajasthan.

Stratigraphy. The Peninsular India is primarily made up of rocks of the Archaean and Precambrian age. The Archaean rocks have been metamorphosed to varying degrees. In addition there exists the Deccan traps and Rajmahal traps of Jurassic to Eocene age. Post Cambrian sedimentary rocks occur in the Gondwana basin and occassionally along the coastal tracts of the Peninsular India.

8.8.2. Indo-Gangetic Plain

The Indo-Gangetic Plain is a deep crustal trough filled with Quaternary sediments. Its origin and structure is intimately related to the rise of Himalaya. This plain extends from Assam in the east, through Bengal, Bihar and U.P., upto Punjab in the west (Fig. 8.2).

Physiography. The Indo-Gangetic Plain is the very extensive alluvial plain which is sloping with a very small gradient towards the sea.

Structure. The Indo-Gangetic Plain is made up of the undisturbed layers of Quaternary sediments which have been deposited by the rivers of the Himalayan region.

The bottom of the Indo-Gangetic basin is asymmetrical. The northern margin of the Peninsular India dips gently northward. Hence the thickness of the Quaternary sediments gradually increases towards north and the maximum thickness is found at the northern extremity near the Outer Himalaya. The bottom of this trough is not stable and some changes are still taking place which give rise to earthquakes.

In the Indo-Gangetic Plain, three transverse "*highs*" have been recognised. These highs are :

(*i*) Delhi–Haridwar Ridge, (*ii*) Faizabad Ridge, and (*iii*) Monghyr–Saharsa Ridge (Fig. 8.2). These highs divide the Indo-Gangetic Plain into four shelf areas : (*i*) Punjab shelf, (*ii*) west U.P. shelf, (*iii*) east U.P. shelf, and (*iv*) Bengal shelf.

Stratigraphy. The Indo-Gangetic Plain is chiefly made up of sands and clays of Pleistocene and Recent age. The basement of the Punjab shelf is made up of the Precambrian rocks, while that of the east and west U.P. shelves contain Precambrian and Vindhyan rocks. The Bengal shelf is believed to contain rocks of Gondwana age and Rajmahal traps.

8.8.3. Extra Peninsular India

The Extra-Peninsular India lies at the northern extremity of the country. It is made up of the Himalayan mountain ranges in the north and Arakan–Yoma ranges in the east. The upper reaches of Indus and Brahmputra rivers mark its northern boundary.

Physiography. The Extra-Peninsular India is made up of the tectonic mountains and the frontal foredeep folded belt of Tertiary age. The frontal foredeep belt is also called the "*Siwalik Range*" or "*Outer Himalaya*".

The Himalayan belt extends in the E—W direction and its total length is about 2400 Km. At its western end this belt takes a sharp arcuate trun. This turn is called the "*syntaxial bend*". A bend of similar nature is also present at the eastern end of the Himalaya where the NE—SW trend changes into the NNE—SSW trend.

Structure and Stratigraphy. The rockformations of the Extra- Peninsular India have been disturbed greatly by the complex folding, faulting and overthrusting. The Extra-Peninsular India has been subdivided into four longitudinal geomorphic zones :

(*i*) Tethyan Himalayan zone, (*ii*) Central crystalline zone of the Higher Himalaya, (*iii*) Lesser Himalayan zone, and (*iv*) Foredeep folded belt.

(*i*) *Tethyan Himalayan Zone.* This zone is at the northern extremity of the Extra-Peninsular India. Here the Himalayan mountains rise to an average altitude of about 6000 meters. This zone consists of the marine rock beds of Palaeozoic and Mesozoic ages. This succession rests unconformably over the Precambrian basement.

(*ii*) *Central Zone of Higher Himalaya.* In this zone the average height of the mountains is also about 6000 meters but they are chiefly made up of the Precambrian basement and the granitic plutons of Tertiary age.

(*iii*) *Lesser Himalayan Zone.* The average height of mountains in this zone is between 2000—3000 meters. Many antecedent rivers flow through this zone. These rivers originate in the Tethyan Himalayan zone and flow across the Higher Himalayan and Lesser Himalayan ranges by cutting deep gorges. The rockformations of this zone are relatively less metamorphosed. They are unfossiliferous and therefore their correlation can not be done. The structure of these rocks is very complex. They are affected by a series of thrust faults due to which the stratigraphic succession has been reversed in many places. The lower part of the unfossiliferous rockformations is believed to be of Precambrian age. These are overlain by rockformations of Gondwana age. Above these are the rocks of Tertiary age.

(*iv*) *Foredeep Folded Belt.* This zone lies at the southern margin of the Extra-Peninsular India. It is also called the "*Siwalik Range*". The low lying hills of this belt are mainly made up of the sediments of Mio-Pliocene age. The southern boundary of this belt is marked by the "*Main boundary faults*".

8.9. ARCHAEAN SYSTEM

The Archaean system is made up of very ancient rocks such as gneisses, schists, and granites. These rocks form a basement on which all younger sedimentary rockformations rest. The general characters of the Archaean rocks are as follows.

1. They are unfossiliferous. It suggests that there was no life on the earth at the time of formation of the Archaean rocks.
2. They are generally highly metamorphosed.

3. They are contorted and subjected to intense folding and faulting.
4. They are intruded by igneous rocks of acid to ultrabasic composition.

As the structure and composition of the Archaean rocks are very complex, they are often called "*Fundamental gneiss*" or "*Basement complex*". The Archaean gneisses are typically migmatitic gneisses which contain alternate bands of amphibolites and tonalites.

8.9.1. Distribution

The Archaean rocks cover nearly two thirds of the Peninsular India (Fig. 8.3.). The areas where they are very well exposed, are: (*i*) South India, M.P., Bihar and Orissa, (*ii*) Gujrat and Rajasthan, (*iii*) Assan Plateau, and (*iv*)

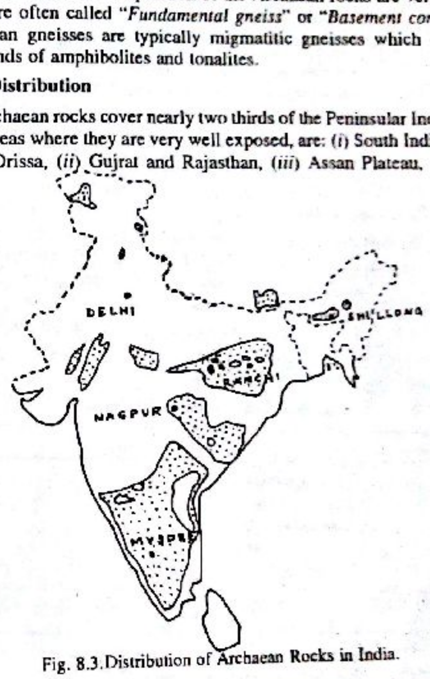


Fig. 8.3. Distribution of Archaean Rocks in India.

Central Himalayan region. Besides these areas, the Archaean rocks are believed to extend below the Deccan traps between Karnataka and Rajasthan, and below the alluvium of the Ganga river between Bihar and Assam. For convinience of study, the Archaean rocks of Peninsular India have been divided into five zones.

1. Archaean rocks of South India.
2. Archaean rocks of Eastern Ghat.
3. Archaean rocks of M.P. and Maharashtra.
4. Archaean rocks of Bihar and Orissa.
5. Archaean rocks of Rajasthan.

8.10. DHARWAR SUPERGROUP

The Archaean rocks of South India are described as the *"Dharwar Supergroup"*. They are best developed in Karnataka and the adjoining states. The sediments of the Dharwar supergroup were deposited over a basement of the *"Fundamental gneissic complex"*.

8.10.1. Lithology and Structure

The chief rock types of the Dharwar supergroup are gneisses and granites. They cover the major part of South India. Many elongated belts of schistose rocks are found enclosed within these rocks. The schistose rocks have been folded isoclinally and exhibit a steep dip towards east. The regional strike of these rocks is NNW–SSE. In south Karnataka this strike becomes N–S and even NE–SW.

8.10.2. Classification

In 1915, W.F. Smeeth studied the Dharwar rocks and regarded them as of igneous origin. On the basis of the difference in the chemical characters, he divided the Dharwar succession into two groups: (*i*) the lower *"Hornblendic division"*, and (*ii*) the upper *"Chloritic division"*.

In 1940, B.Ramarao found many sedimentary structures, such as current bedding and ripple marks, in the Dharwar rocks. He proposed a threefold classification which is shown in Table 8.4.

Table 8.4. Succession of Dharwars

Division	*Rock Formations*
Igneous Intrusions	Felsite and Porphyry dykes Closepet granite Charnockites Peninsular gneiss Champion gneiss
	Unconformity
Upper Dharwars	Ferruginous quartzite, Limestones, Calcarious silts, Quartzite, and Conglomerate
Middle Dharwars	Granitic rocks with gneissose structure, Banded–hematite–quartzite, Crystalline limestone, Chlorite–schist, Sericite–schist, Quartzite and Conglomerate
Lower Dharwars	Micaceous–quartz–schist (Metamorphosed acid lavas) Greenstone, Hornblende–schist (Metamorphosed basic lavas)
	Base not known.

Lower Dharwars. This division comprises mainly rocks of igneous origin. In the lower part there are mafic lavas over which lie the rhyolite and tuff. These rocks have been metamorphosed to hornblende-schist, quartz-schist, and gneisses.

Middle Dharwars. This division is mainly made up of rocks of sedimentary origin. The typical rocks are banded-hematite- quartzite, limestone, chlorite-schist, micaceous-quartzite and conglomerate. Bosses of granite-porphyry have been intruded in these rocks. The conglomerate contains pebbles derived from different rock types and the quartzites contain current bedding.

Upper Dharwars. The rocks belonging to this group are of sedimentary origin. The chief rock types are conglomerate, calcarious silts, slate and ferruginous quartzite. Rain prints and sun cracks have been found in these rocks.

8.10.3. Igneous Intrusions

Champion Gneiss. Champion gneiss is a sheared micaceous gneiss. It is characterized by the presence of opalascent quartz grains with grayish tint. This gneiss is best developed along the eastern border of the Kolar-schist-belt.

Peninsular Gneiss. Peninsular gneiss is a complex of granite and granite-gneiss which covers a very large part of South India. This gneiss is younger than the Champion gneiss.

Charnockites. The charnockites are coarse grained gneissose rocks rich in hypersthene. They range in composition from acid to ultrabasic. The charnockites possess characters of both the igneous and metamorphic rocks.

Closepet Granite. This granite occurs mainly in the mountain ranges of Karnataka. Here the 15—25 Km wide belt of mountain ranges extends in a north-south direction for over 500 Kms from Closepet to Bellery districts. The Closepet-granite is a coarse grained, porphyritic biotite-granite which shows intrusive relation to the Peninsular gneiss.

8.11. EASTERN GHATS

The mountain ranges of the Eastern Ghats extend in the NE–SW direction along the eastern coast of India from Orissa to Tamil Nadu. The Archaean rocks are exposed in this belt of mountain ranges which is 50—80 Km wide. Here the chief rock types are highly metamorphosed gneisses, charnockites, khondalites and kodurites. In these rocks garnet and sillimanite occur in abundance. The charnockites show intrusive relationship with khondalites.

Charnockites. The charnockites are coarse grained gneissose rocks rich in hypersthene. They range in composition from acid to ultrabasic. The charnockites possess characters of both igneous and metamorphic rocks.

They show intrusive relation with the country rocks and they also show foliated structure. The charnockites of acidic composition are characterized by the presence of bluish grey grains of quartz. The charnockites occur in most of the mountain ranges of the Eastern Ghats, such as Sheveroy hills, Nilgiri hills, and Palni hills.

Views differ on the question of origin of charnockites. T.H. Holland (1900) has said that the charnockites are of igneous origin. P.K. Ghosh (1941), however, has regarded them as of metamorphic origin. He suggested that the charnockites are formed from the metamorphism of sediments rich in Fe, Mg and Ca under deep seated conditions. Pitchamuthu (1965) has suggested that the charnockites of Karnataka are of two types: (*i*) the granulitic, and (*ii*) the granitic. The granulitic type is formed by the high grade metamorphism whereas the granitic type has formed due to palingenetic fusion and metasomatism.

Khondalites. The garnet-sillimanite-schists are called the "*Khondalites*". They are named after the khond tribes of Andhra Pradesh. They are often banded and contain quartz, felspar and graphite. The khondalites are believed to have formed by plutonic metamorphism of argillaceous sediments. The felspathic khondalites are thought to have originated by granitization. On weathering these rocks give rise to laterite and bauxite. Khondalites often contain graphite deposits of commercial importance.

Kodurites. The manganese rich gneisses are called the "*Kodurites*". They are composed of potash felspar, manganese garnet, manganese pyroxene, quartz and apatite. The kodurites are hybrid rocks formed by the assimilation of metamorphosed manganiferous sediment and acid igneous rocks. On weathering they give rise to manganese ore deposits.

Gondites. Gondite is a manganese bearing high grade metamorphic rock. It is composed of quartz, spessartite, rhodonite and small percentage of apatite. The gondites are formed by the plutonic metamorphism of sediments rich in manganese oxides. Gondites are commonly found in the Archaean succession of Balaghat - Chindwara area of Madhya Pradesh.

8.12. M.P. AND MAHARASHTRA

In Madhya Pradesh and Maharashtra region, the typical exposures of the Archaean rocks are found in the four areas : (*i*) Baster region, (*ii*) Bilaspur –Balaghat area, (*iii*) Nagpur–Bhandara area, and (*iv*) Nagpur–Chindwara area.

8.12.1. Baster Region

The Archaean succession of Baster region consists mainly of schists and gneisses. They are both of igneous and sedimentary origin. These rocks are intruded by igneous bodies of acid and basic composition. The regional strike of the foliation is NW - SE and is similar to the Dharwar rocks of South India. The succession of the Archaean rocks of Baster region is given in the Table 8.5.

Table 8.5. Archaean Succession of Baster

Division	*Lithology*
Igneous Intrusions	Pegmatites, Dolerite, Basalts Granite, Charnockites
Kopayi Stage	Quartzite
Bailadila Series	Calc–schist, Amphibolite, Banded ferruginous–quartzite, Quartz–schist
Bengpal Series	Schist, Andalusite–gneiss, Slate, Quartzite and Basaltic lavaflows

8.12.2. Bilaspur–Balaghat Area

The Archaean succession of Bilaspur - Balaghat area has been divided into two groups: (*i*) Sonawani group, and (*ii*) Chilpi Ghat group.

Sonawani Group. The Archaean rocks which occur in the northern part of Balaghat area are called the "*Sonawani group*". The chief rock types of this group are calc-gneiss, crystalline limestone, schist and managanese ore. The Sonawani group has been considered older than the Chilpi Ghat group.

Chilpi Ghat Group. The Archaean rocks which are exposed to the north and north-west of the Chattisgarh Cuddapah basin are called the "*Chilpi Ghat group*". This group rests over the Sonawani group and has been correlated with a part of the succession of the Sausor group. The chief rock types of the Chilpi Ghat group are phyllites, slates and mica-schists with quartzites and conglomerates. This succession also contains some manganese ore. The strike of these rocks is roughly N–S. Table 8.6 Shows the succession of the Chilpi Ghat group. The rocks of the Sonawani group and Chilpi Ghat group have been intruded by biotite- gneisses, augen gneisses and Amla granite.

Table 8.6. Chilpi Ghat Group

Division	*Lithology*
Chilpi Ghat Group (Thickness 2850 m.)	Phyllites, Sericite–schist, Felspathic tuff Blue slates, Slaty quartzites, Phyllites Manganese ore Phyllites, Jasperoid quartzite Basal conglomerate and Grit

8.12.3. Nagpur–Bhandara and Nagpur–Chindwara Areas

Towards west the rocks of the Chilpi Ghat group split into two strips. The northern strip which goes into Nagpur-Chindwara area, is called the "*Sausor group*" and the southern strip which goes into Nagpur-Bhandara area, is called the "*Sakoli group*".

The rocks of the Sausor and Sakoli groups differ considerably from one another. However, the Sakoli group may be regarded as an upward continuation of the Sausor group. The important characters of the rocks of the two groups are as follows.

1. The rocks of the two groups show different grades of metamorphism. The Skoli group contains low grade metamorphic rocks, such as chlorite-schist, sericite-schist, etc., while the Sausor group contains high grade metamorphic rocks, such as calc- granulites, marbles, garnetiferous schists etc.
2. The Strata of the Sakoli group dip generally to NNW while those of the Sausor group to the SSE. Thus the middle or axial zone may be a zone of overthrusting.
3. The Sakoli group does not contain manganese ore. Hence it differs from the Sausor and Chilpi Ghat groups in this respect.

Sakoli Group. The rocks of the Sakoli group occur in a Triangular belt which is situated in the Nagpur, Bhandara and Chanda districts. The Sakoli group is made up of low grade metamorphic rocks, such as chlorite-schist, sericite-schist, quartzites, slates and phyllites. This group does not contain manganese ore.

On the basis of structure, the Sakoli group has been considered older than the Sausor group (Sarkar and Saha, 1982). The age of the Sausor and Sakoli groups together is Early and Middle Archaean. Hence they may be considered equivalent to the Dharwar succession of South India.

Sausor Group. The Archaean rocks of Nagpur-Chindwara area are called the "*Sausor group*". This group consists of about 4.5 Km thick succession of highly metamorphosed rocks. The chief rock types are hornblende-granulites, marbles, gondites, quartzites and garnetiferous schists. This group is of economic importance as it contains deposits of manganese ore. The rocks of this group are mostly of sedimentary origin. Subsequently they were metamorphosed and intruded by plutonic igneous rocks of acid and basic composition.

The structure of the Sausor group is very complex. The rocks have been deformed intensely. There is a southern belt of overturned isoclinal folds and a nothern belt of recumbent folds and nappes. The rocks of the Sausor group exhibit a regional dip toward south or SSE.

The Sausor group has been classified into nine divisions as shown in Table 8.7. Due to intrusion of igneous rocks composite gneisses of granitic and granodioritic composition are found associated with the rocks of this group.

The deposits of manganese ore occur mainly in the Mansar formation at two or three different horizons. In addition there is also a little manganese ore in the marbles of the Lohangi formation.

Table 8.7. Succession of Sausor Group

Formation	*Lithology*
Sitapur Formation	Hornblende-schists and Amphibolites
Bichua Formation	Dolomitic marbles, Quartzites and Schists
Junewani Formation	Muscovite-biotite schists and Granulites
Chorbaoli Formation	Quartzites and Mica-schists
Mansar Formation	Mica-schists with beds of Manganese ore.
Lohangi Formation	Dolomitic marbles and Manganese ore.
Utekata Formation	Banded calc-granulites.
Kadhikhera Formation	Granulitic rocks with biotite and magnetite
Sitasongi Formation	Felspathic schists and Quartzites.
Tirodi Gneiss	Biotite gneiss, Hornblende-schists and Granulites.

8.13. BIHAR AND ORISSA

In Bihar, the Archaean rocks are well developed in the Singhbhum district, while in Orissa they are exposed in Mayurbhanj, Keonjhar and Sundargarh districts. The Archaean rocks of this region are traversed by a thrust zone called the "*Singhbhum thrust zone*". This thrust zone extends E–W for a distance of about 160 Km. It divides the Singhbhum region into two parts : (*i*) the "*southern Singhbhum region*" containing less metamorphosed rocks, and (*ii*) the "*northern Singhbhum region*" containing highly metamorphosed rocks.

8.13.1. Southern Singhbhum Region

This region lies to the south of the Singhbhum thrust zone. Here the Archaean succession consists of a "*Older metamorphic group*" and the "*Iron-ore group*". The Older metamorphic group is of Lower Archaean age. It formed the basement for the deposition of the rocks of the Iron-ore group (Table 8.8).

Table 8.8. Succession of Singhbhum Area
(Figures in bracket show ages in million years)

Groups	*Formations*
Kolhan Group	(1500—1600)
	Unconformity
Igneous Bodies	Newer dolerite Arkasani granophyre Chota Nagpur granite (2000–2100) Ultramafic intrusives Dalma traps (2100)
	Unconformity
Singhbhum Group	Dalhhum formation Chaibasa formation
	Unconformity
Iron-ore Group	Singhbhum granite (2950) Upper lava formation Upper phyllites Banded hematite quartzite Lower phyllites Lower lava formation Sandstone and Conglomerate
	Unconformity
	Biotite-tonalite-gneiss (3200)
Older Metamorphic Group	(3800)

Older Metamorphic Group. The oldest rocks of the southern Singhbhum region are called the "*Older metamorphic group*". This group consists mainly of hornblende-schists with quartzites and quartz-mica schists. These rocks are intruded by the biotite- tonalite gneiss (age 3200 million years).

Iron Ore Group. The Older metamorphics are overlain unconformably by the rocks of the "*Iron-ore group*". The rocks show a low grade of metamorphism. The succession of this Group starts with the basal sandstone and conglomerate. The basal beds are then followed by lower lava, lower phyllites, banded- hematite-quartzite, upper phyllites and upper lava formations (Table 8.8). The beds of the banded-hematite-quartzites are over 300 meters thick. This formation has given rise to rich iron-ore deposits.

The rocks of the Iron-ore group have been folded and the fold axes trend in the NNE-SSW direction. They are intruded by the Singhbhum granite (age 2950 million years). In addition to this there are other igneous bodies of ultrabasic and basic composition.

8.13.2. Northern Singhbhum Region

Singhbhum Group. The Archaean rocks which lie to the north of the Singhbhum-shear-zone show a higher grade of metamorphism. Here the banded-hematite-quartzites are of minor importance. These rocks have been folded into a series of folds the axes of which trend in the E - W direction. Sarkar and Saha (1977) have named this succession as the "*Singhbhum group*". They are of the opcnion that this group is younger than the Iron-ore group (Table 8.8).

The Singhbhum group has been subdivided into two parts. The lower part is called the "*Chaibasa formation*" and the upper part is called the "*Dalbhum formation*". The Chaibasa formation consists of mica-schists, hornblende-schists and quartz-granulites. These rocks show a high grade of metamorphism. The Dalbhum formation is made up of phyllites and banded-hematite quartzites which show a lower grade of metamorphism. The top of the Singhbhum group is interbedded with lavaflows and tuffs which are called the "*Dalma traps*".

Dhanjori Group. Towards east of Singhbhum and in Mayurbhanj, the rocks of the Dhanjori group rest unconformably over the Singhbhum granite and Iron-ore group. The Dhanjori group consists of a basal conglomerate, arkose, quartzites and extensive lavaflows. The Dhanjori lavaflows are equivalent to the Dalma traps of the northern Singhbhum area.

Kolhan Group. The unmetamorphosed rocks which are exposed in the Singhbhum area are called the "*Kolhan group*". They rest unconformably over the Singhbhum granite and Iron-ore group. The Kolhan group is regarded to be ofCuddapah age. The chief rock types are conglomerates, sandstones, limestones and slate. The conglomerates contain pebbles derived from the Singhbhum granite and the banded-hematite jasper of the Iron-ore group. The rock beds of the Kolhan group are almost undisturbed over a wide area but they become deformed towards the northern margins where they come in contact with the rocks of the Iron-ore group.

8.13.3. Gangpur Area

Gangpur Group. Gangpur area lies to the west of Singhbhum in the Sundargarh district of Orissa. The Archaean rocks of this area are called the "*Gangpur group*". This group has been regarded older than the Iron-ore group. On the basis of lithological similarities, it has been correlated with the Chilpi Ghat group.

The rocks of the Gangpur group have been folded into an anticlinorium which has its axis in the ENE-WSW direction. The Singhbhum shear zone when traced to the west becomes a zone of folding. The chief rock types of the Gangpur group are gondites, quartzites, phyllites, marbles and mica-schists. The gondites contain workable deposits of manganese ore.

8.14. RAJASTHAN

In Rajasthan, the Aravalli mountains extend from Delhi in the NE to the gulf of Cambay in the SW. These mountains are mainly composed of Precambrian rocks of the *"Delhi supergroup"*. The Archaean rocks are exposed chiefly in the central plains, existing between the Aravalli and Vindhyan ranges. The "Great- boundary fault" of Rajasthan which runs in the NE-SW direction, has brought the Vindhyans in the east against the Archaeans in the west. The throw of this fault is about 1600 meters.

The Archaean rocks of Rajasthan include a basement called the *"Banded-gneissic complex"* and a sedimentary succession called the *"Aravalli group"*. The *"Bundelkhand-granite"* which is exposed at the north-eastern margin of the Vindhyan basin, has been considered equivalent to the Banded-gneissic-complex. The Bundelkhand granites are overlain by the *"Gwalior group"*. The *"Raialo group"* which rests unconformably over the Aravalli group may be considered to be of early and middle Cuddapah age. The succession of the Archaean rocks of Rajasthan is shown in Table 8.9.

Table 8.9. Archaean Succession of Rajasthan
(Figures in bracket show thickness in metres)

Supergroup	*Group and Lithology*
Delhi Supergroup	Age—Cuddapah
	——Unconformity——
Archaean Rocks	Raialo Group : Limestone and Marble (700 meter)
	——Unconformity——
	Aravalli Group : Shale, Slate and Phyllite (3000 meters)
	——Unconformity——
	Banded Gneissic Complex, Bundelkhand Granite

Banded Gneissic Complex. The Banded gneissic complex is composed of alternating bands of biotite-gneiss and granite. The banded gneisses are of composite origin. They are formed when the granitic rocks are intruded into the oldest sediments.

Bundelkhand Granite. This granite is mainly a pink nonporphyritic granite of medium grain size. It is traversed by quartz veins and dykes of dolerite. Towards west the Bundelkhand granite changes into gneiss. The age of this granite as determined by the radioactive dating is about 2.5 thousand million years. The Bundelkhand granite and the Banded gneissic complex are probably of the same age. The Bundelkhand granite is overlain by the *"Gwalior group"*.

Aravalli Group. The Aravalli group is composed of mainly argillaceous rocks. The thickness of these rock beds is of the order of 3000 meters. In these rocks the grade of metamorphism increases towards the core of the Aravalli range. Hence these rocks grade from the unmetamorphosed shales in the east through phyllites in the centre to garnetiferous mica-schists in the west. In the Aravalli group impure argillaceous limestones occur in subordinate amounts. The basal beds are quartzites which rest unconformably on the Banded-gneissic complex or Bundelkhand granite.

The rocks of the Aravalli group are intruded by granites and ultrabasic igneous rocks. The later are converted into talc-serpentine-schists. The age of granites as determined by the radioactive dating is about 1900 million years.

The unmetamorphosed rocks of argillaceous composition which occur on the southeast side of Rajasthan at Chittor are called *"Binota shales"*. They are equivalent in age to the Aravalli group.

Raialo Group. The Raialo group rests unconformably over the Aravalli group and is overlain by the Delhi supergroup (Table 8.9). The Raialo group is predominantly calcarious and consists mainly of limestones or marbles with thin beds of quartzites at the base. The maximum thickness of the succession is about 700 meters. Frequently the basal arenaceous beds are missing and the carbonate rocks rest directly over the Aravalli rocks or Banded gneissic complex with a sharp boundary. The outcrop of the Raialo succession near Makrana in the southwest of Ajmer contains marble. This marble provided excellent building stones used in the construction of Taj-mahal at Agra (U.P.). The age of the Raialo group may be early and middle Cuddapah.

Champaner Group. The rocks of this group occur at the southwest side of Rajasthan near Baroda in Gujrat. The Champaner group consists of mainly quartzites, slates and limestones. It also contains manganese ore at some places. This group is considered equivalent in age to the Aravalli group.

Gwalior Group. The rocks of the Gwalior group occur along the northeast end of Rajasthan near Gwalior city in M.P.. They are separated from the Aravalli rocks by a belt of Vindhyans having a width of about 130 kilometers. The Gwalior group rests over the Bundelkhand granite and is made up of sandstones, cherts, conglomerates and grits. Thus the Gwalior group is lithologically similar to the Aravalli group but the rocks are unfolded and unmetamorphosed. This may be due to the distance from the main belt of orogenisis or to the fact that they are of Cuddapah age.

8.14.1. General Characters of Rocks of Rajasthan

The general characters of the various rockformations present in Rajasthan may be summarized as follows.

1. The rock formations of the Delhi supergroup, although youngest, shows the highest grade of metamorphism.
2. The Raialo group is mainly calcarious. Its chief rock types are limestones and marbles.
3. The Aravalli group is mainly argillaceous. Its chief rock types are shale, slate and phyllites. The thickness of this group is immense.
4. Generally the grade of metamorphism decreases from the north-east to southwest. The grade of metamorphism also decreases as the distance from the central axis of folding increases.
5. The area of the Archaean rocks in the east is bounded by a Great boundary fault.

8.15. CORRELATION

The correlation of Archaean rocks of different areas is not easy. The factors which cause difficulties in the correlation are as follows.

1. The Archaean rocks are unfossiliferous. Hence it is difficult to determine their geological age.
2. The Archaean rocks are generally highly metamorphosed. Hence their original characters have been changed completely. The degree of metamorphism also varies at different places. As a result the same original rock appears dissimilar at two places.
3. Magmatic stoping, assimilation and hybridism have produced a wide variety of rocks with complex characters.
4. The Archaean rocks have been subjected to intense folding faulting and thrusting. Hence it is difficult to determine their order of superposition.

8.15.1. Criteria of Correlation

The correlation of the Archaean rocks of India is given in Table 8.10. The chief criteria that have been used for the correlation of the Archaean rocks are as follows.

Stratigraphic Sequence. The stratigraphic sequence established in one area may prove very helpful in the neighbouring areas where the lithological units and grade of metamorphism are similar.

Lithological Composition. The lithological characters of individual beds of a succession are valuable criteria of correlation. However, similar rock beds may occur in formations of widely different ages.

Structural Relationship. Unconformities which separate two groups of strata help greatly in the correlation. The unconformities are often associated with conglomerates but care should be taken to distinguish between the sedimentary conglomerates and crush conglomerates.

Igneous Intrusion. Several periods of intrusion of granitic and mafic igneous rocks have been recognized in the Archaean rocks. If the igneous

history of a perticular area is identical to another area, the rocks of these two places can be correlated. However it is also possible that the rocks of the same age may have different igneous history.

Associated Ore Deposit. If the rocks of the two different areas contain same type of syngenetic ore deposits, they can be correlated.

Grade of Metamorphism. The rocks showing higher grade of metamorphism are normally believed to be older than those showing lower grade of metamorphism.

Radiometric Dating. Once an igneous rock is formed, the radioactive elements present in its minerals keep on decaying all the time and the decay product continues to accumulate in the rock. The age of an igneous rock is determined by measuring the amounts of parent radioactive element and the decay product present in a rock sample. Thus the age of igneous bodies is determined and then they are correlated with one another. Table 8.11 shows the broad succession of the Singhbhum area established on the basis of the radiometric dating.

Table 8.10. Generalized Correlation of Archaeans

South India	*M.P.*	*Bihar-Orissa*	*Rajasthan*
Closepet granite	Granite	Newer dolerite	—
Charnockite	—	Singhbhum granite	—
Peninsular gneiss	Granite gneiss	Chota Nagpur granite and Dalma traps	Bundelkhand granite
Champion gneiss	—	—	—
Upper Dharwar	Bijawar group	Kolhan group and Singhbhum group	Raialo group
Middle Dharwar	Sakoli group and Chilpi Ghat group	Iron Ore group	Aravalli group
Lower Dharwar	Sausar group	Gangpur group	

Table 8.11. Succession of Singhbhum Area

Succession	*Age*
Soda–granite, Granophyre and Granite–gneiss	925 million years (Singhbhum Orogeny)
Dalma traps, Singhbhum group, Kolhan group	1585 to 2000 million years
Singhbhum granite, Iron-ore group	2025 million years (Iron-ore Orogeny)

8.16. HIMALAYAN BELT

The Archaean and Precambrian rockformations occur in the Himalayan belt all along its length. On the basis of the presence of various rock groups, the Himalayan belt can be subdivided into three parts: (*i*) northernmost Himalaya, (*ii*) central Himalaya, and (*iii*) lower Himalaya.

Northernmost Himalaya. In this part a complete sequence of fossiliferous rocks ranging in age from the Cambrian to Eocene is exposed.

Central Himalaya. The high peaks of the Himalaya occur in this zone. These peaks are composed of the gneisses, granites and metamorphosed sediments. Perhaps some of these rocks are of Archaean age.

Lower Himalaya. This part of the Himalaya lies to the north of the Gangetic alluvium. It has been divided into three zones: (*i*) upper zone of the Archaean and Precambrian rocks, (*ii*) middle zone of the Lower Tertiary rocks, and (*iii*) lower zone of the Upper Tertiary rocks (Siwalik group). The Main boundary fault runs between the middle and lower zone.

The Himalayan belt is a highly folded mountain region of Tertiary age. Here it is very difficult to determine the relative ages of the various metamorphic rockformations. The younger rocks which have been metamorphosed by the igneous intrusions, resemble the Archaean rocks of Peninsular India. Hence the correlation of metamorphic rocks, such as schists and gneisses of the Himalaya with the Archaeans of Peninsula, is not reliable. Further as the rockformations of the Himalaya region contain highly complex fold and thrust structures, it is not easy to determine their order of superposition.

8.17. NORTHWEST HIMALAYA

Salkhala Group. The Archaean rocks of Jammu and Kashmir areas are called the "*Salkhala group*". This group is made up of carbonaceous slates, graphitic phyllites, schists, marbles and flaggy quartzites. The basal parts of the succession are commonly associated with bands of migmatitic and augen gneisses. The minimum thickness of the Salkhala group is of the order of 2 to 6 kilometers. The rocks of this group have been deformed into isoclinal folds. The Salkhala group is overlain by "*Dogra slates*" which are probably of Precambrian age.

Vaikrita Group. The Precambrian rocks of Spiti area of Himachal Pradesh are called "*Vaikrita group*". This group is made up of a very thick succession of mica-schists, talc-schists and phyllites. These rocks are highly folded. The rocks of the Vaikrita group are found at several places along the northern slopes of the Higher Himalaya extending from Spiti in the west, through Garhwal and Kumaun regions of U.P., into Nepal in the east.

Jutogh Group. The Archaean rocks of the Sub-Himalaya region near Simla are called the "*Jutogh group*". The chief rock types of this group are quartzites, mica-schist, graphitic-schist and marbles. The succession of the Jutogh group has been regarded as inverted due to the presence of large recumbent fold structures. This succession has been intruded by a granite, called "*Chor granite*". This granite is probably of late Palaeozoic age.

8.18. EASTERN HIMALAYA

Daling Group. In Darjeeling and Sikkim regions of the Eastern Himalaya, the Archaean rocks are called the "*Daling group*". The succession consists mainly of slates and phyllites which grade through micaceous schists into "*Darjeeling gneiss*". The Darjeeling gneiss which appears to overlie the Daling rocks is a product of granitization of the Daling metasediments. In Sikkim, the Daling rocks contain deposits of copper ore.

8.19. ECONOMIC MINERALS

The Archaean rocks contain a large variety of economic minerals. Many metallic ores and industrial minerals are found associated with them. The metallic ores include ores of gold, iron, manganese, copper, lead, zinc and chromium, and amongst industrial minerals the chief minerals are mica, asbestos and kyanite. In addition small deposits of molybdenite, monazite, uranium, vanadium, tin, wolfram and titanium are also found in the Archaean rocks.

Gold. Practically all the gold produced in India is obtained from the Kolar and Hutti gold fields in Karnataka. The gold occurs as auriferous quartz veins within the dark amphibolitic rocks of Dharwar age. The gold lodes are believed to be of high temperature hydrothermal origin.

Iron Ore. Huge deposits of iron ore occur within the Archaean rocks. They are mainly of sedimentary-metamorphic origin. They are found associated with banded-hematite-quartzites from which they are believed to have been derived by leaching out of silica. The deposits of iron ore occur in the following areas.

(*i*) *Bihar and Orissa.* Deposits of iron ore occur in the Singhbhum district of Bihar and in Keonjhar, Bonai, Mayurbhanj and Cuttack districts of Orissa.

(*ii*) *Madhya Pradesh.* Deposits of iron ore occur in the Bailadila hills of Baster and Dhalli-Rajhara areas of Durg district.

(*iii*) *Maharashtra.* The deposits of iron ore occur mainly in Ratnagiri and Chanda districts.

(*iv*) *Karnataka.* Deposits of iron ore are found in Bellary, Hospet, Chikmaglur, Tumkur, Chitaldurg and Simoga districts.

Manganese Ore. The manganese ore deposits which are found in the Archaean rocks, are of sedimentary-metamorphic origin. The principal ore deposits occur mainly in three zones: (*i*) M.P.—Maharashtra zone, (*ii*) Bihar—Orissa zone, and (*iii*) Karnataka—Goa zone. Out of these three zones, the M.P.—Maharashtra zone is the most important, both from the reserves and quality point of view.

Copper Ore. The four major copper belts in the country are : (*i*) Singhbhum copper belt of Bihar, (*ii*) Khetri copper belt of Rajasthan, (*iii*) Malanjkhand copper deposit of M.P., and (*iv*) Agnigundala copper deposit of Andhra Pradesh. The copper deposits of Rajasthan and Andhra Pradesh are probably of Precambrian age while those of other areas are of Archaean age. All these copper ore deposits are of hydrothermal origin.

Lead and Zinc Ores. The ore minerals of lead and zinc commonly occur together. The lead and zinc deposits of India are of hydrothermal origin. The major deposits are confined to the four areas: (*i*) Zawar belt of Rajasthan, (*ii*) Deri-Ambamata belt of Rajasthan and Gujrat, (*iii*) Agnigundala belt of Andhra Pradesh, and (*iv*) Sargipalli area of Orissa. These deposits of lead and zinc are situated mostly in the rocks of Archaean and Precambrian age.

Chromite Deposits. Chromite deposits occur in association with certain types of ultrabasic rocks such as dunites, saxonites, pyroxenites, and norites. These deposits are a product of magmatic segregation. In India, the chromite deposits occur in the Keonjhar district of Orissa, Hassan district of Karnataka, Salem district of Tamil Nadu, Bhandara district of Maharashtra, Singhbhum district of Bihar, and Krishna district of Andhra Pradesh. These deposits are found in the ultrabasic rocks that traverse the Archaean rocks.

Mica Deposit. Mica has high dielectric properties with very low thermal conductivity. Hence it is extensively used in the insulating industry. Deposits of mica occur in pegmatites which traverse mica-schists and mica gneisses of Archaean age. In India mica deposits occur in three important belts: (*i*) mica belt of Bihar, (*ii*) Nellore mica belt of Andhra Pradesh, and (*iii*) Rajasthan mica belt.

8.20. PRECAMBRIAN FORMATIONS

The strongly deformed Archaean rocks are separated from the overlying Precambrian cover by a pronounced unconformity called the "*Eparchaean unconformity*". This unconformity represents a major tectonic cycle. The Precambrian rockformations occur both in the northern and southern parts of Peninsular India (Table 8.12). These rockformations have been grouped into two distinct formations, the lower one is called the "*Cuddapah supergroup*" and the upper is called the "*Vindhyan supergroup*".

Table 8.12. Precambrian Formations

Division	*South India*	*Central India*	*Rajasthan*
Upper Purana	Missing	Upper Vindhyan	Upper Vindhyan
	Kurnool Group	Lower Vidhyan	Malani Volcanics
Lower Purana	Cuddapah Supergroup	Gwalior Group Bijawar Group	Delhi Supergroup

8.21. CUDDAPAH SUPERGROUP

The Cuddapah supergroup has been named after the Cuddapah basin of Andhra Pradesh where it is best developed. As the rocks of this supergroup rest unconformably over the schists and gneisses of Archaean age and is overlain by the Vindhyans, its age is Lower Purana.

Distribution. In India the Cuddapah rockformations occur mainly in four areas : (*i*) Cuddapah basin of Andhra Pradesh, (*ii*) Bijapur district of Maharashtra (Kaladgi group), (*iii*) Chattisgarh area of Madhya Pradesh, and (*iv*) along Aravalli mountain in Rajasthan (Delhi supergroup).

In the main Cuddapah basin, the Cuddapah rocks occupy an area of about 35000 square kilometers. The shape of the basin is crescentic the concave side of which is towards the east. At the concave margin, the length of the basin in the N-S direction is about 300 km and its maximum width is about 140 Km (Fig. 8.4).

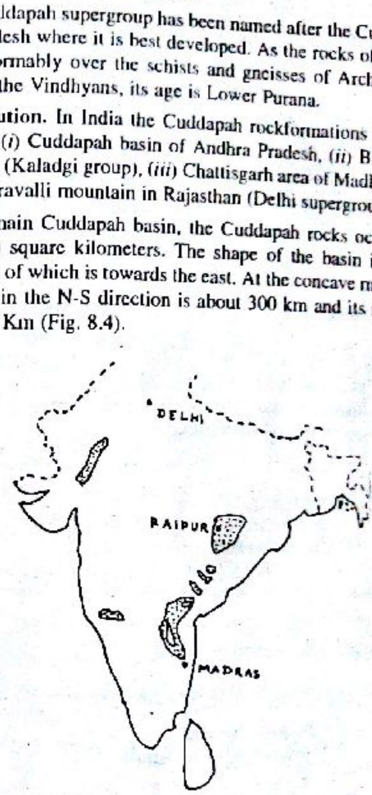


Fig. 8.4. Distribution of Cuddapah Rocks in India.

Lithology. The succession of the Cuddapah supergroup is composed of mainly quartzites and slates or shales. The limestones occur only in subordinate amounts. The total thickness of the succession is over 6 kilometers. The Cuddapah rocks are mostly unfossiliferous. However the presence of stromatolites (Collenia vajurkari) have been reported from the Vempalle limestones.

Structure. The rocks which lie towards the western margin of the Cuddapah basin are undisturbed but those which are situated near the eastern margin have been folded, faulted and slightly metamorphosed. Here the argillaceous strata have been mostly converted into slates.

Classification. The succession of the Cuddapah supergroup has been divided into four groups (Table 8.13). These groups are separated from one another by unconformities. Each group begins with the coarse sediment at its base followed by the finer sediments and carbonate rocks thereby indicating a cycle of deposition.

Igneous Intrusions. In the lower half of the Cuddapah succession there are abundant intrusive sills of dolerite. These basic sills are called the "*Cuddapah traps*". Their age is post-Cheyair and pre-Nallamalai (Table 8.13). The interaction between the sills and the Vempalle limestones has given rise to deposits of asbestos and barytes.

Table 8.13. Classification of Cuddapah Supergroup (Figures in bracket indicate thickness)

Group	*Formation*
Kurnool Group	(Age—Lower Vindhyan)
	Unconformity
Kistna Group (600 m.)	Srisailam quartzite Kolamnala shales Irlakonda quartzite
	Unconformity
Nallamalai Group (1000 m.)	Cumbum shales Bairenkonda quartzite
	Unconformity
Cheyair Group (3300 m.)	Tadpatri shales Pulivendla quartzite
	Unconformity
Papaghani Group (1400 m.)	Vempalle shales and limestone Gulcheru quartzite
	Unconformity
	Archaean schists and gneisses

Papaghani Group. The rocks of this group are exposed in the Papaghani river valley. This group has been divided into two formations. The lower "*Gulcheru formation*" comprises quartzites, grits and conglomerates and is overlain by the "*Vempalle shales and limestones*". The upper formation is three times thicker than the lower formation. The Vempalle limestones have been intruded by basic sills and deposits of asbestos and barytes are found at their contacts.

Cheyair Group. The rocks of this group occur in the Cheyair river and in the upper reaches of the Penner river near Tadpatri. The chief rock types are quartzites and shales. The lower part of this group is mainly arenaceous and is called "*Pulivendla quartzites*". The upper argillaceous part is called "*Tadpatri shales*". There are some thin beds of siliceous limestone, chert and jasper, and basic sills within the succession of the Tadpatri shales.

Nallamalai Group. The succession of this group is exposed in the Nallamalai hills. The Nallamalai group has been divided into two formations: (*i*) the "*Bairenkonda quartzite*" and (*ii*) the "*Cumbum shales*". The whole succession has been folded and the rocks are known to contain ores of lead and copper.

Kistna Group. The rocks of this group are exposed along the Krishna river. The succession has been divided into three formations: (*i*) "*Irlakonda quartzite*", forming the lower part, (*ii*) "*Kolamnala shales*", occuring in the middle, and (*iii*) "*Srisailam quartzite*", forming the upper part.

8.21.1. Other Equivalent Formations

Kaladgi Group. The rocks of Cuddapah age which occur to the south of Bombay in Bijapur district of Maharashtra, are called the "*Kaladgi group*". This group is named after the Kaladgi town. The succession rests unconformably over the Archaean rocks and is overlain by the Deccan traps. The Kaladgi group is made up of 3 to 5 Kilometers thick succession of quartzites, sandstones, conglomerates, limestones and shales.

Pakhal Group. The rocks of the Pakhal group are exposed in the Pakhal hills of the Godavari valley. The succession is composed of coarse pebbly sandstones, conglomerates, siliceous limestones, shales and slates. Its total thickness is about 6300 meters. This group is considered to be of Cuddapah age.

8.22. DELHI SUPERGROUP

The Delhi supergroup is composed of rockformations which are equivalent in age to the Cuddapah supergroup. These rockformations rest unconformably over the Archaean gneisses and are overlain by Vindhyans.

Distribution. The Delhi supergroup is exposed in the Aravalli mountains of Rajasthan. These mountains extend from Delhi in the southwest direction through Haryana and Rajasthan up to Gujrat.

Lithology. The succession of the Delhi supergroup is composed mainly of quartzites, conglomerates, grits, slates and phyllites. Beds of limestones are also present in subordinate quantity. At places these limestones have been converted into calc-schists and calc-gneisses. The total thickness of the Delhi succession is about 7 kilometers.

Structure. The rocks of the Delhi supergroup exhibit extensive folding and faulting, and have been intruded by many igneous bodies. In this respect they differ from the rocks of the main Cuddapah basin where the rockformations show little disturbance.

Classification. The succession of the Delhi supergroup has been divided into two parts. The lower part which is predominantly arenaceous is called the "*Alwar group*", and the upper part which is mainly argillaceous is called the "*Ajabgarh group*" (Table 8.14). In Alwar area, there is a succession of calcarious rock beds in between the Alwar and Ajabgarh groups. These rock beds are called the "*Kushalgarh limestone*".

Table 8.14. Classification of Delhi Supergroup

Group	*Lithology*
Ajahgarh Group	Phyllites and slates with calc–gneisses and calc–schists
Alwar Group	Quartzites, grits and conglomerates
Unconformity	
Raialo Group or Banded gneissic complex	

Igneous Intrusions. The succession of the Delhi supergroup has been intruded by the "*Erinpura granite*".

Alwar Group. The rockformations of the Alwar group rests unconformably over the Raialo group or Aravalli group. The chief rock types of the succession are quartzites, grits and conglomerates with a few beds of shale and impure limestone. The maximum thickness of the Alwar group is over 3 kilometers. In the lower part of the succession there are several lavaflows and sills of basic composition.

Ajabgarh Group. The Ajabgarh group is composed mainly of argillaceous rocks. The succession of argillaceous rocks also contains thin beds of siliceous limestones, calcarious silts and ferruginous quartzites. In the Ajabgarh group, the type of rocks varies at different places depending upon the degree of metamorphism. However the slates and phyllites are the common rocks. These rocks have often been intruded by pegmatites and aplites which have produced composite gneisses. Calc-schists and calc-gneisses are produced due to the metamorphism of the limestone beds.

Kushalgarh Limestone. The Kushalgarh limestone overlies the rocks of Alwar group. It is a banded limestone containing dark grey and black layers. At places where it is highly metamorphosed, it becomes coarsely crystalline. Its maximum thickness is about 700 meters. The Kushalgarh limestone contains a few horizons of brecciated rocks called the "*Hornstone breccia*". This breccia consists of angular pieces of quartz embedded in a fine grained matrix of ferruginous and siliceous matter.

8.22.1. Other Equivalent Formations

Bijawar Group. The rocks of the Bijawar group occur along the southeastern margin of the Bundelkhand granite and along the southeastern margin of the Vindhyan basin. These rocks rest over the gneisses of Archaean age and are overlain by Vindhyans. The Bijawar group comprises a succession of a basal conglomerate and quartzite followed by hornstone breccia, siliceous limestone, phillitic shales and red jaspers. These rocks are associated with dykes, sills and lavaflows of basic composition. The maximum thickness of the Bijawar succession is about 240 meters. The Bijawars have been subjected to intense folding and faulting.

Gwalior Group. The rockformations of the Gwalior group occur at the northwest side of the Bundelkhand granite around Gwalior town in Madhya Pradesh. They rest unconformably over the Bundelkhand granite and are overlain by the Upper Vindhyans. The Gwalior group is composed mainly of sandstones, conglomerates, grits and ferruginous and siliceous shales. In the upper part of the succession there are several horizons of traps. The rocks of the Gwalior group are mostly unfolded and unmetamorphosed.

The Gwalior group has been classified into two formations. The lower formation is called the "*Par formation*". It is mainly composed of sandstones and grits. The upper formation is called the "*Morar formation*". Its chief rock types are siliceous and ferruginous shales which contain several horizons of traps. The lithology of the Gwalior group shows similarity both to the Aravalli group and the Bijawars but its rock beds are comparatively less disturbed. The age of the volcanic rocks as determined by the radiometric dating is 500 million years. This suggests that the Gwalior group is probably of Cuddapah age.

8.22.2. Economic Minerals

The chief economic minerals which are found in the rockformations of Cuddapah age are copper ore, asbestos, barytes, steatite, talc and building stones.

Copper Ore. The copper ore deposits of the Khetri area of Rajasthan occur in the slates and amphibolites of the Delhi supergroup. In the Agnigundala area of Andhra Pradesh, the copper mineralization is found in the Cuddapah rocks.

Asbestos. In the Cuddapah district of Andhra Pradesh, deposits of crysotile asbestos are found in the Vempalle limestone of the Papaghani group. These deposits are formed due to interaction between the mafic sills and the limestone.

Baryte. The Cuddapah traps are also responsible for the formation of veins of baryte in the Vempalle limestones. Deposits of baryte are found in the Cuddapah, Anantpur and Kurnool districts of Andhra Pradesh. Quartzites of the Delhi supergroup are also known to contain veins of baryte near Alwar in Rajasthan.

Steatite and Talc. In the Kurnool and Anantpur districts of Andhra Pradesh, deposits of steatite and talc have developed at the contact of basic sills and dolomitic limestones of the Vempalle formation. In Rajasthan near Ajmer, the ultrabasic rocks of the Delhi supergroup are converted into talc-schists.

Building Stone. Some slates, limestones and grits of the Delhi and Cuddapah supergroup are used for building purposes.

8.23. VINDHYAN SUPERGROUP

The Vindhyan supergroup has been named after the great "*Vindhya Mountains*" of Madhya Pradesh where it is well developed. The Vindhyan succession rests unconformably over the older formations such as Bijawars and Archaeans, and are overlain by the Deccan traps. The Vindhyan supergroup is considered to be of "*Upper Purana*" age.

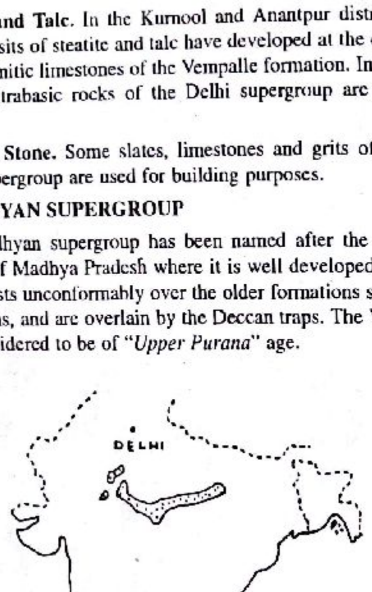


Fig. 8.5. Distribution of Vindhyan Rocks in India.

Distribution. In India, the Vindhyan rockformations occur in four areas: (*i*) main Vindhyan basin in central India, (*ii*) Cuddapah district, Andhra Pradesh (Kurnool group), (*iii*) Bhima and Godavari river valleys, and (*iv*) on the NW side of the Aravalli ranges in Rajasthan.

The succession of the Vindhyan supergroup has best developed in the "*Main Vindhyan basin*" in central India. This basin is very large and is situated to the north of the Narmada and Son rivers (Fig. 8.5). It extends E-W for about 650 kilometers from Sasaram in Bihar to Chittorgarh in Rajasthan, and N-S about 160 kilometers from Bhopal in M.P. to Agra in U.P. The total area of the Vindhyan basin is about 100,000 square kilometers. In addition, an area of about 78000 sq. km is concealed under the Deccan traps of Malwa and the alluvium of Indo-Gangetic plain.

Lithology. The chief rock types of the Vindhyan supergroup are sandstones, shales and limestones. The total thickness of the succession is about 4500 meters. The Vindhyan rocks contain ripple marks, current bedding and other sedimentary structures which suggest that they are of shallow water origin.

Fossils. The Vindhyan rocks are generally unfossiliferous. However presence of some very primitive type of life has been indicated by some traces or fossil impressions found in the Fawn limestone (Lower Vindhyan) and Suket shales (Upper Vindhyan).

The Fawn limestone of the Khenjua formation contains "*Stromatolites*" (Conophyton cylindricus and Collenia columnaris) which indicate that these rock beds are older than 1260 million years. Disc shaped remains of organic origin have been found in the Suket shales of Kaimur group. These forms are believed to represent the genus "*Fermoria*" which is related to the primitive brachiopod "*Acrothele*".

Structure. The rocks of the Vindhyan supergroup are practically undisturbed and unmetamorphosed. They are only slightly tilted. However some disturbances are noticed along the NW and SE margin of the Vindhyan basin.

(*i*) At the northwestern margin of the Vindhyan basin a "*Great boundary fault*" is present. It has brought the Vindhyans against the Archaeans. This fault runs in the NE-SW direction for about 800 km in Rajasthan and its down throw is about 1500 meters.

(*ii*) The line of the Narmada and Son river valleys coincides with the southern and southeastern margin of the Vindhyan basin. Here the Vindhyan rocks exhibit considerable structural disturbances.

(*iii*) Between the Bundelkhand granite and Son valley, the Vindhyan rocks occur in a large flat syncline. The Lower Vindhyans are best developed along the south side of this syncline in the Son valley.

Classification. On the basis of difference in lithology, the Vindhyan supergroup has been divided into two divisions : (*i*) the "*Lower Vindhyans*" (Semri group), and (*ii*) the "*Upper Vindhyans*". The Lower Vindhyans are largely made up of the calcarious rocks of marine origin while the Upper Vindhyans contain mainly the arenaceous rocks of fluviatile origin. These two divisions of the Vindhyan supergroup are of unequal thickness, the upper division being three times thicker than the lower.

The Lower Vindhyan succession is called the "*Semri group*" and the Upper Vindhyan succession has been subdivided into three groups: (*i*) "*Kaimur group*", (*ii*) "*Rewa group*", and (*iii*) "*Bhander group*". Each group of the Vindhyan succession is separated from one another by a diamond bearing conglomerate (Table 8.15).

Igneous Intrusions. The Lower Vindhyans are intruded by dykes of dolerite and basalt in the Son valley area.

Table 8.15. Classification of Vindhyan Supergroup

Groups	*Formations*
Bhander Group (1000 m)	Upper Bhander sandstone Sirbu shales Lower Bhander sandstone Bhander limestone
	Diamond Bearing Conglomerate
Rewa Group (2000 m)	Upper Rewa sandstone Jhiri shales Lower Rewa sandstone Panna shales
	Diamond Bearing Conglomerate
Kaimur Group (400 m)	Upper Kaimur sandstone Bijaigarh shales Lower Kaimur sandstone Suket shales
Semri Group (1300 m)	Rohtas Formation Kheinjua Formation Porcellinite Formation Basal Formation

Semri Group. The rocks of the Semri group (Lower Vindhyan) occur in the Son valley, Dhar forest, and on the NW side of the Aravalli ranges. They rest unconformably over the Bijawars. The succession of the Semri group is about 1300 meters thick and it is composed mainly of the shales and limestones. This succession has been subdivided into four formations as shown in Table 8.16. The Porcellinite formation contains volcanic products which may be contemporaneous with the Malani volcanics of Rajasthan. The age of the glauconitic beds of the Kheinjua formation as determined by the radiometric dating is about 1100 million years.

Table 8.16. Succession of Semri Group

Formation	*Lithology*
Rohtas Formation	Limestones and shales
Kheinjua Formation	Glauconitic beds, Fawn limestone and Olive shales
Porcellinite Formation	Porcellinitic shales and sandstones
Basal Formation	Basal conglomerate and Kajrahat limestones.

Upper Vindhyans. In the Son valley area, the contact of the Lower Vindhyans and Upper Vindhyans is conformable, but in the Dhar forest there is a distinct unconformity between them. In other places, the Lower Vindhyans are missing and the Upper Vindhyans rest directly over the Bundelkhand granite, Gwalior group and Bijawars. The succession of the Upper Vindhyans consists mainly of the sandstones and shales with some limestone. This succession has been divided into three groups known as the Kaimur, Rewa and Bhander groups. These groups are separated from one another by two horizons of diamond bearing conglomerates (Table 8.15).

8.23.1. Vindhyans of Rajasthan

Malani Volcanics. The Malani volcanics include acid volcanic rocks such as rhyolites and tuffs. They cover enormous area around Jodhpur in Rajasthan. This formation is regarded as of Lower Vindhyan age because it rests unconformably over the Aravalli phyllites and are overlain by the "*Jodhpur sandstone*" of Upper Vindhyan age.

In the Malani volcanics formation about 52 flows have been recognised and their total thickness is about 3500 meters. In addition to the acid volcanic rocks, there are Siwana and Jalor granites and dykes of felsic to mafic composition. These igneous bodies are regarded as the intrusive associates of the Malani volcanics.

8.23.2. Vindhyans of South India

Kurnool Group. This group is named after the Kurnool district in Andhra Pradesh where it is best developed. The rocks of the Kurnool group rest unconformably over the Cuddapah supergroup. The succession consists mostly of limestones and shales with some quartzites. The Benganpalle beds which occur at the base contain diamonds. The rocks of the Kurnool group show gentle dips and broad folds. The succession has been subdivided into four formations, known as the "*Kundair*", "*Paniam*", "*Jamalamadugu*" and "*Benganpalle*" formations (Table 8.17).

Table 8.17. Succession of Kurnool Group

Formation	*Lithology*
Kundair Formation (200 m)	Shales and limestones
Paniam Formation (50 m)	Quartzites
Jamalamadugu Formation (200 m)	Shales and limestones
Benganpalle Formation (10 m)	Sandstone and diamond beanring conglomerate.

8.23.3. Economic Minerals

Diamonds. The three groups of the Upper Vindhyans are separated from one another by two horizons of diamond bearing conglomerate. This conglomerate consists of pebbles of vein quartz, jasper and quartzite embedded in the matrix of sand and clay. The diamonds occur as placer deposit in these conglomerates. The Panna diamond field of Madhya Pradesh which is situated in the country of Rewa rockformations, is the only diamond producing area in India. Here diamonds are obtained from two sources : (*i*) from the ultrabasic igneous pipe which is intruded into the Vindhyans, and (*ii*) from the diamond bearing conglomerates.

Limestone. Limestones of good quality are found abundautly in the Vindhyan rockformations. The important deposits of limestone occur in the Son valley region of Bihar and U.P., Rewa and Jabalpur areas of Madhya Pradesh, and Bhima valley region of Andhra Pradesh. These limestones are used in the lime, cement and metallurgical industries.

Pyrite. The Bijaigarh shales of the Kaimur group contain a bed of pyrite which is about one meter thick. This bed outcrops at several places near Amjor in Shahabad district of Bihar. This pyrite is of good quality and contains about 41% sulfur. This pyrite is used mainly in the manufacture of sulfuric acid.

Building Stone. The Vindhyan sandstones and limestones yield excellent building and ornamental stones. The pink sandstones of Bhander group have been used extensively as building stones all over northern India.

Glass Sand. The Vindhyan sandstones at some places yield good sands on weathering and disintegration which can be used in the manufacture of glass. Near Allahabad (U.P.), Vindhyan sands are being mined for this purpose.

8.24 PALAEOZOIC ROCKS

The Palaeozoic Era has been subdivided into six periods : (*i*) Cambrian, (*ii*) Ordovician, (*iii*) Silurian, (*iv*) Devonian, (*v*) Carboniferous, and (*vi*) Permian. The Palaeozoic rocks of marine origin are found only in the Spiti and Kashmir areas of western Himalayas and in Salt Range.

8.25 SALT RANGE

The Salt Range area is in Pakistan. It is situated at the southern side of the Potwar plateau. Here the Cambrian and Permo- carboniferous rocks are well exposed.

8.25.1. Cambrian Rocks

In the Cambrian succession of Salt Range, the "*Saline series*" is at the base. It is then conformably overlain by "*Purple sandstone*", "*Neobolus shales*", "*Magnesian sandstone*" and "*Salt pseudomorph beds*" (Table 8.18). The Neobolus shales have yielded fossils of brachiopod Neobolus and some trilobites (Redlichia) of Lower Cambrian age.

Table 8.18. Cambrian Succession of Salt Range

Formation	*Lithology*
Salt Pseudomorph Beds (105 m)	Shales with pseudomorphs of salt crystals.
Magnesian Sandstone (75 m)	Dolomitic sandstone
Neobulus Shales (45 m)	Fossiliferous grey shales
Purple Sandstone (75—140 m)	Fine grained purple sandstone
Saline Series (450 m)	Gypsum-dolomite, marls, and rock salt.

Saline Series. It is the basal member of the Cambrian succession. It is composed mainly of gypsum, marls and rock-salt with some decomposed lavaflows of basic composition. The Saline series has been subdivided into three parts : (*i*) the lower part, containing gypsum and gypsum-dolomite, (*ii*) the middle part, which is made up of red salt marls and beds of rocksalt, and (*iii*) the upper part, containing gypsum and dolomite. The micro- fossils of Eocene age have been found in the beds of the Saline series.

Purple Sandstone. The beds of purple sandstones overlie the Saline series. They show current bedding and ripple marks and appear similar to the Upper Vindhyan sandstones.

Neobolus Beds. These are the fossiliferous beds of shales which contain brachiopods (Neobolus, Orthis, etc.), trilobites (Redlichia), and gasteropods.

Magnesian Sandstones. These are dolomitic sandstones which are up to 85 meters thick. The main fossil found in these sandstones is a gasteropod called "*Stenotheca*".

Salt Pseudomorph Shales. These shales occur at the top of the Cambrian succession of Salt Range. They contain cubic pseudomorphs of clay. These pseudomorphs are formed by the replacement of salt crystals by clay.

8.25.2. Age of Saline Series

The Age of the Saline series has been a matter of controversy among Indian geologists. According to the law of order of superposition, it may be regarded as of Cambrian age. However, the structural features, micro-fossils and other characters indicate that it may be of Eocene age.

Views in Favour of Eocene Age. B.Sahni, E.H. Pascoe, D.N. Wadia, and L.M. Davies are of the openion that the Saline series is of Eocene age and its present position below the Cambrian succession is due to thrusting. The evidences in favour of Eocene age are as follows.

1. The beds of the Saline series contain micro-fossils of plants and insects of Eocene age.
2. The contact between the Saline series and Purple sandstone is characterized by features which indicate structural disturbances.
3. In the Jogi Tilla and Diljaba areas, the Eocene beds are found thrust over by Cambrian rocks. Although here no salt marl is exposed, its presence at depth is indicated by the saline springs issuing from the fault plane.

Views in Favour of Cambrian Age. The Saline series is conformably overlian by the Cambrian succession. Hence it may be of Cambrian age. This view is favoured by E.S. Pinfold, C.S. Fox, E.R. Gee, E. Lehner and P.K. Ghosh. The evidences which are in favour of Cambrian age, are as follows.

1. E.R. Gee is of the openion that the junction between the Saline series and the Cambrian succession is an undisturbed sedimentary contact and there is no evidence of large scale thrusting.
2. The features which suggest structural disturbances may have been produced due to disharmonic folding of the competent beds of Purple sandstone which rest over the highly incompetent beds of the Saline series.
3. The micro-fossils of Tertiary age which have been found in the Saline series, may have been introduced into it from outside by the groundwater.
4. Lehner (1946) points out that there are saline beds of two different ages in the Tethyan basin of Persia, one of Cambrian age and the other of Miocene age. The Saline series of Salt Range resembles to the Hormuz series of Cambrian age.
5. Schindewolf and Seiacher (1955) have suggested that the Salt pseudomorph beds which occur towards the top of the Cambrian succession indicate the recurrence of the evaporitic conditions which prevailed during the formation of the Saline series. This confirms the continuity in sedimentation from the Saline series to the Cambrian succession.

Thus the evidences given above are conflicting and therefore the problem of the age of the Saline series still remains unsolved. However, the evidences go more in favour of its Cambrian age.

8.25.3. Permo-carboniferous Rocks

In Salt Range, the rocks belonging to the Ordovician, Silurian, Devonian and Lower Carboniferous periods are missing and the Permo-carboniferous rocks are present. They rest directly over the Salt pseudomorph beds of Cambrian succession. The Permo-carboniferous succession of the Salt Range is shown in Table 8.19.

Table 8.19. Permo-carboniferous Rocks of Salt Range

Formation	*Lithology*	*Description*
Permian	Productus limestone (230 m)	Rich in marine fossils.
Upper Carboniferous	Speckled sandstone (100 m)	Shallow water deposits
	Olive Formation (100 m)	Rich in gasteropod (Conularia)
	Glacial boulder bed (3–65 m)	Glacial deposits

Glacial Boulder Bed. This bed rests unconformably over the Cambrian succession. It is composed of glacial boulders of different sizes. The total thickness of this formation is about 60 meters. The upper part of this formation contains plant fossils of Upper Carboniferous (Lower Gondwana) age.

Olive Formation. This formation is composed of olive shales and sandstones. This formation is also called the "*Conularia beds*" because it contains remains of gasteropods (Conularia) in abundance. The other fossils of this formation are lamellibranchs (Eurydesma) of Lower Permian age and plant fossils such as Gangamopteris and Glossopteris.

Speckled Sandstone. This formation is composed mainly of speckled sandstones of light red colour. In the upper part of the succession shales predominate. The rock beds exhibit current bedding and ripple marks which indicate that they are shallow water deposits.

Productus Limestone. The Productus limestone of Salt Range is regarded as one of the best developed Permian formation in the world. It is characterized by rich marine fossils. This formation has been subdivided into three parts.

(*i*) *Lower Products Limestone.* This part of the formation is composed of calcarious sandstones and carbonaceous shales. These beds contain fossils of Lower Permian age. The chief fossils are brachiopods (Productus spiralis, Spirifer and Athyris) and foraminifers (Fusulinids).

(*ii*) *Middle Productus Limestone.* This part is composed of limestones and dolomites. These rock beds are the richest in fossils. The chief fossils are brachiopods (Productus indicus, Productus lineatus, Orthis, Spirifer, Athyris), lamellibranchs (Pseudomonotis), gasteropods (Pleurotomaria), and ammonites (Xenaspis).

(*iii*) *Upper Productus Limestone.* This part of the formation is composed of sandstones and marls. The chief fossils found in these beds are brachiopods (Productus indicus, Productus spiralis), lamellibranchs (Schizodus), gasteropods (Bellerophon), and ammonites (Xenodiscus, Planetoceras).

8.26. KASHMIR

8.26.1 Cambrian Rocks

The Cambrian rocks of Kashmir rest conformably over the fossiliferous *"Dogra slates"* of Precambrian age. The succession is composed chiefly of clays, impure sandstone and greywacks with a few lenticular bands of limestone. The clay beds are fossiliferous and they contain trilobites (Ptychoparia, Solenopleura), brachiopods (Acrothele, Lingulella), pteropods, crinoids, and sponges of Cambrian age.

8.26.2 Ordovician and Silurian Rocks

The Ordovician rocks of Kashmir and adjacent areas are composed of shales, silt and limestones. The shales have yielded well preserved bryozoans, brachiopods and cystoids. The Ordovician rocks are conformably ovelain by a succession of sandstones, slates and greywackes which have yielded fossils of Silurian age.

8.26.3. Devonian Rocks

Muth Quartzite. In the northern parts of Kashmir, Muth quartzites of Devonian age are exposed. They constitute a thickness of about 650 meters. They rest either over the Cambrian rocks or over the rocks of Silurian age and are conformably overlain by the *"Synringothyris limestone"* of Carboniferous age. The Muth quartzites are mostly unfossiliferous.

8.26.4. Permo-carboniferous Rocks

The Permo-carboniferous succession of the Kashmir area has been divided into six formations : (*i*) Syringothyris limestone, (*ii*) Fenestella shales, (*iii*) Agglomeratic slates, (*iv*) Panjal traps, (*v*) Gangamopteris beds, and (*vi*) Zewan formation. These formations are shown in Table 8.20.

Table 8.20. Permo-carboniferous Rocks of Kashmir

Periods	*Formations*	*Lithology*
Permian	Zewan formation	Shales and limestones with marine fossils
	Gangamopteris beds	Slates and pyroclastic beds with plant fossils
Carboniferous	Panjal traps	Basaltic lavaflows
	Agglomeratic slates	Slates and greywackes
	Fenestella shales	Shales and quartzites
	Syringothyris limestone	Limestones
Muth Quartzites (Devonian)		

Syringothyris Limestone. The Muth quartzites are conformably overlain by the *"Syringothyris limestone"*. This formation is composed of thin beds of grey and dark blue limestones with a few beds of shales, quartzites and traps. The limestones are characterized by the presence of the brachiopod *"Syringothyris"* of Lower Carboniferous age.

Fenestella Shales. The Fenestella shales are composed of a 600 meters thick succession of shales and quartzites with a few beds of conglomerates. The shale beds are fossiliferous and contain abundant remains of a polyzoa, called *"Fenestella"*. These beds also contain bryozoans, brachiopods, pelecypods, corals, trilobites and crinoids ranging in age from Lower to Upper Carboniferous.

Agglomeratic Slates. This formation consists of a succession of slates, sandstones, quartzites and conglomerates. These rock beds are considered to be of volcanic origin. The fossils are generally absent in this formation.

Panjal Traps. The Agglomeratic slate formation in overlain by a thick succession of lavaflows of basaltic composition, known as the *"Panjal traps"*. The maximum thickness of these lavaflows is up to 2300 meters. The lavaflows are intercalated with pyroclastic materials and intertrappean beds, and they may be of Upper Carboniferous to Lower Permian age.

Gangamopteris Beds. In some parts of Kashmir, the Panjal traps are overlain by beds of slaty and pyroclastic rocks. These beds have yielded plant fossils of Lower Gondwana (Lower Permian) age. The chief plant fossils are Gangamopteris kashmirensis, Glossopteris indica, and Vertebraria.

Zewan Beds. The Gangamopteris beds are overlain by a 240 meters thick succession of limestones and shales. These beds are rich in marine fossils of Middle and Upper Permian age. The chief fossils are brachiopods (Spirigera, Chonetes, and many species of Productus and Spirifer), bryozoans (Fenestella and Protoretepora), and corals (Zaphrentis).

8.27. SPITI

Table 8.21. Palaeozoic Succession of Spiti

Periods	*Groups*	*Formations*
Permian	Kuling Group	Productus shales
		Calcarious sandstone
		Conglomerates and grits
Carboniferous	Kanawar Group	Po formation
		Lipak formation
Devonian		Muth quartzites
Silurian and Ordovician		Limestones, sandstones, quartzites and shales
Cambrian	Haimanta Group	Quartzites, slates and shales

In the Spiti area of Himachal Pradesh, a complete succession of rocks ranging in a age from the Precambrian to Cretaceous is exposed. The succession of the Palaeozoic rocks of this area is shown in Table 8.21.

8.27.1. Cambrian Rocks

Haimanta Group. The Haimanta group rests over the rocks of the Vaikrita group of Precambrian age. The Haimanta group consists of about 1500 meters thick succession of quartzites, slates and shales with some dolomite. The lower 600 meters thick rock beds are unfossiliferous while the rocks of the upper part of the succession contain a rich collection of trilobites (Redlichia, Agnostus, etc.) and brachiopods (Lingulella, Obolella, Acrothele, etc.). These fossils indicate that the age of the upper part of the Haimanta group ranges between Middle to Upper Cambrian. Hence some members of its lowermost part may be correlated with the Precambrian rocks.

8.27.2. Ordovician and Silurian Rocks

The rocks of the Haimanta group are conformably overlain by a succession of coarse red conglomerate, gritty quartzites, sandstones, shales, limestones and dolomites. The total thickness of the Ordovician and Silurian succession is about 750 meters. The Ordovician rock beds have yielded fossils of trilobites (Asaphus, Illaenus), brachiopods (Orthis, Leptaena, Strophomena), and cephalopods (Goniaceras). The chief fossils of the Silurian rocks are trilobites (Calymene), brachiopods (Orthis, Pentamerus), and corals (Zaphrentis).

8.27.3. Devonian Rocks

Muth Quartzites. This formation of the Spiti area consists of about 100 meter thick succession of white and light green quartzites. The age of the Muth quartzites ranges from Upper Silurian to Devonian.

8.27.4. Permo-carboniferous Rocks

The Permo-carboniferous succession of the Spiti area has been divided into two groups : (*i*) the "*Kanawar group*", and (*ii*) the "*Kuling group*". These two groups are separated by an unconformity which is represented by a conglomerate (Table 8.22).

Kanawar Group. This group has been subdivided into two formations. The lower formation is called the "*Lipak formation*", and the upper one is called the "*Po formation*".

(*i*) *Lipak Formation.* The Lipak formation consists of a succession of limestones and shales. This formation has yielded fossils of Lower Carboniferous age. The chief fossils are trilobites (Phillipsia), brachiopod (Syringothyris cuspidata), and coral (Cyathophyllum).

Table 8.22. Permo-carboniferousa Rocks of Spiti

Group	*Formation*	*Lithology*
Kuling Group (100 m)		Productus shales Calcarious sandstone
(Unconformity) Conglomerate		
Kanawar Group (1300 m)	Po formation Lipak formation	Shales and quartzites Shales and limestone

(*ii*) *Po Formation.* This formation rests conformably ove the Lipak formation. It is made up of a succession of quartzites and shales. The chief fossils of this formation are bryozoans (Fenestella), and brachiopods (Spirifer, Productus).

The Po formation is overlain by a horizon of conglomerate which may be of Upper Carboniferous age. This conglomerate represents an unconformity of a comparatively short interval.

Kuling Group. The "*Kuling group*" is composed of a succession of calcarious sandstones and shales. The calcarious sandstones have yielded brachiopods (Spirifer, Productus) of Middle Permian age. The carbonaceous shales of the upper part of the Kuling group are called the "*Productus shales*". These shales have yielded fossils of brachiopods (Productus), and cephalopods (Xenaspis, Cyclolobus) of Permian age.

8.28. MESOZOIC ROCKS

The Mesozoic Era began at about 230 million years ago and closed at about 65 million years ago. This Era has been divided into three periods : (*i*) Triassic, (*ii*) Jurassic, and (*iii*) Cretaceous. In India, the Mesozoic rock-formations lie unconformably above the Palaeozoic rocks. However, there is a marked difference in the fossil fauna of the two formations. The Mesozoic rocks occur both in the Extra Peninsular region and in the Peninsular region.

8.29. TRIASSIC ROCKS

The Triassic rockformations of marine origin are confined mainly to the Himalayan region, perticularly to Kumaon, Spiti, Kashmir and Salt Range. The Triassic rocks which occur in the Peninsular region are of fluviatile origin and they form a part of the "*Gondwana Supergroup*".

8.29.1. Triassic of Spiti

In the Spiti area of Himachal Pradesh, a complete succession of Mesozoic rocks are exposed. Of this only the Triassic rocks have been described here. The Triassic rocks rest conformably over the Productus shales of Permian age.

The Triassic rocks of the Spiti area are called the "*Lilang group*". This group is composed mainly of about 1100 meters thick succession of limestones and shales. These rockformations have yielded a rich collection of fossils of mostly "*ammonites*" with many species of "*lamellibranchs*" and a few "*brachiopods*".

The Triassic succession of the Spiti area has been classified into three divisions : (*i*) Lower Triassic rocks, (*ii*) Middle Triassic rocks, and (*iii*) Upper Triassic rocks. Each of these divisions is further subdivided into "*Zones*" as shown in Table 8.23.

Table 8.23. Triassic Succession of Spiti

Divisions	*Formations*	*Fossils*
Upper Triassic (930 m)	Quartzite formation Monotis shales Coral limestone Juvavites beds Tropites beds Grey shale beds Halobia beds	Spirigera maniensis Monotis salinaria Spiriferina Juvavites angulatus Tropites subbullatus Joannites Halobia
Middle Triassic (130 m)	Daonella limestone Daonella shales Upper Muschelkalk Lower Muschelkalk Nodular limestone Basal Muschelkalk	Daonella indica Daonella lammeli Ptychites rugifer Spiriferina No important fossils Rhynchonella
Lower Triassic (16 m)	Hedenstroemia beds Meekoceras zone Ophiceras zone Octoceras zone	Hedenstroemia Meekoceras varaha Ophiceras sakuntala Octoceras woodwardi

Lower Triassic Rocks. This division is composed of 16 meters thick beds of limestones and shales. These beds have been subdivided into four zones.

(*i*) *Octoceras Zone.* This zone occurs at the bottom of the Lower Triassic succession and rests conformably over the Productus shales of Permian age. It is composed of about 0.5 meter thick beds of brown limestone which is rich in a characterstic cephalopod called "*Octoceras woodwardi*".

(*ii*) *Ophiceras Zone.* This zone is composed of beds of grey limestones which contain a cephalopod called "*Ophiceras sakuntala*". The thickness of this zone is less than one meter.

(*iii*) *Meekoceras Zone.* This zone is made up of about one meter thick beds of limestones and shales. The chief fossil of this zone is "*Meekoceras varaha*".

(*iv*) *Hedenstroemia Beds.* This zone consists of about 12 meter thick succession of limestones, shales, and shaly limestones. The main fossil of these beds is a cephalopod called "*Hedenstroemia mojsisovicsi*".

Middle Triassic Rocks. The Middle Triassic rocks rest conformably over the Lower Triassic division. The succession is composed mainly of limestones, shales, and shaly limestones. Its total thickness is about 130 meters. This succession has been subdivided into six parts.

(*i*) *Basal Muschelkalk.* This part is composed of about one meter thick beds of shaly limestone. The characterstic fossil of these beds is a brachiopod called "*Rhynchonella griesbachi*".

(*ii*) *Nodular Limestone.* This formation is about 20 meters thick and is composed of nodular limestones. These rock beds are poor in fossils.

(*iii*) *Lower Muschelkalk.* This formation is composed of about 2 meters thick beds of shaly limestone. Its lower part is rich in cephalopods while its upper part contains abundant brachiopods. The chief fossils of this formation are cephalopods, such as "*Sibirites prahlada*", and brachiopods, such as "*Spiriferina" and Rhynchonella*".

(*iv*) *Upper Muschelkalk.* This formation contains mainly limestone beds which are about 6 meters thick. The characterstic fossils of this zone are cephalopods such as "*Ptychites rugifer*" and "*Ceratites*".

(*v*) *Daonella Shales.* This formation consists of about 50 meters thick dark shales and limestones which are rich in fossils of lamellibranchs, such as "*Daonella*" and "*Halobia*". The other important fossils of this formation are brachiopods (Spiriferina and Spirigera), and cephalopods (Ceratites, Ptychites, Trachyceras, and Xenaspis).

(*vi*) *Daonella Limestone.* This formation is composed chiefly of dark coloured hard limestones with a few beds of shales. The total thickness of these beds is about 50 meters. The main fossils of these beds are "*Daonella indica*" and "*Daonella lamelli*".

Upper Triassic Rocks. The Upper Triassic rocks consist of limestones, shales, shaly limestones and quartzites. The total thickness of this succession is over 600 meters. This succession has been subdivided into seven parts.

(*i*) *Halobia Beds.* These beds are made up of about 50 meters thick succession of dark coloured limestones. They contain fossils, such as "*Halobia*" and "*Joannites thenamensis*".

(*ii*) *Grey Shale Beds.* This formation is composed of grey shales and shaly limestone. The total thickness of these beds is about 150 meters. The chief fossils of this formation are "*Joannites cymbiformis*", "*Spiriferina*" and "*Rhynchonella*".

(*iii*) *Tropites Beds.* These beds are made up of dark coloured limestones, shales and dolomitic limestones. They constitute a thickness of about 100 meters. The main fossils of this formation are "*Tropites subbullatus*" and "*Dielasma julicum*".

(*iv*) *Juvavites Beds.* This formation is composed of shales, limestones and sandstones. The total thickness of the succession is about 150 meters. The most important fossil of this formation is "*Juvavites angulatus*".

(*v*) *Coral Limestones.* The total thickness of the coral limestone beds is about 30 meters. These beds contain remains of crinoids, corals and brachiopods. The important fossils of this formation are "*Spiriferina*" and "*Rhynchonella*".

(*vi*) *Monotis Shales.* These shale beds are about 100 meters thick. The main fossils of this formation are "*Monotis salinaria*", "*Spiriferina griesbachi*", "*Pecten*", "*Lima*", and "*Rhynchonella*".

(*vii*) *Quartzite Formation.* This formation is composed of about 100 meters thick succession of quartzites, limestones, and shales. The important fossil of this formation is "*Spirigera maniensis*".

8.29.2. Triassic of Kashmir

The Triassic formation of the Kashmir area overlies the Zewan beds of Permian age. It consists of a thick succession of limestones and shales which yield rich Triassic fauna. This succession has been divided into three divisions: (*i*) Lower Triassic rocks, (*ii*) Middle Triassic rocks, and (*iii*) Upper Triassic rocks.

Lower Triassic Rocks. This division consists of about 100 meters thick succession of limestones interbedded with a few beds of quartzites and shales. In this succession four biostratigraphic zones have been recognised, each containing a characterstic ammonite fauna. These zones in the order from the base upwards are : (*i*) Octoceras zone, (*ii*) Ophiceras zone, (*iii*) Meekoceras zone, and (*iv*) Hedenstroemia zone.

Middle Triassic Rocks. This part consists of a 300 meters thick succession of sandly limestones. The fossil assemblage of this formation is dominated by an ammonite, called "*Ceratites*". The main fossils found in these rocks are cephalopods (Sibirites, Ptychites, Hungarites), lamellibranchs (Myophoria, Anomia), brachiopods (Spiriferina, Dielasma, Rhynchonella), and gasteropod (Conularia).

Upper Triassic Rocks. The Upper Triassic succession of the Kashmir area is composed of a

shales. These rocks are largely unfossiliferous. However a few fossiliferous zones have yielded brachiopods, lamellibranchs, crinoids and corals of Upper Triassic age.

8.30. JURASSIC ROCKS

The Jurassic rockformations occur in Cutch area of Gujrat, Rajasthan, and along eastern coast of the Peninsular India, and in Spiti, Salt Range and Kashmir of the Extra Peninsular region. The Jurassic rocks are perticularly well developed in Cutch and Spiti areas.

8.30.1. Jurassic of Cutch

In Cutch area of Gujrat, the Jurassic rocks cover a large area. The belt of Jurassic rocks extends E-W for about 150 kilometers. They are the oldest rockformations exposed in the Cutch area.

The principal rock types of the Jurassic succession are sandstones, limestones and shales. The total thickness of the succession is about 2000 meters. These rocks are folded into three parallel anticlinal ridges trending E-W. South of Bhuj there is a strike fault which runs in the E-W direction. The Jurassic succession of Cutch is intruded by sills and dykes of basic composition. These sills and dykes are genetically related with the overlying Deccan traps.

Table 8.24. Jurassic Succession of Cutch

Formation	*Subdivisions*	*Fossils*
Umia (1000 m)	Marine sandstone Plant beds Ukra beds Trigonia beds Ammonite beds	Columbiceras waageni Brachyphyllum, Williamsonia Unfossiliferous Trigonia ventricosa Virgatosphinctes
Katrol (750 m)	Gajansar beds Upper Katrol sandstone Middle Katrol sandstone Lower Katrol sandstone Kantkote sandstone	Phylloceras, Hildoglochiceras Unfossiliferous Katroliceras Waagenia Epimayaites
Chari (400 m)	Dhosa oolites Athleta beds Anceps beds Rehmanni beds Macrocephalus beds	Mayaites Peltoceras athleta Perisphinctes anceps Reineckeia rehmanni Macrocephalites
Patcham (300 m)	Coral beds Shell limestone Basal limestone	Stylina, Sivajiceras Trigonia, Corbula Corbula lyrata

The Jurassic rocks of Cutch contain a good assemblage of fossils of lamellibranchs, ammonites, and plant fossils. The Jurassic succession of Cutch has been classified into four divisions: (*i*) Patcham formation, (*ii*) Chari formation, (*iii*) Katrol formation, and (*iv*) Umia formation (Table 8.24).

Patcham Formation. This formation is made up of a 300 meter thick succession of dark pisolitic limestones, olive green shales, cherty limestones and marls. These beds have yielded a rich assemblage of corals, brachiopods, lamellibranchs (Corbula, Eomiodon), and ammonites (Macrocephalites triangularis, Sivajiceras cogener) of Middle Jurassic age.

Chari Formation. This formation rests unconformably over the Patcham formation and is made up of sandy limestones, marls, shales and oolitic limestones. The total thickness of the succession is about 400 meter. The Chari formation is very rich in ammonites of middle Jurassic age. It has been subdivided into five zones.

(*i*) *Macrocephalus Beds*. These beds occur at the base of the Chari formation. They are composed of shales and oolites. The characterstic fossil of these beds is an ammonite called "*Macrocephalites macrocephalus*".

(*ii*) *Rehmanni Beds*. These beds are composed of yellow limestones and their chief fossils are "*Reineckeia rehmanni*" and "*Sivajiceras*".

(*iii*) *Anceps Beds*. These beds are made up of limestones and shales. They have yielded a characterstic ammonite, called "*Perisphinctes anceps*".

(*iv*) *Athleta Beds*. These beds are composed of marls and gypseous shales. The characterstic ammonite of this zone is "*Peltoceras athleta*".

(*v*) *Dhosa Oolites*. This zone contains beds of oolitic limestones. These limestones are very rich in ammonites, such as "*Mayaites maya*", "*Peltoceras*", and "*Perisphinctes*".

Katrol Formation. The chief rock types of the Katrol formation are shales, limestones, sandstones and grits. The total thickness of the succession is about 750 meters. The important fossils of this formation are lamellibranchs (Trigonia) and ammonites (Virgatosphinctes, Aspidoceras, Phylloceras, Oppelia, and Haploceras). These fossils indicate that the Katrol formation is of Upper Jurassic age.

Umia Formation. This formation is composed of about 1000 meters thick succession of sandstones and shales. Its age is between Upper Jurassic to Lower Cretaceous. The Umia formation has been divided into five zones.

(*i*) *Ammonite Beds*. These beds are made up of shales and oolitic sandstones. They are rich in ammonites (Virgatosphinctes, Hildoglochiceras, Umiatites).

(*ii*) *Trigonia Beds*. These beds are composed of sandstones and conglomerates. The characterstic fossil of these beds is a lamellibranch called "*Trigonia*".

(*iii*) *Ukra Beds*. These beds are composed mainly of unfossiliferous sandstones. Their total thickness is about 300 meters. These beds rest over the Trigonia beds.

(*iv*) *Umia Plant Beds*. The Ukra beds are overlain by the Umia plant beds of fresh water origin. The chief rock types of these beds are sandstones and shales which contain plant fossils (Brachyphyllum, Pagiophyllum, and Williamsonia). These fossils indicate that the Umia plant beds are of uppermost Jurassic to Lower Cretaceous age.

(*v*) *Marine Sandstone*. These sandstones rest over the Umia plant beds and contain ammonites (Acanthoceras) of Lower Cretaceous age.

8.30.2. Jurassic of Spiti

In the Spiti area, the Jurassic rocks rest unconformably ove the Quartzite formation of Upper Triassic age. These rocks are composed mainly of shales and limestones and the total thickness of the succession is about 1000 meters. The succession has been divided into two groups, the "*Kioto limestones*" and the "*Spiti shales*", and each group has been further subdivided into three formations as shown in Table 8.25.

Kioto Limestone. The lower part of the Jurassic succession of Spiti is called the "*Kioto limestone*". It is named after the Kioto village in the Spiti valley. The Kioto limestone is also called the "*Megalodon limestone*" as it contains a characterstic lamellibranch called "*Megalodon*". It is chiefly made up of 750 meters thick succession of limestones and dolomites, and contain fossils of lamellibranchs and ammonites of Upper Triassic to Middle Jurassic age. The Kioto limestone has been subdivided into three formations.

Table 8.25. Jurassic Succession of Spiti

Divisions	*Formation (Fossils)*
Spiti Shales (100—300 m)	Lochambal beds (Spiticeras, Hoplites, Blanfordiceras) Chidamu beds (Very rich in ammonites, *e.g.* Perisphinctes) Belemnites gerardi beds (Belemnites gerardi, Mayaites)
Unconformity	
Kioto Limestone (750 m)	Sulcacutus beds (Belemnites sulcacutus) Tagling formation (Stephanoceras coronatum) Para formation (Megalodon, Diceracardium, Lima)

(*i*) ***Para Formation***. The lower part of the Kioto limestone is called the "*Para formation*". Its thickness is about 500 meters. The characterstic fossils of the Para formation are "*Megalodon*", "*Diceracardium*" and "*Spirigera*". These fossils indicate Upper Triassic age.

(*ii*) *Tagling Formation*. The upper part of the Kioto limestone is called the "*Tagling formation*". Its thickness is about 250 meters and contains a characterstic ammonite called "*Stephanoceras coronatum*". This ammonite suggests Jurassic age.

(*iii*) *Sulcacutus Beds*. The Tagling formation is overlain by beds of black ferruginous oolites, called "*Sulcacutus beds*". The characterstic fossilsof these beds are "*Belemnites sulcacutus*".

Spiti Shales. The Spiti shales rest unconformably over the Kioto limestone. These shales are carbonaceous micaceous shales which contain calcarious nodules enclosing ammonites. This formation is distributed very widely throughout the Himalayas The Spiti shales are famous for their great faunal wealth. The fossil assemblage is dominated by ammonites with a few lamellibranchs and gastropods. The thickness of this formation varies from 100 to 300 meters. The Spiti shales have been divided into three parts.

(*i*) *Belemnites Gerardi Beds*. These beds occur at the base of the succession of the Spiti shales. They contain a characterstic fossil called "*Belemnites gerardi*".

(*ii*) *Chidamu Beds*. These beds overlie the Belemnites gerardi beds and contain abundant ammonites. The chief fossils are "*Perisphinctes*" and "*Oppelia*".

(*iii*) *Lochambal Beds*. These beds form the upper part of the Spiti shales. The important fossils of these beds are "*Spiticeras*", "*Blanfordiceras*", and "*Hoplites*".

8.31. CRETACEOUS ROCKS

In India, during the Cretacceous period there is an evidence of a marked transgression of sea over the neighbouring land areas. The Cretaceous rocks of India may be broadly classified into two groups.

1. **Marine Cretaceous Rocks.** The marine Cretaceous rocks occur in the Himalayan region (Spiti, Baluchistan, and Salt Range), along east coast of India (Trichinopoly, and Pondichery) and in the Narmada valley (Bagh beds).
2. **Freshwater Cretaceous Rocks.** These rocks occur in Madhya pradesh (Lameta beds).

8.31.1. Cretaceous of Spiti

The Cretaceous rocks of the Spiti area rest conformably over the Spiti shales of Upper Jurassic age. These rocks occur as outliers in the cores of synclines. The Cretaceous rocks of the Spiti area have been divided into two formations : (*i*) Chikkim limestone, and (*ii*) Giumal sandstone.

Giumal Sandstone. The lower part of the Cretaceous succession of Spiti is called the "*Giumal sandstone*". It consists of about 100 meters thick beds of yellow sandstones and quartzites. The chief fossils found is these beds are lamellibranchs (Cardium, Gryphaea, Pseudomonotis) and ammonites (Holcostephanus, Acanthodiscus, Perisphinctes). These fossils indicate Lower Cretaceous age.

Chikkim Limestone. The Giumal sandstone is conformably overlain by limestones and shales, called "*Chikkim limestone*". The total thickness of these beds are about 80 meters. The limestone beds have yielded cephalopods (Belemnites), lamellibranchs (Hippurites), and foraminifers of Upper Cretaceous age.

8.31.2. Cretaceous of Trichinopoly

The Cretaceous rocks occur along the east coast of India near Trichinopoly, Vridhachalam and Pondichery. In the Trichinopoly area, the Cretaceous rocks are very well developed. Here they rest unconformably over the Archaean or Upper Gondwana rocks.

In Trichinopoly, the Cretaceous rocks are exposed in an area of about 650 square kilometers. They are mainly composed of limestones, sandstones, grits and clays. The total thickness of the succession is about 2500 meters. These rocks are highly fossiliferous and they dip at low angles to the east or ESE. The succession of the Cretaceous rocks of Trichinopoly has been divided into four parts : (*i*) Uttatur formation, (*ii*) Trichinopoly formation, (*iii*) Ariyalur formation, and (*iv*) Niniyur formation (Table 8.26).

Table 8.26. Cretaceous Succession of Trichinopoly

Division	*Lithology (Fossils)*
Niniyur	Sandy limestone and sandstone (Nautilus danicus, Cardita)
Ariyalur	Upper : Sandstone (Unfossiliferous) Lower : Sands and clays (Pachydiscus, Baculites, Gryphaea)
Trichinopoly	Upper : Sandstone and clays (Placenticeras) Lower : Sandstone, clays, shell limestone (Protocardium, Trigonia)
Uttatur	Upper : Sandy beds (Mammites, Nautilus) Middle: Clays (Acanthoceras) Lower : Coral limestone and clays (Turrilites, Hamites, Belemnites)

Uttatur Formation. The Lower part of the Cretaceous succession at Trichinopoly is called the Uttatur formation. It consists mainly of about 700 meter thick beds of coral limestones and clays. In the upper part of this formation, the clay beds contain abundant gypseous and phosphatic nodules which indicate evaporatic conditions of a regressing sea. The Uttatur formation has yielded rich fossils of cephalopods, pelecypods, gastropods, brachiopods, echinoids, corals, and fossil wood. These fossils indicate that the age of this formation ranges from Albian to Turonian. The chief fossils of this formation are as follows.

Cephalopods	: Schloenbachia inflata, Acanthoceras, Mammites.
Lamellibranchs	: Inoceramus, Gryphaea, Exogyra.
Gastropods	: Patella, Turritella.
Brachiopods	: Terebratulla, Rhynchonella.
Corals	: Trochosmilia, Stylina.

Trichinopoly Formation. This formation is composed of sandstones, false bedded grits, clays and shell limestones. The thickness of the succession varies from 300 to 600 meters. The general coarseness of the sediment and the presence of abundant fossil wood and tree trunks indicate that this formation is of shallow water origin. The Trichinopoly formation has yielded fossils of mainly lamellibranchs (Trigonia) and fossil wood. These fossils indicate a Turonian to Lower Senonian age.

Ariyalur Formation. This formation is more arenaceous and more uniformly bedded than the two lower formations. It is mainly composed of sandstones with some clay beds. The total thickness of the succession is about 300 meters. The lower half of this formation is very fossiliferous while the upper half is unfossiliferous. Among the fossils, the lamellibranchs are most common. Some well preserved echinoids are also found. The age of this formation ranges from Senonian to Maestrichtian. The chief fossils of the Ariyalur formation are as follows.

Lamellibranchs	: Gryphaea, Cardium, Inoceramus, Pholadomya.
Echinoids	: Stigmatopygus, Hemiaster, Cyrtoma.
Ammonites	: Pachydiscus, Baculites.
Gastropods	: Voluta, Cypraea.
Corals	: Stylina, Thamnastrea.
Reptiles	: Megalosaurus, Titanosaurus.

Niniyur Formation. This formation is made up of sandy limestones, shales and sandstones. These rock beds are rich in gastropods, algae and foraminifera. The ammonites are absent but "*Nautilus*" is common. The important fossils of the Niniyur formation are "*Nautilus danicus*", "*Cardita*", and "*Orbitoides minor*" (Foraminifer). The age of this formation is Danian.

8.31.3. Cretaceous of Narmada Valley

Bagh Beds. The Cretaceous rocks of marine origin which occur along the Narmada valley, are called the "*Bagh beds*". They rest unconformably over the Archaean gneisses and schists, and are overlain by the Deccan traps. They are named after the Bagh town in the Dhar district of Madhya Pradesh where they are well developed.

The Bagh beds occur in small detached outcrops along the Narmada valley. These outcrops extend in the E–W direction from Rajpipla in the west to near Indore in the east for about 350 kilometers. The Bagh beds occur as inliers where they are surrounded by the Deccan traps of younger age.

The Bagh beds are composed of sandstones, marls and limestones. This succession has been divided into four parts : (*i*) Nimar sandstone, (*ii*) Nodular limestone, (*iii*) Deola marl, and (*iv*) Coralline limestone (Table 8.27).

Table 8.27. Succession of Bagh Beds

Formation	*Subdivision*	*Remark*
Bagh Beds	Coralline limestone (10 m)	Rich in Bryozoa
	Deola marl (3 m)	Rich in fossils
	Nodular limestone (12 m)	Contains fossils
	Nimar sandstone	Unfossiliferous

The chief fossils of the Bagh beds are ammonites (Placenticeras, Namadoceras), lamellibranchs (Ostrea, Inoceramus, Cardium, Protocardium), gastropods (Triton, Turritella, Natica, Cerithium) and echinoids (Hemiaster, Salenia, Cidaris). These fossils indicate that the age of the Bagh beds ranges from Cenomanian to Upper Senonian.

8.31.4. Cretaceous of Madhya Pradesh

Lameta Group. The Cretaceous rocks of fresh water origin which occur in Madhya Pradesh are called the "*Lameta group*". They are named after the Lameta Ghat near Jabalpur where they are well exposed. The Lameta rocks occur as narrow outcrops below the Deccan traps in Sagar, Damoh and Jabalpur areas of M.P. and near Nagpur in Maharashtra.

The Lameta group consists of mainly sandstones, marls, limestones and clays. The thickness of these beds vary from 7 to 30 meters. The Lameta beds have yielded a large number of molluscs (Physa, Paludina, Corbula), dinosaurs (Lametasaurus, Titanosaurus), turtles and fishes of Middle Cretaceous (Turonian) age. The fossil assemblage of the Lameta group indicates that these rocks were deposited during the same time when the marine Bagh beds were being deposited.

8.32. GONDWANA SUPERGROUP

The Gondwana supergroup includes rocks ranging in age from the Upper Carboniferous to Lower Cretaceous. This supergroup has been named after the Gond Kingdom of Madhya Pradesh where these rocks were first studied in 1872. The Gondwana rocks rest unconformably over the older formations, such as the Archaeans and are overlain by the Deccan traps.

Distribution. The Gondwana rocks occur in a series of narrow faulted troughs which are arranged mainly along three linear tracts : (*i*) along the Son-Damodar valley, (*ii*) along the Mahanadi valley, and (*iii*) along the Godavari - Wardha valley (Fig. 8.6.). In addition, the Gondwana rocks are also found in the sub-Himalayan regions of Kashmir, Sikkim, and Assam.

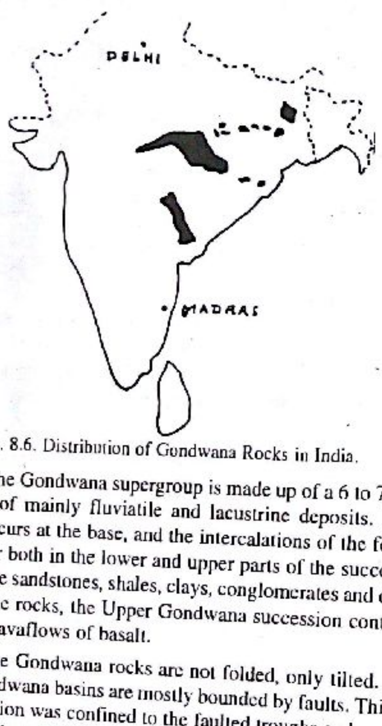


Fig. 8.6. Distribution of Gondwana Rocks in India.

Lithology. The Gondwana supergroup is made up of a 6 to 7 kilometers thick succession of mainly fluviatile and lacustrine deposits. However a glacial deposit occurs at the base, and the intercalations of the fossiliferous marine beds occur both in the lower and upper parts of the succession. The chief rock types are sandstones, shales, clays, conglomerates and coal seams. In addition to these rocks, the Upper Gondwana succession contains about 600 meters thick lavaflows of basalt.

Structure. The Gondwana rocks are not folded, only tilted. Faults are common. The Gondwana basins are mostly bounded by faults. This suggests that the sedimentation was confined to the faulted troughs and was contemporaneous with faulting. In addition there are many faults cutting across the Gondwana basins.

Igneous Instrusions. There was a period of volcanic activity during the Rajmahal times (Upper Gondwana period) which led to the formation of "*Rajmahal traps*". The Lower Gondwana rocks have been intruded by the dykes of dolerite and basalt and sills of micropegmatite and lamprophyre. In the Damodar valley area, they are said to be genetically related to the Rajmahal traps.

Classification. The Gondwana formation includes about 6 to 7 kilometers thick succession of sedimentary rocks. It represents a long period of sedimentation from Upper Carboniferous to Lower Cretaceous. The classification of the Gondwana succession has been a disputed problem. Two types of classification have been proposed : (*i*) three fold classification, and (*ii*) two fold classification.

(*i*) **Three Fold Classification.** The three fold classification of the Gondwana succession has been favoured by O.Feistmantel (1880) and D.N. Wadia (1926). On the basis of difference in lithology, the Gondwana succession has been divided into three parts : (*a*) Lower Gondwana, (*b*) Middle Gondwana, and (*c*) Upper Gondwana. In this case, these three divisions correspond roughly to the Permian, Triassic, and Jurassic periods. Thus the boundaries of the three divisions coincide with the boundaries of the Standard Time Scale.

The "*Lower Gondwana succession*" is mainly made up of rocks deposited in humid subtropical climate and contains a number of coal seams. The "*Middle Gondwanas*" include rocks formed in dry climatic conditions and contain fossils of amphibians and reptiles. The "*Upper Gondwana rocks*" again appear to have formed under milder temperatures and humid conditions.

(*ii*) **Two Fold Classification.** The two fold classification has been supported by C.S.Fox (1931), and adopted by the Geological Survey of India. On the basis of assemblage of plant fossils, the Gondwana succession has been classified into two divisions: (*a*) Lower Gondwana, and (*b*) Upper Gondwana. The "*Lower Gondwana division*" is characterized by the presence of "*Glossopteris flora*" in which equisetales, pteridosperms, and sphenophyllales predominate. The "*Upper Gondwana rocks*", on the other hand contain "*Ptilophyllum flora*" in which cycades and conifers predominate. The line of division has been placed above the "*Panchet formation*" and it is marked by a slight unconformity. However this boundary does not coincide with the boundary of the Standard Time Scale. In the present discussion of the Gondwana supergroup, the two fold classification has been adopted. The two divisions, that is the Lower and Upper Gondwanas, have been further subdivided into Groups and Formations as shown in Table 8.28.

Table 8.28. Succession of Gondwana Rocks

Division	*Group*	*Formation*	*Lithology*
Upper Gondwana	Jabalpur	Umia	Sandstone, shale
		Jabalpur	Clays, sandstone
		Chaugon	Clays, sandstone
	Rajmahal	Kota	Sandstone, grits, coal bands
		Rajmahal	Basaltic lavaflows
	Mahadeva	Maleri	Red clays, sandstone
		Pachmari	Red sandstone, clays
		Unconformity	
Lower Gondwana	Panchet	Panchet	Brown sandstone, shales
	Damuda	Raniganj	Sandstone, shale, coal seam
		Barren measures	Sandstone, ironstone shale
		Barakar	Sandstone, shale, coal seam
		Karaharbari	Sandstone, grits, coal seam
	Talchir	Rikba	Sandstones
		Talchir	Greenish shale
		Boulder bed	Boulder bed

8.32.1. Lower Gondwana Formations

Talchir Group. The rocks of this group rest unconformably over either the Archaean or the Precambrian rocks. The chief rock types are boulder beds, shales and sandstones. The total thickness of the succession varies from 170 to 350 meters. The boulder bed which forms the base of the Talchir group, is of glacial origin. It is composed of polished and striated pebbles and boulders the diameter of which varies up to 4 to 5 meters. The sandstones contain undecomposed felspars thereby indicating a cold climate. The beds of the Talchir group have yielded a few plant fossils, such as "*Gangamopteris cyclopteroids*", "*Glossopteris indica*" and "*Vertebraria indica*". These fossils indicate Upper Carboniferous to Lower Permian age for the rocks.

Damuda Group. This group is named after the Damodar river. It is composed of about 2000 meters thick succession of conglomerates, grits, black shales and coal seams. The coal seams in general are less than 5 meters thick but in some basins they often attain a thickness of about 40 meters. The total thickness of all coal seams of the Damuda group is about 5% of the total thickness of the rocks. The Damuda group has been subdivided into four formations : (*i*) Karharbari, (*ii*) Barakar, (*iii*) Barren measures, and (*iv*) Raniganj.

(*i*) **Karharbari Formation.** It is the basal unit of the Damuda group. It rests unconformably over the rocks of the Talchir group. The Karharbari formation is composed of 60 to 120 meters thick succession of sandstones, grits and conglomerates with some coal seams. The "*Gangamopteris beds*" of Kashmir have been correlated with this formation.

(*ii*) **Barakar Formation.** This formation is named after the Barakar river. It is composed of sandstones, shales, grits and conglomerate with many coal seams. The total thickness of the succession is about 800 meters. The Barakar formation is the most important coal bearing formation of the Lower Gondwana succession. In the Jharia coal field, this formation contains about 25 coal seams. The total thickness of all the coal seams of Barakar formation is about 60 meters. Both the Karharbari and Barakar formations are of Lower Permian age.

(*iii*) **Barren Measures Formation.** This formation is composed of sandstones with intercalations of clay beds. The total thickness of the succession is about 500 meters. The Barren measures rocks do not contain any coal seam. In Raniganj coal field, the Barren measures is represented by 300-400 meter thick beds of red-brown shales, called the "*Iron stone shale*". These beds contain sideritic iron ore in which the iron content is between 35 to 40 percent. In the Narmada valley (Satpura region) the rocks equivalent to the Barren measures are called the "*Motur formation*". The age of this formation is about Middle Permian.

(*iv*) **Raniganj Formation.** This formation is composed of about 1000 meters thick succession of sandstones, shales and coal seams. In this formation there are 9 coal seams in the Raniganj coal field and 7 coal seams in the Jharia coal field. The Raniganj formation is the topmost formation of the Damuda group and its age is Upper Permian. This formation has been correlated with the "*Kamthi formation*" of Nagpur area, and the "*Bijori formation*" of the Satpura area (Narmada valley).

Panchet Group. This group has been named after the Panchet Hills in the Raniganj coal filed where it is well developed. It is composed of about 700 meters thick succession of coarse sandstones and shales. The absence of coal seams and the red colour of the sandstones indicate that these rock beds were formed under arid climatic conditions. The rocks of the Panchet group have yielded a rich assemblage of plant fossils, vertebrates, and freshwater invertebrates. The vertebrate fossils suggest that this group is of Lower Triassic age. The chief fossils of the Panchet rocks are as follows.

Plant Fossils	: Glossopteris, Schizoneura, Pecopteris, etc.
Fishes	: Amblypterus
Amphibians	: Pachygonia and Gonioglyptus.
Reptiles	: Dicynodonts and Lystosaurus.

8.32.2. Upper Gondwana Formations

Mahadeva Group. This group has been named after the Mahadeva Hills near Pachmari in the Satpura area of M.P. The Mahadeva group has been subdivided into two formations : (*i*) Pachmari, and (*ii*) Maleri.

(*i*) **Pachmari Formation.** This formation is best developed around Pachmari in Madhya Pradesh. It consists of about 800 meters thick coarse white sandstone with characterstic ferruginous partings. The beds of "*Denwa clay*" rest over the Pachmari sandstones. The Denwa clay has yielded "*Mastodonasaurus*" indicating a Middle to Upper Triassic age. The Pachmari formation is however of Lower to Middle Triassic age.

(*ii*) **Maleri Formation.** This formation is well developed near Hydrabad in Andhra Pradesh (Godavari basin). It consists of red clays with minor sandstones. The Maleri formation has yielded remains of fishes and reptiles indicating an Upper Triassic age. The "*Tiki beds*" of Rewa, M.P. are equivalent to the Maleri formation.

Rajmahal Group. The Rajmahal group has been divided into two formations : (*i*) Rajmahal, and (*ii*) Kota.

(*i*) **Rajmahal Formation.** This formation is well developed in the Rajmahal Hills of Bihar and West Bengal. It is made up of extensive lavaflows of basic composition, called the "*Rajmahal traps*". The total thickness of this formation is about 650 meters. The lavaflows are associated with sedimentary beds, called the "*Intertrappeans*". The intertrappeans are composed of shales, sandstones and quartzite. More than 15 intercalations of 1.5 to 8 meter thick intertrappeans have been recognised in this formation.

The intertrappean beds have yielded abundant flora rich in cycades. Some of the common plant fossils of the Rajmahal formation are "*Ptilophyllum*", "*Otozamites*", "*Dictyozamites*", etc. These plant fossils indicate the Middle to Upper Jurassic age. The radiometric dating of the Rajmahal traps has shown that they are of Albian age.

(*ii*) **Kota Formation.** The succession of this formation attains a thickness of about 650 meters in the Godavari valley. Here it rests over the Maleri beds. The Kota formation is composed mainly of sandstones and grits with some bands of clay. These beds have yielded abundant fossils of cycades and conifers with fossils of reptiles, fishes, and crustacea. The faunal assemblage of the Kota formation indicates the Lower to Middle Jurassic age.

Jabalpur Group. This group forms the upper part of the Gondwana succession. It is well developed in the Satpura region in central India. The rocks of the Jabalpur group rest unconformably over the Mahadeva group. They are composed of massive sandstones, conglomerates, white clays, red clays, carbonaceous bands and chert. These beds are rich in plant fossils. On the basis of floral assemblage, the succession of the Jabalpur group has been subdivided into two formations : (*i*) "*Chaugon beds*" and (*ii*) "*Jabalpur formation*". The Chaugon beds which form the lower part of the succession, contain "*Taeniopteris*", "*Nilssonia*", "*Dictyozamites*", etc. The main fossils of the Jabalpur formation are "*Ptilophyllum*", "*Otozamites*", "*Brachyphyllum*", etc. The Chaugon and Jabalpur formations are of Middle to Upper Jurassic age.

The topmost formation of the Gondwana succession is called the "*Umia formation*". This formation is well developed in the Cutch area in Gujrat. It is composed of about 100 meters thick succession of sandstones, oolitic limestones and shales. These beds have yielded rich assemblage of plant fossils of Upper Jurassic to Lower Cretaceous age. The Umia plant beds are underlain and overlain by the marine beds.

8.32.3. Marine Beds

On the east coast of India and in Cutch, Saurashtra and Rajasthan, the Upper Gondwana rocks are intercalated with the marine beds of Jurassic age. Similarly in Umaria and Manendragarh areas of eastern Madhya Pradesh, the Lower Gondwana rocks are associated with the marine beds of Upper Carboniferous age.

The marine beds of Umaria occurs in the Karharbari formation and is composed of a 3 meter thick shell limestone. It has yielded fossils such as "*Productus*", "*Spiriferina*", "*Reticularia*", etc., indicating Upper Carboniferous to Lower Permian age. The Marine beds of Manendragarh occur in the basal part of the Talchir formation. These beds are about 5 meter thick and they have yielded fauna such as "*Protoretepora*", "*Spirifer*", "*Aviculapecten*", "*Eurydesma*", etc. The fossil assemblage indicates that these marine beds are different from those of Umaria.

8.32.4. General Characters of Gondwana Rocks

1. The Gondwana succession represents a prolonged period of continental sedimentation. They occur in three river valley grabens: (*i*) Narmada—Son—Damodar valley, (*ii*) Mahanadi valley, and (*iii*) Godavari valley.
2. The climate of the Gondwana period is very variable. The bottom of the Gondwana succession is dominated by arkosic sediments representing a glacial climate. The coal bearing sediments of the Lower Gondwanas, were deposited in humid subtropical climate. Then the Triassic Gondwana sediments were laid down in hot, dry, desert climate. This climate was responsible for the disappearance of the "*Glossopteris flora*". Finally there was a return to another warm moist period during the Upper Gondwana times.

3. There is a marked difference between the floral assemblage of the Lower and Upper Gondwanas. The "*equisetaceous plants*" prevail in the Lower while "*cycades*" and "*conifers*" in the Upper Gondwanas. The "*Glossopteris flora*" which is characterstic of the Lower Gondwana rocks include fossils such as "*Glossopteris*", "*Gangamopteris*", and "*Vertebraria*". The Upper Gondwana rocks, on the other hand, are marked by the "*Ptilophyllum flora*". This flora includes fossils such as "*Ptilophyllum*", "*Nilssonia*" and "*Dictyozamites*".

   The Triassic Gondwana rocks which are included in the Panchet and Mahadeva groups have yielded a rich assemblage of vertebrate fossils. These vertebrates are represented by fresh water fishes, amphibians, reptiles and dinosaurs.

4. Coal seams occur mostly in the Lower Gondwanas. They are formed by the accumulation of the drifted plant material, carried down by rivers and deposited in large swamps. The coal seams are confined almost entirely to the Barakar and Raniganj formations.

8.32.5. Economic Minerals

Coal. The Barakar and Raniganj formations of the Damuda group (Lower Gondwana) constitute the most important coal bearing rockformations. All of the Gondwana coal is of bituminous variety. The ash percentage in this coal is high. It ranges between 15–30%. The best quality coal normally contains 11–13% ash. The moisture percentage varies from 3–10%.

Iron Ore. About 760 meter thick ferruginous shales, known as the "*Iron stone shales*", occur in the Barren measures formation of the Damuda group in the Raniganj coal field. These shales form a deposit of sideritic iron ore which contains about 40–45% iron. The total reserves of iron ore are estimated at about 2000 million tonnes.

Clay. The clays of various types are found in abundance in the Gondwana rocks. These clays are used for making refractory bricks, pottery and china ware.

Building Stone. The Gondwana standstone is generally of inferior quality. However some of it is being used as building stone.

8.33. DECCAN TRAPS

The Deccan traps are largely made up of lavaflows of basic composition. The age of these lavaflows ranges from Upper Cretaceous to Lower Eocene.

Occurrence. The Deccan traps cover an area of over 500 thousand square kilometer in the central and western parts of India. They occupy major parts of Gujrat, Madhya Pradesh, Maharashtra, and some parts of

Andhra Pradesh (Fig. 8.7). The Deccan traps attain a maximum thickness of about 2000 meters near Bombay in Western Ghats. Their thickness decreases towards east and in Shahdol district at Amarkantak they are only about 160 meters thick.

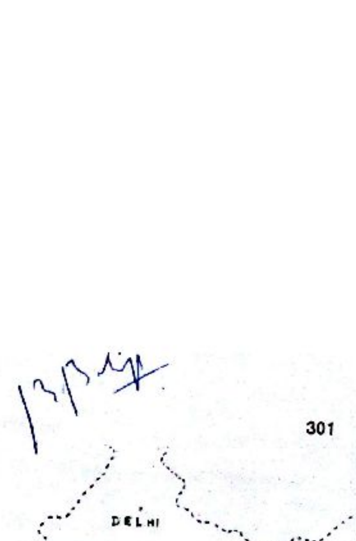


Fig. 8.7. Distribution of Deccan Traps in India.

Structure. The Deccan trap flows are generally horizontal in attitude, but gentle dips of the order of 10° have also been observed at some places. These lavas are believed to have erupted subaerially through fissures in the earth's crust. Such fissures are now seen as dykes in Gujrat, Narmada valley and Konkan. In the Cutch area of Gujrat these dykes trend in the NNE–SSW direction, in the Narmada valley they run in the ENE–WSW direction, and in Konkan their strike is N–S. The later phase of tectonic disturbances which caused the fragmentation of the Gondwana land may have been responsible for the Deccan trap volcanism.

Petrology. The majority of the Deccan trap flows are basalt with a uniform chemical composition, but rocks like rhyolite, granophyre, nepheline syenite, etc. have also been found, perticularly in the Cutch area of Gujrat. The essential minerals present in the Deccan trap basalt are labradorite, augite and iron oxide. Olivine is generally not found. Some flows show vesicular and amygdaloidal structures with quartz, chalcedony, calcite and zeolites as fillings.

General Characters. The total thickness of the succession of Deccan trap flows is about 2000 meters. There is a marked difference in the chemical and palaeomagnetic characters of the lower and upper parts of the succession.

(*i*) In the lower part of the succession, the lavaflows commonly exhibit reversed geomagnetic polarity, whereas in the upper part they show normal polarity.

(*ii*) In the lower part, the lavaflows are mostly theolitic in composition and horizontal in attitude. This suggests that they are formed from quiet type of eruption. However the lavaflows of the upper part show evidences of explosive activity.

Classification. The Deccan traps have been classified into three parts: (*i*) Lower traps, (*ii*) Middle traps, and (*iii*) Upper traps (Table 8.29).

The "*Lower traps*" are exposed in Madhya Pradesh and towards the east of the Deccan trap country. Their thickness is about 160 meters and they contain a number of intertrappean beds. In the Lower traps the ash beds are rare. The "*Middle traps*" occur in the central India and Malwa region. They are composed of 1300 meter thick lavaflows and some ash beds. In this part, the intertrappean beds are almost absent. The "*Upper traps*" are exposed in the northwestern part of the Peninsula, perticularly near Bombay and Kathiawar. They are about 500 meter thick and are associated with intertrappeans and ash beds.

Table 8.29. Classification of Deccan Traps

Divisions	*Distribution*	*Characters*
Upper traps (500 m)	NW Peninsula	Lavaflows with ash beds and intertrappeans.
Middle traps (1300 m)	Central India and Malwa region	Lavaflows with ash beds. Intertrappeans are rare.
Lower traps (160 m)	M.P. and eastern region	Lavaflows with many intertrappeans. Ash beds are rare.

Intertrappean Beds. These are the sedimentary beds found associated with the Deccan trap lavaflows. They are made up of shales, impure limestones and volcanic detritus of lacustrine and fluviatile origin. The individual beds are usually 1 to 3 meter thick and extend laterally for 5 to 8 kilometers. The intertrappean beds have yielded a rich faunal and floral assemblage. The flora is mainly palm (Palmoxylon). The invertebrate fossils include "*Physa princepii*", "*Lymnaea*", "*Paludina*", "*Natica*", etc. The vertebrate fossils are mainly frogs, tortoises and fresh water fishes.

8..33.1. Age of Deccan Traps

The Deccan traps have been regared as of Paleocene age on the basis of the following evidences.

(*i*) The Deccan traps overlie the Bagh and Lameta beds which are of Middle Cretaceous age.

(*ii*) Near Ranikot in Sind (Pakistan), lavaflows similar to the Deccan traps occur interstratified with the "*Cardita beaumonti beds*" of Upper Cretaceous age.

(*iii*) In the Saurashtra area of Gujrat, the "*Nummulitic beds*" of Lower Eocene age rest unconformably over the Deccan traps.

8.32.2. Economic Minerals

Road Metal. The Deccan trap basalts yield excellent road metal because they have high crushing strength and good binding properties.

Building Stones. The light coloured basalts are used as building stones in many parts of India.

Bauxite Deposits. Bauxite deposits are formed due to prolonged weathering of the Deccan traps. Such deposits are found at Belgaum, Jabalpur, Mandla, Sirguja and many other places.

Semi-Precious Stones. The Deccan trap flows contain quartz, amethyst, agate and chalcedony as secondary minerals which are used as semiprecious stones.

Black Soil. The most fertile black Soil of Malwa and Maharashtra have been derived from the Deccan trap basalts.

Aquifers. The vesicular and highly jointed lavaflows form good aquifers from which the ground water is obtained.

8.34. TERTIARY ROCKS

The close of the Mesozoic and beginning of the Tertiary Era was marked by great physical and organic changes.

1. The outpouring of enormus lavaflows which gave rise to the Deccan traps on the Indian Peninsula.
2. Uplifting of the Tethyan geosynclinal sediments and formation of the Himalayan mountains.
3. On land, the reptiles and amphibians which were abundant during the Mesozoic Era, died out rapidly. They were replaced by mammals, birds, and insects. Similarly the characterstic Mesozoic plants, such as ferns, cycades and conifers were replaced by angiosperms (Flowering plants).
4. Among marine invertebrates the ammonites and belemnites died out and they were replaced by gastropods and pelecypods. During the Eocene epoch the nummulites flourished in abundance.

Distribution of Tertiary Rocks. In India, the Tertiary rocks are found mainly in the Extra Peninsular region. Although they occur all along the length of Himalayan and Arakan mountain ranges, they are well developed in Sind-Baluchistan, Jammu-Kashmir, Simla-Garhwal, and Assam regions. In Peninsular India, the Tertiary rocks occur in small patches in western Rajasthan, and along the coastal tracts in Gujrat (Cutch), Orissa, Kerala, and Tamil Nadu. The great thickness of the sediments which fill the Indo-Gangetic Plain are of Quaternary age. The Tertiary rockformations which occur in India are shown in Table 8.30.

Table 8.30. Tertiary Rock Formations of India

Period	*Epoch*	*Rock formations of India*
Quaternary	Recent	Recent
	Pleistocene	Pleistocene
Tertiary	Pilocene	Siwalik Group
	Miocene	Muree rocks etc.
	Oligocene	Absent in some areas
	Eocene	Eocene

8.35. EOCENE ROCKS

The end of the Cretaceous period was marked by a wide spread marine regression. This marine regression accounts for the following.

1. The speciallized group of animals, such as ammonites and the coralloid lamellibranchs (Rudistae) were destroyed.
2. The stratigraphic gap with erosion unconformity which separates the Cretaceous from Tertiary formations was formed.

Distribution of Eocene Rocks. The rocks representing the uppermost part of the Eocene are absent in many areas because that period coincided with the second Himalayan upheaval. The rest of the Eocene succession occurs in the mountainous belt of Sind-Baluchistan, Kashmir, Simla Hills, along the Himalayan foot hills to the Brahmputra gorge and Assam - Arakan region.

8.35.1. Eocene of Sind and Baluchistan

In the Sind-Baluchistan area, the Eocene and Oligocene rocks are largely of marine origin. The geological succession of the Eocene rocks of this area is shown in Table 8.31.

Table 8.31. Eocene of Sind-Bluchistan

Formation	*Lithology*	*Age*
Kirthar (upto 3000 m)	Nummulitic limestone and shale	Upper to Middle Eocene
	Unconformity	
Laki (upto 1000 m)	Shale and limestone with coal seams	Middle Eocene
	Unconformity	
Ranikot (650 m)	Limestone, shale, sandstone with coal seams	Lower Eocene
Cardita beaumonti beds		Danian

Ranikot Formation. This formation rests unconformably over the Deccan traps or Cardita beaumonti beds of Danian (Upper Cretaceous) age. It is composed of about 650 meters thick succession of limestones, shales and sandstones with some coal seams and lignite beds. The limestones have yielded abundant fossils of foraminifers (Nummulites planulatus), corals (Stylina), echinoids (Hemiaster, Cyphosoma) and gastropods.

Laki Formation. This formation is about 1000 meters thick. It rests unconformably over the Ranikot formation. It is mainly made up of shales and limestones. The Laki formation has been subdivided into three parts. The lower part is called "*Meting shales*". It is composed of limestones and shales. The middle part is called the "*Dunghan limestones*". The upper part which contains clays and sandstones with some bands of limestones, coal and gypseous clay, is called the "*Ghazij beds*". The Laki formation has yielded fossils of foraminifers (Nummulites atacicus) and echinoids (Echinolampas) and some gastropods of Lower to Middle Eocene age. The Laki formation is of economic importance as it contains oil bearing horizons.

Kirthar Formation. This formation is of Upper to Middle Eocene age. It is composed of about 3000 meters thick succession of shales, limestones and some sandstones. The characterstic fossils of the Kirthar formation are "*Nummulites complanatus*" and "*Nummulites laevigatus*".

8.35.2. Eocene of Simla Hills

In the Himalayan foot-hills, from Simla to Naini Tal, the Eocene rocks are called the "*Subathu formation*". These rock beds occur in a NW-SE trending belt. This belt is bounded in the north by the Krol thrust and in the south by the Main boundary fault. The Subathu formation is composed mainly of shales with some gypsum and coal. The limestones occur in subordinate amounts. The characterstic fossils of these beds are "*Nummulites atacicus*". The Subathu beds are probably equivalent to the Laki beds in age.

8.35.3. Eocene of Kashmir

In Kashmir, the Eocene rocks occur as a narrow belt along the south of Pir Panjal, bounded on both sides by thrusts. The succession of these rocks has been divided into two parts: (*i*) Ranikot formation, and (*ii*) Chharat formation.

Ranikot Formation. The lower part of the Eocene succession is called the "*Ranikot formation*". It is composed mainly of cherty nummulitic limestones with some beds of anthracite coal.

Chharat Formation. This formation rests over the Ranikot formation. It is composed of nummulitic limestones, shales and marls. This formation has yielded fossils of Middle to Upper Eocene age.

8.35.4. Eocene of Assam

A vast thickness of Tertiary and Quaternary rocks occur in the mountainous belt of Assam and the Shilong plateau. These rocks are relatively poor in fossils and therefore it is difficult to correlate them with the Tertiary rocks of Sind.

In the Assam region, the Eocene rocks occur in two contrasted facies : (*i*) calcarious facies, and (*ii*) argillaceous and arenaceous facies. The calcarious facies occurs along the south and east side of the Shilong plateau, and the argillaceous and arenaceous facies in the Naga hills and extending towards southwest into Manipur district. The former rocks are called the "*Jantia group*" and the later the "*Disang group*". These two groups are of the same age and they are separated from one another by the Haflong thrust fault.

Jantia Group. The rocks of this group rest over the Langpar formation of Danian age. The Jantia group has been subdivided into three formations : (*i*) Therria formation, (*ii*) Sylhet limestone, and (*iii*) Kopali formation

(*i*) **Therria Formation.** The lower part of the Jantia group is called the Therria formation. It is composed of about 100 meters thick succession of sandstones containing thin coal seams. This formation is mainly unfossiliferous. Its age is between Upper Cretaceous and Lower Eocene.

(*ii*) **Sylhet Limestones.** This formation rests over the Therria rocks. It is composed mainly of foraminiferal limestones with some sandstones. The total thickness of this formation is about 600 meters. In fact in the Sylhet limestone formation, there are four horizons of limestones separated by beds of sandstones. These four horizons have been correlated with the Lower Ranikot, Upper Ranikot, Laki, and Kirthar formations of the western India. The limestones have yielded rich fossils of foraminifera (Nummulites thalicus, Assilina papillata, Discocyclina, etc.)

(*iii*) **Kopali Formation.** The Sylhet limestones are conformably overlain by the Kopali formation. It is composed of 380 to 800 meters thick succession of sandstones and shales. These beds contain fossils of foraminifera of Upper Eocene age.

Disang Group. The Upper Cretaceous-Eocene rocks of the Arakan mountains are called the "*Disang group*". This group is composed of about 3000 meters thick beds of argillaceous and arenaceous rocks. The chief rock types are splintary unfossiliferous shales with some sandstones. The upper part of the succession has yielded fossils of foraminifers indicating Upper Eocene age.

Both the Jantia and Disang groups are overlain conformably by the Barail group and therefore they are probably of the same age.

8.35.5. Economic Minerals

Amongst the most important resources of the Eocene rockformations are coal, limestone and clays. In some cases they are also the source rocks of petrolium, though the petrolium may have migrated to other younger formations having suitable structure to act as reservoir rocks.

Coal. The Ranikot and Laki formations of western India and the Sylhet limestones of Assam contain several coal seams. The Dandot seam of Salt Range (Pakistan), Palana lignite of Bikaner district, Rajasthan, and coal seams of the coal fields of Khasi, Garo and Jantia hills of Assam are of Eocene age. The total reserves of the Eocene coal are about 300 million tonnes.

Limestone. The nummulitic limestones are found abundantly in the Eocene rocks. These limestones are used in the manufacture of cement.

Petrolium. The Lower Tertiary rocks of India, Pakistan and Burma are the chief source rocks of petrolium. But these rocks have been severely folded and faulted during the Himalayan orogeny. Hence they do not contain workable petrolium deposits.

8.36. OLIGOCENE - UPPER TERTIARY ROCKS

8.36.1. Sind—Baluchistan

The Oligocene rocks are very poorly developed in northwest India. They occur only in Sind and Baluchistan. The succession of the Oligocene-Pliocene rocks of these areas are shown in Table 8.32.

Table 8.32. Oligocene-Pliocene Rocks of Sind and Baluchistan

Formation	*Lithology*	*Age*
Manchar (3050 m)	Upper : Grey sandstone, conglomerate Lower : Conglomerate	Pliocene Upper Miocene
Gaj (450 m)	Yellow limestone, shales	Lower Miocene
Nari (1800 m)	Upper : Fluviatile sandstones Lower : Marine limestones	Upper Oligocene Lower Oligocene

Nari Formation. This formation is of Oligocene age. It rests unconformably over the Kirthar formation of Middle Eocene age. This break in sedimentation is correlated with the second phase of the Himalayan orogeny. The total thickness of the Nari formation is about 1800 meters.

The Nari formation has been divided into two parts. The "*Lower Nari beds*" are composed of about 600 meters thick succession of fossiliferous limestones of marine origin. These beds have yielded fossils of foraminifera (Lepidocyclina dilata, Nummulites), echinoids (Clypeaster), gastropods and lamellibranchs of Lower Oligocene age. These beds are overlain unconformably by the "*Upper Nari beds*" of fluviatile origin. These beds are composed of about 1200 meters thick succession of unfossiliferous sandstones and shales. They are of Upper Oligocene age.

Gaj Formation. This formation is of Lower Miocene age. It has been subdivided into two parts. The lower part is composed mainly of coral limestones and shales of marine origin. The upper part on the other hand, is made up of red clays and shales with gypsum of esturine origin. The beds of the Gaj formation have yielded fossils of foraminifers and pelecypods with some echinoids and gastropods.

Manchar Formation. The age of this formation is from Upper Miocene to Pliocene. It is made up of about 3050 meters thick sediments of fresh water origin. The chief rock types of the Manchar formation are conglomerates, sandstones and clays. This formation has been correlated with the Lower and Middle Siwalik rocks of the northwestern Himalayas.

8.36.2. Potwar and Kashmir

Murree Group. The age of this group ranges from Middle Eocene to Oligocene. The rocks of this group are well developed in the Potwar region of Pakistan and near Batot in Kashmir. The Murree group is composed of about 2000 meters thick sediments of brakish water and fresh water origin. The chief rock types are conglomerate, red clays and green sandstones. This succession rests unconformably over the Subathu formation of Middle Eocene age. The Murree rocks contain remains of plants, bivalves and mammals. The basal beds of this group have yielded fossils of mammals (Anthracotherium, etc.) of Lower Miocene age.

8.36.3. Simla and Garhwal

The Oligocene-Miocene rocks of the Simla-Garhwal area are called the "*Dagshai*" and "*Kasauli*" formations. These two formations are conformable and exhibit a transition from brakish water deposit (Dagshai formation) below to fresh water deposit above.

Dagshai Formation. This formation is named after the Dagshai town of Simla hills. It is composed of 600 meters thick beds of bright red clays and fine grained sandstones. These beds are nearly unfossiliferous. The age of the Dagshai formation is from Upper Eocene to Oligocene.

Kasauli Formation. This formation rests conformably over the Dagshai formation. It consists of about 2100 meters thick beds of hard brown sandstones and clays with a few plant remains. The age of this formation is from Upper Oligocene to Middle Miocene.

8.36.4. Assam

In the Assam region, the Tertiary rocks are well developed in the northeast and southeast parts of Assam. They exhibit a complete sequence ranging in age from Eocene to Lower Pleistocene. The geological succession of the Oligocene-Lower Pleistocene rocks is shown in Table 8.33

Barail Group. This group is of Oligocene age. It rests conformably over the rocks of Jantia group. The Brail group is composed of about 1200 meters thick succession of sandstones, carbonaceous shales and thin coal seams. These rock beds are mostly unfossiliferous.

Surma Group. This group rests unconformably over the rocks of Barail group. The Surma group is well developed in the Surma valley where its thickness is 3000 to 6500 meters. In Upper Assam, the thickness of these rocks reduces to 650 meters. The Surma group has been subdivided into two formations: (*i*) Bhuban formation, and (*ii*) Boka Bit formation.

Table 8.33. Oligocene-Pleistocene Succession of Assam

Group	*Lithology*	*Age*
Dihing Group (400—800 m)	Boulder beds, sandstones, clays	Pliocene-Lower Pleistocene
	Unconformity	
Dupitila Group (1500—3800 m)	Clays, sandstones, conglomerates	Miocene-Pliocene
	Unconformity	
Tipam Group (1500—4100 m)	Clays, sandstones	Lower Miocene
Surma Group (600—5500 m)	Sandstones, shales	Upper Oligocene
	Unconformity	
Barail Group (1200 m)	Sandstones, shales	Oligocene

(*i*) **Bhuban Formation.** The age of this formation ranges from Upper Oligocene to Lower Miocene. It is composed of 1300 to 2500 meters thick beds of sandstones, sandy shales and conglomerates. These beds have yielded a few fossils of mollusca. The Bhuban formation contains some oil bearing horizons.

(*ii*) **Boka Bit Formation.** This formation rests over the Bhuban rocks. Its thickness varies from 1000 to 1500 meters. The chief rock types are sandstones, sandy shales and silts. The Boka Bit formation has yielded a number of fossils of pelecypods and gastropods of Lower Miocene age.

Tipam Group. This group rests conformably over the Surma group. The Tipam group is composed of 3000 to 4000 meters thick succession of sandstones with subordinate shales and clays. The Tipam group has been subdivided into two formations: (*i*) Tipam sandstones, and (*ii*) Girujan clays.

(*i*) **Tipam Sandstones.** The lower part of the Tipam group is called the "*Tipam sandstones*". This formation is composed of 1000 to 2500 meters thick beds of ferriginous sandstones with some bands of shale and lignite. The Tipam sandstones contain a few oil bearing horizons. This formation has yielded some fossil wood of Lower Miocene age.

(*ii*) **Girujan Clays**. This formation rests over the Tipam sandstones. It is composed mainly of mottled clays intercalated with some beds of sandstones and lignite. The total thickness of this formation is 1000 to 2000 meters. It has yielded some plant fossils of Lower Miocene age.

Dupitila Group. This group rests conformably over the Girujan clays and is of Mio-Pliocene age. It is composed of about 3000 meters thick beds of sandstones and clays. These beds are unfossiliferous. The Dupitila group is exposed in central and lower Assam. In the upper Assam, the Tipam group is overlain unconformably by "*Namsang beds*". These beds are about 800 meters thick and are composed of sandstone, grit and conglomerates. These beds are also said to be of Mio-Pliocene age.

Dihing Group. The age of this group is Pliocene to Lower Pleistocene. The Dihing group rests unconformably over the Namsang beds. It is composed of about 800 meters thick succession of boulder and pebble beds with intercalated lenses of soft sands and clays. These beds have yielded some plant fossils. The Dihing group has been affected by the last phase of the Himalayan upheaval. These rocks often show steep dips. The Tipam and Dihing groups together constitute a succession which is equivalent to the Siwalik group of NW Himalayas.

8.37. SIWALIK ROCKS

The Upper Tertiary rocks which are exposed in the Himalayan foot hill zone, extending from Hardwar in U.P. to Assam, are described as the "*Siwalik group*". These rocks are named after the Siwalik hills near Hardwar. The Siwalik rocks range in age from Middle Miocene to Lower Pleistocene.

Lithology. The Siwalik group is composed of 5000 to 6000 meters thick succession of sedimentary rocks of fluviatile and lacustrine nature. The chief rock types are loosely consolidated and poorly bedded conglomerates, grits, sandstones, silts and clays. These rocks are neither graded nor sorted. In general, the coarseness of rocks increases from the lower to the upper part of the succession. The sediments of the Siwalik rocks were derived from the rising Himalayan mountains in the north and they were deposited in the alluvial plains of a river system called the "*Indo-Brahm river*" (Pascoe 1919).

Fossils. The Siwalik rocks have yielded rich assemblage of the mammalian fauna which have not only helped in classifying the Siwalik succession but also in tracing the evolution of mammals. In addition, the Siwalik group also contains remains of molluscs, Ostrocods, and plants.

Structure. As the Siwalik rocks are involved in the Himalayan orogeny, they are folded, faulted and even overturned and thrusted.

Classification. The factors which have made the classification and correlation of the Siwalik rocks difficult, are as follows.

1. The Siwalik rocks often show a rapid lateral variation.
2. Although the Siwalik rocks have yielded abundant vertebrate fauna, they are found only in certain areas and in certain horizons. Hence it is difficult to demarcate sharp boundaries between palaeontological zones.

However, on the basis of vertebrate fauna, the Siwalik group has been classified into three divisions: (*i*) Lower Siwalik, (*ii*) Middle Siwalik, and (*iii*) Upper Siwalik. The age of these divisions are Middle Miocene, Upper Miocene—Lower Pliocene, and Upper Pliocene—Lower Pleistocene respectively. Each of these three divisions is further subdivided into smaller parts as shown in Table 8.34.

Table 8.34. Classification of Siwalik Succession

Division	*Formation*	*Vertebrate Fossils*
Upper Siwalik (2000–2500 m)	Boulder conglomerate	Equus, Buffelus palaeindicus, Elephas nomadicus
	Pinjor formation	Elephas planiferous, Hemibos, Stegodon
	Tatrot formation	Hypohyus, Leptobos
Middle Siwalik (2000 m)	Dhokpathan formation	Stegodon, Mastodon, Giraffoid, Sus, Mercycopotamus
	Nagri formation	Mastodon, Hipparian, Prostegodon
Lower Siwalik (1000–3000 m)	Chinji formation	Listriodon, Amphicyon, Giraffokeryx, Tetrabelodon
	Kamlial formation	Aceratherium, Telemastodon, Anthropoids, Hyobops, Tetrabelodon.

The three main divisions of the Siwalik group are also marked by the presence of a definite set of heavy minerals. In the lower division, the dominant heavy mineral is staurolite, in the middle division kyanite predominates, while in the upper division hornblende is the characterstic heavy mineral.

In the Siwalik succession there is a general increase in the coarseness of the sediment from below upwards. The "*Lower Siwaliks*" contain brown sandstones with thick beds of red and pruple clays. The characterstic rocks of the "*Middle Siwalik*" are the massive course sandstones, whereas the chief rocks of the "*Upper Siwaliks*" are coarse conglomerates and massive beds of grits and sandstones.

8.37.1. Lower Siwalik

Kamlial Formation. This formation rests over the Murree group of Lower Miocene age. It is composed of red sandstones with nodules of clay (pseudo-conglomerate) and purple shales. The total thickness of the succession is 600 to 1000 meters.

Chinji Formation. This formation is composed of 400 to 1800 meters thick beds of red nodular shales and clays with some sandstones and conglomerate. These beds have yielded a rich assemblage of mammalian fossils.

8.37.2. Middle Siwalik

Nagri Formation. It is composed mainly of massive grey sandstones with some shales. This formation is rather poor in fossils.

Dhokpathan Formation. It is the most important fossil bearing formation of the Siwalik group. This formation is made up of brown sandstones, gravel beds,. shales and clays.

8.37.3. Upper Siwalik

Tatrot Formation. This formation rests unconformably over the Dhokpathan rocks. It is composed of soft massive sandstones, silts, clays and conglomerates.

Pinjor Formation. This formation is composed of conglomerates, coarse grits and sandstones with some clays.

Boulder Conglomerate. This formation is made up mainly of boulder conglomerate containing boulders, pebbles and cobbles of granites, quartzites, slates and limestones.

8.38. KAREWAS

This rockformation which is of lacustrine and fluviatile origin, occurs in the Kashmir valley. It is of Pleistocene age. The total thickness of the Karewas is about 2000 meters. They are composed of gravels, silts, marls, lignite and glacial moraines and varved clays. The lignite beds are more frequent in the lower part of the succession whereas the glacial tills and varved clays are more common in the upper part. The lignite beds often attain a thickness of up to three meters. The Karewa beds contain remains of ostrocods, molluscs, vertebrates and plant fossils. The ostrocod fauna indicates a pleistocene age for this formation.

8.39. RISE OF HIMALAYA

The Himalayan Mountains were formed as a result of the five main uplifting phases which took place during the Tertiary period. These uplifting phases are as follows.

First Phase. The first phase of the Himalayan orogeny started during the Upper Cretaceous-Lower Eocene period. In this phase the sediments of the Tethys sea was folded into longitudinal ridges and basins.

Second Phase. During the Upper Eocene times, the Tethyan Himalayan zone was uplifted to form a land mass. The emplacement of granites took place in the metamorphic rocks of the Higher Himalayan zone. The Lesser Himalayan basins became shallower.

Third Phase. The third upheaval took place during the Middle Eocene period. This orogeny which was very strong, affected mainly the rocks of the Lesser Himalayan zone. During this orogeny, the rocks were folded and nappe structures were developed. The thrust sheets from the northern parts moved southward along low angle thrust faults. The intrusion of granites occurred in the root zone. This was followed by the folding of the thrust sheets, probably in the Upper Miocene times.

The Middle Miocene upheaval also resulted in the formation of a "*Foredeep*" between the Himalayas and the northern edge of the Peninsula. This Foredeep was filled with the sediments brought by rivers from the Himalayan mountains.

Fourth Phase. The fourth phase of the Himalayan orogeny occurred during the Pliocene-Pleistocene period. The Himalayan foot hills rose higher and the broad folds developed in the rocks of the foredeep. A series of longitudinal thrust faults, called the "*Main Bounday Faults*" were also formed. These faults separate the Lesser Himalayan zone from the Outer Himalayan zone.

Fifth Phase. This phase of the Himalayan upheaval was started after the Upper Pleistocene times and is still continueing today. It includes mainly the isostatic adjustments which are being taking place due to the vanishing of the Pleistocene ice sheets.

8.39.1. Plate Tectonic Theory

According to the "*Plate tectonic theory*" the Himalayan mountains were formed due to the collision of the Asian plate and the northward drifting Indian plate. The northward movement of the Indian plate started with the breaking of the Gondwana Land and formation of the Indian ocean during the Jurassic period. The study of the palaeomagnetic data, obtained from the Indian ocean suggests that the northward drift of the Indian plate was most rapid during the Paleocene epoch. This period coincided with the period of extrusion of the Deccan trap lavas.

The movement of the Indian plate was temporarily retarded when it collided with the Asian plate during the Lower Eocene. In the Lower Oligocene times, the Indian plate again started moving but its direction of movement was changed slightly. The syntexial bend which occurs at the northwestern end of the Himalayan mountains was formed due to the rotational movement of this plate.

REVIEW QUESTIONS

1. Describe the criteria used in correlating the ancient schistose rocks with special reference to India.
2. Write an essay on Deccan traps. Discuss their mode of eruption, stratigraphy and age.
3. Give an account of the geology of any one of the following areas.
   (*i*) Cutch, (*ii*) Spiti, and (*iii*) Trichinopoly.
4. Give a classification of the Dharwar rocks of South India. Discuss the views that have been held as to their origin. Give the economic importance of the Dharwar rocks.
5. Classify and describe the rocks of the Vindhyan system.Give the economic importance of the Vindhyan rocks.
6. In what formation does coal occur in India ? Give a brief account of the Gondwana rocks of India. What is their economic importance.
7. Classify and describe the Sausor Rockfonnations of central India with special reference to their economic resources.
8. What are fossils ? Describe the different modes of their preservation in rocks and add a note on the importance of fossils in the study of geology.
9. Give the physiographic classification of India and describe in brief their geological characters.
10. Give a brief account of he Archaean rocks of Singhbhum, Bihar. Discuss their economic importance.
11. Describe briefly any four of the following group of rocks with perticular reference to their distribuion, age and petrological and palaeontological features :
    (*i*) Spiti shales, (*ii*) Lameta beds, (*iii*) Bagh beds (*iv*) Semri group, (*v*) Karewas, (*vi*) Saline series (*vii*) Marine rocks of Gondwanas
12. Give distribution and classification of the Eocene rocks of India. What is their economic importance ?
13. Write a brief essay on the pre-Vindhyan geology of Rajasthan.
14. Give a general account of the structure of Himalayas. Discuss the age of formation of Himalayas.
15. Give a brief account of the Archaean rocks of India. Discuss their economic importance.

9 Ore Deposits

9.1. TERMINOLOGY

Ore Mineral. A mineral from which one or more metals can be extracted at a profit is known as "*ore mineral.*" Examples of ore minerals are hematite,bauxite,galena, etc. The ores may be high grade or low grade depending on the percentage of the metal present in it.

Gangue Mineral. The useless minerals which occur in association with the ore, are called "*gangue minerals*". They are commonly discarded in the treatment of the ore. The common gangue minerals are quartz, calcite, barytes, fluorspar, felspar, and tourmaline.

Ore Deposit. The mixture of ore minerals and gangue forms an "*ore deposit*". The ore deposits are generally found enclosed within the country rocks.

Tenor. The term "*tenor*" describes the metal content of an ore. In order to declare the ore economically workable, a deposit must contains a certain percentage of metal in it and the lowest admissible limit of metallic content of an ore is called its "*tenor*". The tenor of an ore depends on the price of the metal obtained from it. For costly metals the tenor is very low, such as for gold it is 0.01% whereas in case of cheap metals like iron, the tenor is much higher; that is 50% or more.

Syngenetic Ore Deposit. The ore deposits that are formed at the same time as the enclosing rock, are called "*syngenetic ore deposits*". Sedimentary ore deposits are the examples of syngenetic deposits.

Epigenetic Ore Deposits. The ore deposits that are formed later than the enclosing rock, are called "*epigenetic ore deposits*". Hydrothermal ore deposits are the examples of epigenetic deposits.

9.2. CLASSIFICATION OF ORE DEPOSITS

The ore deposits are formed in many different ways. Depending upon the process that may operate to produce them, the ore deposits may be classified as follows.

1. Magmatic ore deposits.
2. Sublimation ore deposits.
3. Pegmatitic ore deposits.
4. Contact metasomatic ore deposits.
5. Hydrothermal ore deposits.
   (*i*) Cavity filling deposits.
   (*ii*) Replacement deposits.
6. Sedimentation ore deposits.
7. Evaporation ore deposits.
8. Residual and mechanical concentration deposits.
9. Oxidation and supergene enrichment deposits.
10. Metamorphic ore deposits.

9.3. MAGMATIC ORE DEPOSITS

The magmatic ore deposits are the magmatic products which crystallize from magmas. They have close relationship with the intrusive igneous rocks. The magmatic ore deposits can be classified as follows.

1. Early magmatic deposits
   (*i*) Dissemination deposits.
   (*ii*) Segregation deposits.
2. Late magmatic deposits.
   (*i*) Residual liquid segregation.
   (*ii*) Residual liquid injection.
   (*iii*) Immiscible liquid segregation.
   (*iv*) Immiscible liquid injection.

9.3.1. Early Magmatic Deposits

Early magmatic deposits are formed during the early stages of the magmatic period. In this case the ore minerals crystallize earlier than the rock silicates. The minerals of nickel,chromium and platinum are usually found as early magmatic deposits. The early magmatic deposits can be subdivided into two groups : (*i*) dissemination deposits, and (*ii*) segregation deposits.

Dissemination Deposits. When a magma crystallizes under deep seated conditions, a granular igneous rock is formed. In such a rock early formed crystals of ore minerals may occur in dissemination. Here grains of ore are found scattered more or less evenly throughout the rock mass (Fig. 9.1). Hence the whole rockmass constitutes the ore deposit. The dissemination deposits occur in the shape of a dyke, pipe or small stock-like mass. An example of dissemination deposit is the diamond pipe of panna, madhya pradesh. Here diamonds occur sparcely scattered in the kimberlite mass.

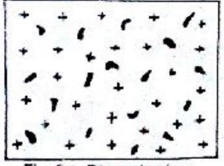


Fig. 9.1. Dissemination deposits.

Segregation Deposits. Early magmatic segregation deposits are formed as a result of gravitative crystallization differentiation. In such cases, the ore minerals which crystallize early, get concen-trated in a perticular part of the igneous mass. The ore deposits thus formed are called "*segregation deposits*" (Fig.9.2). The segregation deposits are generally lenticular in shape and of relatively small size. The segregation of chromite in ultrabasic rocks is an example of this type of ore deposit.

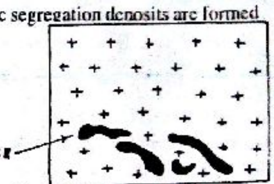


Fig. 9.2. Segregation deposits.

9.3.2 Late Magmatic Deposits

The ore deposits which are formed towards the close of the Magmatic period are called " *late magmatic deposits* ". The late magmatic deposits contain those ore minerals which have crystallized at rather low temperature from a residual magma. The magma which is left after crystallization of the early formed rock silicates, is called "*residual magma*". This magma fre-quently contains many ore minerals. The late magmatic deposits include most of the magmatic deposits of iron and titanium ores. These deposits are almost always associated with mafic igneous rocks.

The late magmatic deposits have been classified into four groups :(*i*) residual liquid segregation (*ii*) residual liquid injection, (*iii*) immiscible liquid segregation and (*iv*) immiscible liquid injection.

Residual Liquid Segregation. In a magma, perticularly the basic magma which is undergoing differentiation, the residual liquid may become enriched in iron and titanium. This heavy residual liquid may segregate and crystallize within the parent igneous mass. Such ore bodies commonly occur in the form of parallel bands and may form valuable ore deposits. An example of this class is the magmatic magnetite deposit which commonly occurs as concordant layer within mafic igneous rocks.

Residual Liquid Injection. The iron rich residual liquid accumulated as a result of differentiation of mafic magma, may get injected into the surrounding country rocks (Fig.9.3). The ore deposits of magnetite and ilmenite formed in this way, are called " *injection ore deposits*". Such deposits usually occur in the form of veins, dykes or sills.

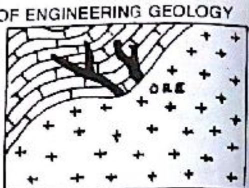


Fig. 9.3. Injection deposit.

Immiscible Liquid Segregation. When a mafic magma cools, the sulfide rich immiscible liquid separates out and accumulates at the bottom of the igneous body. This separation is similar to that of oil and water. The immiscible liquid consists mainly of sulfides of iron,nickel and copper. Upon consolidation it gives rise to the "*sulfide segregation deposit* ". These deposits occur commonly at the bottom of the differentiated mafic intrusives as disconnected bodies.

Immiscible Liquid Injection. The sulfide rich immiscible liquid which separates out during the differentiation of mafic magma, may get injected into the enclosing rock. On consolidation it forms the "*immiscible liquid injection deposit*". Such deposits are usually irregular or dyke-like in form.

9.4. SUBLIMATION DEPOSITS

Sublimation is a very minor process of formation of ore deposits. Sublimation deposits contain only those minerals which have been volatilized by heat and subsequently redeposited in the same form at low temperature and pressure. This process involves direct transition from solid to gaseous state and vice versa. The sublimation deposits are found associated with volcanoes and fumaroles. Sulfur of this origin has been mined in Japan, Italy and Mexico. mexico

9.5. PEGMATITIC DEPOSITS

The late residual magma which is left in the last stage of crystallization, commonly contains silica, alkalies, water, carbon dioxide and concentrations of rare elements and metals. Pegmatites are formed when this residual magma gets injected into the enclosing rocks. Many such pegmatites form valuable mineral deposits. The economic minerals which commonly occur in pegmatites are mica, corundum, gemstones and felspars. Deposits of tantalum, niobium, tin,tungsten, molybdenum and uranium are also found in some pegmatites. Pegmatites of economic importance are mostly found associated with felsic igneous rocks such as quartz dioritic rocks.

9.6. CONTACT METASOMATIC DEPOSITS

Where certain igneous rocks invade carbonate rocks, such as limestones, ore deposits are formed near the contact by the reaction of the magmatic vapours on the host rocks (Fig.9.4). These reactions take place

under conditions of high temperature and pressure. The new minerals that develop may be composed of partly or wholly of the constituents added from the magma.

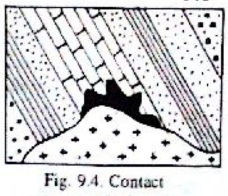


Fig. 9.4. Contact metasomatic deposit.

All magmas do not give rise to contact metasomatic deposits. Mostly felsic intrusives of intermediate composition, such as monzonites and granodiorites yield ore deposits. The reason is that the emanations from such intrusives usually carry constituents of ores which replaces the invaded rocks to form ore deposits.

Contact metasomatic deposits usually carry ores of copper, iron, zinc and more rarely gold, silver and lead. The characteristic gangue minerals which are found associated with these ore deposits are high temperature silicates, such as garnet, diopside, tremolite, wollastonite, and phlogopite. The contact metasomatic deposits are generally discontinuous and irregular in shape. They are in general of comparatively small size.

9.7. HYDROTHERMAL DEPOSITS

The epigenetic ore deposits formed by hydrothermal solutions are called "*hydrothermal ore deposits*". The ore deposits which are commonly formed by the hydrothermal process are of gold, silver, copper, lead, zinc and mercury.

Hydrothermal Solution. The fluid left during the later stage of crystallization of intrusive magma when the main rockforming minerals have already been precipitated, is called "*residual fluid*". Metals originally present in the magma, concentrate in this fluid. This fluid which is a hot watery solution containing mineralized liquids derived from an intrusive magma, is called "*hydrothermal solution*".

The hydrothermal solution move through cracks and openings present in the rocks and deposit their dissolved minerals there. Minerals which have lowest temperatures of crystallization, such as stibnite and cinnabar may migrate very far away while those having higher temperatures of crystallization, such as chalcopyrite, may precipitate close to the parent igneous body.

9.7.1 Classification

On the basic of temperature of deposition, Lindgren has classified the hydrothermal deposits into three groups : (*i*) hypothermal deposits, (*ii*) mesothermal deposits, and (*iii*) epithermal deposits.

Hypothermal Deposits. These are the high temperature deposits which are formed close to the intrusive body. Here the temperature ranges between 300° – 500°C.The chief ore minerals which are commonly found in hypothermal deposits are arsenopyrite, wolframite, native gold and chalcopyrite.

Mesothermal Deposits. These are the intermediate temperature deposits which are formed at some distance outward from the intrusive igneous mass. Here the temperature ranges between 200° – 300°C.The chief ore minerals of methothermal deposits are native gold, bornite, sphalerite, galena and argentite.

Epithermal Deposits. These are the low temperature deposits formed very much away from the intrusive body. Their temperature of formation ranges between 50° – 200°C. The ore minerals which commonly occur in epithermal deposits are ruby silver, stibnite, and cinnabar.

On the basis of mode of formation, the hydrothermal deposits have been classified into two groups : (*i*) cavity filling deposits, and (*ii*) replacement deposits.

Cavity Filling Deposits. These deposits are formed when hydrothermal solutions deposit their dissolved minerals in the various types of openings present in the rocks. In this deposition no replacement is involved. Such a deposition takes place by change of temperature and pressure of the hydrothermal solution. Most of the epithermal deposits are cavity filling type.

Replacement Deposits. These deposits are formed due to chemical interaction between the hydrothermal solution and the country rocks. The ore minerals are deposited from a mineral bearing solution in place of the country rocks, the later being dissolved and removed in solution.

The filling of the rock openings by precipitation and the replacement of their walls, may occur simultaneously. Thus there may be a gradation between these two types of deposits. Replacement dominates under conditions of high temperature and pressure whereas cavity filling dominates under conditions of low temperature and pressure.

9.8. CAVITY FILLING DEPOSITS

Cavity filling deposits are formed when hydrothermal solutions deposit their dissolved minerals in the rock openings. Here precipitation of minerals is chiefly caused by change in the temperature, pressure and chemical character of the mineralizing solutions. The characterstic features of the cavity filling deposits are as follows.

Crustification. The mineral which precipitates first lines the walls of the cavity. Its crystals grow inward and point towards the centre. Generally successive layers of different minerals are deposited upon the first one. This process is repeated until the filling is complete. A filling of this type is called "*crustification*" (Fig.9.5). A vein crustification is said to be "*symmetrical*" when similar mineral crusts occur on both sides of the fissure, and when

unlike layers are present on each side, the crustification is called "*assymmetrical*".

Comb Structure. If in a mineral vein prominent crystals project inward from the walls, it is said to have a "*comb structure*" (Fig.9.5).

Vugs. When a vein is not filled completely with the mineral matter, open spaces are left in the centre. Such unfilled spaces are called "*vugs*" (Fig.9.5).

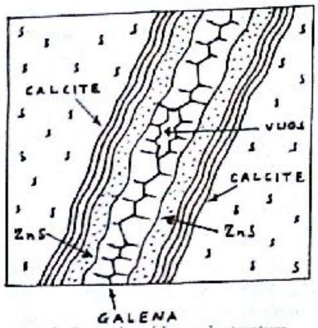


Fig. 9.5. Ore vein with comb structure.

9.8.1. Types of Cavity filling Deposits

Depending on the nature of openings,the cavity filling deposits occur in a variety of shape and size. The common types of cavity filling deposits are: (*i*) fissure veins, (*ii*) shear zone deposits, (*iii*) stockworks, (*iv*) saddle reefs, (*v*) ladder veins, and (*vi*) cave deposits and gash veins

Fissure Veins. A fissure filled with ore is called "*fissure vein*". It is a tabular ore body which occupies one or more fissures within a rock. Fissure vein deposits are the most important of all the cavity filling deposits. They are the chief source of most of the metals like gold, silver, copper, lead, zinc and mercury.

Most fissure veins are narrow and their lengths range from a few hundreds of meters to a few kilometers. They generally have a steep dip. Ore minerals are never equally distributed throughout the fissure vein. Places where large concentrations occur, are called "*ore shoots*". The common types of fissure veins are as follows.

(*i*) **Simple Fissure Veins.** A fissure vein which occupies a single fissure whose walls are nearly straight and parallel, is called "*simple fissure vein*".

(*ii*) **Chambered Veins.** Veins whose walls are irregular and brecciated, are called "*chambered veins*". Such veins branch and join again thereby enclosing "*horses*" of the country rock [Fig. 9.6(*a*)].

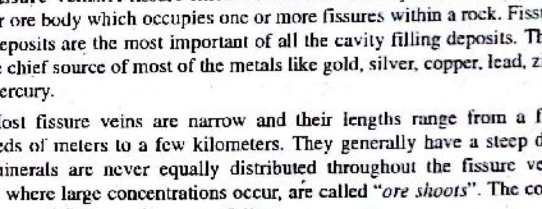


Fig. 9.6. (*a*) Chambered vein, (*b*) Lenticular vein, (*c*) Sheeted vein.

(*iii*) **Dilation or Lenticular Veins.** Generally in schists several disconnected lenses of ore occur together. Such lenses are called "*dilation veins*". Their width ranges from a few centimeters to tens of meters [Fig. 9.6(*b*)].

(*iv*) **Sheeted Veins.** A group of closely spaced parallel veins are called "*sheeted veins*". In this case all the veins together from a lode [Fig. 9.6(*c*)].

(*v*) **Composite veins.** A composite vein is a wide zone of nearly parallel fissures connected by diagonals. The width of such veins is measured in many tens of meters.

Shear Zone Deposits. The shear zones are the zones of thin and closely spaced parallel fractures. Here as the openings are minute, the open space deposition is minor. However, the large specific surface of the openings makes the shear zones very susceptible to replacement. Hence many large and valuable ore deposits are found in the shear zones.

Stockworks. A "*stockwork*" is a mass of rock traversed by a network of small ore bearing veins. Each vein is about one centimeter in width and a few meters in length. The spacing between the adjacent veins varies from a few centimeters to a a few meters. In stockworks the whole rock mass in mined. Stockworks are formed when the hydrothermal solutions percolate through vertical zones of intense shattering which occur in certain igneous intrusions (Fig.9.7).

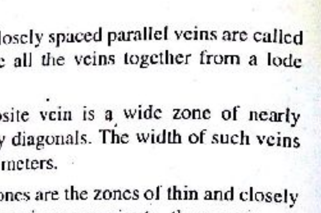


Fig. 9.7. Stockwork.

Saddle Reefs. During folding openings are formed between rock beds at the crests of anticlines. Mineralization along such openings leadsto the development of ore deposits. Because these ore deposits appear like a saddle, they are called "*saddle reefs*" (Fig.9.8).

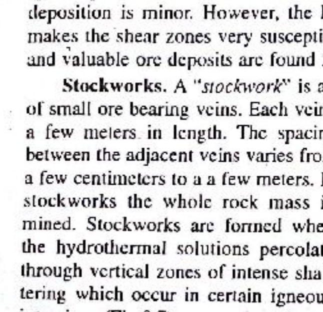


Fig. 9.8. Saddle reef.

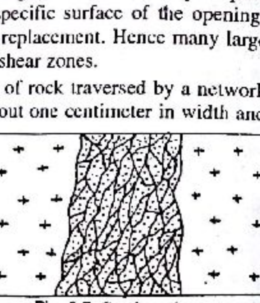


Fig. 9.9. Ladder vein.

Ladder Veins. Ladder veins are commonly found in dykes. They are the short, transverse, roughly parallel fractures that are filled with the ore. Because they appear like a ladder, they are called "*ladder veins*" (Fig. 9.9).

Cave Deposits and Gash Veins. Solution cavities in the from of caves, galleries and gash veins may contain deposits of lead,zinc,copper,mercury,etc. They occur only in soluble rocks like limestones. "*Gash veins*" are the veins which occur along joints and bedding planes in limestones (Fig.9.10).

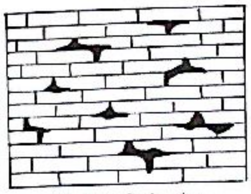


Fig. 9.10. Gash veins.

9.9. REPLACEMENT DEPOSITS

Replacement is one of the important process in the formation of epigenetic mineral deposits. The chief epigenetic mineral deposits are contact metasomatic deposits, supergene mineral deposits and hydrothermal replacement deposits. The replacement deposits commonly contain ores of iron, lead,zinc, copper, silver and many nonmetallic minerals. The process of replacement may be summarized as follows.

1. Replacement is the chemical process of simultaneous capillary solution and deposition. By this process new minerals are substituted for earlier minerals and rocks.
2. Replacement occurs through the action of hot vapours or hydrothermal solutions. The new minerals are carried in solution and the replaced substances are carried away in solution. It is an open circuit not a closed one.
3. The replacement takes place molecule by molecule. Consequently the shape, size, structure and texture of the rocks are faithfully preserved
4. Almost any rock may be replaced by ore, but the rapidly soluble carbonate rocks are the most susceptible. Certain structural features such as fissures may also localize replacement. Closely spaced sheeted fissures and shear zones, because of their large specific surface, give rise to large replacement lodes.

9.9.1. Types of Replacement Deposits

The ore deposits formed by replacement can be subdivided into three groups : (*i*) massive deposits, (*ii*) replacement lodes, and (*iii*) disseminated deposits.

Massive Deposits. Massive replacement ore deposits commonly occur in limestones. The ore terminates abruptly against the host rock. The massive deposits are characterized by great variations in size and extremely irregular form.

Replacement Lode Deposits. The lode deposits are formed when the replacement is localized along thin beds or fissures. In this case the fissure walls are replaced by the ore. The lode deposits resemble fissure veins in form, however they are wider than fissure veins and their walls are wavy and irregular (Fig. 9.11).

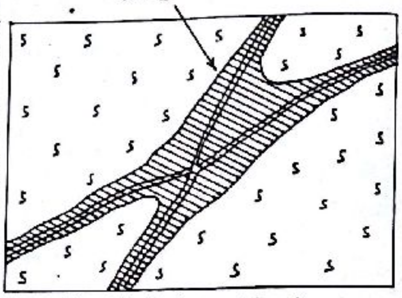


Fig. 9.11. Replacement deposit localized by fissures.

Disseminated Replacement Deposits. These are low grade ore deposits where grains of ore minerals are found scattered throughout the host rock. The size of disseminated ore deposits is generally large.

9.9.2. Features of Replacement

The replacement deposits can be identified by the following features.

1. Preservation of original rock structures, such as stratification, cross- bedding, fossils, etc.

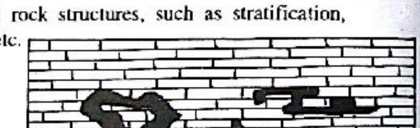


Fig. 9.12. Replacement deposit containing nuclei of hostrock.

2. Presence of unsupported nuclei of the host rock surrounded by the ore (Fig.9.12.). The unsupported nuclei are the small islands of host rock which are found enclosed within the replacement deposits.
3. Presence of mineral psendomorphs, ie. false crystal shapes.
4. Absence of crustification.
5. Extremely irregular outline of the ore body.

9.10. SEDIMENTATION DEPOSITS

Sedimentation deposits are the syngenetic ore deposits which are formed at the same time as the enclosing rock. They occur as beds in the sedimentary rocks. Some of the important sedimentation deposits are iron-ore, manganese ore, copper ore, phosphates, limestone, coal, and clays. These deposits are formed by the process of sedimentation. This process may be summarized as follows.

1. During weathering, the materials are released from the source rock. In this process the valuable mineral constituents are taken into solution. The chief solvents are carbonated water, organic acids and sulfate solutions.

2. Most of the valuable substances are transported either in suspension or in solution by means of river water to the sea.
3. In the sea , the valuable material is deposited mechanically, chemically or biochemically. The chemical precipitation of materials in solution is controlled largely by the pH and Eh of the environment. The pH is responsible for the acidic or alkaline conditions and the Eh for the oxidation-reduction potential.

Example 9.1. Iron is commonly precipitated as carbonate (siderite), hydroxide (goethite),and oxide (hematite). The ferrous carbonate is precipitated at lower pH and Eh while ferric oxide is formed in the presence of air.

Example 9.2. In the formation of manganese ore, iron must be separated from it during deposition. This separation is done as follows.

(*i*) **Precipitation from Carbonate Solutions.** Because manganese carbonate is more stable in solution than iron carbonate, the manganese carbonate is carried further away and is thus separated.

(*ii*) **Precipitation in Oxidising Environment.** The separation of iron and manganese takes place because at any given pH, iron oxides precipitate at lower Eh than manganese oxides. Similarly at a fixed EH,iron oxides precipitate at a lower pH than manganese oxides.

9.10.1. Features of Sedimentation Deposits

The sedimentation mineral deposits show many of the characterstics of normal sedimentary rocks.

(*i*) They commonly show bedding planes, ripple marks and other sedimetary structures.

(*ii*) They normally occur as a bedded sedimentary rock interstratified between rocks of sedimentary origin.

(*iii*) They are often a deposit of great geographical extent.

9.11. EVAPORATION DEPOSITS

Many nonmetallic mineral deposits are formed as a result of evaporation of shallow and isolated bodies of saline water. The chief minerals which occur as evaporation deposits are common salt, gypsum, and other salts of K, Na, Ca, and Mg. The process of evaporation may briefly be summarized as follows.

(*i*) The main source of the evaporation deposits is sea water.

(*ii*) When a body of sea water is cutoff during oscillations of land and sea its water evaporate. This leads to the concentration of soluble salts.

(*iii*) When supersaturation of a salt is reached, that salt is precipitated and thus evaporation deposits are formed.

(*iv*) The evaporation deposits are mostly formed in warm arid climates where evaporation proceeds very rapidly.

9.12. RESIDUAL DEPOSITS

Residual ore deposits are formed as a result of weathering of rocks and enclosed mineral deposits. The economic minerals which commonly occur as residual deposits are iron, manganese, bauxite, clay, ochre, tin, kyanite, etc.

During weathering the rocks undergo chemical decay. In this process the undesirable constituents are removed in solution leaving behind a concentration of valuable minerals at the site of the original rock. The conditions necessary for the formation of residual mineral deposits are as follows.

(*i*) The rock undergoing weathering must contain some valuable minerals.

(*ii*) The valuable minerals must be resistant to chemical weathering.

(*iii*) The outcrop surface should have low relief so that gravity and running water can not remove insoluble products of weathering.

(*iv*) There should be adequate rain to carry away in solution the soluble products of weathering. Hence residual deposits commonly develop in tropical or subtropical climate.

9.13. MECHANICAL CONCENTRATION DEPOSITS

The natural separation of heavy minerals from light ones by means of moving water, air or gravity,is called "*mechanical concentration*". The mineral deposits formed by this process are called "*placers*". The minerals which commonly occur as placer deposits are diamond, gold, platinum, tinstone, magnetite,, chromite, ilmenite and monazite. The process of mechanical concentration may be summarized as follows.

(*i*) The ore minerals are released from the rock by weathering and disintegration.

(*ii*) The disintegrated materials are carried downslope by water, air, etc. Ultimately this material reaches the stream or sea shore.

(*iii*) In the moving water or air, the heavier placer minerals sink to the bottom while the lighter material is carried further. Thus the heavier minerals are separated from the lighter ones.

(*iv*) In this way the heavy minerals get concentrated in particular localities to form placer deposits.

The conditions necessary for the formation of a placer deposit are : (*i*) There must be a primary source, such as an ore deposit,a dissemination deposit, or a low grade deposit which supplies ore minerals; (*ii*) It must be exposed to weathering on a slope from where the disintegrated material may be carried away by water,air,etc.; (*iii*) The ore mineral in the deposit must

be of such chemical composition that it can resist weathering; and (*iv*) For a mineral to be concentrated as a placer deposit, it must have a higher density than the worthless material with which it occurs.

9.13.1. Types of Placer Deposits

The placer deposits have been divided into four groups : (*i*) eluvial placers, (*ii*) stream placers, (*iii*) beach placers, and (*iv*) eolian placers.

Eluvial Placers. The eluvial placer deposits occur along the hill slopes. Here the mineral concentration is caused by gravity. When the debris produced due to weathering of rocks, moves downslope, the heavier particles move more slowly than lighter ones. In this way heavier minerals get concentrated to form an eluvial placer deposit.

Stream Placers. These occur at various places along the stream. Here the mineral concentration is caused by running water. The weathered rock material travels with stream water. The concentration of heavier minerals occurs in those places where the velocity of water slackens. The places where stream placers are found, are as follows.

(*i*) In pot holes and plunge pools which form at the base of waterfalls and rapids.

(*ii*) In the sand bars which occur at the inner curves of meanders [Fig. 9.13(*a*)].

(*iii*) Just downstream to the junction of a tributary to the main river [Fig. 9.13(*b*)].

(*iv*) On the river bed in the vicinity of a low grade deposit [Fig. 9.13(*c*)].

(*v*) In the riffles [Fig. 9.13(*d*)]. Streams flowing across vertical or steeply inclined beds may have uneven floor. Such a floor forms "*riffles*".

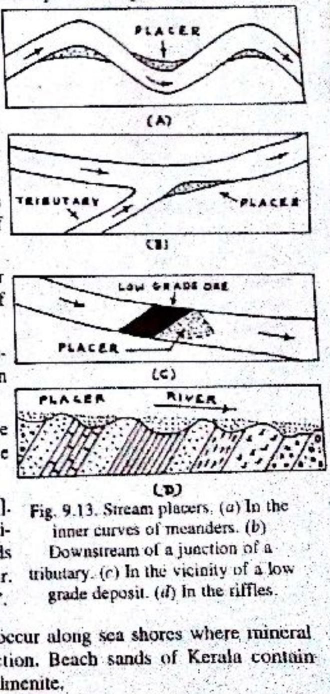


Fig. 9.13. Stream placers. (*a*) In the inner curves of meanders. (*b*) Downstream of a junction of a tributary. (*c*) In the vicinity of a low grade deposit. (*d*) In the riffles.

Beach Placers. These deposits occur along sea shores where mineral concentration is caused by wave action. Beach sands of Kerala contain important deposits of monazite and ilmenite.

Eolian Placers. These occur in arid regions where mineral concentration is caused by wind action. Eolian placers are found in Australia.

9.14. OXIDATION AND SUPERGENE ENRICHMENT DEPOSITS

If an ore deposit is exposed to the ground surface, it undergoes weathering. The surface water oxidizes and dissolves the ore minerals from the weathered zone and carries them downward. The dissolved minerals are redeposited just below the groundwater table. In this way a low grade primary ore deposit may be enriched to form a valuable ore deposit. Such ore deposits are called "*supergene enrichment deposits*" (Fig. 9.14). Three zones have been recognised in the supergene enrichment deposits : (*i*) Zone of oxidation, (*ii*) Supergene enrichment zone, and (*iii*) Primary zone.

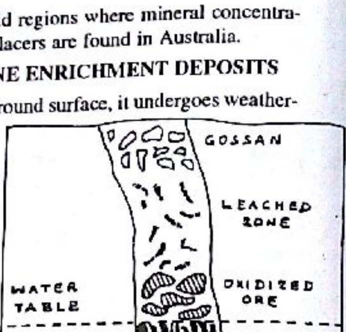


Fig. 9.14. Oxidation and supergene enrichment deposits.

Zone of Oxidation. The oxidized part of the ore deposit is called the "*zone of oxidation*". This zone extends from the ground surface upto the water table. The ore minerals from this part of the ore body are dissolved and removed.

Supergene Enrichment Zone. This zone lies below the water table. In this zone the dissolved ore minerals are precipitated in the form of secondary sulfides.

Primary Zone. The lower unaffected part of the ore body is called the "*primary zone*".

9.14.1. Process of Supergene Enrichment

The process of supergene sulfide enrichment involves three stages : (*i*) oxidation and solution in the zone of oxidation, (*ii*) deposition in the zone of oxidation, and (*iii*) supergene sulfide deposition.

Oxidation and Solution. Most primary sulfide deposits of copper, silver, lead and zinc contain pyrite (FeS_2). The surface water containing dissolved oxygen reacts with pyrite and yields iron sulfate and sulfuric acid, both of which are soluble in water.

$$2FeS_2 + 2H_2O + 7O_2 = 2H_2SO_4 + 2FeSO_4$$

The water containing iron sulfate and sulfuric acid in solution is a strong solvent. It attacks the other primary sulfide ore minerals and produces

soluble sulfates of their metals. The ore minerals of copper, silver and zinc are dissolved in this way.

The solution containing secondary sulfates travels downward to the reducing zone which lies below the water table. Thus the ore minerals are removed from the zone of oxidation.

Deposition in Zone of Oxidation. The cold dilute solution of secondary sulfates moves slowly downward. It may meet some precipitants and may redeposit its metallic content in the zone of oxidation. The ore deposits formed in this way are called "*oxidized ore deposits*". The chief ore minerals which occur as oxidized deposits are native metals, carbonates, silicates, and oxides of copper, zinc, lead and silver.

Supergene Sulfide Deposition. The solution containing sulfates of metals in dissolved state may reach the water table. Below the water table its metallic content is precipitated as sulfide. The ore deposit formed in this way is called " *supergene sulfide deposit*".

Below the water table all the pores of rocks are saturated with water and therefore no air is available for oxidation. This reducing environment favours the precipitation of ore minerals as sulfide. This deposition takes place by the process of replacement where the pre-existing metallic sulfides are replaced. For example, copper sulfide is precipitated from the solution by the replacement of primary sphalerite (ZnS) as follows.

$$CuSO_4 + ZnS = CuS + ZnSO_4$$

The sulfide enrichment starts at the water table and extends for some distance below it. The upper surface of the enrichment zone is sharply separated from the oxidized zone whereas its lower surface is highly irregular and there is a gradational transition to the primary ore (Fig. 9.14).

Gossan. A "*gossan*" is a ferruginous and porous looking residue that forms a superficial cover over an oxidized sulfide deposit (Fig. 9.14). The limonite formed as a result of oxidation of ironbearing sulfides, imparts red and brown colours to the gossans.

The porous nature of gossans is caused by the removal of the soluble materials. The residual limonite of gossans usually shows a honeycomb structure called "*boxwork*". Gossans sometimes serve as an indication for the occurrence of useful ore deposits underneath.

9.15. METAMORPHIC DEPOSITS

Deposits formed due to metamorphism may be divided into two groups : (*i*) deposits formed due to metamorphism of pre-existing ore deposits, and (*ii*) deposits originated due to formation of new minerals during metamorphism of certain rocks. The manganese deposits of Madhya Pradesh and Maharashtra belong to the former group, while the later group includes many valuable nonmetallic deposits. Examples of nonmetallic mineral deposits are asbestos, talc, kyanite, sillimanite and graphite.

9.16. CONTROLS OF ORE DEPOSITION

The ore deposits are usually controlled by certain features of the rocks in which they occur. The factors which control ore localization may be grouped as follows.

1. Structural controls
   (*i*) Orogenic movements.
   (*ii*) Igneous intrusions
   (*iii*) Faults and shear zones.
   (*iv*) Rock openings.
2. Stratigraphic controls.
   (*i*) Basin of deposition
   (*ii*) Unconformities.
   (*iii*) Bedding planes.
   (*iv*) Impervious strata.
3. Physical and chemical controls
   (*i*) Permeability.
   (*ii*) Brittleness.
   (*iii*) Chemical properties.

9.16.1. Structural Control

The structural features of rocks are the most important features which localize ore deposition. They are now being used as a useful guide for finding the ore bodies.

Orogenic Movements. The epigenetic ore deposits generally occur along the fold mountains. These areas are the sites of crustal movement, rock deformation, dislocations and igneous intrusion. The intrusive igneous bodies yield mineralizing fluids which move through the rock openings and deposit the ore minerals there. The openings in the rocks are produced during the mountain building process.

Igneous Intrusions. A number of ore deposits are closely associated with intrusive igneous bodies. They yield mineralizing fluids which produce ore deposits in the nearby rocks.

Faults and Shear Zones. The mineralizing solutions move upwards from depths along faults. Hence ore deposits are usually found associated with the faults. Many of the hypothermal and mesothermal ore bodies have been found along the reverse faults, thrusts and strike slip faults.

Shear zones are the zones that contain intensely fractured rocks. The fractures not only help in producing vein deposits, they also offer large specific surfaces for forming replacement lodes.

Rock Openings. The various types of openings found in the rocks are joints, fractures, solution cavities, pores, etc. The mineralizing solutions move through these openings and deposit their load there.

9.16.2. Stratigraphic Control

Basin of Deposition. The sedimentary mineral deposits such as coal, iron ore, manganese ore, etc. are deposited as beds in sea or lakes. Such basins of deposition control the area of occurrence of these deposits.

Unconformities. The unconformities represent old erosion surfaces. Hence they are the site for the accumulation of residual ore deposits, such as bauxite, and residual iron and manganese ores. The unconformities may also serve as impermeable barriers and therefore they may localize oil, gas and groundwater.

Bedding Planes. The bedding planes are the planes of weakness in sedimentary rocks. The replacement and contact metasomatic deposits are frequently localized along them. The regional foliation and fracture cleavage in metamorphic rocks may also localize ore deposits.

Impervious Strata. Impervious rocks such as shales, serve as barriers to moving mineralizing solutions. Hence many deposits are localized along shale beds.

9.16.3. Physical and Chemical Control

The physical and chemical properties of rocks play an important role in controling ore deposition. These controls operate along with the structural features.

Permeability. The permeability of a rock is its capacity to transmit fluids. It is directly related to the porosity of rocks. The openings present in the rocks serve as channelways for the mineralizing solutions. Therefore the permeability of rocks is an important factor in controling the formation of many epigenetic mineral deposits. It also controls the formation of many oxidized and sulfide enrichment deposits.

Brittleness. Brittle rocks have a tendency to crack readily under stress. As a result they become permeable to mineralizing solutions. Hence mineral deposits are frequently found in brittle rocks. Examples of brittle rocks are rhyolite, quartzite and limestone.

Chemical Properties. The chemical character of the host rock plays a dominent role in the localization of epigenetic ore deposits. The replacement ore deposits are frequently localized along reactive wall rocks. The facts which support this statement, are as follows.

(*i*) Carbonate rocks, such as limestones and dolomites are more congenial to ore deposition than other rocks.

(*ii*) Vein deposits are frequently found against dolerite and not against granite.

(*iii*) In general, highly silicic rocks are not as favourable localizers of ore as less silicic and ultrabasic igneous rocks.

(*iv*) The highly aluminous rocks such as shales are also not favourable for deposition of ores.

9.17. COAL

Coal is the world's leading mineral fuel. It is burned to produce heat which is used to generate electric power. The coke which is made by heating coal to a very high temperature in the absence of air, is used in the metallurgical industry.

The term "*coal*" covers a wide variety of materials, ranging from lignite at one hand to anthracite on the other. It may be defined as a solid stratified rock composed mainly of carbonised plants.

9.17.1. Ranks of Coal

The process of conversion of vegetable matter to coal involves loss of oxygen and hydrogen, and concentration of carbon. The chief stages of coal formation are : (*i*) peat, (*ii*) lignite, (*iii*) bituminous coal, and (*iv*) anthracite. Peat is not a coal though it is fuel. The "*Rank*" of a coal is its position in

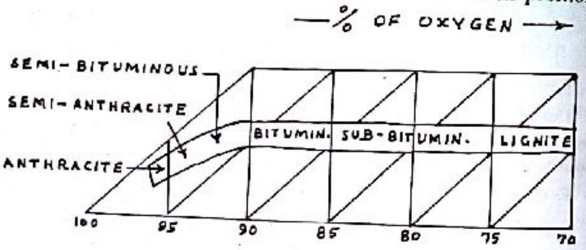


Fig. 9.15. Rank classification of Coal.

the lignite-anthracite series (Fig.9.15.). From lignite to anthracite there is a progressive elimination of water,oxygen and hydrogen and an increase in carbon. In coals carbon occurs in two forms :(*i*) as fixed carbon,and (*ii*) as volatile matter. The ratio of these two (fuel ratio) determines the rank of coal.

9.18. CLASSIFICATION OF COAL

On the basis of rank and quality, the coals are classified into four main groups : (*i*) lignite, (*ii*) bituminous coal, (*iii*) anthracite, and (*iv*) cannel coal. Peat lies above lignite and graphite below anthracite.

Peat. Peat is not considered as coal though it is a fuel. It represents the first stage of coal formation. Peat is a brown porous mass of partly decomposed vegetable material. It contains about 85% moisture, 10.4% volatile matter, and 4.6% carbon. The dried peat burns readily with the long smoky flame. Its calorific value is very low.

Lignite. Lignite is also called "*brown coal*" as its colour is often dark brown. It represents the second stage in coal formation. The lignite is composed of finely divided plant tissues. It contains about 25-45% moisture. Because of high water content, it shrinks, cracks and often disintegrates when dried in air. The lignite burns freely with a long smoky flame and has a low calorific value (11000—12500 B.T.U.).

Bituminous Coal. It is a dense coal of black colour. It shows banded structure in which dull and bright bands alternate. The bituminous coal breaks parallel to bands but the presence of vertical joints makes it to give cubical or rectangular blocks. Its moisture content is low, volatile matter medium and fixed carbon high. It burns easily with a smoky yellow flame. Its calorific value ranges between 13500 to 16000 B.T.U. Higher ranks of bituminous coals have the maximum heating power of all coals (Fig.9.16.).

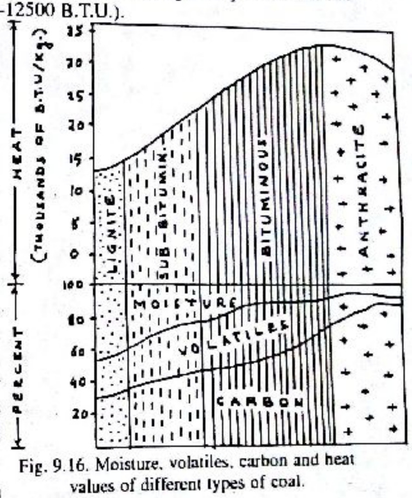


Fig. 9.16. Moisture, volatiles, carbon and heat values of different types of coal.

Anthracite. It is a hard coal with an iron-black colour and submetallic lustre. It does not soil the fingers and commonly breaks with a conchoidal fracture. The anthracite contains about 92—94% carbon and 3—8% volatile matter. It is difficult to ignite but burns with a short blue flame and gives little smoke. Its calorific value ranges between 15000 to 15600 B.T.U.

Cannel Coal. Cannel coal is a special variety of bituminous coal which is very fine grained and is of uniform texture. It has no banded structure like ordinary bituminous coal. Cannel coal is black in colour and has dull lustre. It does not soil fingers. It burns easily with a long candle like flame. It is made up of wind blown spores and pollen. It is commonly found associated with seams of bituminous coal as lenticles or bands upto about half meter thik.. Cannel coal is essentially a drift deposit laid down in shallow lakes.

9.19. BANDED CONSTITUENTS OF COAL

In banded coals four separate kinds of coal constituents have been recognised: (*i*) vitrain, (*ii*) clarain, (*iii*) durain, and (*iv*) fusain.

Vitrain. Vitrain forms thin bright glassy bands of coal which are up to half centimeter thick. It is very brittle and breaks with a conchoidal fracture. The woody structure is not visible with naked eye. Vitrain is a coking constituent of coal.

Clarain. Clarain forms thin bands in coal. It is characterized by bright colour and silky lustre. It is composed largely of attritus. Attritus is the finely divided plant residue which is composed of the more resistant plant products. Clarain is a coking constituent of coal.

Durain. The dull earthy looking bands of coal are called durain. Durain is hard and compact, and has granular texture. Its colour is lead-gray. It consists of cuticles, spores, etc. Durain is the noncoking constituent of coal.

Fusain. Fusain is also called "*mineral charcoal*". It is a soft, powdery, pitch black substance which soils the fingers. It is a minor constituent of coal which occurs in small patches and in the body of durain and clarain. Fusain is high in ash and is a noncoking constituent.

9.20. CHEMICAL PROPERTIES OF COAL

The commercial value of a coal depends on its chemical characters. The main constituents which are determined in the proximate analysis of coal are: (*i*) moisture content, (*ii*) volatile matter, (*iii*) fixed carbon, (*iv*) fuel ratio, (*v*) ash content, (*vi*) sulfur content and (*vii*) calorific value.

Moisture Content. The moisture content of a coal can be driven up at 100°C. It is highest in peat and lignites, and lowest in anthracite.

Volatile Matter. The volatile matter is that which burns in the form of a gas. It consists of combustible gases such as hydrogen, carbon monoxide, methane and other hydrocarbons. These gaseous products are driven off from coal when it is heated in the absence of air to about 900°C. The residue left after driving out all the volatile matter is called "*coke*". The coke consists of fixed carbon and ash.

The percentage of volatiles in coal varies within wide limits and directly affects the coking quality. Coals with volatile matter less than 18% or more than 40% are not good coking coals. Depending on the quality of coke produced from coal through carbonization, coking coals are subdivided into the following groups.

(*i*) **Primary Coking Coal.** Coal with volatile content between 22% and 33% on unit coal basis.

(*ii*) **Medium Coking Coal.** Coal with volatile content between 22% and 25% on unit coal basis.

(*iii*) **Semi Coking Coal.** Coal with volatile content between 18% and 22%, or 38% and 46% on unit coal basis.

Fixed Carbon. When the volatiles and ash are removed from the coal fixed carbon is left. It burns with difficulty and gives intense heat. In anthracite, the fixed carbon is about 96% and in lignite it is about 38%.

Fuel Ratio. Coals contain carbon in two forms: (*i*) as fixed carbon, and (*ii*) as volatile matter. The ratio of these two is called "*fuel ratio*".

$$\text{Fuel ratio} = \frac{\text{Fixed carbon}}{\text{Volatile matter}}$$

Naturally, the fuel ratio will be the lowest in lignite and highest in anthracite. It is the main feature which determines the rank of coal. The rank of a coal produced is largely determined by the pressure to which it has been subjected and the time for which it had remained under such conditions.

Ash Content. Ash is the noncumbustible mineral matter which is left after burning of coal. The main constituents of ash are silt, clay, silica, iron oxides and other mineral substances. Too much ash may put a high rank coal in a low grade. High percentage of iron in the ash produces clinkers.

Sulfur Content. Sulfer is an objectionable impurity of coal. It is commonly present in most coals in the form of pyrite and marcasite. It helps to produce clinkers in the furnace and yields corrosive sulfurous fumes on burning. More than 1.5% sulfur excludes coal for making gas or coke.

Calorific Value. The calorific value of a coal is the amount of heat that the unit weight of coal would produce on burning. It may be stated either in British Thermal Units (B.T.U.), or in calories per kilogram. The calorific value of lignite is about 7500 B.T.U. and that of Bituminous coal is over 15000 B.T.U.

9.21. ORIGIN OF COAL

Coals are sedimentary rocks formed by accumulation of plant materials in swamps. Hence the source material of coal is the vegetation matter. The formation of a coal deposit requires a large accumulation of vegetation matter. This implies large vegetation growth which is possible only in subtropical climate with heavy rainfall well distributed throughout the year.

There are two theories to explain the mode of accumulation of plant materials to give rise to coal seams : (*i*) the in-situ theory, and (*ii*) the drift theory.

9.21.1. In-situ Theory

The in-situ theory suggests that the vegetation matter had accumulated at the place of growth itself in the swamps. This means that the forests grew at the same place where we now find coal seams. The in-situ theory may briefly be summarized as follows.

(i) The vegetable matter was accumulated in the coal forest itself.

(ii) As the land was sinking slowly, the accumulated plant material was kept saturated with water and therefore it was not decomposed and destroyed.

(iii) In the course of time,the rate of sinking of land was increased and the coal forest was submerged under water. This resulted in the geological burial of the vegetable matter below sand and mud layers.

(iv) Then uplifting took place and the land emerged out of water. The coal forests came into existence again and the above said cycle of coal formation was repeated. In this way alternation of strata and coal seams were formed.

Evidences. The evidences in support of in-situ theory are as follows.

1. A huge amount of plant material is accumulating in-situ in the swamps that exist today.
2. In coal seams, the stems of fossil trees are found standing erect with their roots protruding into the underclays.
3. The underclays which are found beneath the coal seams are supposed to represent the original soils on which the vegetation grew.
4. The coal seams contain coal which is relatively pure and free from shale bands. This suggests that the plant material was not transported along with sediments.
5. The uniformity in thickness and composition of coal seams over wide areas suggests that the deposition of the plant material took place in still waters.

9.21.2. Drift Theory

This theory suggests that the plant material was transported by stream action from their place of growth and deposited at suitable places in lakes or sea just like other sediments.

The coal seams of India are of drift origin. The drift theory may briefly be summarized as follows.

(i) The plant material from the coal forest was transported by water and deposited in lakes or sea just like other sediments.

(ii) During transportation the various materials were sorted out as usual, in accordance with their specific gravities.

(iii) The pure coal seam was formed in places to which only the lightest material (plant material) had access.

(iv) A stream with shale bands was formed in places where a temporary change in the water currents and hence the nature of sediment occured.

(v) Rapid and frequent oscillatory earthmovements had given rise to several coal seams one above the other separated by sediments.

Evidences. The evidences in favour of the drift theory are as follows.

1. The rocks associated with coal seams are distinctly sedimentary. The coal seam itself behaves like a sedimentary bed and they are observed to branch out.
2. In some cases the underclays which represent the soil at the root, are not found below the coal seams.
3. The fossil trees are more usually found lying at augles other than the vertical.

9.22. FORMATION OF COAL

The Plant materials were accumulated in swamps, broad deltas, coastal plain areas and interior basins. The climatic conditions that favoured large accumulation of plant material were mild temperate to subtropical. The transformation of plant material into coal consists in the progressive enrichment of carbon content.

Preservation. The land sank slowly with the accumulation of the plant material. Thus the plant material was kept saturated with water. The water or the reducing environment protected the plant material from oxidation and therefore it was not decomposed and destroyed.

Biochemical Change. When plant material falls into water, the decay starts. But it stops soon as the reducing environment and the lack of oxygen prevents further decay. In this process the less resistant parts of the plants such as cellulose and starches are decomposed by the becterial action and the resistant parts such as wax, resin, and cutin along with woody fragments sink to the bottom of the swamp. Thus the partly decomposed plant debris accumulates and it gradually turns into "*peat*".

Carbonization and Metamorphism. With the passage of time peat changes slowly into anthracite. In this process mainly chemical changes take place. These changes are brought about by the increase in the pressure and temperature which is caused due to deep burial. Form peat to anthracite the amount of oxygen goes on decreasing and the amount of fixed carbon goes on increasing.

The change in the rank of coal is largely a result of pressure and time. The older the coal, the greater the depth of burial. Thus with the passage of time, there is increase in the pressure which accelerates metamorphism and turns peat into lignite, bituminous coal or anthracite.

9.23. OCCURRENCE OF COAL

About 98% of the coal produced in India comes from the rockformations of Permo-Carboniferous age, that is Lower Gondwana system, while the rest is obtained from the Tertiary rocks. The coal found in the Lower Gondwana rocks are of bituminous type whereas those found in the tertiary rocks are lignites.

Most of the Gondwana coals are noncoking bituminous coals. The coking coals are found only in Jharia, Girdih and Bokaro coal fields. The reserves of all types of coal occurring within a depth of 600 meters are estimated at 120,000 million tonnes. The reserves of coking coals are about 20,000 million tonnes. The reserves of lignite deposits are estimated to be about 3500 million tonnes. The deposits of lignite occur mainly in the tertiary rocks of Kashmir valley, Assam, Madras(Neyveli) and Rajasthan(Palana).

9.23.1. Lower Gondwana Coal Fields

The Lower Gondwana coal fields of India are situated chiefly in river valleys.

1. **Damodar Valley Region.** Coal fields of West Bengal and Bihar.
   - (*i*) **West Bengal.** Raniganj coal fields.
   - (*ii*) **Bihar.** Jharia, Girdih, Bokaro, Karanpura, and Daltonganj coal fields.
2. **Son-Mahanadi Valley Region.** Coal fields of Madhya Pradesh and Orissa.
   - (*i*) **Madhya Pradesh.** Umaria, Singrauli, Korba, Chirmiri, Sohagpur, Bisrampur, Mohpani and Pench- Kanhan valley coal fields.
   - (*ii*) **Orissa.** Talchir coal fields.
3. **Wardha-Godavari Valley Region.** Coal fields of Andhra Pradesh and Maharashra.
   - (*i*) **Andhra Pradesh.** Singareni coal fields.
   - (*ii*) **Maharashtra.** Wardha valley coal fields.

9.24. PETROLIUM

"*Petrolium*" is the general term used for all the natural hydrocarbons found in rocks. It not only includes the liquid hydrocarbons but gaseous and solid hydrocarbons also. However in common usage, the terms "*petrolium*" refers only to the liquid oil. Gaseous varieties are called "*natural gas*" and highly viscous to solid varieties are called "*bitumen*".

The petrolium is a complex mixture of hundreds of different hydrocarbons. The hydrocarbons fall into several natural series of which parafin series is the most familiar.

9.24.1. Origin of Petrolium

It is now universally believed that petrolium and natural gas are of organic origin. They originate from slow decomposition of lower forms of marine organisms such as foraminifers, diatoms, algae, ostracods etc. The process of formation of petrolium may be summarized as follows.

(*i*) In coastal waters, a large number of marine organisms thrive. Hence in offshore sedimentary basins huge amount of organic matter is deposited along with muddy sediments. Because in the bottom of stagnant water, there is deficiency of oxygen, the organic matter is protected from oxidation. Under such conditions anaerobic bacteria extract oxygen from the organic matter and transform it into fatty and waxy substances.

(*ii*) During the millions of years of deep burial, the organic matter is converted into oil and gas by the slow chemical reactions. The exact process by which this transformation takes place, is not known, but it is believed that becteria, pressure, moderate temperatures, and great lengths of time play an important part.

9.24.2. Migration of Petrolium

The fine grained muddy sediments in which petrolium originates are called "*source rocks*". The source rocks of petrolium are generally shales, silts, and limestones. The petrolium migrates from the source rock into adjacent porous and permeable rocks and accumulates there to form a pool. Such permeable rocks are called "*reservoir rocks*". The common reservoir rocks are sandstones, conglomerates, porous limestones, fractured shales, and jointed igneous and metamorphic rocks. The causes for the migration of petrolium are : (*i*) compaction of the source rock, (*ii*) bouyancy effect, (*iii*) capillary effect, and (*iv*) water flushing. In an oil pool, the oil floats on the top of water and above the oil there is usually a lens of natural gas (Fig. 9.17)

9.25. OIL TRAPS

The oil migrates outward and upward from the source rock and passes into the porous reservoir rock. The migration of oil continues until it meets a suitable structure where its lateral as well as upward movement is checked. At such a place the oil accumulates to from an oil pool. Such places are called "*oil traps*". The conditions necessary for the formation of an oil trap are as follows.

(*i*) The porous reservoir rocks must have a favourable structure such as an anticlinal fold or dome, to hold oil.

(*ii*) There must be an impervious cap rock to check the upward migration of oil. The common cap rocks are shale, clays, salt, gypsum, and dense limestone.

(*iii*) The structural deformation of rocks must not be very severe. Intensely fractured rocks may render traps ineffective by causing leakage.

9.25.1. Types of Oil Traps

The oil traps are classified into two groups : (*i*) Structural traps, and (*ii*) Stratigraphic traps.

Structural Traps. The structural oil traps are formed as a result of folding, faulting and igneous intrusions. The description of some of the important structural traps are as follows.

(*i*) **Anticlines and Domes.** The anticlines and domes are the most important because they form oil traps in practically all the large oil fields of the world. Here the oil and gas migrate up the limbs and collect at the crest below a cap rock [Fig. 9.17. (*a*)].

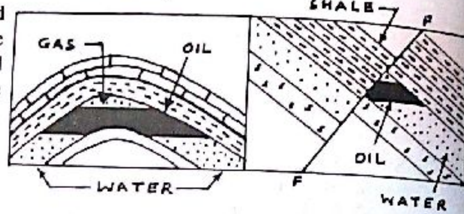


Fig. 9.17. (*a*) Oil trap in an anticline, (*b*) Oil trap along a fault.

(*ii*) **Faults.** When a fault affects inclined strata, a reservoir rock may be blocked off by an impervious shale thereby creating an oil trap [Fig. 9.17. (*b*)].

(*iii*) **Salt Domes.** Where salt domes intrude into the sedimentary rocks, good oil traps are formed. Here the oil accumulates near the upturned edges of the reservoir rock which are sealed by the salt [Fig. 9.18. (*a*)].

(*iv*) **Igneous Intrusions.** The volcanic necks and dykes may seal the upturned edges of the reservoir rock to form oil traps.

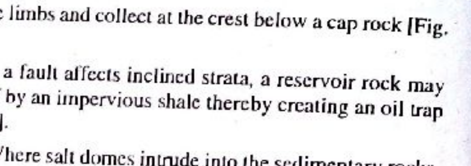


Fig. 9.18. (*a*) Oil trap near a salt dome, (*b*) Oil trap along an unconformity.

Stratigraphic Traps. The stratigraphic oil traps are formed as a result of lateral and vertical changes in the permeability of the reservoir rocks. These changes are caused by variations in the conditions during the deposition of rocks. Some of the important stratigraphic oil traps are as follows.

(*i*) Unconformities in the rock sequence often give rise to oil traps [Fig. 9.18. (*b*)].

(*ii*) The shales which are the source rock of petrolium may contain lenses of sandstone. The oil may accumulate in these sandstone lenses [Fig. 9.19 (*a*)].

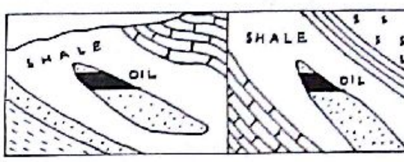


Fig. 9.19. (*a*) Oil trap in a sandstone lens. (*b*) Oil trap in a sandstone which is wedging out.

(*iii*) A porous sandstone may wedge out thereby creating an oil trap [Fig. 9.19 (*b*)].

9.26. PETROLIUM DEPOSITS

In India, resrvoirs of petrolium and natural gas are found in the belts of Tertiary rocks of Assam, Gujrat, Offshore region of Bombay High, and in the Cauveri and Godavari deltatic areas.

9.26.1. Oil Fields of Assam

The chief oil fields of Assam are : (*i*) Digboi, (*ii*) Nahorkatiya, (*ii*) Moran, (*iv*) Rudrasagar, and (*v*) Lakwa.

Digboi Oil Field. This oil field is situated in the Lakhimpur district of Assam. It is 13 km. long and about one kilometer wide. It lies on a tightly folded anticline. The steeper flank of this anticline has been cut by the Naga thrust in the northwest. The Oil bearing formation is the Tipam sandstones of Miocene age. The source rocks in this case are probably Barails. In the Digboi oil field, there are several oil sands and about 400 producing wells of which only 30 are good producer.

Nahorkatiya Oil Field. This oil field is situated in the Brahmputra valley of upper Assam. It lies about 40 km. southwest of Digboi. The oil deposits occur in an anticlinal structure. There are about 5 oil bearing sands all lying within the upper part of the Barail sandstones of Oligocene age. In the overlying Tipams only gas is found. This oil field is cut into a number of blocks by faults.

Moran Oil Field. This oil field lies about 41 km. WSW of Nahorkatia. Here the oil bearing formation are the Barails of Oligocene age. A major fault divides this field into two halves.

Rudrasagar Oil Field. This oil field lies about 40 km. southwest of Moran. Here deposits of oil are found in a gentle dome which is cut by several faults. The oil bearing formations are the Barails of Oligocene age.

Lakwa Oil Field. This oil field is situated about 20 km. SSW of Moran. Here the oil pools are found in the anticlinal structure which is cut by a number of faults. The oil bearing horizons occur both in the Tipams of Miocene age and Barails of Oligocene age.

9.26.2. Oil Fields of Gujrat

The important oil and gas fields of Gujrat are : (*i*) Ankleshwar oil field, (*ii*) Cambay gas field, (*iii*) Kalol oil field and (*iv*) Nawagam oil field.

Ankleshwar Oil Field. This is the most important oil field of Gujrat. It is situated to the south of Narmada river near Broach. The oil pools occur in the anticlinal structure. The oil bearing formations are sands of Eocene age. The oil field is about 20 km. long and its maximum width is about 4 km.

Cambay Gas Field. The Cambay gas field is situated about 9 km. NNW of Cambay town. Huge gas deposits are found in a north-south trending anticline which is faulted on both flanks. The oil and gas bearing sands which are about 150 meters thick, occur in the formations of Oligocene age.

Kalol Oil Field. The Kalol oil field is situated about 25 km. north of Ahmedabad. The deposits of oil are found in an elongated dome trending in the NNW-SSE direction. This dome is cut by a longitudinal fault.Here the oil pools occur in the rock formations of Eocene age.

Nawagam Oil Field. This oil field is situated about 24 km. south of Ahmedabad. The oil pools occur in an anticlinal structure in the Eocene formation.

9.26.3. Bombay High

A huge deposits of oil has been found on the west coast of India, in the offshore structure, called "*Bombay High*". The Bombay High lies in the Arabian sea, about 160 km., NW of Bombay. This has proved to be the richest deposit in the country.

The Bombay High structure covers an area of about 2500 square kilometers. Here the oil bearing rocks are the limestones of Miocene age. The estimated reserves of petrolium in this structure are of the order of 4 billion tonnes.

9.26.4. Other Areas

In addition to the above mentioned oil deposits, there are possibilities of getting oil and gas in the deltas and alluvial troughs of Indus, Ganges, Brahmputra, Cauvery and Godavari. Besides these, other promising areas are offshore region of Tamil Nadu and Andhra Pradesh, and states of Tripura and West Bengal.

9.27. GOLD

The gold is a precious metal. Its main use is for currency. It is stored as bullion to back up in value the paper currency. Large quantity of gold is also required for the manufacture of jewelry.

Mineralogy. The chief mineral of gold is "*native gold*". In nature, native gold is generally found mixed with some silver. It is usually associated with some metallic sulfides, such as pyrrhotite and iron-pyrite.

9.27.1. Types of Deposits

Hydrothermal Deposits. The gold deposits are generally of high temperature hypothermal origin. The ore occurs as lodes, veins or gold bearing quartz reefs in igneous, sedimentary or metamorphic rocks.

Placer Deposits. The gold also occurs as placer deposits in stream beds or on sea shores.

9.27.2. Origin

In India economic deposits of gold are found only in "*Kolar gold field*" and "*Hutti gold field*" of Karnataka. Here gold occurs as gold bearing quartz veins in hornblende-schists, greenstones and amphibolites of Dharwar system. These gold deposits are believed to be of high temperature hypothermal origin. The mineralization is generally controlled by shear zones and faults which strike roughly in the N-S direction.

9.27.3. Distribution

Practically all the gold produced in India is obtained from the Kolar gold field and the Hutti gold field in Karnataka.

Kolar Gold Field. The Kolar gold field is about 15 km. long and 3 km. wide. It is situated in the central part of the "*Kolar-schist belt*". The Kolar-schist belt forms the easternmost part of the Dharwar rocks of South India. It extends in the NNW-SSE direction for about 80 km.

In the Kolar gold field, the country rocks are mainly dark hornblende-schists. They are folded in the form of a major syncline with a number of cross folds. The gold occurs as gold bearing quartz veins which traverse the country rocks. The gold is mostly found in the bluish grey quartz of vitreous lustre. The native gold is associated with some metallic sulfides such as pyrrhotite and pyrite.

The gold bearing lodes occur mainly at the contacts of massive amphibolites with the schistose amphibolites. Along these contacts, the mineralization is localized in the zones of shearing, faults, cross folds, and drag folds.

In the Kolar gold field, there are about 26 gold bearing quartz lodes. Of these only five lodes are of economic importance. These lodes strike in the N-S direction and dip towards the west. The lode which has been worked most is the "*Champion lode*". This is one of the biggest lode which vary in thickness from a mere stringer to as much as 12.2 meters. The important mines of the Kolar gold field are Nundydroog, Champion reef and Mysore. The deepest mine is Champion mine which is about 3350 meters deep. In the Kolar gold field, the tenor of the ore is about 7.42 gram/tonne. The total reserves of the gold ore are about 10.7 million tonnes.

Hutti Gold Field. This field is situated in the Raichur district of Karnataka. Here the gold mining belt is about 3700 meters long and 1220 meters wide. The country rocks are mainly greenstones and chlorite-schists. These rocks are folded and the gold lodes are localized along shear zones. There are six important gold bearing quartz reefs. The native gold is associated with arsenopyrite, chalcopyrite, pyrrhotite and pyrite. The total reserves of gold ore in the Hutti gold field are about 1.3 million tonnes. The gold content of the ore is about 4.8 to 7.5 gm/tonne.

9.28 IRON-ORE

The iron ore is the second largest mineral wealth of India, the coal being on the top. The possible reserves of high grade iron ore are about 17,630 million tonnes of hematite and 1610 million tonnes of magnetite.

Iron is the backbone of modern civilization. Iron ore is chiefly used in the iron and steel industry. Iron is used for making machine, automobiles, trains, ships etc.

Mineralogy. The chief ore mineral of iron is hematite (Fe_2O_3). The other minerals of minor importance are magnetite (Fe_3O_4), siderite ($FeCO_3$) and limonite [$FeO(OH).nH_2O$].

9.28.1. Types of Deposits

Magmatic Deposits. Deposits of magnetite and titaniferous magnetite may occur as magmatic deposits in some basic igneous rocks.

Contact Metasomatic Deposits. The magnetite may occur as contact metasomatic deposits is some limestones.

Replacement Deposits. Deposits of both magnetite and hematite may occur as replacement deposits in limestones.

Sedimentary Deposits. Deposits of hematite, limonite and siderite may occur as beds in sedimentary rocks.

Residual Deposits. Deposits of high grade hematite, magnetite and limonite may also occur as residual deposits.

9.28.2. Origin

Almost all the major Indian iron ore deposits are of sedimentary and residual origin. They occur in the rocks of the Iron-Ore series (Archaean) and their equivalents. They are closely associated with the banded-hematite-quartzites and are derived from them.

The banded-hematite-quartzites are of sedimentary origin. This rock contains about 28-30% iron. Subsequently the silica of this rock is removed by leaching and the concentrated iron ore is left behind to form residual iron ore deposits. These deposits occur in beds which are up to 40 meters thick.

The iron ores consist of massive, laminated and powdery hematite containing 60-69% iron.

9.28.3. Distribution

Bihar and Orissa. The iron ore deposits occur in Singhbhum district of Bihar, and in Keonjhar, Sundargarh and Mayurbhanj districts of Orissa. In these areas the iron-ores are associated with the banded-hematite-quartzites and banded-hematite-jasper. The iron contents of the hematite ranges from 55-69%. The total reserve is about 5700 million tonnes.

Madhya Pradesh and Maharashtra. Large deposits of iron ore occur in Baster and Durg districts of M.P. and in Ratnagiri and Chanda districts of Maharashtra. The total reserves of iron ore in this zone is about 3000 million tonnes.

In M.P. the important deposits are in Dhalli Rajhara area of Durg and Bailadila area of Baster. Of these, the deposits of Bailadia are of special importance. These deposits are one of the most extensive and richest deposits in the world. The hematite of Bailadila contains 65-68% iron. These deposits are mostly situated on high hills. The belt of iron ore extends over a length of 35 km and a width of 9 km. The trend of this belt is N- S. The ores are mainly massive and laminated hematite which change to blue dust at depth. The thickness of the ore deposits ranges between 305 to 610 meters.

Goa. In Goa region the iron ore deposits are closely associated with pink phyllitic horizon in rocks belonging to the Archaean system. The ore deposits occur in a belt 95 km long and 2 km wide. The iron ore deposits occupy crests and slopes of hills. At the surface the ore is generally hard and lumpy but in depth it is soft and powdery consisting mainly of the blue dust. The iron content of the ore varies from 59-62%. The total reserves of iron ore in this area are about 397 million tonnes.

Karnataka. The iron ore deposits of commercial importance are found in Bellary, Bijapur, North Kanara, Chitradurga and Tumkur districts. The total reserves of iron ore in this area are about 1450 millions tonnes.

Tamil Nadu. Deposits of magnetite are found in Tiruchirapalli and Salem districts. The total reserves of magnetite are about 447.7 million tonnes.

9.29. MANGANESE ORE

Of all the metals used in steel alloys, manganese is the most important. Manganese is mainly used in making high manganese steels and carbon steels. The manganese steel is used where hardness and toughness are desired, *e.g.* in the manufacture of armor plate, car wheels, safes, crushers, machine tools etc.

Mineralogy. The principal ore minerals of manganese are pyrolusite (MnO_2), manganite ($Mn_2O_3.H_2O$), psilomelane ($MnO.MnO_2.2H_2O$), braunite ($Mn_2O_3.MnSiO_3$), and wad. Wad is the massive earthy form of manganese oxide.

9.29.1. Type of Deposits

Syngenetic Gonditic Deposits. These deposits of manganese ore are found in M.P. - Maharashtra zone. They are associated with rocks of Sausor series (Archaean) including gondites. A "*gondite*" is a spessartite - quartz rock which is formed as a result of metamorphism of manganiferous sediment.

Syngenetic Reef Deposits. These deposits are found in Orissa- Andhra Pradesh zone. They are associated with kodurite rocks. A "*kodurite*" is a metamorphic rock which normally consists of quartz, orthoclase, garnet and manganese-pyroxene.

Replacement Deposits. These deposits of manganese ore are found in rocks of the Iron-ore series in Bihar and Orissa, and in the Dharwar rocks in Karnataka and Goa.

Lateritoid Deposits. These deposits occur within lateritic cappings and are of residual origin. Lateritoid deposits are associated with almost all the above deposits.

9.29.2. Origin

The manganese ore deposits of India are essentially of sedimentary and residual origin. Originally the manganese was deposited as manganiferous sediment and later it was metamorphosed. Where the manganiferous sediment was pure, directly oxide ore, mainly braunite was formed but where the manganiferous sediment was impure, gondites or kodurites were formed.

The gondite is a metamorphic rock which consists of spessartite, rhodonite and quartz. The gonditic manganese ore deposits are formed from the oxidation of gondites. During weathering, most of the silica and alumina are removed and manganese minerals, chiefly psilomelane, pyrolusite and wad are formed. In this way residual enrichment deposits are formed at many places.

9.29.3. Distribution

Extensive deposits of manganese ore are found in India. The total reserves of manganese ore are estimated at about 135 million tonnes, of which about 100 million tonnes are in the M.P.-Maharashtra zone and 35 million tonnes in the other areas. The deposits of manganese ore occur mainly in the following zones.

Madhya Pradesh-Maharashtra Zone. Rich deposits of manganese ore occur in Chhindwara and Balaghat districts of M.P., and in Nagpur and Bhandara districts of Maharashtra. These deposits are associated with rocks of the Sausor series including gondites. These deposits are mainly of primary bedded type and are the most important both from reserves and quality point

of view. In this zone the reserves of manganese ore are of the order of 100 million tonnes and manganese content of the ore is about 45%.

Bihar-Orissa-Andhra Pradesh Zone. In this zone the deposits of manganese ore are found in the following areas. These deposits occur mostly in association with rocks of the Iron-ore series.

(*i*) **Bihar.** Chaibasa area of Singhbhum district.

(*ii*) **Orissa.** Keonjhar, Gangpur and Sundargarh districts.

(*iii*) **Andhra Pradesh.** Shrikakulam and Vishakhapatnam districts.

Karnataka-Goa Zone. Economic deposits of manganese ore are found in North Kanara, Chitaldurg, Simoga, Tumkur and Bellary districts of Karnataka and in south Goa. These deposits occur in rocks belonging to the Archaean system.

9.30. COPPER ORE

Copper is one of the very essential elements in modern industry. In is used mainly in the electrical industry and for making various metal alloys, such as bronze and brass.

Mineralogy. Mineralogically copper ores can be divided into four groups: (*i*) native copper, (*ii*) sulfide ores, (*iii*) oxidized ore, and (*iv*) complex ore. Of these sulfide ores are the most valuable. The ores in which copper is found admixed with Pb, Zn, Au, and Ag are called "*complex ores*". The principal copper ore minerals are chalcopyrite ($CuFeS_2$), chalcocite (Cu_2S), bornite (Cu_5FeS_4), cuprite (Cu_2O), malachite [$Cu_2CO_3(OH)_2$], and azurite [$Cu_3(CO_3)_2(OH)_2$].

9.30.1. Types of Deposits

Magmatic Deposits. The copper-nickel deposits of magmatic origin occur in some mafic igneous rocks.

Hydrothermal Deposits. The copper ore deposits of hydrothermal origin are most common. These deposits occur as cavity filling and replacement, and the mineralization is generally in the form of massive lodes or disseminations.

Oxidation and Supergene Enrichment Deposits. Many copper deposits show signs of oxidation and supergene enrichment.

9.30.2. Origin

Most copper deposits of India are of hydrothermal origin. In these deposits the replacement dominates over cavity filling. Most copper deposits have undergone oxidation and some supergene enrichment. Copper deposits generally show complex geometrical shapes. The mineralization is commonly in the form of stringers, disseminations, veins and massive lenses.

9.30.3. Distribution

The important copper ore deposits of India are as follows.

1. Singhbhum copper belt of Bihar.
2. Khetri copper belt of Rajasthan.
3. Malanjkhand copper deposits of Madhya Pradesh.
4. Agnigundala copper deposit of Andhra Pradesh.
5. Sikkim copper deposit.

Singhbhum Copper Belt. The Singhbhum copper belt of Bihar is 128 km long. It extends from Duarpuram in the west through Dhalbhum to Baharagora in the SE. The six main mines of this belt from south to north are: (*i*) Badia, (*ii*) Dhobani (*iii*) Mosabani, (*iv*) Pathargora, (*v*) South Surda, and (*vi*) Surda.

The veins and lodes of copper occur within soda granite, quartz schist and epidiorites belonging to the Iron-ore series. The copper ore is mainly chalcopyrite which is associated with magnetite, pyrite, pyrrhotite, pentlandite and arsenopyrite. The ore contains 2.5 - 1.5% copper.

In the Singhbhum copper belt, the copper mineralization is controlled by the shear zone and the ore shoots are parallel to the slip direction. It is believed that the soda granites and granophyres are responsible for this mineralization. In this belt the total reserves of copper ore are about 100 million tonnes.

Khetri Copper Belt. The Khetri copper belt of Rajasthan is situated in Jhunjhun and Sikar districts. It extends over a distance of 80 km in the NNE-SSW direction from Singhana to Raghunathgarh. The richly mineralized areas of this belt are Madhan, Kudhan, Kolihan, and Akhwali. The main ore mineral is chalcopyrite which is associated with pyrite, pyrrhotite and secondary copper minerals such as azurite, malachite, covellite and chalcocite. The copper content of the ore ranges from 2.46% to 0.8%.

The ore bodies occur in highly folded and faulted phyllites, schists and quartzites belonging to the Delhi system of Precambrian age. The mineralization is localized in the fractures and shear zones related to the major faults. The total reserves of the copper ore in the Khetri copper belt are bout 226 million tonnes.

Malanjkhand Copper Deposit. The Malanjkhand copper deposit is situated in the Balaghat district of Madhya Pradesh. The chief rock types of this area are Chilpighat metasediments, granite, basic dykes and quartz veins of Archaean age. The metasediments are folded in an anticline which plunges in the WSW direction. This fold is traversed by a number of faults. The biotite granite exists in the core of this anticline.

The predominent rock of the Malanjkhand area is biotite granite. The copper mineralization is in the form of specks and veins of chalcopyrite in the crushed quartz veins. The mineralization is localized to the fractures and shear planes in the quartz veins in the vicinity of faults. The chief ore mineral is calcopyrite with subordinate quantities of galena, sphalerite and molybdenite. The copper content of the ore is about 1.35%. The total reserves of the ore are about 140 million tonnes.

Agnigundala Copper Deposit. This copper belt is situated at the NE extremity of the Cuddapah basin in Guntur district, Andhra Pradesh. In this belt lead ores are also associated with the copper ores. The mineralization is chiefly confined to quartzites and dolomites of Upper Cuddapah age. This mineralization is in the form of disseminations and stringers of chalcopyrite in steeply dipping quartz veins which traverse quartzites and dolomites. The chief ore minerals are chalcopyrite and bornite with minor amounts of pyrite, galena and sphalerite. The copper content of the ore is about 1.35%. The total reserves of the copper ore are about 14 million tonnes.

Sikkim Copper Deposits. In Sikkim, deposits of copper ore are found in Bhotang, Dik-Chu, Chakong, and Rangit valley areas. The mineralization mainly occurs in slates, phyllites and schists of Archaean age in the vicinity of large granite intrusives. The lodes and stringers of copper ore are found in quartz veins which traverse these rocks. The chief ore mineral is chalcopyrite. It is associated with pyrite, pyrrhotite, sphalerite and galena. The copper content of the ore ranges from 4% to 6.8%.

9.31. LEAD AND ZINC ORES

Next to copper, lead and zinc are the most essential nonferrous metals that are used in modern industry. The chief uses of lead are for storage batteries, ammunition, electrical cables, pipe, solder, and lead pigments. Zinc is used mainly in galvanizing and die castings. It is alloyed with copper to form brass.

Mineralogy. Most of the lead and zinc metals are obtained from either the sulfide ores or from their oxidation products. The sulfide ores are galena (PbS) and zinc blende (ZnS). The zinc blend is also called sphalerite. The oxidation compounds are cerrussite ($PbCO_3$), anglesite ($PbSO_4$), smithsonite ($ZnCO_3$), and zincite (ZnO).

Galena and zinc blende are commonly found together, and form mixed lead and zinc ore deposits. The galena frequently contains some silver and such ores are called "*argentiferous galena*". Pyrite and chalcopyrite are commonly found in association with galena and zinc blende.

9.31.1. Origin

Most of the deposits of lead and zinc ores are of hydrothermal origin. The galena and zinc blende are commonly deposited by low temperature hydrothermal solutions. The deposits of lead and zinc ores mostly occur as cavity fillings and replacement in limestones and dolomites. Many deposits may show signs of oxidation.

9.31.2. Distribution

Although lead and zinc ores occur at several places in India, the main producer of the ore is Zawar belt of Rajasthan. The important lead and zinc deposits of India are as follows.

1. Zawar belt of Rajasthan.
2. Amba Mata deposit of Gujrat.
3. Sargipalli deposit of Orissa.
4. Agnigundala deposit of Andhra Pradesh.

Zawar Belt of Rajasthan. The Zawar belt is situated in Udaipur district of Rajasthan. The bulk of the lead and zinc ores produced in India, is obtained from this belt. The Zawar belt extends for a distance of 20 km and its important ore bearing areas are Mochia Mogra, Baori Mogra, Balaria and Zawar Mala. Of these the Mochia-Balaria area which extends for a length of 6.4 km is the most productive.

In the Mochia-Balaria area, the country rocks are quartzites, dolomites, slates and phyllites of Aravalli system. In these rocks the quartz veins are very common. The mineralization is largely confined to the dolomitic horizon. The ore occurs largely in the form of sheeted veins. The mineralization follow the lines of bedding and fractures of the shear zones.

Dariba-Rajpura belt is also in Udaipur district. The belt is a continuation of the Zawar lead-zinc belt. Here the lead and zinc ores occur in folded graphitic mica-schists and dolomites. The mineralized belt of Dariba-Rajpura is about 17 km long and it occurs on the western limb of a major fold. The mineralization contains sphalerite, galena and chalcopyrite with minor amount of pyrite and pyrrhotite. Here cadmium, arsenic and antimony ores occur in association with the Pb-Zn ores. The Pb-Zn ores are localized within the graphitic schists and in a fault zone between these schists and dolomitic rocks.

The total reserves of the lead-zinc ores in the Zawar belt is about 116 million tonnes. The average Pb—Zn content of the ore is about 3%.

Amba Mata Deposits of Gujrat. In Gujrat, a multimetal deposit of Pb, Zn and Cu occurs at Amba Mata in Banaskantha district. Here the galena-sphalerite-chalcopyrite mineralization occurs in the biotite talc-schists of Delhi age. The mineralization is controlled chiefly by the strike faults traversing the southwestern limb of a cross folded syncline. In Amba Mata area, the total reserves of the ore are about 5.5 million tonnes with average metal (Pb + Zn + Cu) content of 9.5%.

Sargipalli Deposits of Orissa. This deposit is situated in Sundargarh district of Orissa. In this area the country rocks are dark grey quartz-biotite schists, biotite-chlorite schists and dolomitic limestones belonging to the Gangpur series. These rocks are usually folded and faulted. The galena is commonly concentrated in the dark schists along shear zones. The ore occurs in the form of lodes, veins and stringers which show pinch and swell structure. In addition to galena, minor amounts of sphalerite, chalcopyrite and bornite are also found. The total reserves of the ore are about 5.6 million tonnes with an average grade of 5.7 % lead metal.

Agnigundala Deposits of Andhra Pradesh. The Agnigundala deposit is situated in Guntur district of Andhra Pradesh. Here the host rocks are dolomites and dolomitic limestones. The galena occurs in veins and stringers along with small amounts of chalcopyrite, sphalerite and pyrite.

9.32. ALUMINIUM ORE

Aluminium is a light, strong and durable metal. These properties together with its electrical conductivity make it a popular modern metal. It is used mainly in the aircraft construction, in the electrical industry and for making kitchen ware. Bauxite is used in the manufacture of abrasives, refractories and chemicals.

Mineralogy. The typical minerals of aluminium are gibbsite ($Al_2O_3.3H_2O$), boehmite ($Al_2O_3.H_2O$) and diaspore [$AlO(OH)$]. "*Bauxite*" is a rock which contains a mixture of gibbsite, boehmite and diaspore minerals. In bauxites the alumina content varies considerably.

Bauxite ($Al_2O_3.2H_2O$) is the major ore of aluminium. It occurs in association with laterite. "*Laterite*" is a weathered rock product in which Al_2O_3 is below 40% and Fe_2O_3 is between 20-30 %. A laterite containing above 50% Al_2O_3 is called bauxite. Bauxite occurs in three forms : (*i*) pisolitic, (*ii*) sponge ore and (*iii*) amorphus or clay ore.

9.32.1. Origin

Bauxite deposits are of residual origin. They are formed at or near the surface by weathering under tropical or subtropical climate. Bauxite deposits are produced from rocks which are rich in alumina such as granite, syenite, gneiss, shales, basalts, etc. During weathering the rock silicates are broken down, silica is removed, iron is partially removed, and alumina along with titanium and ferric oxide become concentrated in the residue. This alumina rich solid material is called "*Bauxite*". The conditions necessary for the formation of a bauxite deposit are as follows.

1. The source rock must be rich in alumina.
2. The climate should be humid tropical or subtropical.
3. There should be abundant precipitation to cause break down of rock silicates and solution of silica at specific pH and Eh conditions.
4. The terrain should be flat to permit slow downward infiltration.

9.32.2. Distribution

On the basis of mode of occurrence, the bauxite deposits can be classified into three groups :

(*i*) "*blanket deposits*" which occur at or near the surface, (*ii*) "*inter-stratified bedded deposits*" which lie on erosional unconformities, and (*iii*) "*pocket deposits*" which occupy solution or erosional depressions in limestones and dolomites.

Most of the Indian bauxite deposits are the blanket deposits which occur on the tops of Deccan trap plateaus. In India, the total reserves of bauxite are about 1900 million tonnes. The major bauxite deposits are as follows.

(*i*) **Bihar.** In Ranchi and Palamau districts. In Lohardaga area of Ranchi district, bauxite deposits occur in the laterite cappings on the top of granite and gneisses.

(*ii*) **Madhya Pradesh.** In Surguja, Bilaspur, Shahdol, Mandla and Jabalpur districts. Large deposits of bauxite are found on the Amarkantak plateau which falls in Mandla, Shahdol and Bilaspur districts. Here the bauxite deposits occur in the laterite cappings over Deccan traps.

(*iii*) **Maharashtra.** In Kolhapur, Ratnagiri and Kolaba districts. Here bauxite deposits occur in the laterite cappings on the Deccan traps.

(*iv*) **Orissa.** In Sambalpur, Koraput and Kalahandi districts. Here bauxite deposits occur as lenses and pockets in the khondalite rocks.

(*v*) **Andhra Pradesh.** In Visakhapatnam district. Here bauxite deposits occur over khondalite rocks.

(*vi*) **Karnataka.** In the Western Ghat belt of Belgaum, North Kanara and South Kanara districts. These bauxite deposits are derived from the Deccan trap lavas.

(*vii*) **Tamil Nadu.** In Shevaroy hills in Salem district. These bauxite deposits are derived from the charnockites.

9.33. CHROMITE

Chromite is an important ore of chromium metal. It is used for making chrome-steels, refractory materials and chromium chemicals. To steels chromium imparts strength, toughness, hardness and resistance to oxidation and corrosion.

Mineralogy. Chromite ($FeCr_2O_4$) is the only ore of chromium. Primary chromite deposits occur only in ultrabasic or closely related anorthosite rocks in the form of lenses, layers, massive veins and disseminations. Examples of ultrabasic rocks are peridotite dunite, pyroxenite and serpentine.

9.33.1. Origin

Almost all primary chromite deposits that occur within ultrabasic rocks are of magmatic origin. They usually occur as magmatic segregation or dissemination. Chromite also forms placer deposits because it is heavy and resists chemical weahtering.

9.33.2. Distribution

(*i*) **Orissa.** It is the major chromite producing area in India. The chromite deposits occur in Keonjhar, Cuttack and Dhenkanyal districts in talc-serpentine rock among the Iron-ore series. The ore is of high grade with 40—50% Cr_2O_3.

(*ii*) **Bihar.** In Bihar the chromite deposits are found near Jojohatu and Roroburu areas of Singhbhum district. These deposits occur in dunite and saxonite which intrude into the rocks of Iron-ore series. On the average the ore of this area contains about 53% Cr_2O_3.

(*iii*) **Maharashtra.** The chromite deposits are found in Ratnagiri and Bhandara districts. The chromite is worked near Pauni in Bhandara district. Here chromite occurs as thin layers in serpentinites of Sakoli series. The ore is of variable composition with Cr_2O_3 between 35% to 50%.

(*iv*) **Karnataka.** Important chromite deposits are found in Hassan and Mysore districts. Chromite occurs in serpentinized peridotites and amphibolites among Dharwars.

(*v*) **Andhra Pradesh.** In Andhra Pradesh chromite deposits are found near Kondapalle in Krishna district . Here chromite occurs in serpentinized ultrabasic charnockites.

(*vi*) **Tamil Nadu.** In this state, chromite deposits are found near Sitampundi in Salem district. Here the chromite occurs in anorthosites and pyroxenites which are intruded as sheets in the biotite-gneiss.

9.34 MICA

Mica is a hydrous silicate of aluminium with varying amounts of K, Na, Ca, Mg and Fe. It is characterized by a perfect basal cheavage. Mica occurs in the form of books or large sheets in pegmatites where it is associated mainly with quartz and felspars. There are several varieties of mica.

1. Muscovite (K, Mica). It is a colourless transparent mica.
2. Biotite (Fe, Mg, Mica). It is a dark coloured or black mica.
3. Phlogopite (Mg, Mica). It is an amber coloured mica.
4. Lepidolite (Li, Mica). It is a pale coloured mica.

Of these the muscovite and phlogopite are of great economic value. Mica is chiefly used in the manufacture of electrical goods where it serves as an insulating medium. It is also used in plastic and rubber industries.

9.34.1. Origin

The main source of commercial mica is the pegmatites which occur within the metamorphic rocks, such as schists and gneisses of Archaean age. The pegmatites are the intrusive igneous bodies which are formed from the late residual magma. The magma which is left in the last stage of crystallization is called "*late residual magma*". This magma mostly contains silica, alkalies, water, carbon dioxide and rare elements.

9.34.2. Distribution

In India, deposits of mica occur in three important belts: (*i*) mica belt of Bihar, (*ii*) mica belt of Andhra Pradesh, and (*iii*) mica belt of Rajasthan.

Mica Belt of Bihar. This belt extends in the ENE-WSW direction for a distance of about 150 km. Its width is about 20 km. This mica belt starts from Gaya district in the west and runs through Hazaribagh and Mongyr districts to Bhagalpur district in the east. The country rocks are mainly mica-schists of Archaean age. These rocks have been intruded by dykes of metadolerite and pegmatites.

Bihar mica belt contains mica of ruby-red colour. The commercial deposits of mica are found in those pegmatites which occur within mica-schists and mica-gneisses. There are about 600 mines in this belt. The mining activities are mainly centred in the Kodarma area of Hazaribagh district.

Mica Belt of Andhra Pradesh. In Andhar Pradesh, the mica is obtained chiefly from the "*Nellore-mica-belt*". This belt is about 96 km long and 16 km wide. It extends in the NW-SE direction between Gudur and Sangam. The host rocks are mica-schists, chlorite-schists and hornblende-gneisses of Archaean age. These rocks contain sheets, lenses and masses of pegmatite which contain mica. The common Nellore-mica is of green colour.

Mica Belt of Rajasthan. In Rajasthan, deposits of mica are found in Ajmer-Merwara, Mewar, Jaipur and Bhilwara districts. The mica pegmatites occur as intrusives in the gneisses and schists of Archaean age. The usual quality of mica is of the ruby-red type but green mica is also produced in small quantity.

9.35. METALLOGENIC EPOCHS

Cycles of erosion, deposition, folding, faulting, igneous activity and ore deposition have been repeated through geologic time. These cycles of ore formation have given rise to metallogenic epochs.

Most of the mineral deposits of one type are formed in regions during definite periods in the earth's history. Such deposits constitute the "*metallogenic epochs*". For example, the chromite deposits found in the Archaean rocks are affiliated to ultrabasic igneous rocks. They are formed in regions of crustal disturbance during period of igneous intrusion. These deposits constitute a metallogenic epoch.

The deposits of coal, iron ore, and manganese ore are of sedimentary origin. They are formed during periods of quiet sedimentation. Hence they also constitute metallogenic epochs. However, the ore deposits formed due to weathering, do not form any metallogenic epoch because the process of weathering has operated at all times in the earth's history.

9.35.1. Metallogenic Epochs of India

Archaean Period. In India, several metallogenic epochs have been recognised in the Archaean period. Periods of igneous activity and accompanying ore formation alternated with periods of sedimentation and accompanying mineral deposition. All the important deposits of Fe, Mn, Au, Cu, Pb, Zn, Cr, and mica were formed in this period. In the shield areas of India, the five main belts of Archaean rockformations are: (*i*) Karnataka and adjoining states, (*ii*) Eastern Ghat, (*iii*) Singhbhum-Gangpur area of Bihar and Orissa, (*iv*) Nagpur-Durg area of central India, and (*v*) Aravalli belt of Rajasthan. In these belts the following epochs of ore formation have been recognised.

(*i*) **Sedimentary-Metamorphic Deposits.** The deposits of iron and manganese ore found in various regions in the Archaean rocks, are of sedimentary-metamorphic origion.

(*ii*) **Magmatic Deposits.** The Archaean rocks have been intruded by basic and ultrabasic rocks which have given rise to magmatic deposits of chromite, nickel, and titaniferous and vanadiferous magnetite.

(*iii*) **Hydrothermal Deposits.** The Archaean rocks contain economic ore deposits of gold, copper, lead, zinc and uranium. these hydrothermal deposits are believed to have been derived from the granitic and gneissic intrusions.

(*iv*) **Pegmatitic Deposits.** The deposits of mica belong to this category.

Cuddapah Period. The main Cuddapah basin is situated in Andhra Pradesh. The important mineral deposits found in the cuddapah rocks are copper, lead, zinc, asbestos and barytes.

Delhi Period. The Delhi rockformations occur along the Aravalli mountains in Rajasthan. These rocks contain mainly the hydrothermal deposits of copper, lead and zinc. The mineralization is caused by the acid magmatism.

Vindhyan Period. The Vindhyan rockformations show extensive development in central India. No major metallogenic epoch has been recognised in this period.

Gondwana Period. The Lower Gondwana rocks contain coal seams. The coal seams are formed during periods of quiet sedimentation. Hence they constitute a mineralogenic epoch.

9.36. METALLOGENIC PROVINCES

The regions where mineral deposits of specific types are found abundantly, are called "*metallogenic provinces*". A metallogenic province may contain mineralization of more than one epoch. Examples of metallogenic provinces of India are as follows.

1. **Bihar-West Bengal Area.** This area may be regarded as a coal province, as most of the coal fields of India are concentrated in this region.
2. **M.P.-Maharashtra Area.** This region may be regarded as manganese province, as large deposits of manganese ore are situated in this area.
3. **Karnataka.** The Kolar gold field may be regarded as a gold province.

REVIEW QUESTIONS

1. List the common processes of formation of mineral deposits. Describe the placer deposits in detail.
2. What do you understand by ore and gangue minerals? Give examples. Describe the ore deposits formed by weathering.
3. What is a hydrothermal deposit. Give the classification of hydrothermal deposits. Describe the vein deposits in detail.
4. Give the classification of the processes of formation of mineral deposits. Describe either the magmatic deposits or the supergene enrichment deposits.
5. Describe the various chemical properties of coal which determine its commercial value. Give the occurrence of coal in India.
6. Give the various theories about the origin of coal. Out of these theories which is applicable to Indian coals and why?
7. What is a bituminous coal ? Write about the banded constituents of coal. Explain the origin and mode of occurrence of coal seams.
8. Write short notes on the following.

   Tenor, Contact metasomatic deposits, Gossan, Rank of coal, Replacement deposits, Fissure vein, and Oil traps.
9. Describe the factors that control the mineral localization.
10. Describe in brief the origin and occurrence of petrolium. Where does the petrolium occur in India.
11. Describe in brief about the industrial use, origin, mode of occurrence and distribution of chromite.

12. What is bauxite ? Where does bauxite occurs in India? Write about the origin of bauxite.
13. What do you understand by base metal deposits ? Describe the origin and occurrence of the base metal deposits of India.
14. Describe with sketches the geological conditions favourable for accumulation of petrolium.
15. Write a brief essay on the occurrence of petrolium deposits in India.
16. What is petrolium ? Discuss the modern theory of petrolium formation. Describe the process of its accumulation.
17. Name the important ores of copper. Describe the origin and mode of occurrence of copper ores with reference to the deposits in India.
18. Describe the iron ore or manganese ore deposits of India with special reference to origin, mode of occurrence and distribution.
19. Indicate the important geological periods or epochs when formation of mineral deposits of economic importance took place in india.
20. Write short notes on the following.

    Metallogenic epochs and provinces, Gold deposits of India, Migration of petrolium, Bombay High, Mica deposits and Controls of mineral localization.

10 Engineering Geology

10.1. GEOLOGY AND CIVIL ENGINEERING

The value of geology in *"Mining"* has long been known but its use in *"Civil Engineering"* has been recognised only in comparatively recent years. The importance of geology in civil engineering may briefly be outlined as follows.

1. Geology provides a systematic knowledge of construction material, its occurrence, composition, durability and other properties. Examples of such construction materials are building stones, road metal, clays, limestones, and laterite.
2. The knowledge of the geological work of natural agencies such as water, wind, ice and earthquakes helps in planning and carrying out major civil engineering works. For example the knowledge of erosion, transportation and deposition helps greatly in solving the expensive problems of river control, coastal and harbour work and soil conservation.
3. Ground water is the water which occurs in the subsurface rocks. The knowledge about its quantity and depth of occurrence is required in connection with water supply, irrigation, excavation and many other civil engineering works.
4. The foundation problems of dams, bridges and buildings are directly concerned with the geology of the area where they are to be built. In these works drilling is commonly undertaken to explore the ground conditions. Geology helps greatly in interpretating the drilling data.
5. In tunneling, constructing roads, canals, docks, and in determining the stability of cuts and slopes, the knowledge about the nature and structure of rocks is very necessary.

6. Before starting a major engineering project at a place, a detailed geological report which is accompanied by geological maps and sections, is prepared. Such a report helps in planning and constructing the project.
7. The stability of the civil engineering structures is considerably increased if the geological features like faults, joints, bedding planes, folding, solution channels, etc. in the rock beds are properly located and suitably treated.
8. In the study of soil mechanics, it is necessary to know how the soil materials are formed in nature.
9. The cost of engineering works will considerably be reduced if the geological survey of the area concerned is done before hand.

For a major engineering project precise geological survey is carried out and the results thus obtained are used in solving engineering problems at hand. Although the geological work is done by an engineering geologist, this does not mean that the civil engineers have nothing to do with the geology. For the civil engineers, the knowledge of geology is essential for understanding the geological reports and for using the geological data for solving engineering problems. If adequate geological investigations are carried out before constructing major engineering works, many disasters can be prevented and human life and properties can be saved.

10.2. BUILDING STONES

The building stones are products of rocks that are used in constructing buildings, dams, bridges, etc. The rock material used for construction includes : (*i*) building stones—in the form of masonry blocks, (*ii*) rubbles —in the form of small irregular fragments, (*iii*) crushed stones—to make concrete, and (*iv*) limestones—to make lime and cement.

10.2.1. Properties of Building Stones

In order to select the rock material for construction, the properties that are commonly examined are : (*i*) mineral composition, (*ii*) texture, (*iii*) structure, (*iv*) porosity, (*v*) permeability, (*vi*) durability, (*vii*) strength of rock, and (*viii*) heat resistance.

Mineral Composition. The rocks are aggregates of minerals. If the mineral constituents of a rock are hard, free from cleavage and resistant to weathering, it is likely to be strong and durable. The rocks which are rich in weak minerals, such as micas, chlorite, talc, felspars and clay minerals, are not durable.

Texture. Fine grained rocks are generally more dense and stronger than coarse grained rocks. It is for this reason that the basalts and dolerites are widely used as road metal.

Structure. Many rocks contain structures like stratification, lamination, foliation and cleavage. Such rocks bear greater loads if they are placed in the construction parallel to the planes of weakness (*Fig. 10.1*). Further, since laminated or banded rocks may scale badly due to weathering, it will not be wise to place them in the civil engineering works with the cleavage or bedding planes vertical.

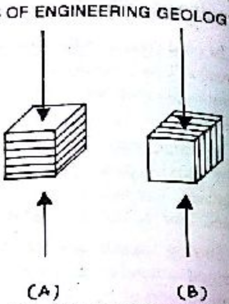


Fig. 10.1 (*a*) High crushing strength, (*b*) Low crushing strength.

Porosity. The porosity of a rock is the ratio of the volume occupied by pores to the total volume of the rock sample. It is generally expressed in percentage of the volume of the sample. If W_1 is the weight of the dry rock sample, W_2 is the weight of the sample when it is made saturated with water, and V is its total volume, the porosity P can be determined as follows.

$$P = \frac{W_2 - W_1}{V} \cdot 100$$

A less porous rock is generally more durable and strong and therefore it is preferred for construction purposes.

Strength of Rock. The strength of a rock is determined by knowing its crushing strength, shearing strength and resistance to abrasion. The *"crushing strength"* is the resistance offered by a stone to pressure. The resistance offered by a stone to shear stresses which tend to move one part of a specimen with respect to the other, is called *"shearing strength"*. The stones which are to be put in the foundation of civil engineering structures, must have high crushing and shearing strength. For making road metal the rocks having high crushing strength are selected.

The resistance of a stone to scratching or rubbing action is called its *"resistance to abrasion"*. The stone used for paving and flooring purposes must have high resistance to abrasion.

Permeability. Permeability is the capacity of a rock to transmit water. It indicates the ease with which the water can percolate through the openings of the rocks. The permeability of rocks is particularly important in a number of engineering problems such as those connected with dams, reservoirs, water supply, sanitary engineering and other structures. The permeable rocks are considered harmful because they cause seepage of water which may even lead to the destruction of the structure.

Durability. The durability of a stone is its capacity to retain its original size, strength and appearence throughout a long period. Some rocks which do not resist weathering, decay and loose strength early. The durability of a rock is directly related to its mineral composition and texture.

In cold countries the frost action plays an important part in disintegrating rocks. The water which enters into the openings of a rock, freezes during the night. On freezing it induces tensile stresses due to which cracks develop in the rocks.

Building stones in big cities are severely affected by carbon dioxide and sulfur dioxide gases which are released into the atmosphere by various industries. The calcite present in the limestones and marbles may be transformed into sulfate and scaling may result.

During continuous rain the pores in a stone may be filled with a saturated salt solution. Then the crystallization of salt occurs which causes disintegration of stones.

Heat Resistance. When rocks are heated to a high temperature and then cooled, they may get damaged. This is perticularly the case if they are rich in minerals like calcite and felspars. The rocks in the order of decreasing resistance to damage by fire are sandstones, granites, limestones, gneiss and marble.

10.2.2. Rocks and Building Stones

The rocks which are commonly used for construction works are as follows.

(*i*) **Granites.** Granites are used for construction purposes on account of their high crushing strength, low porosity and pleasing pink or grey colours. They are capable of taking good polish. Granites are commonly used for massive masonries, and for architectural and ornamental work. The granites occur abundantly in regions occupied by the Archaean rocks.

(*ii*) **Basalts and Dolerites.** The basalts and dolerite are fine grained igneous rocks of basic composition. These rocks serve as excellent road metal because of their high crushing strength. Although the basalts are easily workable and durable stones, they are not used commonly as building stone due to their dull and unpleasant colour. The basalts which are commonly known as the Deccan traps occupy a wide region of western and central India.

(*iii*) **Sandstones and Quartzites.** Well cemented sandstones generally have all the characters of a good building stone. In India the Upper Vindhyan sandstones are widely used for building work. They are used both for masonry work and as flagstones. Many historical buildings of Delhi, Agra and Rajashtan are made up of the Vindhyan sandstone. Quartzites do not form good building stone because their extremely hard nature renders their working difficult.

(*iv*) **Limestones and Marbles.** Because of their homogeneous texture, easy workability and pleasing colours, limestones and marbles form good building and ornamental stones. The limestones are not only used as building stones, they are also used for making lime and cement.

(*v*) **Slate.** The slate is a metamorphic work which can be broken easily into thin smooth slabs. It is used chiefly for roofing and paving in buildings.

10.3. GEOLOGY OF DAM SITES

10.3.1. Dams

The dams are barriers which are constructed across rivers to store water. They are built mainly to control floods, for irrigating lands, for generating electricity and for supplying water to industries and cities. A dam that serves more than one purpose is called a *"multipurpose dam"*.

10.3.2. Terminology

Spillway. It is a structure made to discharge the surplus water from storage reservoir into the river on the downstream side of the dam. Through the spillways and gates, the flood water can pass safely without causing any damage to the dam.

Heel of Dam. The portion of a dam that touches the ground on the upstream side, is called the *"heel of a dam"* (*Fig. 10.2*).

Toe of Dam. The portion of a dam that touches the ground on the downstream side, is called the *"toe of a dam"* (*Fig. 10.2*).

Axis of Dam. It is an imaginary line that passes along the length of a dam through its centre.

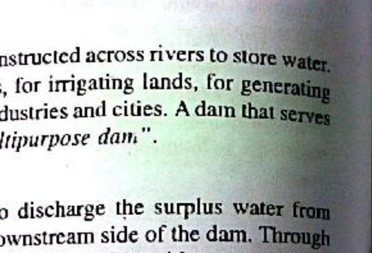


Fig. 10.2. Showing heel and toe of a dam.

Abutments. The sloping sides of a river valley upon which the sides of a dam are keyed, are called *"abutments"*.

Grouting. Grouting is a method in which suitable mixture of cement - water, cement - calcium chloride, cement - clay, asphaltic emulsions, or other material is injected into the rocks to seal the openings. The grouting mixture is usually pumped through holes drilled in the rocks for this purpose. Grouting is done to consolidate the rocks and to check the seepage of water through them.

10.3.3. Types of Dam

The dams may be classified into two groups : (*i*) concrete and masonry dams, and (*ii*) earth fill dams. The concrete and masonry dams are commonly built to big heights. The earth dams, however, are used for small projects with a maximum height of about 100 meters. The main types of dams are as follows.

(*i*) **Gravity Dam.** It is a massive structure of concrete or masonry which stands by its own weight. Generally a sound foundation rock is required for the construction of gravity dams.

(*ii*) **Arch Dam.** It is an arch-shaped structure of a single concrete wall, the convex side of which faces upstream. The arch dams transmit water pressures to the abutments by arch action. Hence very strong abutment rocks are required for constructing arch dams.

(*iii*) **Buttress Dam.** In this type of dams buttresses are constructed at the downstream side to support an upstream deck of reinforced concrete. The buttress dams are usually constructed on a good foundation rock.

(*iv*) **Earth Dam.** The earth dams are constructed mainly by soil or earth. These dams have an advantage as they can be built on earth or poor rock conditions.

10.3.4. Forces Acting on Dams

Water Pressure. In *Fig. 10.2*, T is the pressure of reservoir water which tends to displace the dam horizontally, W is the weight of the dam which acts downwards and tends to key the dam in position and R is the resultant of forces T and W which indiates that when the reservoir is full, the toe of the dam is overloaded and the heel is relieved. Therefore in order to make the dam stable, the ratio T/W has to be kept smaller.

Pore Pressure. The water entering in permeable rocks below the dam, exerts an upward pressure on the base of it. This pressure which is equivalent to the hydrostatic pressure, is called the *"pore pressure or uplift pressure"*. It acts against the weight of the dam and thus helps in sliding or overturning it.

10.3.5. Problems Associated with Dam Sites

Most of the dam failures that have occured in the past are not due to faulty design or construction but mainly due to neglect of the geological flaws. The main geological problems that are usually met with at dam sites are as follows.

(*i*) Dams on shales

(*ii*) Dams on soluble rocks.

(*iii*) Dams on strata dipping upstream.

(*iv*) Dams on strata dipping downstream.

(*v*) Dams built across strike of rocks.

(*vi*) Dams on jointed and permeable rocks.

(*vii*) Dams on faults.

(*viii*) Abutment problems.

(*i*) **Dams on Shales.** Shales are of two types : (*i*) cementation shales, and (*ii*) compaction shales. The cementation shales are stronger and do not disintegrate when subjected to wetting and drying. The compaction shales on the other hand are soft and they slake when subjected to alternate wetting and drying. Their bearing strength is low and they become plastic when wetted. The compaction shales have a tendency to flow away from the loaded area and therefore the structure settles. Swelling and caving may result during the excavation work which may cause trouble. If dams have to be built on compaction shales, heavier structures like gravity dams should be avoided. After excavating the weathered rock either concrete should be placed immediately without delay or its surface should be coated with asphalt to avoid swelling and caving.

(*ii*) **Dams on Soluble Rocks.** The soluble rocks include limestones, dolomites and marbles. These rocks are generally sufficiently strong to support the weight of the dam, but they may contain underground solution channels and caverns. If such solution channels are present at a dam site, the leakage through them may be on such a large scale that the reservoir may not hold water for long. The treatment of such openings is very expensive therefore they should be carefully looked for in the soluble rocks before constructing a dam.

(*iii*) **Dams on Strata Dipping Upstream.** The dams located on rocks dipping upstream represent ideal foundation conditions. They are the most capable of supporting the weight of dams and the pressure of the reservoir because the resultant of these two forces acts nearly at right angles to the bedding planes of rocks (*Fig. 10.3*). Further, the upstream dip of rocks does not allow the water in the reservoir to percolate below the dam. As a result the leakage of water and the development of uplift pressure will be minimum.

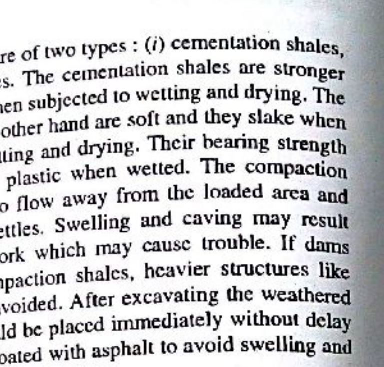


Fig. 10.3. Dam on rocks dipping upstream.

(*iv*) **Dams on Strata Dipping Downstream.** The dams constructed on rocks dipping downstream (*Fig. 10.4*) may not be safe due to the following reasons.

(*a*) The percolation of water may lubricate the junctions of rock beds which may facilitate sliding of dams.

(*b*) The water percolating through the strata dissolves the cementing material of rocks and enlarges the openings by mechanical erosion. This undermines the strength of the rocks and increases the seepage of water.

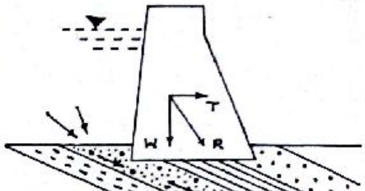


Fig. 10.4. Dam on strata dipping downstream.

(*c*) The water which enters into the openings of rocks below the dam, causes the development of uplift pressure which tends to decrease the stability of the structure.

(*d*) In *Fig. 10.4, R* is the resultant of the weight of the dam and pressure of the reservoir water. In this case, this resultant acts nearly parallel to the bedding planes and endangers the stability of the dam.

(*v*) **Dams Built Across Strike of Rocks.** The best foundation condition is when only one uniform rock is present along the length of a dam. If a dam is aligned across the strike of strata, its foundation will be on different rock types of varying properties. In such a case, there are chances of unequal settlement of the dam. Further, as the bedding planes of strata lie across the axis of the dam, there is a possibility of serious leakage of water not only through the porous beds but through bedding planes also (*Fig. 10.5*).

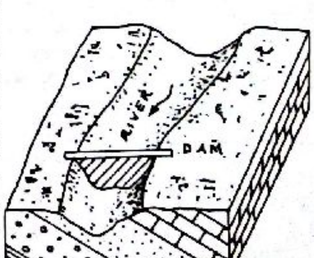


Fig. 10.5. Dam aligned across the strike of rocks.

(*vi*) **Dams on Jointed and Permeable Rocks.** Where highly fissured, jointed and permeable rocks exist below the dam, they will not only cause leakage of water, but also build uplift pressure at the base of the dam. The uplift pressure acts opposite to the weight of the structure and it may cause sliding. Such rocks may be consolidated by grouting.

(*vii*) **Dams on Faults.** Faults are most troublesome if they are encountered across the length of the dam. It is better to avoid fault zones for the construction of dams. The fault zones cause the following troubles.

(*a*) It is difficult to seal the fault zones and prevent leakage of water from the reservoir at reasonable cost.

(*b*) The rocks may weather upto a great depth along a fault zone. This requires digging and scraping of the weathered rock to a great depth and refilling the trench with concrete.

(*c*) The crushed and fissured rocks that exist along a fault zone in the foundation, have to be grouted intensively to increase their bearing strength.

(*d*) Along a fault some displacement of strata is always expected, perticularly during an earthquake. Such a movement will not only reopen the fault fissure but also rupture the dam.

(*e*) A site where the fault is known to have been active in recent years, should always be discarded.

(*viii*) **Abutment Problems.** Careful attention should be given to the orientation of joints, bedding planes, foliations and weak zones that are present in the abutment rocks. If such weak zones lie parallel to the thrust of water in the reservoir, the stability of the structure may be endangered. The rocks that exist in the abutments of an arch dam, should be strong enough to resists the pressure without being crushed.

10.4. GEOLOGY OF RESERVOIRS

The artificial lakes which are created by constructing dams across rivers, are called *"reservoirs"*. A reservoir may fail either due to excessive leakage of water or as a result of rapid sedimentation.

10.4.1. Problems Associated with Reservoirs

The main geological problems connected with the reservoirs are : (*i*) groundwater conditions, (*ii*) permeable rocks, and (*iii*) silting.

(*i*) **Groundwater Conditions.** The amount of leakage of water from the reservoir is controled by the depth of water table. If the water table is so near the ground surface that the water level in the reservoir does not rise above it, no serious loss by leakage will occur (*Fig. 10.6*). On the other hand, if water table lies deep below the ground surface, the water level in the reservoir will stand

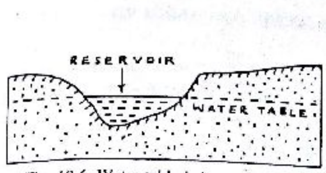


Fig. 10.6. Water table being near to the ground surface, serious leakage will not occur.

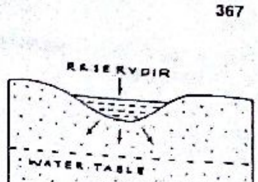


Fig. 10.7. Showing leakage due to deep water table.

above it. As a result, leakage will occur and its amount will depend on the permeability of rocks (Fig. 10.7).

(*ii*) **Permeable Rocks.** During the geological investigation it is necessary to locate the highly permeable rocks that are present in the reservoir area. The rocks which are highly fissured, intensely jointed, faulted or have solution channels, are likely to cause serious leakage from the reservoir.

Generally the leakage of water from the strata that have downstream dip, will be more than those which have upstream dip. If a permeable rock bed outcrops on the valley slopes in the reservoir, it may not only cause leakage but may also cause land-slide (Fig. 10.8). Such a landslide may produce an opening in the reservoir rim through which the stored water may escape.

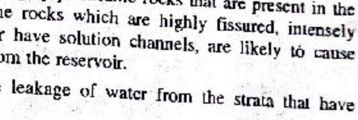


Fig. 10.8. Showing possibility of leakage and landslide.

(*iii*) **Silting of Reservoir.** The reservoirs built on rivers which carry large amount of sediment, may silt up very soon and its water storage capacity may be reduced considerably. The amount of silt produced and supplied to the rivers depends mainly upon the lithological character and topography of the catchment area. The rivers flowing over the soft rocks and high gradient areas, carry greater amount of silt. On such rivers silt traps may be constructed upstream in order to check the rate of silting in the reservoir. Provisions should also be made for washing out the silt through the passages in the dam.

10.5. GEOLOGICAL INVESTIGATION OF DAMS AND RESERVOIRS

The geological investigation of the area is done to detect geological flaws and to select a suitable site for the dam and reservoir to be constructed. The objects of this investigation may be summarized as follows.

1. To study the physiographic features of the area.
2. To determine nature and depth of filling in the river channel at the dam site.
3. To delineate areas favourable for the location of spillways, diversion tunnel, power house, etc.
4. To determine the lithological composition and structure of the rocks present in the area.
5. To locate structural defects such as faults, fractures, joints, solution channels, etc. in the rocks.
6. To locate potential leakage zones in the vicinity of the dam and reservoir.
7. To evaluate the rate of silting in the reservoir.
8. To locate construction materials in the vicinity of the dam.

10.5.1. Geological Survey

Air-photos and geologic map of the area under investigation is obtained which serves as a guide for detailed geological survey. The geological investigation is normally started with the interpretation of air-photos and maps, followed by field work and laboratory testing, and ends with the preparation of field report. This investigation may broadly be subdivided into three groups : (*i*) study of physiography, (*ii*) study of lithology, and (*iii*) study of geological structures.

(*i*) **Study of Physiography.** The physiographic characters of the reservoir area are studied on the air-photographs. This gives idea abut : (*i*) shape and size of the river valley, (*ii*) its stage of development, (*iii*) stability of valley slopes, and (*iv*) potential areas of scouring and erosion.

The bed rocks in the river valleys are often covered up with a layer of alluvium of variable thickness. It is necessary to know about the thickness of filling at the dam site. An idea about it may be obtained from the stage of development of the river valley and from the geophysical investigations.

In a river valley, the existence of a concealed fault is always suspected. This is perticularly the case where a river cuts through a mountain range.

By studying the topography and rock outcrops of the valley sides, the potential areas for locating spillways, diversion tunnel, power house, etc. may be delineated.

(*ii*) **Study of Lithology.** During field work a detailed geological map is prepared and the lithological characters of the rocks present in the area are examined.

The pervious and impervious strata are located and the potential leakage zones are delineated. Where rocks contain joints, fissures, solution channels, shear zones and faults, there is every possibility of seepage of water.

The rocks present in the foundation and abutments of the dam, must be sound enough to withstand the expected static and dynamic pressures. The rocks exposed in the reservoir rim must be resistant to solution, erosion and other damaging effects of water. By studying the lithology and topography of the catchment area of the river, the amount of silt likely to be contributed annually to the reservoir must be estimated.

Efforts should also be made to locate the construction materials near the dam site. This will cut down the transport cost considerably. The important construction materials are masonry stones for rip rap, gravels and sands for aggregate and clay for impervious filling.

(*iii*) **Study of Geologic Structures.** The geological structures of the rocks present in the area, have an important bearing on the design and stability of the dam. A site where the strata dip upstream is preferred to that where they dip downstream.

The rocks existing in the foundation of a dam and reservoir walls should be watertight. If some potential leakage zones are present, they should be delineated. Further, the leakage of water through a porous bed may give rise to landslides. If rocks exposed in the foundation and abutments of the dam are highly jointed, the spacing and intensity of jointing, are recorded. This will help in assessing the grouting problem. Faults if present should be carefully delineated because they would require expensive treatment.

10.6. TUNNELS

A "*tunnel*" is a nearly horizontal underground passage which is open at both the ends to the ground surface. Tunnels are constructed below cities, rivers, and through mountains for carrying railways, roads, canals, water supply and sewage.

A tunnel which functions as a part of pipe line and carries water under pressure is called "*pressure tunnel*". Such water tunnels are used in producing hydroelectricity. The lining of a pressure tunnel is subjected to three types of pressures : (*i*) internal hydrostatic pressure, (*ii*) external rock pressure, and (*iii*) external hydraulic pressure. The external hydraulic pressure develops when water from the tunnel seeps into the adjacent country rocks. In water tunnels an important function of lining is to reduce the frictional losses.

10.6.1. Constructional Features

Tunnel Lining. In hard, massive and unfractured rocks the tunnels may be constructed without lining. However in weak, thinly bedded and fractured rocks lining has to be given to support the roof load and to prevent the seepage of large volume of water into the tunnel. The concrete, plain or reinforced is generally used for the lining.

Tunnel Support. While tunneling through the rock or soil, supports are generally required to prevent the rock material from caving. If tunnel supports are not placed, the material will fall piece by piece and *"overbreak"* will result. The tunnel walls and roof are supported by wood and steel. These supports may be removed prior to lining or they may be allowed to remain in place and are embedded in the concrete.

Overbreak. During the excavation work some rock outside the desired perimeter of the tunnel is removed so that a concrete lining of proper thickness may be placed. The rock excavated beyond the required cross-section of the tunnel is known as *"overbreak"*. (*Fig. 10.9*). As the overbreak has to be filled back with the concrete, it increases the cost of lining. The chief factors which cause overbreak are : (*i*) presence of hard and tough rocks, (*ii*) presence of closely spaced joints and fractures, (*iii*) presence of thinly bedded rocks, and (*iv*) delay in placing roof supports.

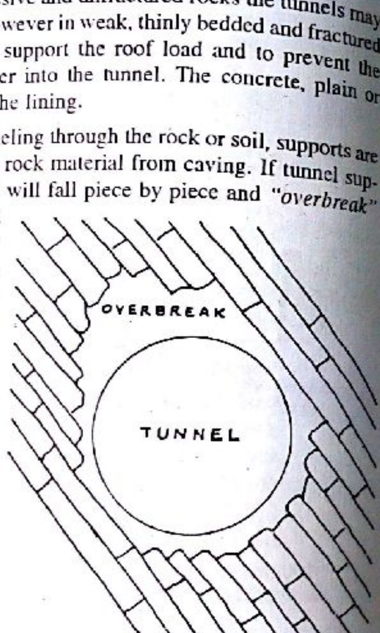


Fig. 10.9. Overbreak in inclined strata.

10.6.2. Tunnels in Soft Ground

The soft ground includes those soft and unconsolidated materials which possess little or no cohesion and have a very low crushing strength. These materials consist of gravels, sands, silts, clays and soft shales. They may be dry or water bearing. Excavation through such a ground does not require blasting. Arch supports are always necessary. The soft ground may be divided into three groups.

(*i*) **Revelling Ground.** The material of the revelling ground flakes and breaks into pieces sometime after it is exposed.

(*ii*) **Running Ground.** Such a ground consists of clean loose gravels or sands which run into the excavation.

(*iii*) **Squeezing Ground.** The squeezing ground consists of material that contains a large amount of clay. Such a material flows into the tunnel plastically.

In shallow tunnels that are driven in the soft ground, the roof load is enormous. It will be equivalent to the full weight of the overlying material and therefore, a very strong lining is required to support it. In some cases, an inverted arch has to be put on the floor of the tunnel to prevent the wet material from being pushed up into the tunnel. Because of these difficulties shallow tunnels are not constructed and deep open cuts are generally made instead.

In deep tunnels where the thickness of the roof material exceeds three times the diameter of the tunnel, the roof load is insignificant. It is shown by W_2 in *Fig. 10.10.* However, if the cohesion of the material deteriorates, the weight may increase to W_1 which is still not much.

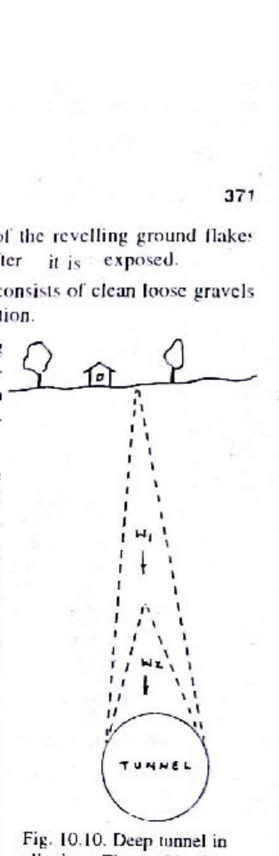


Fig. 10.10. Deep tunnel in alluvium. The roof load is insignificant.

10.6.3. Tunnels in Rocks

Tunneling through rocks requires blasting. If the rocks met with are structurally poor, support is often placed under the tunnel ceiling to prevent the rocks from falling during blasting. The geological factors which influence tunneling are as follows.

(*i*) Swelling rocks.
(*ii*) Inclined strata.
(*iii*) Folded rocks.
(*iv*) Fault zones.
(*v*) Jointed rocks.
(*vi*) Water bearing rocks.

(*i*) **Swelling Rocks.** If a tunnel is to be constructed through swelling rocks, it will require special treatment. The examples of swelling rocks are shale, unconsolidated tuff and anhydrite. Such rocks when exposed, absorb moisture and swell. In such cases very strong supports should be used. The swelling rocks should also be protected from wetting to the greatest possible degree.

(*ii*) **Inclined Strata.** In inclined rock beds when a tunnel is driven parallel to the strike direction, there is a tendency in the rocks to fall into the tunnel from the side where the beds dip into the tunnel (*Fig. 10.11*). This is perticularly the case if the hard and soft rocks, such as sandstone and shale are interbedded.

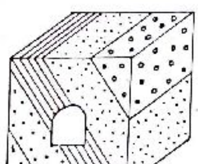


Fig. 10.11. Tunnel along the strike of strata. Pressure concentration is at one side of the tunnel.

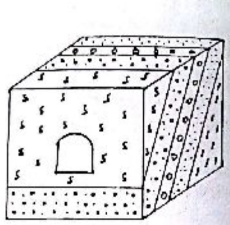


Fig. 10.12. Tunnel across the strike of strata. Pressure is downward from the roof.[1]

When a tunnel is made across the strike of rocks, it will traverse beds of different rocks (*Fig. 10.12*). In such cases there will be downward pressure from the roof. Water troubles are likely to be encountered where porous beds are found.

(*iii*) **Folded Rocks.** In tunnels that are driven through synclinal folds, the joint blocks form inverted keystones in the arch and cause rockfalls. In case the rocks happen to be water-bearing, the water flows into the tunnel and causes great difficulties (*Fig. 10.13 and 10.15*).

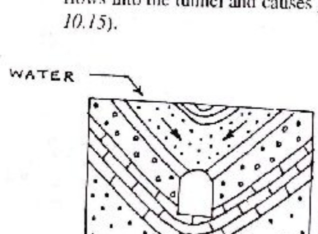


Fig. 10.13. Tunnel along the axis of a syncline. Pressure on the roof and sides is more.

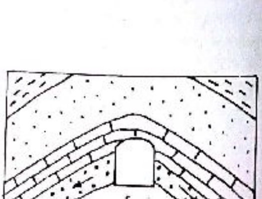


Fig. 10.14. Tunnel along the axis of an anticline. Pressure on the roof and sides is less and water troubles are also less.

In a tunnel that cuts through an anticline, the danger from sudden rockfalls is less because the joint blocks will be in the shape of normal keystones and therefore they are unlikely to fall into the tunnel. If the water-bearing strata are met with, the water trouble will be less because in anticlines the water flows away from it (*Fig. 10.14 and 10.16*).

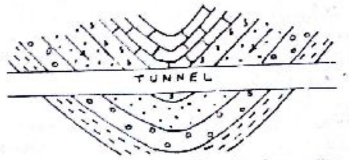


Fig. 10.15. Tunnel across the axis of a syncline.

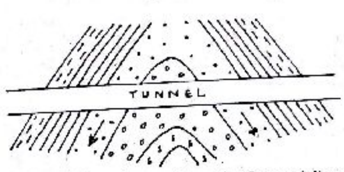


Fig. 10.16. Tunnel across the axis of an anticline.

(*iv*) **Fault Zones.** Faults are commonly found associated with a zone of highly crushed rock or clay gouge. The crushed rocks being highly permeable allows groundwater to seep into the tunnel. Besides this they also form unstable roof rock. The clay gouge is a very fine and soft material. On wetting it becomes plastic and caves into the tunnel. Faults therefore, are a source of major trouble in tunneling. It is always better to deviate the tunnel alignment and avoid fault zones. If this is not possible, the tunnel should be driven at right angles to the fault so as to meet the disturbed zone for a minimum distance. Exceedingly strong lining is required to be put in the fault zone sections.

(*v*) **Jointed Rocks.** Joints at one hand may help in excavating the rocks but on the other hand they may present difficulties in tunneling. If the joins are closely spaced and water-bearing, rockfalls and groundwater seepage may occur into the tunnel. If a lake, canal or river is present in the vicinity of the tunnel, its water may drain into the excavation through open joints and fissures.

(*vi*) **Waterbearing Rocks.** Driving a tunnel though water-bearing rocks is a difficult job. During excavation the groundwater rushes into the tunnel and causes flooding. This makes construction work difficult. If some clayey rocks are present, their strength may be strongly affected by the flow of water through them.

10.7. GEOLOGICAL SURVEY OF TUNNELS

In majority of cases, the location and alignment of tunnels and size of the bore are established prior to the geological survey. Before starting the geological investigation, photo-geologic interpretation should be done along the tunnel alignment. This will provide information on the topography, nature of surface material, broad geologic structures, water conditions and vegetation.

The geological investigation is done to disclose the nature and structure of the surface material and subsurface rocks. The geological defects such as faults, shear zones, joints, and water-bearing horizons, if present along, the proposed tunnel lines are carefully outlined. In this job the help of drilling and geophysical survey are also taken. This makes it possible to demarcate precisely the zones which may cause troubles in tunneling. The prediction of such trouble zones before hand is of great importance, as it helps in making preparations at a right time to avoid the hazards. This not only increases the safety of workers but also makes the construction economical.

A study of the hydrological conditions is another important aspect of the geological survey. This involves in finding the depth of water table, direction and velocity of movement of groundwater, and the seasonal change of the water table. A tunnel which is located above the water table will be safe from groundwater invasion and seasonal flooding.

The outline of the geological survey for constructing a tunnel is as follows.

(*i*) A detailed geological map is prepared showing various rock types present in the area. Their lithological characters, textures and mechanical properties are determined. The geological structures such as dips, folds, faults, joints, shear zones, etc. are studied and marked on the geological map.

(*ii*) The surface water seepages, if any, and depth of water table at various places along the tunnel alignment are also shown on the map.

(*iii*) The results of the geological survey may be confirmed by drilling and geophysical survey. In geophysical survey, mainly the electrical resistivity survey is carried out to provide information on the extent of faulting and fracturing, depth of bed rock under soil cover and location of a perticular rockformation.

The above said geological survey provides enough data to prepare geological sections along the tunnel alignment. Such sections show clearly the various lithological units, their structures, depth of buried rock surfaces at various places, position and depth of water-bearing horizons, faults and fracture zones. This helps in choosing the proper excavation methods and in forecasting the troubles in tunneling. Thus the geological survey is of great help to the design and construction engineers.

10.8. BRIDGES

Bridges form an important part of the transportation rutes. They are constructed across the rivers to carry highways and railways. In a country,

roads and railways often follow the shortest rute and therefore their alignment is determined much before the construction of bridges. As a result, the site of a bridge does not allow much freedom of choice.

10.8.1. Terminology

Abutment. The abutment is a terminal support of the bridge. It is built on either side of a river valley where the road or railway joins the bridge (*Fig. 10.17*).

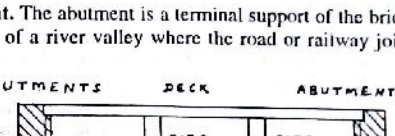


Fig. 10.17. Bridge abutments and piers.

Piers. In a multispan bridge piller-like supports are constructed between the abutments. These supports are called *"piers"* (*Fig. 10.17*). The piers are built mostly of concrete, plain or reinforced. They are commonly faced with dimension stones. The rock selected for this purpose must be able to withstand the constant impact of running water.

Multispan Bridge. When a bridge is supported by abutments on either side of a valley and there are no piers in between, it is called *"one span bridge"*. In a *"multispan bridge"* there are several piers and hence several spans. The multispan bridges are built in the middle or lower reaches of rivers where the valleys are generally very wide.

Suspension Bridge. A bridge which is suspended with the help of cables (wire ropes) and steel towers across a deep and narrow river valley, is called *"suspension bridge"*. In a suspension bridge the ends of the cable are firmly anchored in the hard rock or massive concrete wall on either side of the

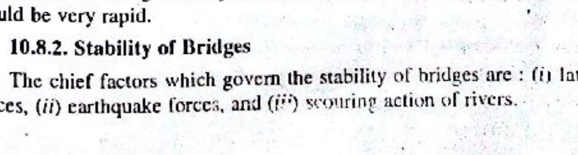


Fig. 10.18. Suspension bridge.

valley (*Fig. 10.18*). The suspension bridges are usually built on the mountain rivers because : (*i*) their valleys being narrow and deep, the height of the piers would be out of proportion as compared to the length of the bridge, and (*ii*) the scouring of the pier foundation in the narrow stream channel would be very rapid.

10.8.2. Stability of Bridges

The chief factors which govern the stability of bridges are : (*i*) lateral forces, (*ii*) earthquake forces, and (*iii*) scouring action of rivers.

(*i*) **Lateral Forces.** The pressure of the wind and the running water are the main lateral forces which operate on bridges. These forces have a tendency to push the structure on the lee side where the overloading of the foundation is caused. If the foundation of piers are not keyed sufficiently deep, the stability of the bridge may become critical. But in modern bridge constructions where the foundation of piers are generally kept deep, the lateral forces are of little importance.

(*ii*) **Earthquake Forces.** The earthquakes undoubtedly reduces the stability of bridges. The accelerations produced by the earthquakes depend on the intensity of shock and on the nature of the ground. The chances of damage are maximum in those bridges which are situated close to an active fault or founded on loose earth materials. Therefore while, constructing bridges in the earthquake effected regions, suitable precautionary measures should be taken.

(*iii*) **Scouring Action of Rivers.** The scouring action of a river is very nearly proportional to the square of its velocity. However this is complicated by various factors such as roughness of the river bed, uniformity of the channel, nature of rocks in the river bed, and the amount of suspended matter in the flowing water. Where the river flows straight, the maximum velocity is found half way between the banks but at bends the water currents of maximum velocity lie near the concave bank.

The rivers whose channels are composed of alluvial material may give a false impression of the level of the river bed during low water. During floods when the velocity of the flowing water is increased, the river bed is vigorously scoured and deepened, and when the flood recedes, it is filled up again to the level when the river was low. The piers should be founded at such a depth where they remain safe from the erosion during high water period.

The piers of the bridge constructed in a river channel, obstruct a part of the channel. As a result, there will be an increase in the velocity around the piers which causes enhanced scouring.

10.8.3. Foundation of Bridges

The weight of the bridge, the load of the traffic and pressure of the wind and flowing water are ultimately transmitted to the foundation of the piers and abutments. Therefore the design and construction of bridges is governed largely by : (*i*) nature of rocks, (*ii*) structure of rocks, (*iii*) faults, and (*iv*) type of river channel.

(*i*) **Nature of Rocks.** The rocks over which the piers and abutments are to be founded must be strong and durable. They should be free from closely spaced joints, fissures, shear zones, solution channels and other zones of weakness. Poorly cemented, thinly bedded and soft sedimentary rocks should be avoided. The rocks having joints and fractures may be consolidated by grouting.

For placing the abutments of a bridge, the valley walls are thoroughly examined. The valley walls where the strata dip into the river channel form unstable slope because they have a tendency to slide into the river channel. Such unstable valley slopes should be avoided.

(*ii*) **Structure of Rocks.** If a bridge is aligned across the strike of the country rocks, different types of rock beds having varying strength and composition are met with along the foundation. In such cases a close examination of the foundation rock under each pier and abutment should be done by putting bore holes. If thinly bedded soft rocks such as shales are exposed in the river bed, the water currents would easily cut deep grooves parallel to the bedding and hence would undermine the foundation of piers.

(*iii*) **Faults.** A fault, if it is running across the bridge alignment, is a source of many troubles. The highly crushed and weathered rocks which exist in the fault zones, make the foundation treatment extremely expensive. It is therefore advised that the possibility of avoiding the fault by shifting the bridge alignment upstream or downstream may seriously be considered.

(*iv*) **Type of River Channel.** In alluvial channels the thickness of loose sands and gravels may be so great that it is not economical to reach the bed rock for placing the piers. In such cases pile foundation is used. The piles are generally driven through the alluvial material to the bed rock. Friction piles are used where the bed rock is not available upto a great depth.

10.9. LANDSLIDES

The study of landslides is important because they affect many types of engineering works, perticularly highways and railways. Loose rock material ordinarily creeps downhill under the force of gravity. However on the sloping surfaces, in presence of water, the creeping may become a fast moving landslide. Thus the rate of movement of earth materials varies from very slow to very rapid. The movement of the earth material can be classified into two major groups : (*i*) earthflows, and (*ii*) landslides.

10.9.1. Earthflows

In earthflows the unconsolidated material flows slowly downhill under the pull of gravity. The movements are distributed though the mass and the well defined slip surface which is characterstic of landslides, does not occur.

The various types of earthflows are : (*i*) soil creep, (*ii*) rock creep, (*iii*) solifluction, and (*iv*) mudflows.

(*i*) **Soil Creep.** When the unconsolidated earth material moves slowly and continuously down the slope, it is called *"soil creep"*. The rate of soil creep on a hill side depends mainly on : (*a*) temperature changes, (*b*) amount of rainfall, (*c*) angle of slope, (*d*) type of soil, and (*e*) nature of parent material. The soil creep is indicated by the presence of tilted fence posts and telegraph poles, curved tree trunks, broken and displaced retaining walls, lines of stone accumulation in the soil, displacement of railway and highway alignments, and many other features.

(*ii*) **Rock Creep.** Where the well jointed rock-formations outcrop along a hillslope, the large joint blocks are displaced by the

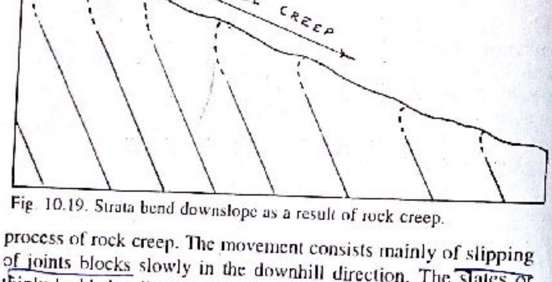


Fig. 10.19. Strata bend downslope as a result of rock creep.

process of rock creep. The movement consists mainly of slipping of joints blocks slowly in the downhill direction. The slates or thinly bedded sedimentary rocks, if exposed on a hillside, often bend downslope and may show reversal of true dip direction (*Fig. 10.19*).

(*iii*) **Solifluction.** Solifluction is a type of creep which takes place in regions of cold climate where the ground freezes to a considerable depth. During the summer the ground thaws and the upper soil layer becomes saturated with water. This mass of water-saturated soil moves slowly downhill over the frozen material at greater depth.

(*iv*) **Mudflows.** Mudflows differ from soil creep in the respect that they move more rapidly and usually follow old stream channels. Mudflows are produced in those steep mountain areas where large amounts of loose earth materials are available and where abundant water is supplied by heavy rain or melting of snow. Mudflows

have destoyed buildings, roads, and useful land at may places in semiarid regions.

10.9.2. Landslides

Where a mass of earth or rock slides down the slope along a definite zone or surface, the movement is called a *"landslide"*. This movement takes place under gravity and is facilitated by moisture which acts as a lubricating agent. The landslide starts with slow movements along a slip surface, followed by a more rapid movement of the separated portion of the earth mass. The slip surface is usually bounded by a crack which distinguishes a slide from creep in which a continuous crack is often absent. The chief types of landslides are : (*i*) slump, (*ii*) rock slides, and (*iii*) rockfalls.

Slump. In a nearly homogeneous cohesive material, such as clays and some soils, a slope fails primarily by shear and the slip surface is approximately cylinderical or spoon shaped. The movement of the mass starts by cracking along a shearing surface and then the separated mass slides down rapidly. Such a slide is called a *"slump"* or *"shear slide"*. Slump is often accompanied by bulges at the toe (*Fig. 10.20*).

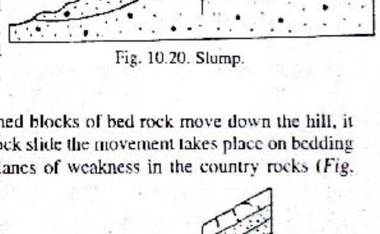


Fig. 10.20. Slump.

Rock Slide. When detached blocks of bed rock move down the hill, it is called a *"rock slide"*. In a rock slide the movement takes place on bedding planes, joints or any other planes of weakness in the country rocks (*Fig. 10.21*).

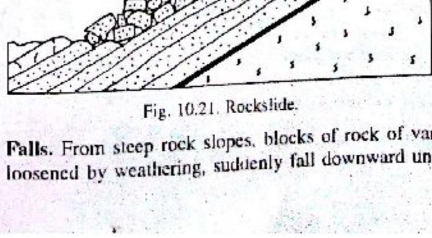


Fig. 10.21. Rockslide.

Rock Falls. From steep rock slopes, blocks of rock of varying sizes which are loosened by weathering, suddenly fall downward under the influence of gravity. This phenomenon is called *"rockfall"*. The rockfalls supply *"talus"* which are commonly found at the foot of cliffs in the higher mountain regions.

10.9.3. Causes of Landslides

The factors which promote landslides are : (*i*) water, (*ii*) slopes, (*iii*) nature of rocks, (*iv*) structure of rocks, and (*v*) disturbance of equilibrium.

(*i*) **Water.** The essential conditions which cause landslides, are lack of support in front and lubrication behind. Thus water is an important factor in causing landslides. It acts in three ways :

(*a*) Water diminishes the strength of rocks and thus help in their movement.

(*b*) The water that seeps into the rock or soil, not only produces lubrication but also exerts additional force on the grains tending to displace them along the direction of water movement.

(*c*) It adds weight to the material. Hence many landslides occur after rains.

(*d*) On freezing it exerts an expansive force.

(*ii*) **Slope.** It has been observed that majority of the earth or rock failures are confined to slopes. This indicates that slopes are directly responsible for landslides. As a rule, steeper the slope, greater is the instability of such a mass.

(*iii*) **Nature of Rocks.** Unconsolidated sediments, such as clay, sand, gravel, etc. can not stand permanently along slopes greater than their angle of repose (about 35°) and are likely to be affected by landslides. Where weak and slippery rocks like shale, volcanic tuff, phyllites or mica-schists are present, they are not likely to remain stable on steep slopes for a considerable period of time.

(*iv*) **Structure of Rocks.** Joints, fractures, shear zones and bedding planes usually become the slip surface in case of rock slides. Landslides are perticularly common on hill slopes where dip of rock beds is also in the same direction (*Fig. 10.22*).

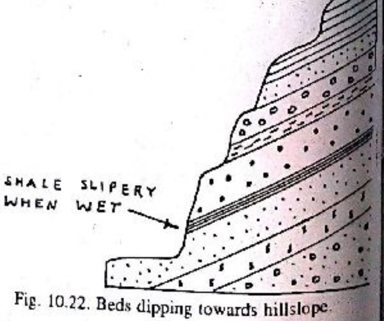


Fig. 10.22. Beds dipping towards hillslope.

10.9.4. Prevention of Landslides

The methods which are commonly used for prevention of landslides are as follows.

1. Slides in the impervious material are prevented by reducing slopes. Efforts should also be made not to allow the additional water to enter into the material.
2. In order to check the surface water to enter into the unstable ground, it is diverted and made to run off as rapidly as possible away from that area.
3. In pervious materials, the landslides may be prevented by increasing the internal friction of the mass by lowering the water content. Their water may be removed by drain pipes, by drainage through tunnels or by pumping from wells.
4. In situations where slides may cause loss of life and property, the loose rock material is prevented from sliding by constructing retaining walls, concrete piers or by use of piling.
5. At some places the unstable unconsolidated material may be consolidated by cement grouting, chemical means, and artificial freezing.

REVIEW QUESTIONS

1. Give a brief account of the importance of geology in civil engineering. Explain your answer by giving suitable examples.
2. Explain the importance of the geological investigation of dams. Describe the various geological factors that may cause trouble in the construction of a dam.
3. What is a tunnel ? Describe the various geological problems met during the construction of tunnels both in the soft ground and in the hard rocks.
4. Give the importance of the geological survey of the dams and reservoirs. Outline the scheme of doing the geological investigation.
5. (*a*) Describe the, various geological factors which affect the stability of bridges.
   (*b*) Discuss the factors that help in selecting the rocks for building purposes.
6. (*a*) Describe the problems that are met in constructing dams on bedded rocks, faults, and shales.
   (*b*) Give a brief outline of the geological survey of tunnels.
7. Write short on any two of the following.
   (*i*) Factors promoting landslides.
   (*ii*) Tunnels in stratified rocks

(iii) Factors affecting stability of bridges

(iv) Geology of reservoirs.

8. What are landslides ? How are they caused ? Describe the various methods of prevention of landslides.

9. Give the various geological and engineering properties that are important in the selection of rocks for building purposes. Describe some common building stones, roofing stones, and stones used for road metal.

10. Give the importance of the geological survey of tunnels. Outline the scheme of doing the geological survey.

11. Write short notes on the following.

(i) Silting of reservoirs.

(ii) Overbreak in Tunnels.

(iii) Landslides

(iv) Dams on bedded rocks

(v) Stability of Bridges.

11 Field Work and Prospecting Methods

11.1. FIELD WORK

The geological field work is carried out to search mineral deposits and to explore ground for many civil engineering works. During the geological survey sufficient data are gathered to prepare geologic maps and reports about a perticular area of interest.

11.1.1. Field Equipments

The equipments that are commonly required for doing a geological field work are as follows.

(i) Topographic map.

(ii) Compass

(iii) Hammer

(iv) Haversack

(v) Altimeter

(vi) Measuring tape

(vii) Field notebook.

Topographic Map. First the topographic map of the area to be investigated is procured. It is the most important tool of the geological field work. The map should show topographic details on a sufficiently large scale, that is 1cm = 2.5 km or 1 : 50,000. It serves as a base map for systematic field work and geological mapping.

Compass. A magnetic compass is used for finding directions, taking traverses and locating one's own position on the map. The magnetic needle of the compass always points towards the magnetic north. The chief compasses used by geologists for the field work are : (a) *"clinometer compass"*, and (b) *"Brunton compass"*. These compasses have some additional arrangements for measuring dips of bedding planes. Brunton in superior to clinometer as it can also be used as a hand level.

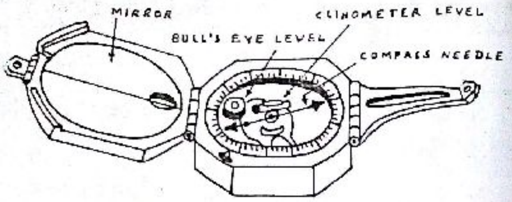


Fig. 11.1. Brunton compass.

The various parts of a Brunton compass are shown in *Fig. 11.1.* It consists of three units : (*a*) a clinometer, used for measuring dip angles, (*b*) a compass, used for measuring directions, and (*c*) a sighting device, used in taking bearings and in hand laveling. While measuring dip, not only angle but direction of dip must also be noted. The sides of the body of Brunton are made plane and parallel. One of these sides is placed on an inclined bedding plane in the direction of dip. In this position the dial of the instrument lies in the vertical plane. The tube bubble of the clinometer is then centred by rotating a lever. The amount of dip is read on the inner scale in degrees.

The compass direction of the horizontal line on an inclined plane, is called "*strike*". In order to measure a compass direction, the Brunton is held face up. It is then leveled by using the circular level bubble. The hinged mirror and sight help in taking bearings of selected points. The reading of directions are taken on the outer circular scale.

Hammer. A hammer is essential for chipping rocks and collecting rock samples. Geological hammers generally have one chisel end and another flat end. The flat end is used for breaking rocks while the chisel end is used for trimming and sizing the specimens. The common field hammers may weigh 0.5 to 1.0 kilogram.

Haversack. It is used for carrying compass, notebooks and rock samples collected in the field.

Altimeter. Altimeter is a barometer which is used for determining ground elevations. Along with compass, altimeter greatly helps in locating outcrops in mountainous areas.

Measuring Tape. A steel or metallic tape of 30 meter length and a pocket steel tape of 2 meter length is required for the field work. The first is used for ground measurements, measuring traverse lines, etc., and the other for measuring shorter units such as thickness of strata, veins, etc.

Field Notebook. A field notebook is used for keeping a record of observations made in the field. Field notes should be brief but clear. It must contain the following information.

1. The exact location of an outcrop.
2. Nature of the rock as seen in the outcrop.
3. Dip and strike of rock beds and other structural features like ripple marks, current bedding, etc.
4. Location of samples collected.
5. Relation between different rock types
6. Any other special information.

11.1.2. Method of Field Work

Preliminary Survey. Before doing filed mapping one should first undertake a rapid reconnaissance of the target area by taking topographical map. This will help in choosing suitable mapping procedures and in getting the general idea about the geological problems. The reconnaissance traverses should be planned in such a manner as to come across the different rock types present in the area. This is usually done by moving along the direction of dip of rocks.

Geological Mapping. After the preliminary survey detailed examination is conducted and geological mapping is started. The traverses should be carefully planned and followed, and contacts between rock types are marked on the topographical map. Whenever exposures of rocks are met with, they should be examined carefully. All available information about the outcrop should be recorded in the field notebook. If necessary, sketches may be drawn and photographs may be taken.

Representative samples of rocks of proper size (10cm x 7.5cm x 2.5cm) are collected for laboratory study. They are labelled properly. The label should bear sample number, the locality from which the samples are taken, name of the rock, and other details about the sample.

While marking the boundaries of rock types and making a geological map, the location and altitude of contacts must be determined or inferred. On a topographical map many locations can be determined accurately

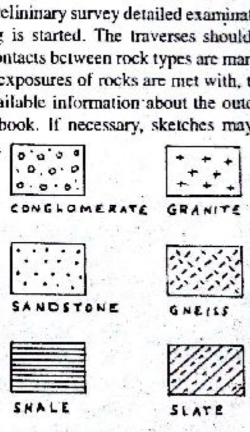


Fig. 11.2. Lithological symbols.

without instrumental measurements. Cultural features that are generally shown on topographic maps are especially useful in establishing locations. Where outcrops of rocks are concealed under soil, the boundaries may be inferred by topography and variations in the soil colour. Frequently portions of the boundaries have to be interpolated between exposures of two rock types.

In this way the whole area in question is covered and the geological map is completed. The different rock units are shown by different colours or symbols (*Fig. 11.2*). Dip, strike, cleavage, joints, faults, etc. are also

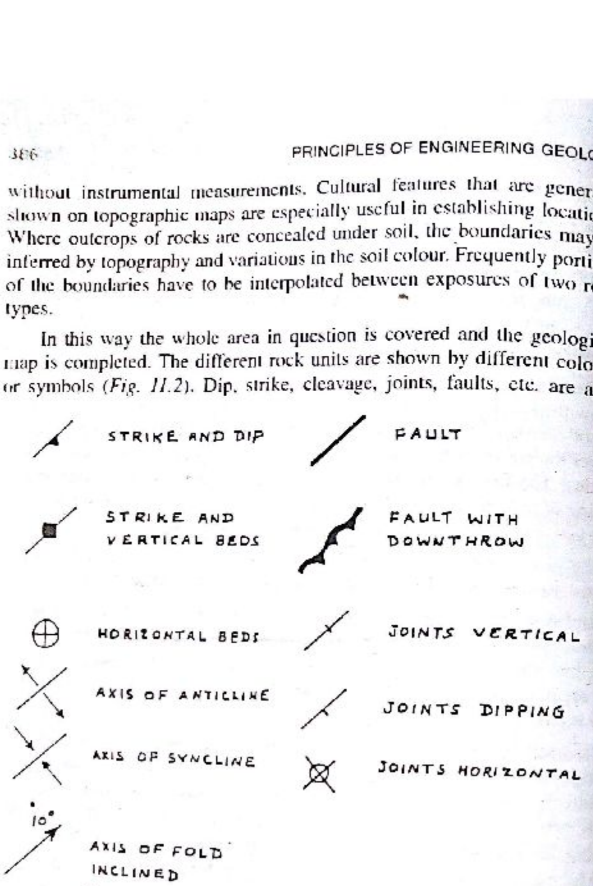


Fig. 11.3. Structural symbols used on geological maps.

indicated on the map by suitable symbols (*Fig. 11.3*). The rock samples collected during the field work should be arranged and packed properly.

Laboratory Work. After completing the field work, the rock samples are brought in the laboratory for correct identification. Thin sections of the samples are prepared and examined under the petrological microscope. Such studies lead to the understanding of mineral composition and texture of the rock. A correlated picture of the geological structure of the area is also made during the laboratory work.

Writing of Report. The information obtained from the field work and laboratory work is compiled in the form of a neat report. Its outline is as follows.

(*a*) Introduction.

(*b*) A brief account of the earlier work, if any.

(*c*) Statement of actual observations, findings and inferences made as a result of the field work and laboratory work.

(*d*) The report should be accompanied by the prepared geological map and sections to show the geological structures and history of the area.

11.2. PROSPECTING METHODS

The object of prospecting of an area is : (*i*) to search ore deposits, (*ii*) to know the nature of overburden, (*iii*) to determine depth, shape, size, and grade of ore deposits, (*iv*) to determine the geologic structures, and (*v*) to discover the ground water conditions. The mineral exploration includes two activities. The first is *"prospecting"* which is mainly concerned with the outlining of mineral targets for exploration, and the second is *"exploration"* which consists of proving of targets outlined during prospecting.

The prospecting methods are broadly classified into two groups : (*i*) airborne prospecting methods, and (*ii*) ground prospecting methods.

Airborne Prospecting Methods. The airborne prospecting methods include *"remote sensing methods"* in which photogeological study is undertaken, and *"aerial geophysical prospecting methods"*. By these methods large areas are covered quickly and target areas are outlined for ground prospecting.

Ground Prospecting Methods. The ground prospecting methods are broadly classified into two groups : (*i*) surface methods, and (*ii*) geophysical methods. In surface prospecting methods data are obtained by direct observation. Most of the information comes from natural exposures and artificial openings such as pitting, trenching, drilling, etc. In the geophysical methods, the information is obtained indirectly by studying the physical properties of rocks.

1. Surface prospecting methods
   (*i*) Geological mapping.
   (*ii*) Test pitting, trenching, and aditing.
   (*iii*) Augering and washboring.
   (*iv*) Drilling.
2. Geophysical methods
   (*i*) Gravity methods
   (*ii*) Magnetic methods
   (*iii*) Electrical methods
   (*iv*) Seismic methods.

11.3. SURFACE PROSPECTING METHODS

Geological Mapping. Before starting the prospecting work, a target area that can yield mineral deposits, is selected. Then its geological map is prepared on a suitable scale. Such a map shows topography, rock outcrops, and structural features such as dip, strike, folds, faults, etc. This sort of map gives an idea of the length and width of the deposit. It also serves as a base map for planning out a trenching, pitting or drilling programme.

Trenching. A *"trench"* is a narrow linear excavation which is made to expose ore bodies concealed under soil cover. The trenches may be 6 to 9 meter long, 1 to 1.5 meter wide, and 2 to 2.5 meter deep. They are commonly dug across the strike of the ore body at intervals of 15 to 150 meters. The spacing of trenches depends upon the consistency of data. Prospecting by trenching is generally done when the ore outcrops are narrow and the soil cover is thin (about one meter). The trenching gives reliable information about the geology, structure, extension and grade variation of the ore body. This method has been adopted as a major prospecting method in may iron ore and bauxite deposits.

Pitting. The process of digging rectangular openings to penetrate soil cover to reach ore bodies concealed underneath is called *"pitting"*. The common dimension of pits is 1.2m x 1.2m x 6m. However pits may be sunk to a depth of about 10 meters beyond which they become very expensive. Pitting is a very useful method of prospecting those ore bodies which are flat or gently dipping and lying near the ground surface. For steeply dipping ore bodies and those having linear and narrow outcrops, pitting would not be favourable. The pattern of the layout of the pits may be regular or irregular. In a regular system pits are sunk in rows in grid or triangular pattern. Pitting is an important method of prospecting in many bauxite and iron ore deposits.

Aditting. The *"adits"* are horizontal openings which are dug in mountainous terrain to explore ore bodies. An adit many be driven across or along the strike of rocks. It should be dug in such a way so that at a later stage it could be used as an opening for exploiting the ore.

Augering and Washboring. Augering and washboring are commonly used for prospecting of flat and homogeneous deposits like clays which are concedaled under a thin cover of softandunconsolidated materials. *"Augering"* is a simple method of putting down holes of about 2.5 cm in diameter to depths upto 6 meters in soft soils. An auger consists of a screw blade mounted on a steel pipe. It is screwed into the ground by turning on a T-pipe attached to the upper end.

In *"washboring"* a hole is dug in the soft ground by forcing a jet of water through the wash-pipe. The soil thus eroded comes to the surface as a suspension in water where it is examined and identified.

Drilling. Drilling is an important method of prospecting subsurface rocks and ore deposits. In drilling data are collected by direct penetration of subsurface rocks by drill holes. The samples of rocks are obtained in the form of cylindrical cores or rock fragments. The drill holes provide the following informations.

1. Size, shape and morphology of the ore body.
2. Geological structures and number of lodes present.
3. Nature of the host rocks.
4. Composition and grade of the ore body.

During prospecting, drill holes are located at certain intervals in certain directions depending upon the regularity of the ore body and its structure. In most cases, the test holes are drilled systematically in a grid pattern. In this pattern, the system of *"diminishing squares"* is adopted. First a gird of large squares is laid out and the holes are drilled at each corner of the squares. In case of simple deposits the grid lines may be kept 300—400 meters apart, while in complex and intricate deposits, this interval may be reduced to 200—300 meters and 100—200 meters respectively. Subsequently for closer examination, each grid is subdivided into four small squares and more holes are drilled at their corners. Thus systematic geological data are obtained for the entire deposit.

For every drill hole cores should be carefully logged and vertical sections of the geological formations penetrated should be prepared. The positions of drill holes are marked properly on the base map of the area, and a map showing variations of grade of the ore is prepared. Then the portions of it which have the proper tenor of ore are delineated and the area computed for estimating the reserve.

11.4. GEOPHYSICAL PROSPECTING

In geophysical prospecting certain physical properties of the underground rocks are measured from the surface. The properties of rocks measured commonly are density, magnetism, electrical conductivity and elasticity. In the radiometric surveys mainly the γ-ray (gamma-ray) radiations are measured. The measured data are then interpreted to give information about the presence of ore bodies, buried anticlines, faults, igneous intrusions, and other geological structures. The main geophysical prospecting methods are as follows.

1. Gravity methods.
2. Magnetic methods.
3. Electrical methods.
4. Seismic methods.
5. Radioactive methods.

11.5. GRAVITY METHODS

The gravimetric survey is based on the measurement of density contrast between the anomaly producing body and the surrounding rock.

Use. (*i*) The gravity methods are used chiefly for the exploration of oil and gas. These have been used successfully for outlining anticlines, buried ridges, igneous intrusions, faults and other geological structures.

(*ii*) The gravity survey has also been utilized for the exploration of metallic ore bodies such as massive sulfide ore, iron ore, and chromite ore.

Method. The instruments which are commonly used to measure gravitational deflections are : (*i*) pendulum, (*ii*) torsion balance, and (*iii*) gravimeter. Of these the gravimeter is the most useful. For covering larger areas rapidly, airborne gravity survey is done.

In the area of search, traverses are laid at suitable intervals. Then the values of gravitational deflections are measured at predetermined points. The readings thus obtained are plotted on a graph with distances on x-axis and deflections on the y-axis. If a dense rock or a massive ore body is present in the area, the graph will show an anomaly in the form of a peak as shown in *Fig. 11.4*. The difference between the normal value and the observed value of deflection is called *"anomaly"*.

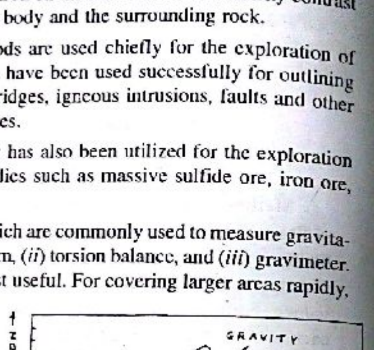


Fig. 11.4. Showing gravity profile of an ore body.

The gravity data can also be interpreted by contouring the anomaly. In this case the gravity anomaly for each station is plotted on a base map and then lines of equal gravity anomaly are drawn in the same way as contour lines.

11.6. MAGNETIC METHODS

The magnetic surveys are based on the measurement of value of magnetic anomalies. In these surveys the vertical component of the earth's magnetic field is measured.

Use. (*i*) The magnetic surveys have been used widely for the exploration of oil and magnetic ore bodies such as deposits of magnetite, pyrrhotite and ilmenite.

(*ii*) At places faults may bring together rocks of different magnetic properties. Hence they may be delineated from magnetic data.

(*iii*) The magnetite and pyrrhotite are more abundant in basic igneous rocks than in acid rocks. Hence the former can be detected by the magnetic surveys.

(*iv*) Certain mineral deposits which contain magnetic minerals in subordinate amount, such as magnetite with asbestos and pyrrhotite with base metals, can be detected by magnetic surveys.

Method. The magnetometers are used to measure the magnetic intensity of the ground at various stations. For covering large areas rapidly, airborne magnetic surveys are conducted.

In the area of search, traverses are laid at suitable intervals. Then the values of magnetic intensities are measured at closely spaced stations. For each station, the observed value is compared with the normal value. The difference between them is the *"magnetic anomaly"*.

The values of anomaly are plotted on a base map. Then the lines of equal magnetic anomaly are drawn in the same way as contour lines. From such a map, the area of the magnetic body can be readily delineated. The anomaly data may also be interpreted by constructing magnetic profiles in the same way as done for gravity data (*Fig. 11.4*).

11.7. ELECTRICAL METHODS

The electrical methods are used mainly for the exploration of metallic mineral deposits. The electrical survey methods are of four types : (*i*) self potential method, (*ii*) equipotential method , (*iii*) electromagnetic method, and (*iv*) resistivity method.

11.7.1. Self Potential Method

In this method the electrical energy produced by the ore body itself is directly measured and no outside energizing force is required. Certain ore bodies, perticularly those containing sulfide minerals when subjected to

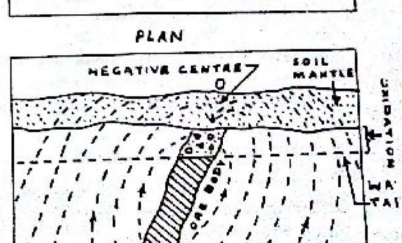


Fig. 11.5. Showing self potential currents of an ore body.

oxidation, produce electrical currents. These currents are called *"telluric currents"*. By measuring these currents the presence of the hidden ore body can be detected.

Fig. 11.5 shows a sulfide ore body which is undergoing oxidation. Its upper end which is in contact with the soil mantle, is chemically more active then the lower part. Hence a potential difference is created and electric currents flow down through the ore body and return upward through the surrounding rock. Because the country rocks have high resistivity, the currents spread out to great distances. On the ground lying immediately above the ore body, the currents flow towards the negative centre '*O*' as shown in *Fig. 11.5*. The centre *O* of the ore body can be located by constructing an equipotential diagram (*Fig. 11.5*).

11.7.2. Equipotential Method

The equipotential method is best suited to shallow deposits in the regions not too wet. It can be used to locate ore bodies in the glacial drift and for determining structure beneath the soil. This method is also used to study the geological formations with steep or vertical contacts such as igneous intrusions.

Method. The current is introduced into the ground by means of two line electrodes. A *"line electrode"* is a bare copper wire which is pegged into the ground at intervals (*Fig. 11.6*). The current flows between them through the ground because of the difference in potential.

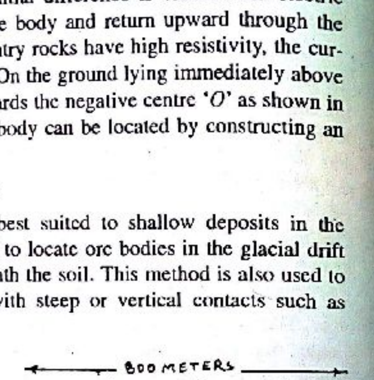


Fig. 11.6. Equipotential method.

If the intervening ground is of uniform conductivity, the lines of equal potential will be parallel to the line electrodes. This is shown in *Fig. 11.6* by dotted lines *a, b, c*, etc. On the other hand, if an ore body which is a better conductor than the surrounding rock, is present in the ground, the lines of equal potential will be distorted. This is shown in the Figure by solid lines 1, 2, 3, etc. Hence by noting the distortion in the equipotential lines, the hidden ore body can be demarcated.

11.7.3. Electromagnetic Method

Out of the electrical methods, the electromagnetic method is the most favoured method for search of ore bodies. It is more precise and yields greater information regarding shape, size and position of the hidden ore body. The electromagnetic method can be used for rocky ground, barren mountain region, dry sands and ice covered ground.

When an alternating current is passed through a conductor, induced currents are produced around it. If a conductor, such as an ore body, lies within the induced field, it sets up a secondary induced currents around it which can be measured.

Method. A rectangular loop of insulated cable is placed on or above the ground. Then an alternating current is supplied to the loop (*Fig. 11.7*). The loop sets up a *"primary magnetic field"* within the surrounding ground which diminishes with distance from the loop.

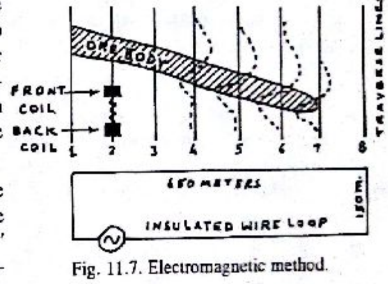


Fig. 11.7. Electromagnetic method.

If a conductor (ore body) is present within the ground, a *"secondary field"* is induced about the conductor. Because both the primary and secondary fields are present at the same place, the primary field gets distorted. The ore body is outlined by measuring the distortion by sensitive receivers. In order to detect the distortion, traverse lines are laid normal to the longer axis of the loop and normal to the hidden ore body (*Fig. 11.7*). These traverse lines are then surveyed by the receiver. If the ground is uniform, the readings of the field will decrease with distance. On the other hand if an ore body is hidden in the ground, the readings will rise at the boundary of the ore body as shown in *Fig. 11.7*.

11.8. RESISTIVITY METHODS

In resistivity surveys the amount of resistance met by an electric current which is passed through a portion of the earth, is measured. The measure of resistivity is presumed to be a measure of the fluid content and porosity of rocks. Therefore the resistivity measurements help in making distinction between saturated and unsaturated rocks, and also between rocks of differing porosity.

Uses. The resistivity surveys are very effective in the investigation of horizontal or gently dipping rocks. These are used in detecting the following.

1. The thickness of overburden or depth to bed rock is determined very accurately.
2. The resistivity surveys have been used in the exploration of the placer deposits and bedded deposits.

3. The resistivity methods have been used widely for the exploration of groundwater. In regions of gentle dips the presence of aquifers can be determined.
4. Fault zones may be determined as they contain electrolyte in solution.
5. Resistivity surveys can be used for discovering the subsurface structure and lithology. The buried anticlines can be traced by determining depths to strata of greater or lesser resistivity. Hence they are also used in the exploration of petrolium.

11.8.1 Wenner Method. In resistivity surveying various electrode arrangements are employed but the arrangements shown by Wenner is widely used.

In the Wenner method the spacing between the electrodes are kept equal. In *Fig. 11.8* this spacing is designated as '*d*'. The current is introduced into the ground by two current electrodes C_1 and C_2, and the potential difference

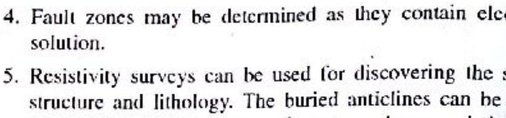


Fig. 11.8. Showing electrode arrangement in Wenner method.

between the inner electrodes P_1 and P_2 is measured. All the four electrodes are placed in a line as shown in *Fig. 11.8.* The resistivity of the ground is determined by the following equation.

$$\rho = 2\pi d \frac{V}{I}$$

Where ρ is resistivity, *d* is the distance between electrodes, *V* is the difference in potential between inner electrodes, and *I* is the current flowing between the end electrodes. In this case, the depth of exploration is approximately equal to the electrode separation. By Wenner method two types of resistivity surveys are carried out : (*i*) resistivity traversing, and (*ii*) resistivity sounding.

11.8.2. Resistivity Traversing

This method is also called *"resistivity trenching"*. It is used to investigate variations of rock beds in the horizontal direction at constant depth.

The spacing of the electrodes are kept constant while they are moved along a traverse line. The resistivity measurements are made at various stations. From the data thus obtained, the resistivity curves are drawn by plotting the distance of stations on *X*-axis and resistivity values on the *Y*-axis. An abrupt change in the curvature of a resistivity profile indicates a change in the nature of the underlying material (*Fig. 11.9*).

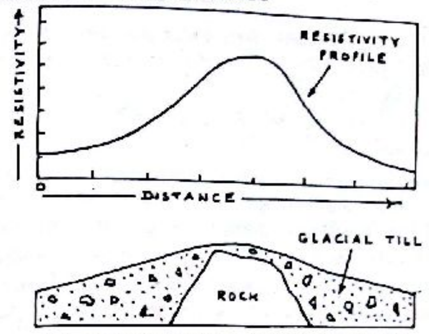


Fig. 11.9. Resistivity profile showing change in the nature of the underlying material horizontally.

11.8.3. Resistivity Sounding

This method is used to investigate the nature of subsurface strata at depth. In resistivity sounding, the resistivity is measured by increasing the electrode separation progressively about a central fixed point '*x*' (*Fig. 11.8*).

As the distance between the electrodes is increased, the depth of penetration of the current is also increased. In this way the data on variation of resistivity with depth are obtained. Then the resistivity-depth curves are drawn by plotting the resistivity values on *X*-axis and electrode spacing on *Y*-axis (*Fig. 11.10*).

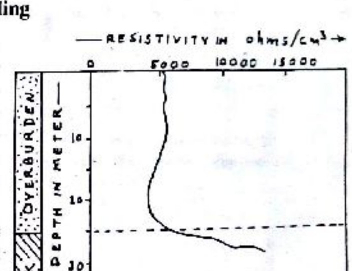


Fig. 11.10. Resistivity curve showing depth of overburden.

11.9. SEISMIC METHODS

In seismic methods, the variations in the seismic wave velocity are measured in different rock layers. The values of the seismic velocities are obtained from the time-distance curves. Since this velocity is directly proportional to the density of rocks, by noting the differences in the velocities, the structure of the subsurface rocks can be worked out.

Method. In seismic surveys, truck mounted drilling rigs and recording systems are used. Small charges of explosives are detonated in shallow boreholes drilled in the surface rocks. The seismic waves thus generated are transmitted through the rocks and are picked up by a series of geophones carefully spaced along a line of traverse [*Fig. 11.11 (a)*].

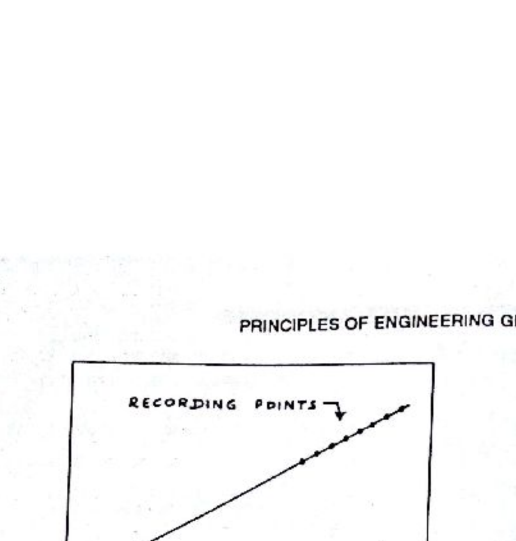


Fig. 11.11. Seismic method. (*a*) Showing shot points and geophones along a line of traverse. (*b*) Seismogram showing interval of time t between instant of shot and arrival of first wave at a geophone.

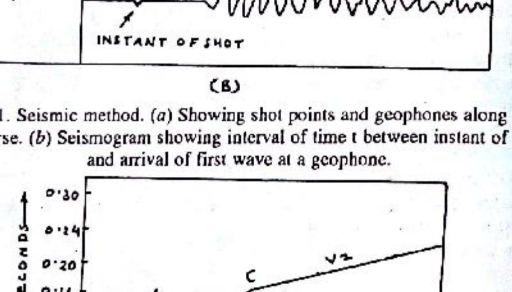


Fig. 11.12. Travel time curve. (*a*) Obtained from the seismic survey of the ground shown in (*b*).

The geophones record the vibrations on a rapidly moving photographic paper. The instant of explosion is also marked on this paper [*Fig. 11.11 (b)*]. From this photographic record (seismogram) the time-distance curves are prepared (*Fig. 11.12*). Then the velocity of seismic waves is determined by the following equation.

$$V = \frac{x_2 - x_1}{t_2 - t_1}$$

Where V is the velocity of seismic waves, x_1 and x_2 are the distances of any two recording stations from the shot point, and t_1 and t_2 are the times of arriaval of the seismic wave at the same stations.

The velocity of seismic waves differ in different kinds of rocks. Hence from the velocity data, the structure of subsurface rocks can be worked out. The seismic methods are of two types : (*i*) refraction survey, and (*ii*) reflection survey.

11.9.1. Refraction Survey

The seismic waves undergo reflections and refractions at the rock boundaries. In the refraction method only the refracted waves are recorded and used for determining the structure of rocks. The refraction survey is commonly used for the following.

(*i*) For determining the structure of rocks lying at relatively shallow depth. It is widely used for civil engineering explorations.

(*ii*) For the location of shallow salt domes and the oil pools associated with them.

11.9.2. Reflection Survey

In this method the reflection waves from a reflecting surface are recorded and used for determining the rock structures. The reflection survey is generally used for deep explorations (600 meters ore more). Hence it is widely used for oil exploration. This method accurately delineates the subsurface structural traps and salt domes.

11.10. RADIOMETRIC SURVEYING

The radioactive elements, such as uranium-238 and thorium-232, constantly undergo a process of disintegration. During disintegration they emit radiations of three types : (*i*) α rays, (*ii*) β rays, and (*iii*) γ rays.

(*i*) **α-Rays.** These are the beams of positively charged particles. These particles are the nuclei of helium atoms (2 protons + 2 neutrons). They travel with velocities of thousands of kilometers per second.

(*ii*) **β-Rays.** These are the beams of negatively charged particles. They travel faster than α rays.

(*iii*) **γ-Rays.** These are the rays of very short wave length like *x*-rays. They travel with velocity of light and have a very high penetrating power.

Of the three above said radiations, only the γ-rays are useful from the point of view of radiometric surveys. The instruments commonly used for radiometric surveys are : (*i*) Geiger Mueller counters, and (*ii*) scintillation counters.

Geiger Mueller Counter. This instruments is fitted with an ionization chamber, meters and count registers. These make it possible to measures the intensity of γ-rays.

The γ-rays are detected by the ionization chamber. This chamber consists of a closed tube containing an ionisable gas under pressure. An electrical potential is applied to produce an electrical field inside the tube. As a result the positive ions move towards the negative electrode and the negative ions towards the positive electrode. A beam of incoming γ-rays librates a large number of ions inside the tube and produces an impulse of electric current.

Scintillation Counter. This is a very sensitive instrument which measures the intensity of γ-ryas (gamma rays) in terms of electrical signals.

11.10.1. Types of Radiometric Surveys

Depending on whether the measurements are made from air, at the ground, or along drill holes, the radioactive surveys are classified into three groups : (*i*) airborne radiometric surveys, (*ii*) ground radiometric surveys, and (*iii*) radioactive logging of bore holes.

Airborne Radiometric Surveys. In airborne surveys, scintillation counters are used for recording the γ-rays from the air. These surveys are usually carried out along with the aeromagnetic and aeroelectromagnetic surveys. By airborne radiometric surveys the deposits of radioactive substances and boundaries between various rocktypes may be outlined.

Ground Radiometric Surveys. The ground radiometric surveys are used mainly : (*i*) to search deposits of radioactive substances, and (*ii*) to outline geological structures such as faults.

(*i*) **To Search Deposits of Radio-active Ores.** In ground surveys, the G.M. counter is commonly used to detect the intensity of γ-rays. A radioactive deposit which is hidden beneath a thick cover of soil, may not be detected because most of the radioactive emanations are absorbed by the soil cover. In such a case the detection of the hidden deposit depends on the migration of the radioactive elements from the source. This migration is caused in two ways : (*a*) the radioactive substances may migrate in solution after the deposition of the ore, and (*b*) the radon which is the gaseous member of the radioactive series may diffuse through the overlying cover.

The process of migration of radioactive elements may result in the formation of an *"aureole"*, or in the localization of radioactivity along faults or fissures. By detecting these clues, the hidden ore body may be outlined.

(*ii*) **To Outline Faults.** Certain groundwaters contain radon and soluble radioactive materials in appreciable amounts. Faults containing such radioactive fluid may be outlined by measuring variations in the radioactivity of rocks.

Radioactive Logging. The *"radioactive logging"* is an operation in which γ-ray counts of various rockformations met in a borehole are recorded continuously along the depth. This depthwise record is called *"radioactive log"*. The radioactive logging is used for (*i*) correlating rockbeds, and (*ii*) determining porosity and permeability of rocks.

(*i*) **For Correlating Rocks.** Every rockformation contains some natural radioactivity in measurable degrees. As a rule, acid rocks are more radioactive then basic rocks. Because different rocks have different amount of radioactivity, they may be correlated by using this criteria.

(*ii*) **For Determining Porosity.** The radioactivity counts of different rocks vary with their densities. The more dense rocks have higher values of radioactivity than those of less dense rocks. Hence from the density, the porosity of rocks may be determined.

11.11. GEOCHEMICAL PROSPECTING

The geochemical prospecting is very effective is locating deposits of base metals, such as Cu, Pb, Zn, etc. In India this method is used commonly for this purpose. The essential principle of geochemical prospecting is as follows.

1. Samples of the surface soil or sediment of the target area are taken systematically from grid points.
2. The metal content of the samples are determined precisely by rapid geochemical analyses.
3. The distribution of the metal content in the surface soil or sediment is determined by plotting the values on a base map of the target area.
4. Then the comparision of these values is made with the known *"background"* values.
5. This comparision will give the idea about the presence of the mineral deposit hidden below the ground.

Method. The main steps involved in the geochemical prospecting are : (*i*) sampling, (*ii*) geochemical analyses, and (*iii*) interpretation of data.

(*i*) **Sampling.** The geochemical prospecting of a target area is started with the collection of samples. The samples of surface soil, stream sediment, water or rock chips are collected at regular intervals. Generally a large number of samples are collected from grid points at fixed intervals. The grid lines are drawn transverse to the strike of the suspected zones of mineralization.

(*a*) **Soil Sampling.** The soils always contain mineral particles present in the parent rock. The soils caped over the ore body commonly shows anomalously high values of metal concentration. In soil sampling, the samples weighing about 100 gm. are collected from each grid point.

(*b*) **Stream Sediment Sampling.** In geochemical surveys, the stream sediment sampling is commonly done. In this case, samples of fine stream sediments are colleceted from stream channels. These sediments usually carry mineral particles derived from their original source rock. The samples of stream sediment are normally collected at intervals of 0.15 km.

(*c*) **Water Sampling.** Water sampling is done mainly for uranium deposits and rarely for zinc and copper deposits. The water samples are collected from lakes, rivers, and underground sources.

(*d*) **Rock Sampling.** In case of rock sampling, chips of rocks are collected from visible outcrops at regular intervals. These chips are then crushed to –100 mesh size and analysed for the metal content.

(*ii*) **Geochemical Analysis.** Each sample is analysed precisely by rapid geochemical methods to determine its metal content. Thus for a single geochemical survey, individual readings of the order of 50,000 to 60,000 are obtained.

(*iii*) **Interpretation of Data.** The data obtained from the geochemical analyses are interpreted with the help of graphical statistical procedures or by computer methods. The method of interpretation may briefly be summarized as follows.

1. The area under investigation shows three types of values : (*a*) background values, (*b*) threshold values, and (*c*) anomalous values. The average values of the metal content of the area are called *"background values"*. The *"threshold values"* are those which demarcate the zone separating the average values and the anomalous values. The values which are above the threshold values are called *"anomalous values"*.

2. The area of anomalous values outlines the mineral deposit hidden below the ground.

12.12. GEOCHEMICAL SURVEY FOR OIL AND GAS

The gases associated with petrolium are mainly methane, ethane and propane with minor amounts of N_2, CO_2 and SO_2. Since the gases are highly mobile, they move upward through the rocks and reach the ground surface. As a result the soils get enriched in the methane. The petrolium may also be searched by determining the presence of oil bitumens in the rocks, soils and waters.

In the geochemical survey, the samples of soil, rock and water are collected systematically from grid points. These samples are then analysed chemically to determine the presence of hydrocarbon gases and bitumens. The data thus obtained give clues to the presence of petrolium deposit hidden underneath.

The geochemical methods of prospecting for oil has been divided into two groups : (*i*) direct methods, and (*ii*) indirect methods. In the *"direct methods"* mainly gas and bitumen are used as indicators, while in the *"indirect methods"* hydrochemical, soil salts, physico-chemical, and microbiological indicators are used.

Gas Survey. Of the direct methods, the gas survey is the most important. It has helped in discovering many oil formations independently. In this method, the migrating hydrocarbon gases which are directly associated with the oil or gas deposit, are detected. The most difficult part of gas survey is sampling. The samples of subsoil gas are taken from shallow wells dug at grid points. The samples are taken in such a manner that the atmospheric air does not dilute them.

Each sample of the subsoil gas is analysed chemically to determine the amount of hydrocarbon gases present in it. The results thus obtained are recorded on a map. Then the area of oil and gas deposit may be outlined.

REVIEW QUESTIONS

1. List the various equipments required for doing geological field work. Explain briefly their use.
2. Describe in brief the basic requirements, methods and proper procedure for carrying out geological mapping of a region.
3. Describe in detail the method of doing geological field work in a region.
4. Give a broad outline of the various surface methods that are adopted in prospecting for minerals.
5. Describe the procedure for prospecting a bedded mineral deposit.

6. List the various geophysical methods of prospecting. Describe the electrical methods in detail.
7. Describe the specific methods of geophysical exploration used in groundwater survey.
8. Describe in brief the electrical and electromagnetic methodsof geophysical exploration for location of sulfide ore bodies.
9. Differentiate between anomaly and background. Describe the geochemical method of exploration of a zinc deposit.
10. Explain the scheme of exploration of oil and gas deposits by geochemical method.
11. Describe the principle and applications of radiometric survey.

12 Geological Maps and Sections

12.1. GEOLOGICAL MAPS

A geological map shows the geological set-up of an area in terms of occurrence and distribution of various rock types. In addition to outcrops, such a map also reveals the attitudes and structure of rocks, and their association with topography and drainage. Geological maps, therefore, provide the key for understanding the structure and geological history of any perticular region. These maps have a wide range of application in mineral prospecting, mining and civil engineering works.

The important characteristics of a geological map are as follows.

(*i*) The geological map shows the contacts between various rocks units.

(*ii*) The relative ages of strata are commonly shown by an index. In the index the different rocks beds are arranged in the order of decreasing age from the bottom upward. The oldest formation is placed at the bottom of the column while the youngest at the top.

(*iii*) On the geological map the observed dip and strike of a rockbed are also shown. The angles of dip are indicated by values placed above the dip and strike symbol.

(*iv*) In areas of folded strata, individual rockformations appear on the map in belts whose pattern indicates the nature and types of folds involved.

(*v*) Faults are indicated where such patterns are offset abruptly.

12.2. TOPOGRAPHIC MAPS

A topographic map is one which shows the configuration of the land surface and drainage details of the area. It also shows man made features such as roads, railways, villages, towns, etc. Contour lines are commonly used to depict elevations on the topographic maps.

Contour Lines. A contour line is a line on a map which has the same elevation above sea level along its entire length. Most maps show only the two horizontal dimensions. Contour lines are, however, an effective device for representing the third dimension on a map. Some useful facts regarding contour lines are as follows.

1. Contour lines bend upstream. They form Vs that point up the valley.
2. Near upper part of hills, contour lines form closures.
3. Contour lines are widely spaced on gentle slopes and closely spaced on steep slopes. Evenly spaced contours indicate an uniform slope.
4. Contour lines usually do not cross each other.

12.3. OUTCROP

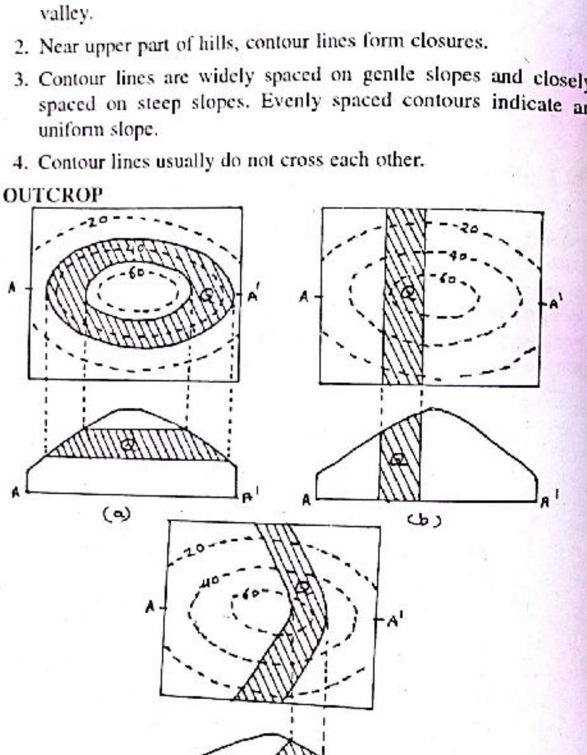


Fig. 12.1. Relationship between contours and the dip of strata. (*a*) Showing a horizontal bed, (*b*)Sshowing a vertical bed (*c*) Showing an inclined bed.

The exposure of rockbeds on the ground surface is called *"outcrop"*. Geological maps show a variety of outcrop patterns. Outcrop pattern of strata is determined by two factors : (*i*) dip and strike of strata, and (*ii*) the topography of the area.

(*a*) **Horizontal Ground.** On horizontal ground the outcrops are always straight lines irrespective of the dip of strata.

(*b*) **Undulating Ground.** On undulating ground, the outcrop pattern varies with the dip of strata.

(*i*) **Horizontal beds.** In this case the outcrops run parallel to the contours. For a bed of constant thickness, the width of outcrop will be more where the ground slope is gentle and less where the ground slope is steep [*Fig. 12.1* (*a*)].

(*ii*) **Vertical beds.** In this case the outcrops are straight lines irrespective of the topography [*Fig. 12.1* (*b*)]. The width of the outcrop will be equal to the true thickness of strata.

(*iii*) **Inclined beds.** In this case the outcrops are curved and they cut across the contours [*Fig. 12.1* (*c*)]. As a rule the smaller the dip, the more sinuous the outcrop; the higher the dip the more nearly do the outcrops approach straight lines. The width of the outcrop is controlled by the dip of strata and by the slope of the ground.

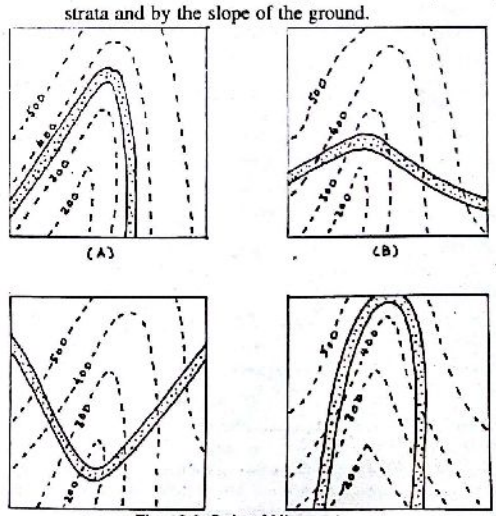


Fig. 12.2. Rule of V's.

12.3.1. Rule of Vs

In a valley the outcrops of rockbeds generally form a V-pattern. The approximate value of dip can be determined by applying the *"rule of Vs"* to these outcrops.

1. In a valley, the outcrop of horizontal strata form a *"V"*, the apex of which points upstream [Fig. 12.2 (*a*)]. However in case of the vertical beds, the outcrops run as straight lines and topography has no control on it.
2. The outcrop of dipping beds also give a V-pattern in valleys. Gentle dips give rise to *"long Vs"* while steep dips produce *"short Vs"*.
   (*a*) When beds dip up the valley, the *"V"* points upstream [*Fig. 12.2 (b)*].
   (*b*) When beds dip down the valley, two cases arise.
      (*i*) If the angle of dip is greater than the valley slope, the *"V"* points downstream [*Fig. 12.2 (c)*].
      (*ii*) If the angle of dip is less than the valley slope, the *"V"* points upstream [*Fig. 12.2 (d)*].

12.4. OUTCROP PATTERNS AND GEOLOGIC STRUCTURES

Geologic maps show various types of outcrop patterns. By studying these patterns the geologic structures such as folds, faults, unconformities and igneous intrusions can easily be recognised.

Folds. In case of folding, the repetition of outcrop of a bed takes place. If folding is open, the two successive outcrops will show the reversal of dip direction (*Fig. 12.7*). Anticlines and synclines can be distinguished by the relative position of the older beds. Older beds occur in the core of anticlines and younger beds in the core of synclines. Plunging anticlines and synclines are indicated by U-shaped outcrops.

Faults. A vertical fault outcrops as a straight line and inclined faults show changes in direction across the area. The dip of a fault plane can be estimated in the same way as the dip of bedding planes. Dip faults cause lateral displacement of beds (*Fig. 7.35*), while strike faults cause elimination or repetition of strata (*Fig. 7.36* and *7.37*). The up-throw and down-throw sides of a fault can be identified on maps by applying the rule that younger beds are found on the down-throw side and older beds on the up-throw side.

Unconformities. Unconformities can be recognised on geological maps by intersecting boundaries of sedimentary strata and by truncation of dykes, faults or other structures. Low angle faults may also give patterns similar to those of an unconformity.

Igneous Intrusions. Except sills which run parallel to the boundaries of sedimentary rocks, all other igneous intrusions intersect geological boundaries. Dykes usually run straight while batholiths have very irregular boundaries on the map.

12.5. GEOLOGIC CROSS SECTIONS

For understanding the structure of a region, geological cross sections are constructed. They are drawn from geological maps along certain given lines. These sections represent the conditions which are to be found at depth. Such subsurface conditions are inferred from the geology observed at the surface. The factors which help in constructing the geological section are as follows.

(*i*) **Contour lines.** These help in drawing topographic profile along the line of section.

(*ii*) **Structural attitude of strata.** It is indicated by the component of dip computed along the line of cross section.

(*iii*) **Thickness of each formation.** This may be obtained from the drill hole records or computed with the help of scale of map, width of outcrop and the dip.

12.6. DETERMINATION OF STRIKE

A *"strike line"* is a line which joints two points of equal elevation on a perticular bedding plane. In may also be defined as the direction of the line formed by intersection of a bedding plane and horizontal plane. The strike lines are always at right angles to the dip direction. The strike lines are important because they show dip of inclined strata just as the contours show the topographic slope on the map. Similar to topographic contours they have altitudes (*Fig. 12.3*).

To draw a strike line for a perticular boundary of a bed on a geological map, two points of equal elevation are located on it. These two points are

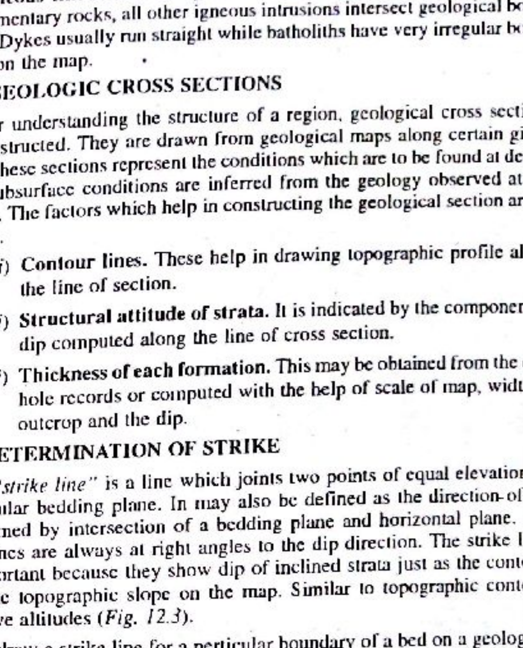


Fig. 12.3. Strike lines on an inclined bedding ...

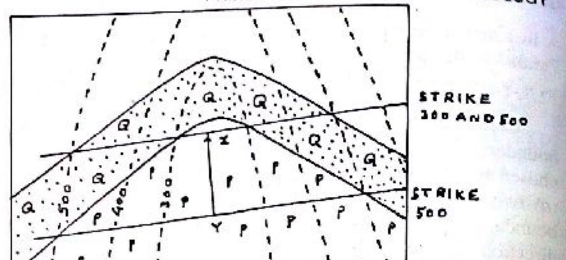


Fig. 12.4 (*a*) Determination of strike and dip on a map.
(*b*) Determination of dip by graphical method.

where a perticular contour crosses the boundary at two places. The line formed by joining the two points will give a strike line. Its altitude will be the same as that of the corresponding contour. *Fig. 12.4* (*a*) shows two strike lines of levels 300 and 500 meters drawn for the boundary between rockbeds *P* and *Q*. If the inclination of the bed is uniform throughout, all strike lines will be parallel.

In cases where a contour line does not intersect a given rock boundary at two places, the strike line is determined from any three points of known elevation on that boundary. The three points of known elevation are the points where the contours cross the rock boundary (*Fig. 12.5*). These points are connected to form a triangle. On the side of the triangle which joins the highest and lowest elevation points, a point is located which has the same elevation as the intermediate corner of the triangle.

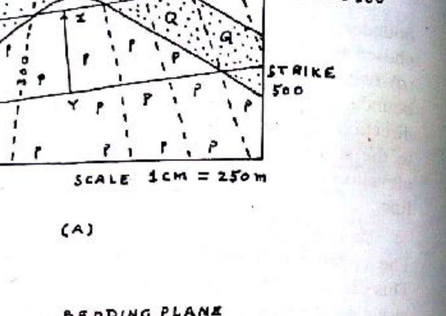


Fig. 12.5. Determination of Strike.

A line drawn through two points of equal elevation will be a strike line. Parallel to this another strike line of known elevation is drawn.

12.7. DETERMINATION OF DIP

Each rock bed has two boundaries, the top boundary and the bottom boundary. To determine the dip of an inclined bed, any one boundary is chosen and two strike lines of different altitude are drawn on it. In *Fig. 12.4* (*a*) two such strike lines of levels 300 m and 500 m are drawn for the boundary between beds *P* and *Q*. The dip will be at right angles to the strike direction. In order to find the dip direction, a line *xy* is drawn at right angles to the strike lines. The *"dip direction"* will be from the strike of higher elevation to that of lower elevation. It is indicated by the arrow on the *xy* line.

To determine the *"amount of dip"*, the length of *xy* line is measured. The *xy* line represents the horizontal distance between the two strike lines. This distance is 400 meters according to the scale of the map. The difference in elevation between these strike lines is (500 m—300 m) 200 meters. It means that the bedding plane, after a horizontal distance of 400 meters falls 200 meters vertically. The dip angle θ is computed as follows.

$$\tan\theta = \frac{\text{Vertical drop}}{\text{Horizontal distance}}$$

or, $$\theta = \tan^{-1}\frac{200}{400}$$

or, $$\text{Dip} = 26°34' \ (27° \text{ approximately})$$

Thus dip of the bedding plane is 27° in the direction NE.

The dip can also be determined by the graphical method as shown in *Fig. 12.4* (*b*). The line *xy* which represents the shortest distance between the two strike lines, is measured. A line having the same length is drawn on a drawing paper. From one end, a perpendicular of length equal to the strike interval (500 m – 300 m = 200 m) is constructed as per the scale of the map. The angle formed by joining its top with the other end of the line will be the dip angle.

12.8. DRAWING GEOLOGIC SECTION

It is frequently required to construct a geological cross section across a geological map to show the most reliable picture of the subsurface strata. Geologic sections are of two types : (*i*) normal sections, and (*ii*) oblique sections. Sections made in the direction normal to the strike are called *"normal sections"* whereas those constructed in the direction oblique to the strike are called *"oblique sections"*. The base line of the section should, in general, represent sea level. The steps involved in the construction of a geological section are as follows.

(*i*) Drawing a topographic profile

(*ii*) Determination of dip and strike.

(*iii*) Filling of geological details.

12.8.1. Topographic Profile

Most geologic maps contain contours which depict the topography of the terrain. A strip of paper is laid along the line of section and positions of consecutive contours are marked on it. These height spots are then transferred on the base line from the strip of paper. Perpendiculars equal to relevant heights are raised at various points as per the scale of the map. The tops of these perpendiculars are then joined by a free hand curve to make the topographic profile which now represents the ground surface. *Fig. 12.7 (a)* shows the topographic profile constructed along *xy* line of the geological map shown in *Fig. 12.6*.

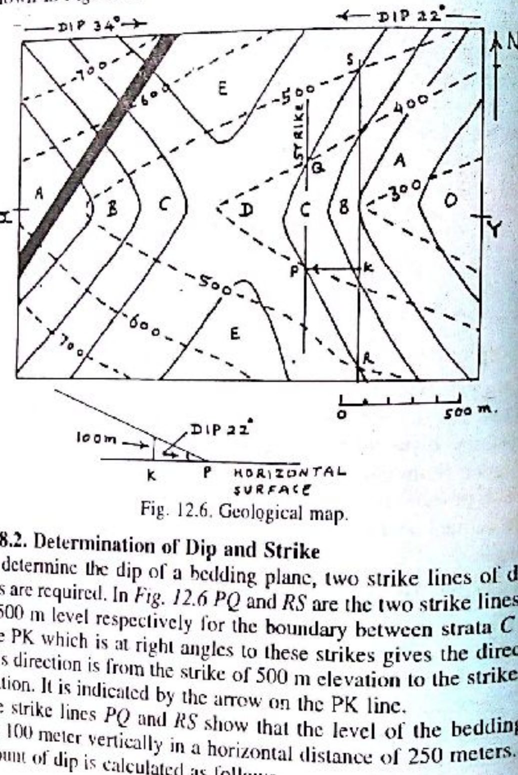


Fig. 12.6. Geological map.

12.8.2. Determination of Dip and Strike

To determine the dip of a bedding plane, two strike lines of different altitudes are required. In *Fig. 12.6 PQ* and *RS* are the two strike lines of 400 m and 500 m level respectively for the boundary between strata *C* and *D*. The line PK which is at right angles to these strikes gives the direction of dip. This direction is from the strike of 500 m elevation to the strike of 400 m elevation. It is indicated by the arrow on the PK line.

The strike lines *PQ* and *RS* show that the level of the bedding plane falls by 100 meter vertically in a horizontal distance of 250 meters. Hence the amount of dip is calculated as follows.

$$\text{Dip} = \tan^{-1}\frac{100}{250}$$

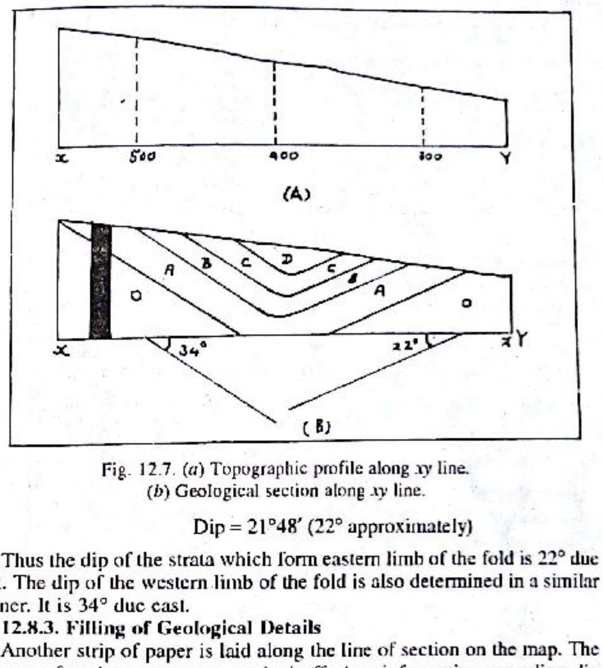


Fig. 12.7. (*a*) Topographic profile along *xy* line.
(*b*) Geological section along *xy* line.

or $$\text{Dip} = 21°48' \text{ (22° approximately)}$$

Thus the dip of the strata which form eastern limb of the fold is 22° due west. The dip of the western limb of the fold is also determined in a similar manner. It is 34° due east.

12.8.3. Filling of Geological Details

Another strip of paper is laid along the line of section on the map. The outcrops of various strata are marked off. Any information regrading dip and faults, etc. are also recorded. This record is first marked on the base line and then transferred to the surface profile. In order to do this, the various points are projected up vertically to cut the surface profile. The geological details are then added in the steps as shown below

(*a*) First, all faults that are present along the line of section are inserted. They are usually represented as vertical lines running from the ground surface downward. The strata must be shown displaced along these faults [*Fig. 12.8* (*b*)].

(*b*) Then strata are added. These are drawn from each point of outcrop and are shown dipping at angles computed for this purpose or stated on the map. This is usually done by drawing angles of dip first at the base line and then drawing parallel lines from the corresponding points at the surface profile [*Fig. 12.7* (*b*)].

(*c*) Anticlines and synclines are generally indicated on the map by change of dip or by repetition of strata. They must be made in the section accordingly (*Fig. 12.7*).

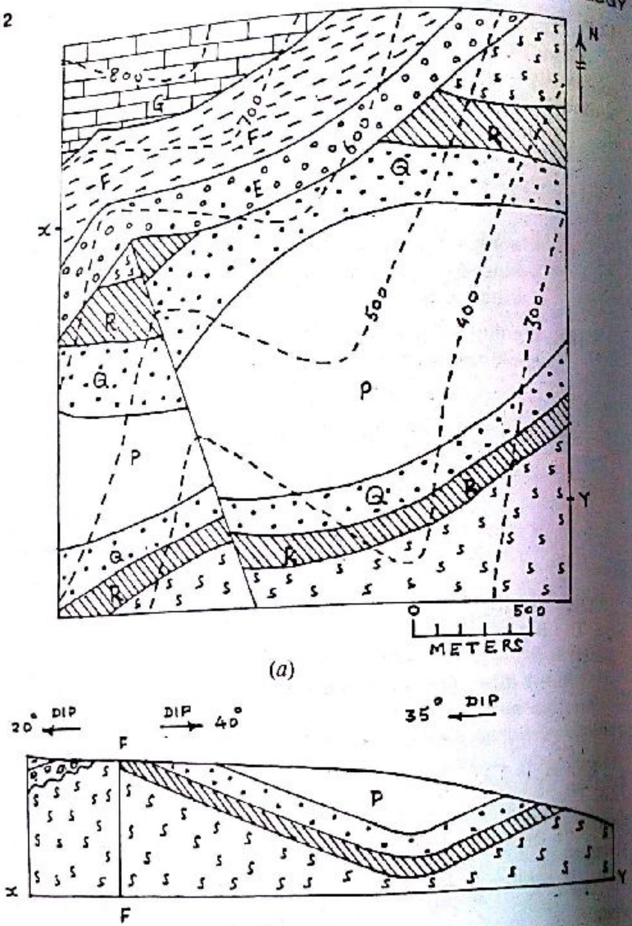


Fig. 12.8. (*a*) Geological map, (*b*) Geological section along *xy*.

(*d*) Unconformable beds must always be indicated in the section by a marked change in dip.

(*e*) Dykes should be indicated as nearly vertical beds with parallel walls, cutting through the older strata. Sills should be inserted as intrusions running more or less parallel to the bedding planes. Bosses are indicated as irregular shaped masses intruded through the strata.

12.9. DESCRIPTION OF MAPS

Geologic maps and sections illustrate the geological information in a concise form. They are usually accompanied by a detailed description. The outline of the procedure of describing a geologic map is as follows.

(*i*) **Introduction.** Give scale of the map. Look at the contours and describe the topography of the area in terms of hills and valleys. Indicate nature and number of various rock units, series or formations.

(*ii*) **Geologic Succession.** Show sequence of rock beds from oldest to youngest by making an index. Mention also the thickness of various beds.

(*iii*) **Geologic Structure.** Give a brief description of the various geologic structures present in the area.

(*a*) In case of inclined beds, give the amount and direction of dip.

(*b*) In case of folds, give the direction of axis and the nature of folds.

(*c*) In case of faults, give their nature, direction and down-throw.

(*d*) In case of an unconformity, give the number of beds present in each series of rocks and also describe their structure.

(*e*) In case of an igneous body, give its nature and geographical location.

(*iv*) **Geologic History.** Describe in brief the geologic history of the area by showing periods of sedimentation, uplift, submergence, erosion, igneous intrusion and sequence of faulting. Discuss the relative ages of folds, faults, and igneous bodies.

Example 12.1. For an illustration, let us describe the map shown in *Fig. 12.8.* The ground surface of the area is a valley which is sloping in the SE direction. Here seven rock beds are exposed. The oldest bed is '*S*' and the youngest is '*G*'.

There is an angular unconformity which separates the older series of strata from the younger series. The beds of the younger series dip with an angle of 20° in the NW direction, while those of the older series series are folded in a syncline. The axis of the fold is running in the NE-SW direction. It is an asymmetrical fold as the dip of the two limbs are unequal. The beds of the older series are traversed by a transverse fault extending NW-SE. The throw of the fault is 100 meter and the down-throw side is towards east.

The sequence of events experienced by the area are as follows.

(*i*) Deposition of four sedimentary beds *P*, *Q*, *R* and *S*.

(*ii*) Uplifting and emergence of these beds above sea level. Folding and faulting.

(*iii*) Erosion of the region.

(*iv*) Submergence under water followed by deposition of three more beds *E*, *F* and *G*.

(*v*) Uplifting and tilting of the entire region.

(*vi*) Erosion of the region to give present topography.

12.10. RELATIVE AGES OF BEDS

(*i*) In case of an unconformity, younger beds overlap older rocks.

(*ii*) The outcrops of dipping beds in a valley will always point upstream unless the dip is in the same direction as the slope of the valley, and at a greater angle. In this case progressively older beds occur in the upstream direction.

(*iii*) In anticlines the older beds outcrop toward the centre of the fold and in synclines the reverse applies.

(*iv*) Out of two adjacent beds outcropping on opposite side of a fault, the younger bed is always on the down-throw side.

(*v*) When igneous intrusions or faults cut through older rocks, they are assumed to be younger than the strata they cut.

12.11. THICKNESS OF BEDS

The thickness of horizontal and vertical beds can be obtained directly from the geologic map. Horizontal beds run parallel to the topographic contours and therefore, their thickness can be determined by interpolation. For example, in *Fig. 12.1* (*a*), the thickness of bed *Q* is 20 meters. In case of a vertical bed, such as a dyke, the perpendicular distance from one contact to the another on the map will give the thickness.

The thickness of an inclined bed can be determined in three ways : (*i*) from geologic maps and sections, (*ii*) from width of outcrops, and (*iii*) from bore hole data.

12.11.1. From Geologic Maps and Sections

In order to determine the thickness of a bed on a geologic map, a contact of the bed is selected and a strike line is drawn. This strike line is then extended so that it cuts the other contact at a different level. The difference between these two levels will give the thickness of the bed in the vertical direction. In *Fig. 12.4* the 300 m strike of one contact of the bed Q cuts its other contact at 500 m level. Hence its vertical thickness will be 200 m.

The thickness of a bed can also be determined from a geologic section constructed along the true dip direction of strata. In this case the thickness of beds is measured directly on such a section.

12.11.2. From Width of Outcrop

The width of outcrop of a bed depends on three factors : (*i*) the thickness of the bed, (*ii*) the angle of dip, and (*iii*) the topographic slope and its direction.

(*a*) **On Horizontal Ground.** If the thickness of a bed is constant, the width of outcrop varies with the dip angle. It is minimum when the bed is vertical, being in fact equal to the true thickness of the bed, and as the dip decreases the width of outcrop increases. In *Fig. 12.9* (*a*) '*ab*' is the width of outcrop and 'θ' the angle of dip. The true thickness '*bc*' of the bed can be calculated as follows.

True Thickness $bc = ab \times \sin\theta$

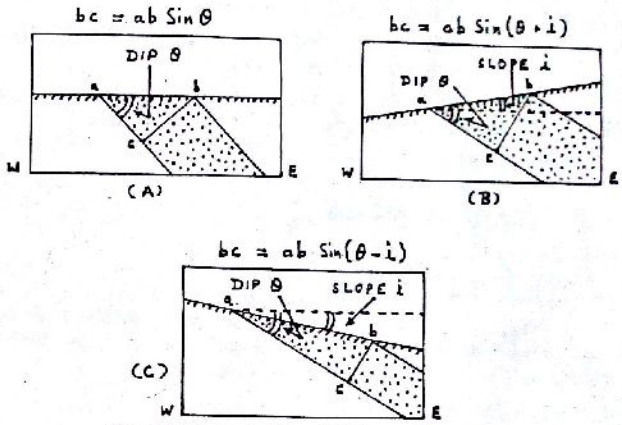


Fig. 12.9. Determination of thickness of a bed.
(*a*) Ground surface level. (*b*) Slope of ground opposite to the dip.
(*c*) Ground sloping in the same direction as the dip.

(*b*) **Slope of Ground Opposite to Dip.** In *Fig. 12.9* (*b*) the strata dip at an angle 'θ' towards east and the ground slopes at an angle '*i*' to the west. The true thickness of a bed whose width of outcrop is 'ab' can be calculated from the following equation.

True Thickness $bc = ab \times \sin(\theta + i)$

(*c*) **Ground Sloping in the Same Direction as Dip.** In *Fig. 12.9* (*c*) the slope of ground and the dip of strata both are in the same direction, the angles being '*i*' and 'θ' respectively. The true thickness of a bed whose width of outcrop is '*ab*' can be calculated as follows.

True Thickness $bc = ab \times \sin(\theta - i)$

Example 12.2. In an area, a bed of sandstone is exposed. The slope of the ground and the dip of the bed are 10° W and 20° E respectively. If the width of outcrop is 60 meter determine the true thickness of the sandstone bed.

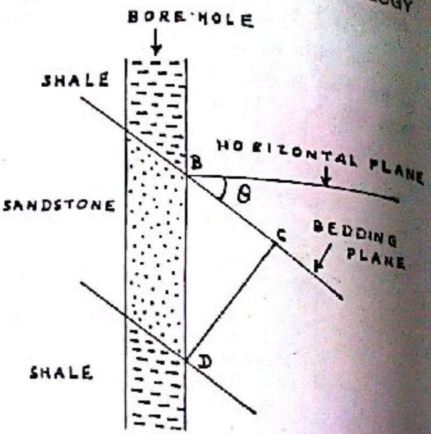


Fig. 12.10. Determination of thickness of a bed from bore hole data.

Solution.

Dip of sandstone bed

= 20°E

Slope of the ground

= 10°W

Thus the dip and the slope are in opposite directions.

True Thickness

$$= \text{Width of outcrop} \times \sin(\theta + i)$$
$$= 60 \times \sin(20° + 10°)$$
$$= 30 \text{ meters.}$$

12.11.3. From Bore Hole Data

In *Fig. 12.10* inclined strata are traversed by a vertical bore hole. In this case the true thickness of a bed can be calculated from the following equation.

True Thickness

$$CD = BD \times \cos\theta$$

where *BD* is the thickness of the bed in the bore hole and θ is the dip angle.

12.12. DIP AND STRIKE PROBLEMS

12.12.1. Strike and Dip by Three Point Method

The strike and dip of gently dipping beds can be determined from three points that lie at different elevations on the same bedding plane. The bedding plane must be identified with certainty at each outcrop. The distances and directions between the three points should also be known. the distances and directions can be measured from the map of the area. *Fig. 12.11* illustrates the graphical construction used to determine the strike and dip from the three outcrops *A*, *B* and *C*. In order to find a strike line, a point D is located which has the same elevation as the intermediate point *B*. The point *D* will be on

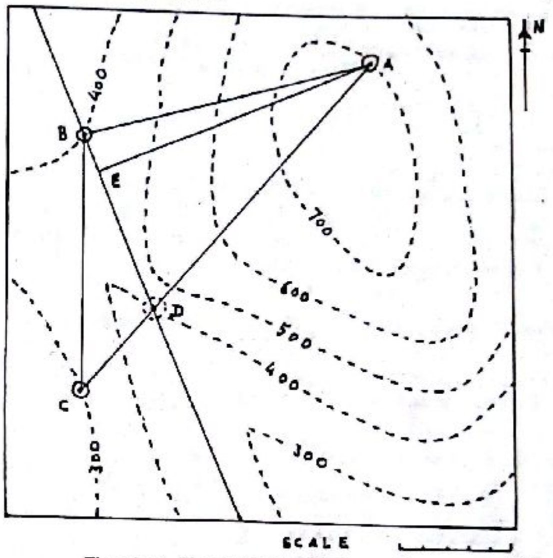


Fig. 12.11. Three point problem.

the line *AC* which joins the points of highest and lowest altitudes. Its position on the *AC* line can be determined by the following equation.

$$AD = AC \cdot \frac{\text{Difference in elevation between } A \text{ and } B}{\text{Difference in elevation between } A \text{ and } C}$$

The line *BD* which joints points of equal elevation is the strike line. To determine dip *AE*, a perpendicular to the strike is drawn. The distance *AE* is measured and the dip is determined from the following relation.

$$\text{Tangent of Dip} = \frac{\text{Difference in elevation between } A \text{ and } B}{\text{Distance } AE}$$

The dip angle is then found out from the table of tangents. The dip may also be determined graphically as explained in the section 12.7.

Example 12.3. Let us solve the problem shown in *Fig. 12.11*. The altitudes of the points *A*, *B*, and *C*, where a bed outcrops are 700 m, 400 m and 300 m respectively. The position of the point *D* is found out as follows.

$$AD = AC \cdot \frac{\text{Difference in elevation between } A \text{ and } B}{\text{Difference in elevation between } A \text{ and } C}$$

$$AD = \frac{8.0 \times 300}{400} = 6.0 \text{ cm.}$$

BD **is joined which gives the required strike line of the bedding plane. The dip of the bed is determined by the following relation.**

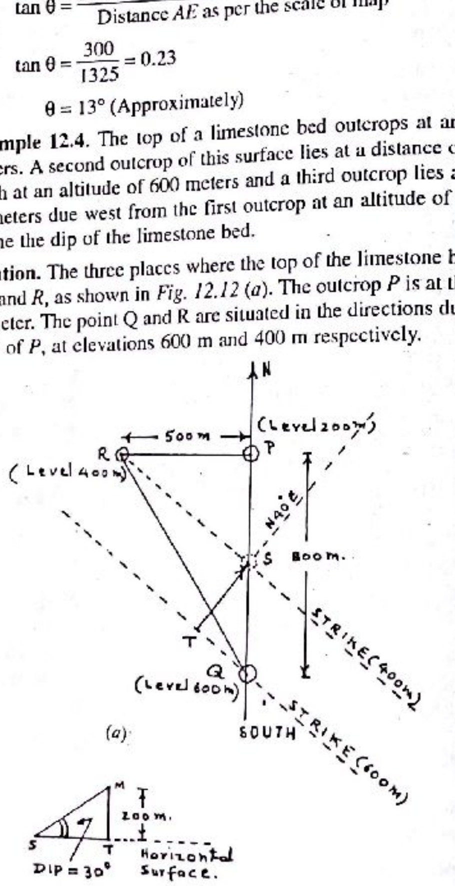
$$\tan\theta = \frac{\text{Difference in elevation between } A \text{ and } B}{\text{Distance } AE \text{ as per the scale of map}}$$

$$\tan\theta = \frac{300}{1325} = 0.23$$

$\theta = 13°$ (Approximately)

Example 12.4. The top of a limestone bed outcrops at an altitude of 200 meters. A second outcrop of this surface lies at a distance of 800 meter due south at an altitude of 600 meters and a third outcrop lies at a distance of 500 meters due west from the first outcrop at an altitude of 400 meters. Determine the dip of the limestone bed.

Solution. The three places where the top of the limestone bed outcrops are P, Q and R, as shown in *Fig. 12.12 (a)*. The outcrop P is at the elevation of 200 meter. The point Q and R are situated in the directions due south and due west of P, at elevations 600 m and 400 m respectively.



SCALE 1cm = 200m

Fig. 12.12. Determination of dip and strike from three outcrops of a limestone bed.

On the line PQ a point S is determined which is at the same elevation as the intermediate point R. The line RS formed by joining points of 400 m elevation, will be the strike line of 400 m. The direction of dip will be at right angles to the strike, from the strike line of higher altitude to that of lower altitude. It is indicated by the arrow head along the line ST. The dip direction is N40°E.

The amount of dip of the limestone bed is determined by a simple graphical construction shown in *Fig. 12.12 (b)*. The horizontal side of the right angle triangle is equal to the perpendicular distance ST between the two strike lines of different altitudes. The vertical side TM represents the difference in elevation between the two above said strike lines. The dip angle of the limestone bed as measured from the right angle triangle, is 30° in the direction N40°E.

Example 12.5. A, B, C and D are four stations at the corners of a square of side 900 meters on level ground. B is due west of A and C is due south of B. A coal seam is met with in bore holes that are put at A, B and C at depths of 200 m, 50 m and 100 m respectively. Determine the dip of the coal seam. At what depth will the seam occur at D.

Solution. *Fig. 12.13* illustrates the location of four stations A, B, C and D on the level ground surface. At stations A, B, and C a coal seam is struck

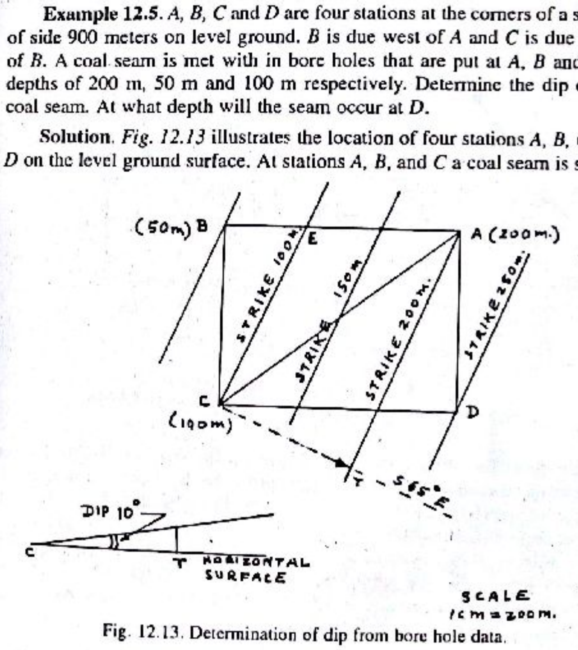


Fig. 12.13. Determination of dip from bore hole data.

at depths of 200 m, 50 m, and 100 m respectively. A triangle is constructed by joining these three points. On the line AB which connects points of the highest (200 m) and lowest depth (50 m), a point E is located where the coal seam will be at a depth of 100m. A line formed by joining C and E, the points of equal depth, will give a strike line of 100m. Parallel to this other strike lines are drawn from the points of 150 m, 200 m, 250 m and so on till the station D is reached. As the dip of the coal seam is assumed uniform, the strike lines are parallel and equidistant. A strike line of 250 m passes through the station D which suggests that the coal seam here exists at a depth of 250 m.

The amount and direction of dip is determined graphically as shown in *Fig. 12.12 (b)*. The dip of the coal seam is 10° in the direction S65°E. It should be noted that the dip direction in this case is from the strike line of smaller depth to that of grater depth.

Example 12.6. In the map shown in *Fig. 12.14*, *A*, *B* and *C* are the three stations where a coal seam is met with in bore holes at depths of 150 m, 50 m and 100 m respectively. Determine the direction and amount of dip of the soal seam.

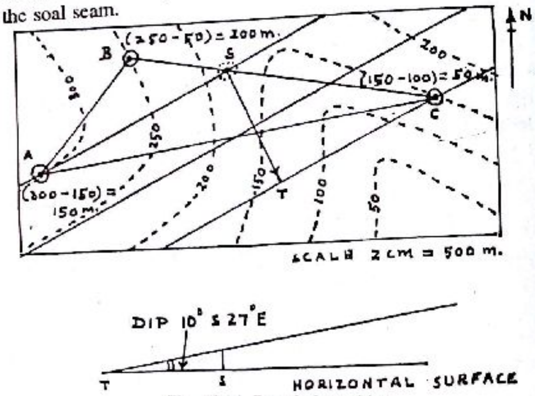


Fig. 12.14. Bore hole problem.

Solution. The altitudes of the coal seam at the stations *A*, *B* and *C* are determined by subtracting the value of depth from the value of corresponding contour on which the stations are situated. Thus the altitudes of the coal seam at these stations will be (300 – 150) = 150 m, (250 – 50) = 200 m and (150 – 100) = 50 m respectively. Now the triangle *ABC* is constructed as shown in *Fig. 12.14*. The point *S* is located on the *BC* line where the coal seam will occur at the altitude of 150 m. It can be located with the help of the following equation.

$$BS = BC \cdot \frac{\text{Difference in elevation between } A \text{ and } B}{\text{Difference in elevation between } B \text{ and } C}$$

or $$BS = BC \cdot \frac{50}{150}$$

or $$BS = \frac{BC}{3}$$

Now *A* and *S* are the two points where the coal seam occurs at the same altitude. A line drawn connecting *A* and *S* will give a strike line of 150 m. Then other strike lines are drawn and the dip is determined. The dip of the coal seam is 10° in the direction S27°E.

12.12.2. Determination of Apparent Dip from True Dip

If the true dip of a bed is known, the apparent dip in a given direction can easily be worked out with the help of the following relation.

$$\tan \alpha = \tan \theta \times \cos \beta$$

where α is apparent dip, θ is true dip and β is the horizontal angle between the true dip and apparent dip directions. It may be noted that such problems can also be solved by the graphical method.

Example 12.7. A coal seam dips at 11° in the direction due north. What will be its apparent dip in the direction N60°E.

Solution. $\tan \alpha = \tan \theta \times \cos \beta$

$$\tan \alpha = \tan 11° \times \cos 60°$$

$$= 0.194 \times 0.50 = 0.097$$

or, $\alpha = 5°35'$ (Apparent dip)

Graphical Method

The dip of coal seam = 11°

cot 11° = 5.144 or 5.0 (Approximately)

Hence, the dip of coal seam = 1 in 5.

Draw a line from a point '*O*' in the direction due north (*Fig. 12.15*) and make *OB* equal to 5 units. *BC* is a perpendicular drawn to *OB*. It represents the strike direction of the coal seam. Them a line *OC* is drawn in the direction N60°E which meets *BC* at *C*. *OC* is measured which is found to be 10 units. Hence the value of the required apparent dip is 1 in 10, or 5°.

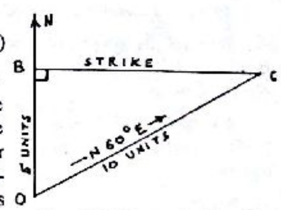


Fig. 12.15. Determination of apparent dip from true dip.

Example 12.8. The true dip of a coal seam is 14° in the direction due south. Find the direction in which the apparent dip will be 8°.

Solution.

$$\tan \alpha = \tan \theta \times \cos \beta$$

$$\tan 8° = \tan 14° \times \cos \beta$$

or, $$\cos \beta = \frac{\tan 8°}{\tan 14°} = \frac{0.14}{0.25}$$

or, $$\cos \beta = 0.56$$

or, $\beta = 56°$

Hence, the direction of apparent dip will be S56°W and S56°E.

Graphical Method

(*i*) The true dip of the coal seam = 14°

cot 14° = 4.0

Hence, true dip = 1 in 4.

(*ii*) The apparent dip of the coal seam = 8°

cot 8° = 7.11

Hence, apparent dip = 1 in 7

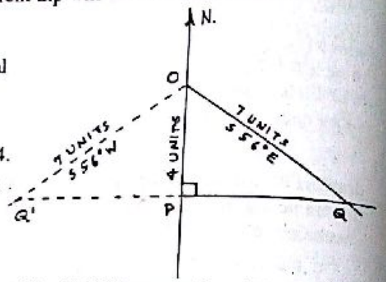


Fig. 12.16. Determination of direction of apparent dip.

Draw a line from a point '*O*' in the N-S direction and, make *OP* equal to 4 units (*Fig. 12.16*). Draw a perpendicular *PQ* to *OP*. It represents the strike direction of the coal seam. Now a point *Q* is located such that *OQ* is equal to 7 units. The direction of the line *OQ* is the required direction. There are two directions along which the apparent dip of coal seam is 8°. These are S56°E and S56°W.

12.12.3. Determination of True Dip

It is not always possible to measure true dip in the filed. It is easier to measure apparent dips of a bed along two directions and then calculate true dip from these.

Example 12.9. Two apparent dips of a coal seam are 11° in the direction N50°W, and 17° in the direction N60°E. Find the amount and direction of true dip.

Solution.

(*i*) In the direction N50°W, the apparent dip = 11°
cot 11° = 5.14 or 5.0 (Approximately)
Hence, the apparent dip = 1 in 5.

(*ii*) In the direction N60°E, the apparent dip = 17°
cot 17° = 3.27 or 3.3 (Approximately)
Hence, the apparent dip = 1 in 3.3

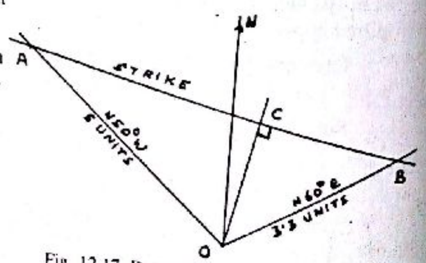


Fig. 12.17. Determination of true dip from apparent dips.

As shown in *Fig. 12.17*, from a central point *O* make *OA* 5 units long in the direction N50°W, and *OB* 3.3 units long in the direction N60°E. Connect *A* and *B*. The line *AB* will give the direction of strike of the coal seam. Dram *OC* perpendicular to *AB* from *O*. Measure *OC* which is found to be 2.2 units. The angle *NOC* is also measured which comes to be 13°. Thus the true dip of coal seam is 1 in 2.2, or 24° in the direction N13°E.

12.13. COMPLETION OF OUTCROPS

In areas where outcrops of rock beds are not enough to permit the drawing of rock boundaries, geometrical analysis of the map is done. It helps in completing the concealed boundaries of inclined beds. It also serves as a check on the field work.

If a bed outcrops on the ground surface at three points that lie at different elevations, its boundary on the map can be traced with the help of the three point method (section 12.12).

Example 12.10. In the map shown in *Fig. 12.18*, the lower surface of a 50 meter thick limestone bed is exposed on the ground surface at three points *A*, *B*, and *C*. Complete its outcrop.

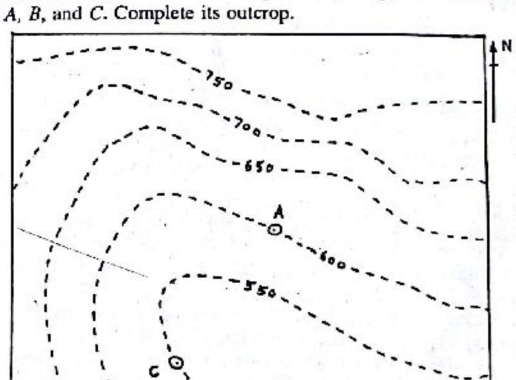


Fig. 12.18. Completion of outcrops.

Solution. The three points *A*, *B* and *C* where the lower boundary of the limestone outcrops, lie at different elevations. The elevations of these points are 600, 500 and 550 meters respectively. For drawing the geologic boundary, the first step is to draw strike lines from these points by the *"three point* *method*". As the contour interval on the map is 50 m, construct additional strike lines at the interval of 50 meter throughout the map (*Fig. 12.19*).

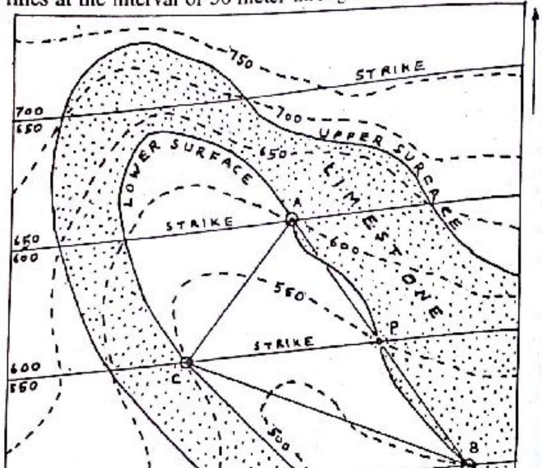


Fig. 12.19. Showing completed outcrop.

The next step is to mark the intersection points of the strike lines and the topographic contours having equal values. All these points will be on the lower boundary of the limestone bed. The free hand curve drawn by connecting these map points will be the required lower boundary of the limestone bed (*Fig. 12.19*).

The thickness of the limestone bed is 50 meters. To construct its upper boundary add 50 m to the value of each strike line already drawn. The strike lines having new values will act as strike lines for the upper boundary of the limestone bed. Now follow the same procedure and draw the upper boundary (*Fig. 12.19*).

Example 12.11. At point A on the map shown in *Fig. 12.20*, the contact between shale and overlying sandstone is exposed. These beds dip 14° in the direction S40°E. Trace the contact.

Solution.

(*i*) The strike is always at right angles to the true dip. Since the beds dip in the direction S40°E, the strike will be in the direction N50°E—S50°W.

(*ii*) As the point A, in *Fig. 12.20*, is on the 700 m contour, a line drawn through it in the direction N50°E—S50°W will be the strike line of 700 m.

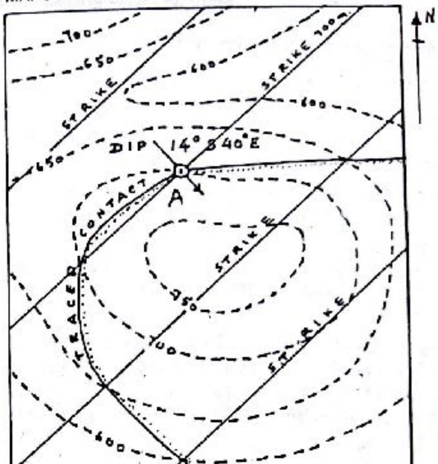


Fig. 12.20. Showing completion of outcrop.

(*iii*) The horizontal distance for the strike interval of 50 meters is determined by the following relation.

Horizontal distance = 50 × cot 14° (dip angle)

= 200 meter.

(*iv*) Other strike lines are drawn at the spacing of 200 m (2.0 cm. as per the scale) on the map parallel to the 700 m. Strike line.

(*v*) The intersection points of the strike lines and the topographic contours of equal values are marked. The curved line formed by joining the these points will be the trace of the contact between the shale and sandstone beds (*Fig. 12.20*).

REVIEW QUESTIONS

1. Explain briefly the characteristics of a geological map. Describe how a geological section can be drawn across a geological map.
2. What is an outcrop ? How does the pattern of outcrop of strata vary with the dip and surface relief.
3. Describe in brief the various criteria for the recognition of folds, faults and unconformities on geological maps.
4. Draw a geological cross section of an area shown in *Fig. 12.8*. Give a brief account of the geological history of the area.

5. Determine the thickness of a shale that strike strikes N90°E and dips 34° in the direction due south. The width of outcrop measured in a due north direction is 125 meters. The region is of no relief.

6. In a region of no relief a conglomerate strikes NE-SW and dips 45° SE. The width of the outcrop as measured along NW-SE line on the surface is 140 meters. Calculate thickness of the conglomerate.

7. A coal seam has been bored through and shows a vertical thickness of 4.0 meters. The strata dip at 1 in 3. Find the true thickness of the coal seam.

8. The width of outcrop of a limestone bed on a sloping ground is 20 meters. The slope of the ground and the dip of the strata are in the same direction and their amounts being 25° and 10° respectively. Calculate the thickness of the limestone bed.

9. The top of a shale bed outcrops at an altitude of 200 meters. A second outcrop of this horizon lies at a distance of 800 meters due north at an altitude of 600 meters, and a third outcrop lies at a distance of 500 meters due west from the first outcrop at an altitude of 400 meters. Determine the strike and dip of the shale bed.

10. The top of a clay bed outcrops at two places *X* and *Y*. *Y* is at a distance of 2700 m from *X* in the direction N30°W and their surface levels are 60 m and 240 m respectively. The same bed is struck in a bore hole at a depth of 300 m at *Z* which is at a distance of 4500 from *Y* in the direction N50°E. Calculate the dip of the clay bed.

11. A coal seam is struck in the three bore holes *X*, *Y*, and *Z* at depths 120 m, 170 m and 180 m respectively. *Y* is situated at a distance of 550 m in the direction S80°W from *X*, and *Z* is 270 m in the direction S50°W. The surface levels of the bore holes are the same. Find the dip of the coal seam.

12. A coal seam is met with in three bore holes *A*, *B* and *C*. The surface levels of bore holes are 22 m, 14 m and 30 m, and the depth of bore holes are 40 m, 20 m and 25 m respectively. The bore hole *B* is 480 m away from *A* in the direction N30°E and bore hole C is 350 m from B in the direction S30°E. Calculate the dip of the coal seam.

13. A sandstone bed has a true dip of 30° in the direction N45°W. Calculate the apparent dip in the N5°W direction.

14. The true dip of a coal seam is 14° in the direction N30°W. Find its apparent dip in the direction N25°E.

15. The two apparent dips of a limestone bed are 36° in the direction N80°E, and 47° in the direction N60°W. Find its true dip.

16. The apparent dip of sandstone bed is 6° in the direction S24°W and 10° in the direction S37°E. Determine true dip of the sandstone bed.

Appendix-A

Tables for Identification of Rockforming Minerals.

Rock Forming Minerals

Name, Composition	*Hardeness*	*Colour*	*Lustre*	*Cleavage, Fracture*	*Form Distinctive Feature*
Actinolite Hydrous silicate of Ca, Mg, Fe	5 — 6	Green	Vitreous	2 Perfect at 55° and 124°	Fibrous (Asbestos), Long prismatic crystals, Radiating agregates
Agate Microcrystalline silica	6.5	Different coloured bands.	Vitreous	Conchoidal fracture	Banded structure
Andalusite Al_2SiO_5	7.5	Grey, Pink, Red	Vitreous	Poor	Columnar crystals, Granular.
Apatite $Ca_5F(PO_4)_3$	5	Greenish, Bluish, Reddish, Yellow	Vitreous	Poor	Hexagonal crystals, Massive
Asbestos $Mg_6Si_4O_{10}(OH)_8$	2	Yellow	Silky	Perfect	Fibrous
Augite Ca, Mg, Fe, Al, silicate	5 — 6	Black, Dark green	Vitreous	2 Good at 90°	Short prismatic crystals. Square, rectangular or octagonal prisms.
Beryl $Be_3Al_2(SiO_3)_6$	7.5 — 8	White, Yellow, Greenish or Bluish green.	Vitreous	Poor	Hexagonal crystals, Massive
Biotite Silicate of K, Mg, Fe, Al with H_2O	2.5 — 3	Black, Dark brown	Sub-metallic, Pearly	Perfect basal	Foliated masses, Scaly aggregates. Thin elastic laminae.

Rock Forming Minerals (contd...)

Name, Composition	*Hardeness*	*Colour*	*Lustre*	*Cleavage, Fracture*	*Form Distinctive Feature*
Calcite $CaCO_3$	3	Colourless or White. Also with grey, yellow or red tints.	Vitreous	3 Perfect at oblique angles. Yields rhombohedral pieces	Coarsely to finely crystalline. Good crystals common. Vigorous bubbling beneath a drop of dilute HCl.
Chalcedony Microcrystalline SiO_2	6.5	White, Grey, Blue, Brown, Black	Waxy Greasy	Conchoidal fracture	Botryoidal, Stalactitic. Occurs in veins or banded aggregates.
Chert Microcrystalline SiO_2	6.5	Black, Grey	Greasy	—	Bands. Irregular nodules
Chlorite Complex silicate of Fe, Mg, Al with H_2O	2 — 2.5	Green, Black	Resinous, Pearly	Perfect	Foliated masses, Scales, Grains, Greasy feel
Corundum Al_2O_3	9	Brown, Pink, Blue, Gem varieties : ruby, sapphire	Vitreous	Uneven fracture	Rounded, barrel shaped crystals. Often as granular masses (emry).
Dolomite $CaMg(CO_3)_2$	3.5 — 4	Colourless, White, variously coloured by impurities	Vitreous, Dull	3 Perfect	Rhombohedral crystals, Granular, Massive. Less vigorous effer-vescence in cold HCl.
Flint Microcrystalline SiO_2	7	Black, Shades of grey.	Greasy, Waxy	—	Bands, Irregular nodules.

Rock Forming Minerals (contd...)

Name, Composition	*Hardeness*	*Colour*	*Lustre*	*Cleavage, Fracture*	*Form Distinctive Feature*
Fluorite CaF_2	4	Colourless, Purple, Violet, Blue, Green, Yellow.	Vitreous	Perfect octahedral	Octahedrons, Cubes. Also granular
Garnet Ca, Mg, Fe, Al silicate	7.5	Red, Brown	Resinous Vitreous	Conchoidal fracture	Isometric crystal or rounded, Specific gravity 3.6 — 4.3
Gypsum $CaSO_4 2H_2O$	2	Colourless, White. Also grey, Yellowish or Red.	Pearly Silky	Pefect	Granular, Earthy, Tabular crystals, Fibrous
Hornblende Complex silicate of Ca, Na, Mg, Fe, Al with (OH) ions.	5 — 6	Black, Greenish black	Vitreous	2 good at 56° and 124°.	Long crystals usually 6 – sided. Also in granular masses.
Jasper Microcrystalline SiO_2	7	Red, Yellow, Brown, Green	Greasy	—	Massive
Kaolinite Hydrous silicate of Al.	1 — 2	White, Grey, Yellowish	Earthy, Dull	Uneven fracture	Massive, Greasy feel and argillaceous smell.
Kyanite Al_2SiO_5	5 lengthwise and 7 across crystals.	White, Pale, Blue, Grey, Green	Vitreous, Pearly	1 Perfect	Long bladed habit
Microcline $KAlSi_3O_8$	6	Green, Bluish green, Pink, Grey	Pearly, Vitreous	2 At right angles.	Massive, Prismatic crystals. Striations on basal pinacoid due to twinning.

Rock Forming Minerals (contd...)

Name, Composition	*Hardeness*	*Colour*	*Lustre*	*Cleavage, Fracture*	*Form Distinctive Feature*
Muscovite Hydrous silicate of Al and K.	2 — 3	Transparent white.	Pearly	Perfect basal	Foliated. Thin flexible elastic laminae
Opal Amorphus silica SiO_2nH_2O	5.5 — 6.5	White, Grey, Yellow, Red.	Greasy	—	Massive. Shows play of colour.
Orthoclase $KAlSi_3O_8$	6	White, Red, Grey	Vitreous, Pearly	2 Perfect at right angles	Prismatic crystals, Tabular, Massive
Olivine $[(Mg.Fe)_2SiO_4]$	6.5 — 7	Olive-green, Brown	Vitreous	Conchoidal fracture	Granular masses.
Plagioclase (Soda-lime felspars) Na. Ca. Al silicate	6	While to grey	Vitreous	2 Perfect at right angles	Tabular. Fine parallel striations on perfect cleavage.
Quartz SiO_2	7	Purple (Amethyst), Dark-grey (Smoky quartz), Colourless (Rock crystal), Pink (Rose quartz)	Vitreous	Conchoidal fracture	6 sided prismatic crystals. Also granular and massive.
Serpentine $Mg_6Si_4O_{10}(OH)_8$	4 — 6	Green, Yellow, Brown	Waxy, Greasy, Silky	Splintery fracture	Fibrous or Platy masses.

Rock Forming Minerals (contd...)

Name, Composition	*Hardeness*	*Colour*	*Lustre*	*Cleavage, Fracture*	*Form Distinctive Feature*
Sillimanite Al_2SiO_5	6 — 7	Grey, White, Brown	Vitreous	1 Perfect	Long needle-shaped crystals. Felted masses
Staurolite Hydrous silicate of Al and Fe	7	Brown, Brownish black, Yellow	Resinous	Poor	Short prismatic crystals, some cross-shaped.
Talc $Mg_3Si_4O_{10}(OH)_2$	1	White, Pale-green.	Pearly, Greasy	1 Perfect	Foliated, Massive, Soapy feel.
Topaz $(AlF)_2SiO_4$	8	Colourless, Yellow, Bluish, Greenish	Vitreous	1 Good	Prismatic crsystals, Granular, Massive
Tourmaline Complex boro-silicate of Al, with Na, Fe, Mg, Ca and K	7.5	Black, Blue, Green	Vitreous	—	Crystal hexagonal or triangular in cross-section.
Tremolite Hydrous silicate of Ca, Mg	5 — 6	White, Grey	Vitreous	2 Perfect	Radiating fibrous crystals.

Appendix-B

Tables for Identification of Ore Minerals

Ore Minerals

Name, Composition	Hardness	Colour, Streak	Lustre Sp. Gr.	Cleavage, Fracture	Form, Distinctive Feature.
Arsenopyrite FeAsS	5.5 — 6	Silver – white. Tarnishes to pale copper colour. Streak: Grey black	Metallic sp. gr. 6.2	Poor	Massive, Granular, Crystals. When rubbed against stone it emits a garlic odour.
Azurite $2CuCO_3Cu(OH)_2$	3.5 — 4	Blue, Streak : Blue	Earthy, Vitreous, sp. gr. 3.77	Not seen	Earthy, Fibrous, Intimately associated with malachite
Barytes $BaSO_4$	3 — 3.5	White, Light yelllow. Streak : White	Vitreous, sp. gr. 4.3 – 4.6	3 Good	Tabular. Recognised by high sp. gr.
Bauxite $Al_2O_3nH_2O$	1 — 3	White, Grey, Yellow, Red. Streak : same colour as mineral.	Earthy	—	Commonly Pisolitic. Also earthy and oolitic.
Bornite Cu_5FeS_4	3	Bronzy, Streak : Grey – black	Metallic sp.gr. 5.07	None	Massive. Purplish tarnish.
Braunite $(Mn.\ Si)_2O_3$	6 — 6.5	Brownish – black. Streak : Brownish black	Sub-metallic sp.gr. 4.8	None	Massive
Chalcopyrite $CuFeS_2$	3.5 — 4	Brass to Gold yellow : Streak : Greenish black	Metallic. sp. gr. 4.2	Uneven fracture	Massive, Granular, Disseminated crystals.

Ore Minerals (contd...)

Name, Composition	Hardness	Colour, Streak	Lustre Sp. Gr.	Cleavage, Fracture	Form, Distinctive Feature.
Chalcocite Cu_2S	2.5 — 3	Lead-grey to black	Metallic, sp. gr. 5.5 — 5.8	Conchoidal fracture	Fine grained masses. May tarnish to green or blue.
Chromite $FeCr_2O_4$	5.5	Black, Streak : Brown	Sub-metallic, sp. gr. 4.5 — 4.8	None	Granular. Found in basic igneous rocks.
Cinnabar HgS	2 — 2.5	Red. Streak : Red	Resinous, sp. gr. 8.1	Perfect	Massive, Granular, Crystal
Galena PbS	2.5	Silver-grey, Streak : Lead grey	Metallic, sp. gr. 7.6	3 Good at 90°	Granular masses, Cubic crystals.
Graphite C	1—2	Black. Streak : shining black	Metallic, sp. gr. 2.1	Perfect basal	Foliated masses, Greasy feel. Marks paper.
Hematite Fe_2O_3	5.5 — 6.5	Raddish - brown to black. Streak : Red-brown	Sub-metallic, metallic. Dull. sp. gr. 5.3	Uneven fracture	Granular, Reniform, Massive or Foliated
Ilmenite $FeTiO_3$	5 — 6	Iron-black, Streak : Black	Metallic to submetallic sp. gr. 4.79	Conchoidal fracture	Massive, Granular, Thin plates

Ore Minerals (contd...)

Name, Composition	*Hardness*	*Colour, Streak*	*Lustre Sp. Gr.*	*Cleavage, Fracture*	*Form, Distinctive Feature.*
Limonite $2Fe_2O_3 \cdot 3H_2O$	5 — 5.5	Yellowish – Brown, Dark Brown, Black. Streak: Yellow, Brown	Dull, silky, sp. gr. 3.6 — 4	None	Earthy, Granular, Fibrous, Botryoidal. Alteration product of iron minerals.
Magnesite $MgCO_3$	3.5 — 4.5	White, Grey, Brown, Yellow. Streak : White	Dull, sp. gr. 2.8 — 3	None	Massive, Granular, Occurs along with serpentine masses
Magnetite Fe_3O_4	6	Black, Streak : Black	Metallic, sp. gr. 5.18	None	Disseminated grains, Granular masses, Octahedral isometric crystals.
Malachite $CuCO_3Cu(OH)_2$	3.5 — 4	Green, Streak : Green	Vitreous, Earthy, sp. gr. 3.6 — 4	Not seen	Fibrous, Earthy
Marcasite FeS_2	6 — 6.5	Bronze-yellow, Streak : Greenish black	Metallic, sp. gr. 4.9	—	Tabular. Colour lighter than pyrite
Molybdenite MoS_2	1 — 1.5	Lead grey Streak : Lead grey	Metallic, sp. gr. 4.8	perfect basal	Scaly, Granular, Foliated. Bluish tint distinguishes it from graphite.
Monazite (Ce, La, Y, Th) PO_4	5 — 5.5	Yellowish - brown, Streak : White	Resinous, sp. gr. 4.6–5.4	—	Tiny crystals
Orpiment As_2S_3	1.5 — 2	Lemon-yellow, Streak : Yellow	Resinous, sp. gr. 3.5	1 Perfect	Foliated, Massive

Ore Minerals (contd...)

Name, Composition	*Hardness*	*Colour, Streak*	*Lustre Sp. Gr.*	*Cleavage, Fracture*	*Form, Distinctive Feature.*
Psilomelane Hydrated oxide of Mn with BaO and K_2O	5 — 6	Black, Grey Streak : Black	Submetallic, sp. gr. 3.7–4.7	—	Massive, Reniform, Botryoidal
Pyrite FeS_2	6 — 6.5	Pale brass–yellow. Streak : Dark green	Metallic, sp. gr. 5.02	—	Granular masses, Cubic crystals, Massive.
Pyrolusite MnO_2	2 — 2.5	Dark grey, Streak : Black	Metallic, sp. gr. 4.8	—	Massive, Reniform, Soils the finger
Pyrrhotite Fe_7S_8	3.5 — 4.5	Bronze colour, Streak : Dark grey	Metallic, sp. gr. 4.6	—	Massive, Granular. Softer than pyrite
Realgar AsS	1.5 — 2	Red, Orrange, Streak : Red, orrange	Resinous, sp. gr. 3.56	—	Massive, Granular
Siderite $FeCO_3$	3.5 — 4	Yellow, Brown, Black Streak : White	Vitreous, sp. gr. 3.9	3 Good	Crystals, Massive, Grains.
Sphalerite ZnS	3.5 — 4	Yellow Brown, Green, Red, Streak : Light pale	Resinous to submetallic, sp. gr. 3.9–4.1	6 Good	Crystals, Grains, Massive
Stibnite S_3	2	Lead- grey, Silver–white. Streak : Dark grey	Metallic, sp. gr. 4.63	Pefect lengthwise	Long crystals, Columnar, Massive. Striations lengthwise on crystals.

Appendix - C

Tables for Identification of Rocks

Identification of Rocks

The rocks may be distinguished from one another by their composition and physical characters. In all cases care should be taken to examine fresh unweathered surfaces.

Igneous Rocks : Igneous rocks are usually nonstratified and characterized by their crystalline structure in which crystals lie in all directions with no preferred orientation. It is not difficult to see whether a given rock specimen is coarse grained, equigranular, inequigranular, porphyritic, fine grained, or glassy. Ordinarily basic igneous rocks may be distinguished from acid rocks by their darker colour and heavier weight.

Sedimentary Rocks : There is usually little difficulty in identifying whether a sedimentary rock is argillaceous, arenaceous, calcarious, or carbonaceous in character. Unlike igneous rocks which are crystalline, sedimentary rocks are fragmental. The proof of sedimentary origin may be provided by the presence of stratification, lamination, current bedding, ripple marks, or fossil content.

Metamorphic Rocks : The crystalline metamorphic rocks differ from igneous rocks in that their crystals are aligned in the parallel direction. Thus they are clearly distinguished by their foliated character. Slates have slaty cleavage, schists have schistosity, and gneisses have banded structure. The nonfoliated metamorphic rocks like marbles and quartzites are easily distinguished by their composition and relative hardness. Marbles have low hardness while quartzites are extremely hard and tough.

Igneous Rocks (Fragmental)

Name	*Texture*	*Description*
Tuff	Pyroclastic or fragmetal (Fine grained)	Consolidated volcanic ash or dust (mostly small particles of glass or pumice and occasional mineral or rock grains).
Volcanic breccia	— do — (Coarse grained)	Consolidated lapilli, pumice, pebbles, cinders, and bombs
Agglomerate	— do — (Very coarse gained)	Consolidated coarse blocks (found near vents)

Igneous Rocks (Glassy)

Name	*Texture*	*Description*
Obsidian	Glassy (Noncrystalline)	All glassy and compact, often with conchoidal fracture
Pumice	Glassy (Finely vesicular)	Volcanic froth of glassy texture and acidic composition
Scoria	Glassy (Coarsely vesicular)	Volcanic froth of glassy texture

Igneous Rocks (Fine grained)

Name	*Texture*	*Description*
Rhyolite	Crystalline, Fine grained, Aphanitic	Extrusive, acidic composition, quartz present, light coloured (Red), flow structure often present
Trachyte	— do —	Extrusive, acidic composition, quartz absent, light coloured (Red).
Basalt	— do —	Extrusive, basic composition, dark grey to black in colour

Note : Rhyolite, trachyte, and basalt may be porphyritic, vesicular, amygdaloidal or even partly glassy.

Igneous Rocks (Coarse grained)

Name	Texture	Description
Granite	Coarse grained, Phaneric	Intrusive, light coloured, acidic : rich in orthoclase and quartz.
Syenite	— do —	Intrusive, light coloured (Red), acidic : composed of orthoclase and sodium rich plagioclase ; quartz absent
Diorite	— do —	Intrusive, grey coloured : composed of soda-lime plagioclase with hornblende
Gabbro	— do —	Intrusive, dark coloured or green, basic : composed of calcium rich plagioclase, augite and iron oxide.
Peridotite, Pyroxenite, Dunite	— do —	Intrusive, dark coloured or green, ultrabasic : no felspars, all olivine, pyroxene or hornblende, magnetite or ilmenite.

Sedimentary Rocks (Arenaceous and Argillaceous)

Name	Texture	Description
Breccia	Very coarse grained	Contains angular fragments of rocks and minerals.
Conglomerate	— do —	Pebbles or gravels (rounded fragments) are cemented together.
Sandstone	Granular	Sand grains cemented together. Many varieties depending up-on the nature of cementing material
Arkose	— do —	The constituent grains are rich in felspar, quartz, and mica
Graywacke	— do —	Colour grey, composed of fragments of granite, and other rock and mineral fragments in muddy matrix
Shale	Fine grained, Massive	Composed of clay and silt and its structure may be laminated.

Sedimentary Rocks (Calcarious and Siliceous)

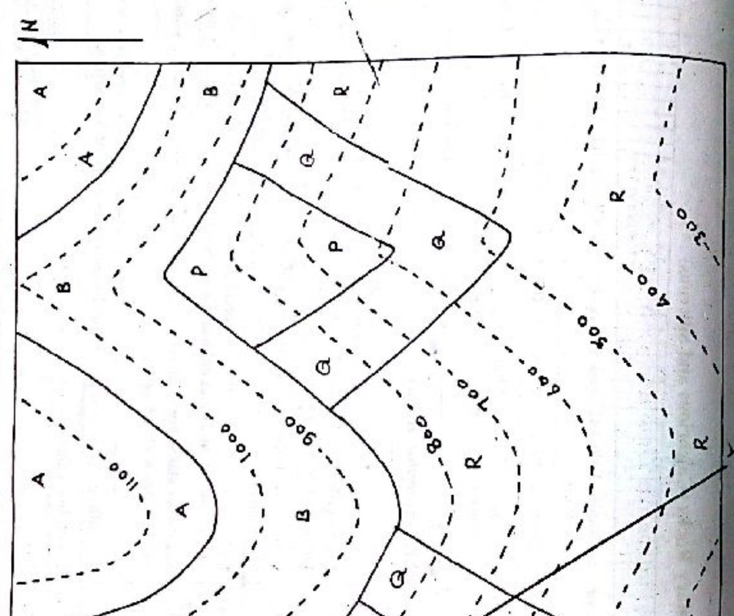
Name	Texture	Description
Limestone	Massive, Granular, Oolitic, or Crystalline	Usually light coloured, composed of $CaCO_3$, soluble in cold dilute HCl with effervescence of CO_2
Dolomite	— do —	Light coloured, composed of $CaMg(CO_3)_2$, soluble only in hot or strong acid.
Chert Flint Jasper	Noncrystalline, Dense	Colour : Chert - White, grey or any colour ; Flint - Black ; Jasper - Red. Composed of noncrystalline SiO_2

Metamorphic Rocks

Name	Texture	Description
Gneiss	Coarsely crystalline, Banded (Gneissose)	Light coloured bands of quartz and felspar alternate with dark bands of ferromagnesian minerals.
Schist	Foliated, cleavable (Schistose)	Composed of platy or flaky minerals like mica, hornblende, talc, or chlorite. It may also contain metacrysts of garnet, staurolite, kyanite and andalusite
Slate	Fine grained, Dense with slaty cleavage	Due to slaty cleavage the rock breaks into thin sheets that have smooth surfaces. The grains of mica, and chlorite are too small to be distinguished by naked eye.
Phyllite	Fine grained, Dense, with secondary cleavage well developed	Similar to slates but their constituent minerals are more coarsely crystalline, and the rock has a glossy lustre.
Quartzite	Granulose	Crystalline siliceous rock. Original sand grains more or less visible.
Marble	— do —	Crystalline calcarious or dolomitic rock

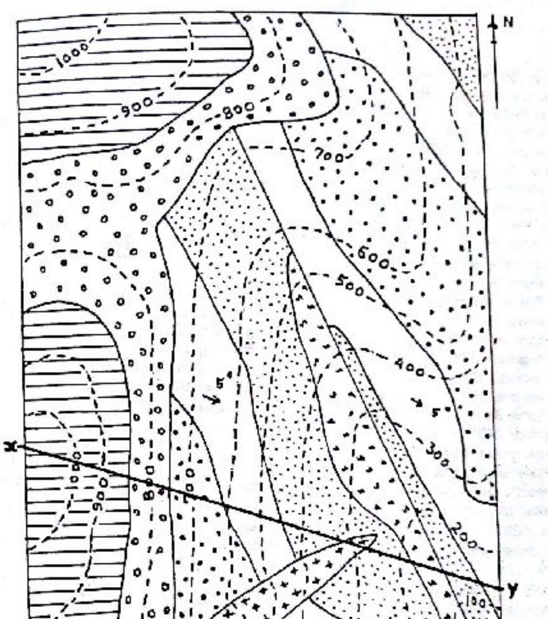
Appendix - D

Geological Map No. 1



Map No. 1. Draw geological

Geological Map No. 2



Map No. 2. (*a*) Geological map. (*b*) Geological section along x-y line.