Chapter 2
Composition of the Earth and Mineral Resources

2.1 Crust of the Earth

The crust of the earth is about 30–70-km-thick form of the outer layer of the planet in which all rocks and minerals are found. Beneath the crystal layer is the zone known as the **Mohorovičić** discontinuity, which is followed by heavy rocks of a thickness of 3000 km. This is followed by a 1800-km-thick outer core of iron and nickel in a hot semi-plastic condition, which in turn is followed down to the centre by an inner core of 1000 km thickness.

The earth's surface of which the crust is a part is divided into the following components:

(i) lithosphere, which is the solid rock portion of the earth constituting the continents and extending beneath the ocean floor;
(ii) hydrosphere, which includes oceans, lakes and other water bodies, and rivers; and
(iii) atmosphere or the blanket of air which covers the continental crust.

The distribution of minerals in the earth's crust is shown in Table 2.1.

Out of 118 elements, as few as eight are known to be present in quantities exceeding one percent. The outer crust which is about 16 km deep is made up of the following elements—oxygen, silicon, hydrogen, calcium, sodium, potassium, magnesium, titanium, phosphorus, hydrogen, carbon and manganese. These elements constitute 99.5% of the crustal rock material. Elements like platinum, gold, silver, copper, lead, zinc, tin, nickel and others constitute the remaining 0.5%.

The hydrosphere, which comprises oceans, lakes, rivers and other water bodies, contains elements and compound in a dissolved form. The composition of water from various bodies is shown in Table 2.2.

As a whole, the crust contains broadly 1600 mineral species. Amongst these, 50 are rock-forming minerals of which 29 are most common. The remaining 1521 come from ore minerals. In order to understand the mode of occurrence of

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Table 2.1 Major minerals in the crust of the earth

Mineral	Percentage of incidence
Feldspar	49
Quartz	21
Pyroxene, amphibole and olivine	15
Mica	8
Magnetite	3
Titanite and ilmenite	1
Others	3
	–
	100

Table 2.2 Composition of various water bodies (dissolved matter only)

Element/compound	Water of lakes, reservoirs of dams, smaller water bodies like rivers	Sea water
CO_3	35.15	0.41 (as HCO_3)
SO_4	12.14	7.68
Cl	5.68	55.04
NO_3	0.90	–
Ca	20.39	1.15
Mg	3.41	3.69
Na	5.79	30.62
K	2.12	1.10
SiO_2	11.67	–
Sr, M_3BO_3, Br	–	0.31
Total	97.25	100.00

economic mineral deposits, it is necessary to know about the various types of minerals and rocks, particularly their field occurrence, and methods of identification.

2.1.1 Common Rock Forming Minerals

A geologist defines a mineral as a naturally occurring, crystalline solid of specific chemical composition, structural arrangement of component atoms and physical properties, e.g. quartz, pyrite and diamond. Minerals combine to form rocks, defined and naturally occurring accumulation or mixtures of minerals formed by geological process, e.g. granite, limestone and oil shale. An inorganic substance naturally occurring in nature, though not always of inorganic origin, has (i) a definite chemical composition, more commonly with a characteristic range of chemical composition and (ii) distinctive physical properties or molecular structure. With a few exceptions, such as opal (amorphous) and mercury (liquid), minerals are crystalline and solids.

Although genesis is the major criterion for classifying rocks, a given rock derives its name, from characteristics and distinctiveness by virtue of its mineral constituent. In order to study the rocks, an understanding of minerals is a basic requirement. It may not always be possible to be conversant with all the known minerals. The best one may be taken for is to be able to recognize important minerals in the area of interest. Guide books for this are available to help in identifying the minerals in the field. Primarily aimed to guide basically mineral and ore collectors, they can also be used in exploration and prospecting.

2.1.2 Physical Characteristics of Minerals

There are certain common criteria to recognize minerals in the field. They are (i) colour, (ii) streak, (iii) lustre, (iv) hardness, (v) habit, (vi) fusibility, (vii) cleavage and fracture, (viii) tenacity and (ix) crystal system.

Form

This is one of the first observations made when a mineral is examined in a hand specimen. The form represents the common mode of occurrence of a mineral in nature. It is also called habit or structure of the mineral. To some extent, this is a function of the atomic structure of the mineral. Modes of formation, cleavage character, etc. of the mineral also contribute to the typical form of a mineral. Since some minerals consistently exhibit the same form, often it provides a valuable clue for mineral identification. But due caution should be exercised in arriving at a conclusion based on this property, because the same mineral may exhibit different forms or different minerals may exhibit the same form. So this should be treated only as a supporting clue, and the mineral should be identified by considering other clues also, obtained by different physical properties observed.

The following is the list of some common forms and the minerals (Table 2.3) which characteristically exhibits them, i.e. the appearance of a particular form is indicative of a certain specific mineral.

(i) Colour: The colour of a mineral is usually described in comparison with certain well-known objects of similar colour, e.g. ruby-red, leaf-green. Table 2.4 gives a summary of important characters of mineral.

(ii) Streak: Streak is the colour of the powdered mineral and is not influenced by impurities. It is identified by rubbing the mineral against a streak plate—a piece of white chert or any surface which can show the colour of the rubbed power. In the case of soft or powdery forms of minerals, the smear of powder on a piece of white paper will help its identification. The streak of certain important elements and minerals is given in Table 2.5.

Table 2.3 Characteristic forms of minerals

S. N.	Name of the form	Description	Example
1	Lamellar form	Mineral appears as thin separable layers	Different varieties of mica
2	Tabular form	Mineral appears as slabs of uniform thickness	Feldspars, gypsum
3	Fibrous form	Mineral appears to be made up of fine threads. Fibres may or may not be separable	Parallel fibres: asbestos types, satin spar *Radiating fibres*: Stibnite, some zeolites, malachite goethite, pyrite, pyrolusite
4	Pisolitic form	Mineral appears to be made up of small spherical grains (pea-size)	Bauxite
5	Oolitic form	Similar to pisolitic form but grains are of still smaller size (like fish eggs)	Some limestones
6	Rhombic form	Rhombic shape	Calcite, dolomite
7	Bladed form	Mineral appears as cluster or as independent lath-shaped (i.e. rectangular) grains	Kyanite
8	Granular form	Mineral appears to be made up of innumerable equidimensional grains of coarse or medium or fine size	Chromite, magnetite, pyrite
9	Reni form	Kidney-shaped. Mineral appears with number of overlapping smooth and somewhat large curved surfaces	Hematite
10	Botryoidal form	Similar to reniform but with smaller curved faces like bunch of grapes	Chalceodony, psilomelane, hematite
11	Mammillary form	Mineral appears with large mutually interfering spheroidal surfaces similar to reniform	Malachite
12	Acicular form	Mineral appears to be made up of thin needles	Natrolite, actinolite
13	Columnar form	Mineral appears as long slender prism	Tourmaline, precious topaz
14	Prismatic form	As elongated, independent crystals	Staurolite, beryl, apatite, quartz
15	Spongy form	Porous	Pyrolusite, bauxite
16	Banded form	Mineral occurs with numerous parallel bands (straight or curved) of similar or dissimilar colours	Agate
17	Crustal form	Polyhedral, geometrical shapes	Garnets, some zeolites, quartz, amethyst, pyrite, galena
18	Interpenetrating twin form	–	Staurolite, fluorite, pyrite, calcite
19	Massive form	No definite shape for mineral	Graphite, olivine quartz, jasper

(continued)

Table 2.3 (continued)

S. N.	Name of the form	Description	Example
20	Concretionary form	Porous and appears due to accretion of small irregularly shaped masses	Laterite
21	Nodular form	Irregularly shaped compact bodies with curved surfaces	Flint, limestone

Table 2.4 Characteristic colours of minerals

Colour	Mineral of element
Silver-white, tin-white	Native silver, antimony, arsenopyrite
Steel-grey	Platinum, manganite, chalcocite
Blue-grey	Molybdenite, galena
Lead-grey	Galena, stibnite
Iron-black	Graphite, magnetite, hematite
Black	Ilmenite, columbite, wolframite, mica, some amphiboles
Copper-red	Native copper
Bronze-red	Bornite, niccolite
Bronze-yellow	Pyrrhotite, pentlandite
Brass-yellow	Pyrrhotite, pentlandite
Gold-yellow	Chalcopyrite, millerite, pyrite
White with greenish tinge	Amphibole, pyroxene
Blue	Azurite, lapis-lazuli, sapphire, kyanite, beryl, fluorite, calamine
Green	Serpentine, malachite, spodumene, jadeite, talc, garnet
Yellow	Sulphur, orpiment, topaz, barite, sphalerite, siderite, goethite
Red	Ruby (corundum), garnet, cuprite, cinnabar, zircon, zincite, realgar, rhodochrosite
Brown	Staurolite, rutile, tourmaline, quartz

(iii) Lustre: Lustre is a measure of the reflectivity of the mineral surface and varies in degree and quality. Lustre is described as dull, feeble, brilliant and splendent. Other terms used to describe lustre are adamantine, resinous, pearl, vitreous, silky, metallic, etc., which are self-explanatory.

(iv) Hardness: Hardness is the resistance to abrasion and is expressed on the Moh's scale given in Tables 2.6 and 2.7 and a scale can also be used effectively in the field.

(v) Habit: Habit defines the size and shape of the crystal, and the structure and form taken by the aggregates. Crystals may be referred to as tabular (mica),

Table 2.5 Streaks of some important minerals

Streak colour	Element/minerals
Golden yellow	Gold
Silvery white	Silver
Copper-red	Copper
Greyish white	Platinum
Black	Pyrolusite, argentite, graphite (shining black), tetrahedrite, ilmenite, magnetite, columbite
Greenish black	Chalcopyrite, millerite, pyrite
Brownish black	Niccolite, pyrite, marcasite, wolframite
Greyish black	Chalcocite, bornite, galena, pyrrhotite, covallite (shining), stibnite, cobaltite, marcasite, arsenopyrite
Grey	Antimony, graphite (shining grey)
Brown	Sphalerite, tetrahedrite (Dark) rutile (pale)
Brownish red	Cuprite (shining), hematite, manganite
Brownish yellow	Goethite
Red	Cinnabar, pyrargyrite (dark), hematite
Orange-red	Realgar
Orange-yellow	Crocoite
Yellow	Orpiment (pale), vanadinite
Green	Malachite (pale), vivianite (very pale)
Blue	Azurite, lazurite
Purple	Vivianite

Table 2.6 Hardness scale of minerals

Mineral	Hardness on Moh's scale
Talc	1
Gypsum	2
Calcite	3
Fluorite	4
Apatite	5
Felspar	6
Quartz	7
Topaz	8
Corundum	9
Diamond	10

prismatic (quartz), or acicular (kyanite), depending on the ratio of length to thickness. Aggregates may be radiating (stibnite), fibrous (asbestos), bladed (mica), columnar (quartz), granular (hematite), etc. Minerals without any crystal form but showing circular outlines are described as coliform. Other terms in use are botryoidal (iron ore), reniform, etc.

(vi) Fusibility: This measures the ability of the minerals to melt. A scale showing the ease of the melting of various minerals is given in Table 2.8.

(vii) Cleavage and fracture: When a mineral is broken, it splits along a crystal place or an irregular surface. When the fracture occurs along a crystal plane, it is called cleavage and is described as indistinct, poor, good, perfect, or eminent. When the breaking is not along a regular plane, it is described as a fracture. Fracture is described as uneven, hackly, splintery, fibrous, earthy, or conchoidal. Some common types of fractures shown by the most typical minerals are given in Table 2.9 and tenacity in Table 2.10 which measures the ease with which mineral breaks are described below for some minerals.

For the criteria described above area guide, several criteria are required for a correct identification of a mineral properly. There are, however, some ores and minerals which can be identified by a single criterion.

Table 2.7 Determination of hardness during exploration work

Hardness		
2–2.5	Can be scratched by	Fingernail
3–3.5	Can be scratched by	Copper coin
5.5	Can be scratched by	Glass, knife blade
6	Can be scratched by	Vesuvianite
6.5	Can be scratched by	Vesuvianite
7	Can be scratched by	file

Table 2.8 Scale of fusibility

Mineral	Melting point, °C
Stibnite	525
Natrolite (chalcopyrite)	965
Almandite garnet	1200
Orthoclase	1200
Actinolite	1296
Bronzite	1380
Quartz	1600

Table 2.9 Types of mineral fracture

Fracture	Mineral
Conchoidal	Obsidian, flint, chalcocite, sphalerite, quartz, halite
Subconchoidal	Rutile, stibnite, argentite, cordierite, staurolite
Even	Galena
Uneven	Cinnabar, millerite, chalcopyrite
Hackly	Native iron

Table 2.10 Tenacity of common minerals

Tenacity	Mineral
Brittle	Calcite
Sectile	Gypsum
Malleable	Native gold and silver
Flexible	Talc

2.1.3 Importance of Mineralogical Characteristics

2.1.3.1 Grain Size

The classification of any material according to the size of occurrence or the size to which they need to be crushed or pulverized is very important and, therefore, the sizes have to be described with precision.

The particle sizes of some of the naturally occurring material are given in Table 2.11.

In the case of pulverized material, there are standard sieve sizes as per the British standard, the ASTM standard, or the Indian standard. All of these specifications in terms of mesh sizes are not always common in all. Therefore, it is essential to know in inches or in millimetres the exact specifications and standard tables to the same (see Table 2.12).

The grain sizes are of great significance in the beneficiation tests. Normally, the microscopic size varies from 0.001 to −0.25 mm, whereas the megascopic sizes range from +0.25 to 100 mm or 150 mm which could be identified by magnifying lens. The effect of grain size has a great bearing on the method of beneficiation. The best results under various methods are expected at the following grain sizes.

Table 2.11 Size ranges of naturally occurring materials

Main classification	Secondary classification	Diameter in mm	Example
Gravel	Boulder	256	Conglomerate
Gravel	Cobble	256–64	Conglomerate
Gravel	Pebble	64–4	Conglomerate-
Gravel	Granule	4–2	Conglomerate
Sand	Very coarse	2–1	Sandstone
Sand	Coarse	1–0.5	Sandstone
Sand	Medium	0.5–0.25	Sandstone
Sand	Fine	0.25–0.125	Sandstone
Sand	Very fine	0.125–0.062	Sandstone
Silt	–	0.062–0.005	Siltstone
Clay	–	<0.005	Shale

Table 2.12 Size separation and minerals

	Method of beneficiation	Best result at grain size, in mm
1	Heavy media up to specific gravity of the medium (water, salt bath, etc.) being 5.2	2.0–10
2	Heavy media solutions	10.0–80.0
3	Jigging	1.0–25.0
4	Tabling	0.1–2.5
5	Humphrey spiral	0.1–1.0
6	Cyclone	0.5–3.0
7	Magnetic concentration	0.075–75.0
8	Electrostatic separation	0.10–2.5
9	Froth floatation	0.01–0.25

Table 2.12 emphasizes the importance of the grain size of the mineral to which the ore has to be ground for making it suitable for beneficiation by various methods.

2.1.4 Mineralogical Identification

Mineralogical identification is a necessary need in the initial stages of prospecting and exploration but more so in the adoption of specific process of mineral beneficiation and processing whenever such beneficiation is called for. To cite an example, the general term bauxite may cover both monohydrate and trihydrate ore minerals either as boehmite and diaspore or gibbsite. The mineralogy of bauxite and the loss on ignition as per the chemical composition are stated to be related. An exploration geologist is required to give special attention to texture and to the ore mineralogy of bauxite since it would guide in the production of alumina.

Similarly, in the case of chromites, though they are spinels with the general composition of $FeCr_2O_4$ some are rich in iron and in some others magnesium replaces iron. A combination of precise chemical and mineralogical analysis shall guide if chromite ore meets a grade with the desired Cr/Fe ratio.

In the case of iron ores, the tolerance of FeO which is the index of magnetite content (Fe_3O_4) in the otherwise hematite (Fe_2O_3) ore is important, and the presence of hydroxide minerals such as limonite and goethite is considered deleterious. Magnetic separation can be worked on magnetite iron ores. Likewise, if the deposit is mainly limonite and goethite ores, it will be possible to work them as direct pelletizing ores by driving out the LOI and enriching the ores.

Similarly, we would like to know if zinc ores are of gahnite (aluminate) or sphalerite (sulphide), lead ores are of galena (sulphide) or cerussite (carbonate) and titanium ores are of rutile or ilmenite minerals.

Nature of mineralogy is important for the above examples in respect of ore minerals need to be kept in mind. In fact, an understanding of ore mineralogy is pre-requisite to plan mineral processing. A basic knowledge will be of help for exploration geologists as to the ore processing since understanding of ore textures will help in deciding the appropriate method and grinding of ores for the best release of metals.

2.1.4.1 Specific Gravity of Minerals

The specific gravity of a mineral is one of the important criteria for its identification. Application of specific gravity in exploration and subsequently a proper evaluation of tonnage, ore processing and beneficiation are significant.

The in situ bulk density (true specific gravity) is the sum total of the weighted average specific gravities of all the mineral present, weighted by the proportion in which the different minerals are present. Therefore, except while dealing with a mono-mineral deposit without any gangue or associated minerals, which is rare, in all other cases, the bulk density has to be determined. Besides, the word bulk density connotes specific gravity corrected for porosity voids, joints, etc. The best practical approach is to determine how much a specific volume of the material weighs and then to determine the volume-to-weight ratio directly. For example, if an accurately measured one cubic metre (m^3) of ore in situ is taken out and weighs 3 tonnes, the bulk density of the material would be 3.

To determine the specific gravity of dense and non-porous rocks like igneous and metamorphic rocks, a Walker's Steelyard balance is used. In other cases such as bauxite and sandstone, which are porous, the specific gravity is determined by applying wax on the specimen and using a steelyard balance. However, a pycnometer is used for determining the true specific gravity of porous material. It is possible to use geophysical methods, such as densitometer tool, for determining the bulk density that is measuring the bulk density using radioactive method.

In multi-metal ores having highly variable specific gravity of ore minerals such as chalcopyrite and galena (4.2 and 7.5), it would be essential to find out the proportion of the minerals present in the ore and then apply the respective specific gravities for the two ore minerals and a common specific gravity for all the gangue minerals so that the bulk density for the ore as a whole can represent a weighted average. Unless duly weighted to the proportion of minerals of varying specific gravities, the tonnage factor adopted will not be accurate.

It will be useful to use or prepare ready-made tables (such as Table 2.13) so that an idea of what tonnage factor is to be considered for ores of different specific gravities could be ascertained. Table 2.13 shows the tonnage factor to be considered for various specific gravities at one percent base metal assay. This table can be conveniently used for varying percentages of assay of a combination of assays.

Table 2.13 Tonnage factors for specific gravity

S. No.	Specific gravity	Tonnes of ore per m^3	kg. of base metal in m^3
1	2.5	2.5	25
2	3.0	3.0	30
3	3.5	3.5	35
4	4.0	4.0	40
5	4.5	4.5	45
6	5.0	5.0	50
7	5.5	5.5	55
8	6.0	6.0	60
9	6.5	6.5	65
10	7.0	7.0	70
11	7.5	7.5	75

2.2 Formation of Rocks and Mineral Deposits

In Geological evolution of the lithosphere, there are three main processes responsible for the formation of rocks and mineral deposits. They are (i) magmatism, (ii) sedimentation and (iii) metamorphism. These three processes give rise to three major groups of rocks, respectively, viz.

(1) igneous rocks, (2) sedimentary rocks and (3) metamorphic rocks

Since most of the mineral deposits are associated genetically with these three types of rocks, a study for understanding of these rocks is required and helpful in mineral exploration programme.

2.2.1 Igneous Rocks

All igneous rocks are formed from cooling of molten magma. Varying conditions of genesis, coupled with varying chemical and mineralogical composition of the magmas, have been instrumental in producing various types of rocks. Igneous rocks have been classified on the basis of crystallization/grain size, mineral and chemical composition. A field classification is shown in Table 2.14 based on texture, mineral content and chemical composition of individual rocks is ideally suited for the needs of exploration geologists.

Table 2.14 Igneous rocks—criteria for recognizing in the field

(i)	Dimensions	Shape and structural relationship to adjacent rocks
(ii)	Contacts	Sharp, transitional, shape (plane, undulating, grooved, irregular with dimensions of irregularities), structure (jointing, faulting, brecciation) metamorphism (width of zone, mineralization, texture attitude strike, dip, etc.)
(iii)	Colour	Wet, dry, fresh, weathered conditions
(iv)	Composition	Minerals recognizable with hand lens and their estimated proportions, estimated composition and proportion of ground mass
(v)	Texture	Degree of crystallization, porphyrite, equigranular, etc.
(vi)	Structure	Platy or linear with attitudes, columnar jointing, flow perlitic, spherulitic, orbicular, gneissic or other
(vii)	Hardness	Friability, partings
(viii)	Erosion	Erosion and weathering products
(ix)	Identification	Interpretation as to the mode of emplacement, e.g. hydrothermal or other

2.2.1.1 Guide to Study and Recording Igneous Rocks in the Field

In studying igneous rocks, it is important to follow a set routine, so that their identification becomes easy, particularly in the field. Broadly, igneous rocks may be either (a) intrusive or (b) extrusive.

(a) Intrusive igneous rocks: the following sequence of observations, with the accompanying terminology, may be used in studying and reporting intrusive igneous rocks.
(b) Extrusive igneous rocks: In studying and reporting extrusive igneous rocks, the following sequence may be employed.
(i) Dimensions—Width, length and thickness; (ii) Shape or variation in dimensions; (iii) Relation to overlying or underlying adjacent formations; (iv) Contacts, top and bottom described pre-existing surface, textural difference, fault, overlap, attitude and alteration effects; and (v) Type of accumulation—Pyroclastic or flow, viscous liquid breccia flow and reworking by wind or water.

By sequential recording of data under the headings discussed above and systematic correlation and analysis, full or partial identification of most of the igneous rocks is possible. Where precise determinations are required, thin sections need to be studied. The aim of an exploration geologist is to locate ores and minerals which form economic deposits. An exploration geologist often looks for any changes that have occurred in the lithology such as hydrothermal alteration, weathering and mineral occurrences.

2.2.1.2 Guide to Identification of Igneous Rocks in the Field

Table 2.14 classifies the igneous rocks rather broadly. There are several other rocks with intermediary compositions. Identification of rocks in the field is very important. Some of the criteria which help in identifying the major rock units in the field are given below:

(a) **Granite**: Minerals—feldspar, quartz, with minor minerals like biotite, hornblende, magnetite, etc. Minerals are easily seen without the help of a hand lens. Minerals may be intergrown. The rock is light in colour, and moderate specific gravity means moderate weight. Granite is generally hard and tough. Common economic mineral deposits are cassiterite, wolframite, galena, sphalerite and others coming through hydrothermal fluids, and gold coming in epithermal quartz veins.

(b) **Pegmatite**: Minerals—feldspar, quartz, muscovite and very coarse grains. Minerals show intergrowth texture. Pegmatites are light in colour as well as weight. They occur in a vein-like pattern. The economic mineral deposits associated with pegmatites are mica, quartz, feldspar, tourmaline, beryl and a host of others.

(c) **Granite porphyry**: This rock has a granite ground mass, phenocrysts of felspar, quartz, etc.

(d) **Monzonite**: Minerals—feldspar, biotite, hornblende and pyroxene. Minerals are mutually intergrown and are visible to the naked eye. The rock is light coloured and light in weight. The economic mineral deposits associated with granite porphyry and monzonite are copper, lead, zinc, gold, etc.

(e) **Syenite**: Minerals—feldspar, biotite and hornblende. They are visible to the naked eye and are intergrown. The rock is light in colour and weight. Sometimes they form porphyries with phenocrysts of feldspars. When syenite contains nepheline mineral, it is called nepheline syenite. Corundum deposits show a genetic relationship with nepheline syenite.

(f) **Diorite**: Minerals—amphiboles, biotite or pyroxenes, plagioclase and feldspars. This rock is grey or dull green in colour.

(g) **Gabbro**: Minerals—feldspar, pyroxene, hornblende and olivine. Mutually intergrown minerals are visible to the naked eye. In colour, the rock is dark and of heavy weight. Gabbro and anorthosite show economic concentrations of titaniferous magnetite, magnetite and ilmentie.

(h) **Periodotite**: Minerals are composed of olivine, pyroxene and hornblende, and are visible to the naked eye and exhibit mutual intergrowth. The rock is usually dark in colour and heavy in weight. Peridotites occur as intrusives. Diamonds occur in kimberlite, a variety of peridotite. Other deposits are of platinum and chromite.

(i) **Basalt**: Minerals composed of pyroxene and olivine and are not visible to the naked eye. The rock is fine grained and dark grey to black in colour and cannot be split into layers. It occurs as lava flows, dykes and sills.

2.2.1.3 Mineral Deposits Associated with Igneous Rocks

During the course of emplacement of magma, various minor and accessory constituents start getting progressively concentrated till a stage is reached when the end product is rich in some constituent which under favourable conditions gives rise to economic mineral deposits. These favourable conditions are generated by three processes:

(a) magmatic concentration
(b) contact metasomatism
(c) hydrothermal processes.

Magmatic Concentration

Magmatic concentration occurs as a result of cooling/crystallization, or concentration by differentiation of intrusive igneous rocks. Deposits of this type are associated with intermediate and deep-seated intrusive igneous rocks. Two stages of magmatic concentration have been recognized, e.g. (i) early magmatic and (ii) late magmatic. The important processes are dissemination, segregation and injection. Dissemination is a simple crystallization process without any concentration. Diamond bearing kimberlite is formed by this process. Segregation is the process of crystallization, differentiation and accumulation. Chromite and corundum deposits are formed by this way.

Contact Metasomatism

During the consolidation of a magma, high-temperature gases emanate from it. These gases usually contain certain mineral matter in gaseous form. When these gases travel through various rocks which are already existing, metamorphism and metasomatism (high-temperature replacement) take place. Certain rocks are particularly amenable to these chemical reactions and such favourable rocks become a preferred target for the accumulation of economic mineral deposits. The effect of this reaction is to chemically transform the already existing minerals into new forms, such as limestone and dolomite become marble, carbonaceous matter becomes graphite and sandstone becomes quartzite.

All magmas do not give rise to conditions of contact metamorphism. It is exclusively associated with intrusive magmas, which give rise to intrusive bodies like stocks and batholiths. Rocks which give rise to contact metamorphism generally have a granular ground mass which suggests a slow cooling of the magma. Rocks which are most susceptible to contact metasomatism are limestone, dolomite and limestone with impurities like silica, alumina, iron, manganese and others. Any rock structures, such as cleavage, bedding plane, joints and fracture systems, accelerate the invading process.

Mineral deposits associated with contact metamorphism are relatively small in size and irregular in shape, and therefore difficult to locate in the field. An understanding of field occurrence is micro-tectonics and structures of rocks. Since deposits of this type occur near intrusive bodies, granular ground mass, as seen in impure calcareous rocks, helps in locating them. The most typical field evidences for locating contact metamorphism deposits are chilled or quenched borders, evidence of dolomitization, effects of baking, hardening, partial or full recrystallization near contacts.

Economic mineral deposits are formed when the contact metamorphism takes place due to intrusions of quartz monzonite, monzonite, granodiorite, diorite and others.

The common deposits resulting are iron, copper, zinc, lead, tin, tungsten, molybdenum, emery, garnets and corundum.

Hydrothermal Process

The end product of the emplacement of magma is a fluid which generally carries metals in solution. These liquids get injected into the country rocks which offer the maximum pore spaces and other openings like fracture and fault planes. By the processes of cavity filling and replacement, various mineral deposits of economic importance are formed. Various stages of mineralization are recognized in the hydrothermal process. The three stages most commonly recognized are (i) hypothermal, (ii) mesothermal and (iii) epithermal. These stages have been recognized on the basis of certain distinct temperature and pressure conditions accompanying the formation of minerals.

Hydrothermal deposits are formed under certain optimal conditions such as (i) the availability of mineralizing solutions capable of dissolving and transporting mineral matter, (ii) the availability of openings in the rocks through which the solutions may be channelized, (iii) the availability of sites for the deposition of mineral content, (iv) chemical reactions promoting the formation of deposits and (v) sufficiently concentrated mineral matter to form a workable deposit.

These processes give rise to the following types of deposits: (i) fissure veins, (ii) shear zone deposits, (iii) stock works, (iv) saddle reefs, (v) ladder veins, (vi) pitches and flats, (viii) breccia fillings, (viii) solution cavity fillings, (ix) pore space fillings and (x) vesicular fillings.

In hydrothermal deposits also, there is no distinct ore to rock associations which could help recognize the deposits in the field. However, the combination of shear zones and intrusive igneous ore bodies nearby provides indications for ore search and locating a deposit. Typical field guides for locating hydrothermal mineralization are alteration haloes, sericitization, argillic alteration, silicification, chloritization and serpentinization which can readily be recognized as they are clearly visible on the rocks and thus on the ground.

2.2.2 *Sedimentary Rocks*

The sedimentary or detrital rocks are those formed by the deposition of solid materials carried in suspension by the agencies of transport. A number of different sedimentary rock units can be recognized.

Weathering of rocks produces soluble and insoluble components: The soluble products, like calcium and magnesium, are carried away in solution. The solids are transported by water, wind, etc. Deposition of the soluble components takes place when the carrying solutions reach the point of chemical saturation usually in bodies of water which are relatively calm. The process of precipitation may be augmented by the presence of bacteria. Iron and manganese are considered to have deposited by this process. However, the most common deposits are limestone and dolomite.

The solids wear down to small sizes: When the transporting medium loses its natural velocity, deposition takes place. The resulting rocks may be sandstone, shale, siltstone, etc. Mineral deposits of economic value are found in some of these rock types, but without any known genetic link. However, placer deposits are by-products of the process of sedimentation.

Table 2.15 shows general classification of sedimentary rocks. For more precise classification, the reader may refer to standard books on the subject.

Table 2.15 Classification of sedimentary rocks

Rock type	Inorganic	Organic
Talus	Coarse fragmentary material resulting from weathering	Lime made from shells—chalk, coral rock, etc.
Breccia	The above when cemented	Silica from the shells of plants diatomaceous earth, etc.
Soil	Unsorted material resulting from rock weathering	Carbon from plants, peat, lignite, coal, etc.
Gravel	Coarse fragments rounded by the action of water and wind	Hydrocarbons from animals—petroleum asphalt, amber, etc.
Conglomerate	The above when cemented	Phosphates from animals—Guano, phosphate rocks, etc.
Sand	Finer material deposited by water or wind	
Sandstone	The same material when cemented	
Clay	The finest material mostly kaolin, deposited by water	
Loess	The finest material deposited by wind	
Shale	The same material when cemented	
Marl	Fine particles of lime, pure or impure	
Limestone	The same material when cemented	
Till	Unsorted material left by glacial ice	
Tillite	The same material when cemented	

Methods to study sedimentary rocks in the field: In studying and reporting sedimentary rocks in the field, the following sequence and terminology may be adopted:

(a) External form of rock unit: lenticular persistent, very regular in thickness, dimensions, relation to overlying or underlying units.
(b) Colour: Colour of the unit as a whole, wet or dry colour of individual particles.
(c) Bedding:

   (i) How manifest, sharp by parting, by difference in texture, colour, transitional.
   (ii) Shape of bedding surface, plane, undulating, ripple marks, irregular, if not plane; record details of form and dimensions of features.
   (iii) Thickness of beds: comparative thickness and different orders. Relation of thicknesses, rhythmic, random, etc, and if variable, relation between thickness and composition and bedding.
   (iv) Attitude and direction of bedding surface: horizontal, inclined and curved. Relation to each other; parallel, intersecting, tangential; angles between different attitudes and directions, dips, strikes, dimensions, relation of size, composition, shape to attitude and direction; and relation of composition to different types of bedding.
   (v) Markings of bedding surface: mud cracks, rain prints, bubble impressing, ice crystal impressions, trails and footprints.
   (vi) Disturbances of bedding: edge-wise of intraformational conglomerates, folding or crumbling of individual beds before consolidation.

2.2.2.1 Guide to Study Sedimentary Rocks in the Field

The more common sedimentary rocks are (a) sandstone, (b) limestone, (c) shale and (d) conglomerate. They are identified in the field as follows:

(a) **Sandstone**: Mineral—quartz, cemented together by silica, lime or iron oxide. Coarse sandstone grades into conglomerate whereas fine sandstone grades into sandy shale. Sandstones may show fossil, current bedding ripple marks.
(b) **Limestone**: Mineral—calcite; individual grains are invisible to the naked eye, a stony appearance. Effervescence is given in the HCl acid test.
(c) **Shale**: Mineral—clay; individual grains are invisible to the naked eye, a stony appearance; it can be split into layers.
(d) **Conglomerate**: Minerals—quartz, feldspars and various other rocks and mineral pieces; individual minerals can be easily identified with the naked eye. The grains have normally varied sizes and shapes. Sand fillings or some other matrix can be seen between the grains.

There are also different intermediary varieties of specific type within sedimentary rocks.

2.2.2.2 Mineral Deposits Associated with Sedimentary Rocks

Two major ore-forming processes are involved in this. They are (a) sedimentation and (b) evaporation. Besides, the processes of sedimentation are manifested in the formation of placer and certain residual deposits. These will not, however, be considered here.

Sedimentation

Sedimentation involves various processes. Detritus material gathered from various sources by water are transported to the site of accumulation, usually a basin, where the material is deposited. Compaction, diagenesis and chemical alteration follow, giving rise to mineral deposits.

All rocks contain elements like iron, copper, manganese, etc. in varying proportions and in combination with other compounds. These elements are released from their parent rock during weathering.

Solutions charged with carbonic acid, humic or other organic acids react on the rocks to dissolve elements. Certain minerals like clay which are not chemically active are carried away in suspension. The solutions containing such suspension remain stable so long as there is no change in their physical and chemical environment. As soon as there are some changes in the above conditions, the dissolved elements precipitate and are deposited on the floor of the basin. There are also bodies of water which are fed by mineralizing solutions like fumeroles and hot springs. A stage is reached when the dissolved minerals precipitate to form deposits.

Evaporation

By a process of rapid evaporation, the dissolved material can accumulate to form deposits. Such deposition is typical in arid and desert terrains.

Important mineral deposits formed by sedimentation include iron ore, manganese ore, copper ore and uranium ore, and industrial minerals like limestone, phosphorite, gypsum, salt and clay.

2.2.3 Metamorphic Rocks

Metamorphic rocks are formed by the mineralogical and structural adjustment of solid rocks to new physical or chemical conditions that happen at depths below the surface zones of weathering and concentration and which differ from the conditions under which the rocks in question are originated. They are classified on the basis of

(a) field occurrence, (b) structure and texture, (c) mineralogical composition and (d) chemical composition .

Four major metamorphic processes are recognized.

(a) cataclastic metamorphism,
(b) thermal metamorphism,
(c) dynamo-thermal metamorphism and
(d) plutonic metamorphism

(i) **Cataclastic metamorphism**: Here, the minerals are crushed and granulated through the development of small amounts of stress and low temperatures. The typical features produced by this process are crush breccias, micro-breccias, mylonites, flow cleavage, fracture cleavage and stain–slip cleavage, which guides in recognizing the phenomenon in the field.
(ii) **Thermal metamorphism**: This is connected to the intrusion of large igneous rock bodies. Metamorphic changes take place due to the heat of intrusion and produce zones of mineral and textural around the intrusive, which is recognizing an aureole. The typical rocks produced by this process are hornfels, calc-silicate hornfel, quartz-hornfel, crystalline limestone, marble, serpentinous rocks, etc. Mineral deposits of economic value are asbestos, limestone, marble and graphite.
(iii) **Dynanomothermal metamorphism**: In this process, the rocks are recrystallized and ions formed by directed pressure and heat. The rock produced are phyllite, mica schist, quartz schist and gneisses. Economic mineral deposits are soapstone, talc, sillimanite, kyanite and andalusite.
(iv) **Plutonic metamorphism**: Changes take place in rocks due to the combined effect of great heat and uniform pressure, a condition of great depths. Typical products are granulites, leptites, leptynites and gneisses.

Method to study metamorphic rocks in the field: The following sequence and terminology shall help to study metamosphric rocks in the field (Table 2.16).

Table 2.16 Terminology used in describing metamorphic rocks in the field

(a)	Type of metamorphism	Cataclastic, thermal, dynamo-thermal or plutonic
(b)	Form and field name of the rock unit	Shape, lenticularity, regularity of thickness and shape, dimensions, etc.
(c)	Structural relation to adjacent formulation	
(d)	Contacts	(i) How manifest; sharp, transitional intrusive (ii) Shape of contacts: plane, undulating, grooved, irregular, record of dimensions (iii) Strike and dip (iv) Disturbances of contacts: intraformational conglomerates, brecciation, jointing, faulting, alteration

(continued)

Table 2.16 (continued)

(e)	Colour	Colour of the mass as a whole; wet or dry, colour of individual parts on particle, inclusions
(f)	Composition	List of identifiable minerals and proportion of each; compositional banding, inclusions, lateral or vertical variations
(g)	Texture and structure	(i) Degree of crystallization and granularity, porphyroblasts, relic phenocrysts or pebbles (ii) Foliation, gneissic, schistose, slaty, banded, lenticular (iii) Contortions of compositional bands or foliation (iv) Relic textures and structure, ripple marks, spherulites, flow lines (v) Lateral or vertical variations in texture and structure
(h)	Hardness	Friability, flakiness, cases or parting due to foliation
(i)	Erosion and weathering products	Soil, sediments

2.2.3.1 Guide to Recognizing Metamorphic Rocks in the Field

Some criteria which help identify a few of the metamorphic rocks in the field are given in Table 2.17.

Table 2.17 Field identification of metamorphic rocks

(a)	Hornfels	Non-schistose rock of equidimensional grains. Occur typically in contact aureoles
(b)	Buchites	Partially-fused hornfelsic rocks occurring as xenoliths in basalts, diabases, etc.
(c)	Slates	Fine-grained rocks with perfect planar schistosity but lacking in segregation banding
(d)	Phyllites	Similar to salates, but grains are coarser. New mica and chlorite impart a lustrous sheen to schistosity
(e)	Schists	Strongly schistose, commonly lineated metamorphic rocks in which the grains are coarse enough to allow microscopic identification of the component minerals
(f)	Gneisses	Coarse-grained irregularly banded rocks with discontinuous rather poorly defined schistosity. They are products of high-grade regional metamorphism
(g)	Granulites	Even grained metamosphic rocks, poor in mica and rich in quartz, feldspar, pyroxenes and garnet which lack a prismatic or tabular habit
(h)	Mylonites	Fine-grained, flinty-looking, strongly coherent, banded or streaked rocks resulting from extreme granulation of coarse-grained rocks without any special chemical composition
(i)	Cataclasites	These are rocks formed by ruptural deformation. Cataclasites may grade into mylonites

(continued)

Table 2.17 (continued)

(j)	Phyllonites	These rocks resemble phyllites, but are formed by mechanical degradation of initially coarse rocks
(k)	Quartzites	Metamorphic rocks composed of recrystallized quartz. Quartzites are generally produced by regional metamorphism of sandstones
(l)	Marbles	Marbles are produced by the regional metamorphism of calcareous sediments. The rock is composed of calcite or dolomite
(m)	Amphibolites	Metamorphic rocks composed or hornblende or plagioclase
(n)	Serpentines and soapstones	Composed of serpentinous minerals, talc, chlorite, etc. and formed by metasomatism of peridotites

2.2.3.2 Mineral Deposits Associated with Metamorphic Rocks

The process of metamorphism may alter an old deposit and produce a new one or may act on any rock and produce deposit, provided the original minerals are conductive to such a transformation. The source rocks undergo recrystallization or recombination or both. The major deposits produced by metamorphism are asbestos, graphite, talc, soapstone, sillimanite, kyanite and garnet. Mineral deposits formed due to metamorphism are in the form of whole rocks like marble or in lenticular, linear concentrations like soapstone and asbestos. These deposits can form from any favourable source rock and hence do not generally show any rock to ore deposit association or give any clear field evidence for their location.

2.3 Other Ore-Forming Processes and the Resultant Mineral Deposits

Apart from those discussed above, there are two other processes which have given rise to important mineral deposits. These are:

(a) Mechanical and residual concentrations and
(b) Oxidation and supergene enrichment.

(a) **Mechanical and Residual Concentration**

Due to the continuous action of weathering agents, rocks are disintegrated mechanically and decomposed chemically. Unstable minerals like feldspars, pyroxenes, amphiboles, etc. are chemically altered, and the compounds are dissolved, olivine transported by water and wind. Stable minerals like quartz and gold are not transformed chemically but released out of enclosing matrix. Due to the continuing action of transporting agents like running water and wind, the particles get worn down to very small sizes and are transported to great distances. Deep and continuous weathering offers a large variety of products in the form of mechanical fragments and in the dissolved chemical form. The action of weathering and transportation creates two types of mineral deposits:

(i) Residual concentrations and
(ii) Mechanical concentrations (placer formation).

(i) **Residual Concentration**: Due to weathering and transportation, various rock constituents are removed; the residues accumulate till they attain sufficient concentration, purity and size to form a mineral deposit. Certain conditions are necessary for their formation, such as a rock containing valuable minerals, favourable climate, conditions of chemical decay and a mode of selective transportation where only the undesirable constituents are washed off. Mineral deposits which have formed by this process include iron ore, manganese, bauxite, clay, nickel, phosphate, barites, tin and ochre.

(ii) **Mechanical Concentration**: Mechanical concentration is basically a physical separation of the lighter constituents from heavier constituents accomplished by running water or moving air. This takes place in two stages, viz. (i) weathering and separation of stable minerals from their matrix and (ii) their concentration. The minerals involved in this process may come from the already existing mineral deposits or from rocks which contain some valuable mineral deposits or from rocks which contain some valuable mineral constituents in a much disseminated form. The resultants are known called deposits which may be of four types, viz. (a) eluvial placers, (b) stream or alluvial placers, (c) beach placers and (d) eolian placers.

(a) **Eluvial Placers**: Eluvial placers are formed on hill slopes. Material released from outcrops upslope is roughly sorted, the heavier staying close to the outcrop and the lighter moving downhill. Some field guides to locate such deposits are areas of breaks in the slope, hillside talus, scree accumulations, etc. Important deposits of tin, gold iron and manganese are formed by this way.

(b) **Alluvial placers (stream placers)**: Minerals and rocks released during weathering are transported downstream by rivers and streams. During floods, the material is carried rapidly downstream. Whenever there is a fall in the velocity of water, the heavy minerals settle down. A sufficient concentration of one mineral ultimately gives rise to an important mineral deposit. Such deposits are formed in meander bends and near natural obstructions in the stream course. Placer deposits of gold and diamond are formed in this way. Some field guides to locate such deposits are meander bends, stream junctions, alluvial fans, cones, accumulation near points of a sudden drop in velocity, etc.

(c) **Beach Placer**: Due to wave and shore action, placers are formed along seashores. Sorting of heavy and light minerals takes place due to wave action. Deposits formed this way include gold, ilmenite, magnetite, monazite and diamonds. Some field guides are meander bends, unusual colouration in a beach sand, sparkle and scintillation effects in reflected sunlight, etc.

Table 2.18 Important products of the oxidation of ore deposits

Metal	Original composition	Oxidized product
Iron	Sulphides Carbonates Oxide	Hematite, limonite sulphate Limonite, ferric hydroxide Hydrous ferric oxide
Copper	Sulphides	Carbonates, oxides, native copper, silicate
Zinc	Sulphides	Carbonate, silicate
Lead	Sulphide	Sulphate, carbonate
Tin	Oxide or sulphide	Oxide
Aluminium	Silicate	Oxide, silicate

(d) **Eolian placers**: These are formed in acid regions. The material is released during weathering in desert or arid by wind action and sorted during transportation. When the wind current meets with an obstruction, the heavy minerals settle down. Economic deposits of salt and gypsum found in Rajasthan desert are formed in this way.

(b) **Oxidiation and Supergene Enrichment**

Mineral deposits get exposed to the atmospheric action as a result of weathering. Surfaces water results in the outcrops yielding solvents which in turn dissolve another one. This process takes place up to the top of the water table. If the solutions penetrate the water table, their metallic content gets precipitated and rich secondary cross develops. Both oxidation and enrichment have produced base metals deposits.

Important products of oxidation of primary ore deposits are listed in Table 2.18.

2.3.1 Guide to Locate Oxidation Enrichment Ores

Look for the presence of gossans cover, zone of leaching and limonitic caps. Gossans have a high diagnostic value for the buried mineral deposits.

Gossan capping is a result of chemical reaction taking place within the rocks and mineral as a sequel to interaction/reaction of water and air. This occurs near the surface or very near the surface. The surface features thus produced help in guiding towards mineralization. Gossan represents a combination of oxides, silicates, carbonates and finally sulphides. Sulphides enrichment is a chemical process, explained as the secondary environment. Physical feature of oxidized caps is an indicator of sulphides, as concealed ore body. Gossans represent a high level of weathering but retain distinctive characters which help in locating mineralization. In southeast Rajasthan at Dariba-Rajpura, India, Cu, Zn–Pb mineralization was

Table 2.19 Gossan caps and expected buried sulphide mineralization

	Nature of gossan	Nature of deposit
(a)	Form and size	Generally the outcrop faithfully outlines the shape of orebody
(b)	Collapsed gossan, voids in gossan	
	(i) Abundant (ii) Shape (iii) No void	Sulphides If square, galena, pyrite No important deposit likely
(c)	Colour of limonite	
	(i) Brown, maroon, orange, etc. (ii) Yellow, brick red (iii) Deep brown/brick red, yellowish (iv) Chocolate (v) Deep maroon (vi) Tan to brown (vii) Orange	Copper Pyrite Chalocopyrite Bornite Chalcocite Sphalerite Galena
(d)	of box work	
	(i) Coarse, cellular with blebs, masses, coarse and angular walls (ii) Fine, cellular, thin, small, friable walls spaces, blebs (iii) Coarse, cellular, siliceous, thin, rigid angular walls (iv) Cellular spongy (v) Fine cellular, shriveled (vi) Triangular, crusted, curved (vii) Porous (viii) Pitchlike limonite, no cells (ix) Limonite crusts (x) Cleavage (xi) Diamond mesh (xii) Pyramidal (xiii) Foliated	Chalcopyrite Bornite–chalcopyrite Sphalerite Sphalerite Sphalerite Bornite Chalcocite, covellite, bornite Chalcocite bornite Chalcocite Galena Galena Galena Molybdenite

discovered through gossan. However, it is important to make a distinction between a gossan and a false gossan. An example of false gossan is also available in NW Rajasthan in Khetri copper belt. While Cu-mineralization exists at Khetri, the southern side of this plunging anticlinorium does show gossan but are only pyrites bearing, as seen at Saladipura. Broadly, we know that gossan related to economic mineralization show anomalous geochemistry as compared to the hydrous, iron oxides as seen in Saladipura in NW Rajasthan, India. Some of the diagnostic features of gossans are listed in Table 2.19.

Table 2.20 Zoningin Gossan cover

(i)	Presence of vertical zoning	Oxide—top followed by supergene sulphide enrichment and primary—protore
(ii)	Presence of gossans and capping	As described above
(iii)	Mineralogy	Sooty chalcocite, covellite, native silver, native gold, marcasite for sulphides and goethite, hematite for iron ore, pyrolusite and psilomelane for manganese

Generally, the process of oxidation gives rise to secondary enrichment which produce rich sulphide deposits below the zone of oxidation. Criteria for the recognition of such enrichments are listed in Table 2.20.

2.4 Geological Structures

It has been discussed earlier that mineral deposits are formed under complex geological environments. Although the formation of a deposit is largely controlled by the ore-forming processes, it is the geological structure which helps in localizing mineral deposits. These structures may be regional or purely local. Our knowledge of the structure of earth's crust is derived from the continents. The continents themselves offer two regions which have a separate tectonic and structural history, the mobile belts and the cratons. The mobile belts are those characterized by igneous activity and earthquakes. There are also areas of rapid sediment accumulation giving rise to geosynclines and geanticlines. When a mobile belt is characterized by geosynclines and geanticlines they are called orogens which are the loci of mountain building activity thus structurally complex. Compared with the mobile belts, the cratons are static and stable. From the point of view of ore-genesis, the structurally complex mobile belts of the geological past are important mineral deposit sites. A study of the elementary to the complex type of geological structures is a part of exploration geology. Structures thus studied are as follows:

(a) Structure of igneous rocks,
(b) Structure of sedimentary rocks and
(c) Structure of metamorphic rocks.

2.4.1 Structure of Igneous Rocks

Two types of rock structures are recognized in igneous rocks: (a) structure due to flow and (b) structure due to fracture.

(a) **Structure due to flow**: Two types of structures may be identified.

   (i) Linear flow structure: The parallel orientation of needle-shaped inclusions constitutes linear flow structure.
   (ii) Platy flow structure: The parallelism of the flat surfaces of tabular, or platy inclusions like phenocrysts, xenoliths and schlieren (flow layer) constitutes platy flow structures. It may lie in the plane of foliation but may form an angle with it.

(b) **Structures due to fracture**: Under this come joints, sheets and faults.

   (i) Columnar jointing: The rock is divided into hexagonal column formed at right angles to the cooling surface.
   (ii) Joints: Joints which lie perpendicular to the flow lines are termed cross joints (Q joints) and tension joints are formed due to the upwelling of the liquid magma in the centre of the intrusion; 'S' joints are steeply dipping joints which strike parallel to the flow lines.
   (iii) Sheeting: They consist of gently curved joints which divide the rock into flat lenses parallel to the topographic surfaces. When they are closely spaced, they are called mural joints.
   (iv) Faults: Normal and thrust faults of purely local significance are seen on the border of large intrusive. The extent of slip along the planes is usually very small. A number of such faults may be arranged in echelon. Flat lying normal faults are also not uncommon.

Besides these, broad regional structures like ring dykes and cone sheets are also present.

2.4.2 Structures of Sedimentary Rocks

A large number of structures are recognizable in sedimentary rocks. Some of them are described below:

(a) **Beddings or stratification planes**: Sedimentary rocks are arranged in layers. The plane which separates the various layers is called bedding or stratification plane.
(b) **Graded bedding**: Beds show some gradation in size from bottom to top. The coarser grains are at the bottom and the finer ones are at the top. This textural arrangement of sedimentary bed is known as graded bedding.
(c) **Initial dip**: Initial dip is different from dip exhibited in an exposure. Initial dip is the slope of the stratification plane during sedimentation. It is common for sediments formed in basins to exhibit this dip.
(d) **Discordant bedding**: Normally bedding planes and beds are parallel to each other. When this parallelism is lost, the bedding planes become discordant.

Terms like current bedding, cross bedding and false bedding are also applied to discordant bedding.

(e) **Ripple marks**: Ripple marks are those ridge like prominences seen on sediments. These are created by the movement of air or water over unconsolidated sediments.

(f) **Rain, Drip and Hail Impressions**: These are impressions formed on loose sediments by rain and hails, dripping from trees or plants. The upper surface of these is concave which can help in recognizing the orientation of beds.

(g) **Mud cracks**: Mud cracks are formed by the exposure of soft mud to sun's rays. They have wide mouths and tapering bottoms which help in recognizing the top and bottom of beds.

Various other structures are also noticeable in sedimentary rocks. Since they are of no direct use in studying the strata sequence (top and bottom of beds particularly), they are not being discussed. The structures described above can be directly used for establishing the top and bottom of sedimentary formations.

2.4.3 Structures of Metamorphic Rocks

No distinct structures which are exclusive to metamorphic rocks can be recognized unless features like schistosity and gneissosity are considered. Although they are primary to metamosphic rocks, they are modifications of existing structures of the original rocks. Interpretation of rock structures is very important in studying major and minor geological structures. In certain types of geotechnical studies connected with open pit design and stability of slopes also, the rock structures are important.

2.4.4 Other Structures

2.4.4.1 Dip and Strike

When strata are affected by tectonic forces, structures developed, which tells the position orientation of rocks in place. This comprises two factors known as strike and dip. Strike refers to the direction in which a geological structure (such as a bed, a fault plane, or a joint plane) is present. When an inclined bed is suitably exposed on the surface, its direction of occurrence, its direction of inclination and amount of inclination can be actually measured directly by a clinometer. The strike direction is defined as the direction of the trace of the intersection between the bedding plane and a horizontal plane. The dip amount is the angle of inclination between the bedding plane and a horizontal plane. The dip shows the direction along which the inclination of the bedding plane occurs. As regards inclined strata, in a direction perpendicular to the strike direction, the inclination of bedding planes is maximum

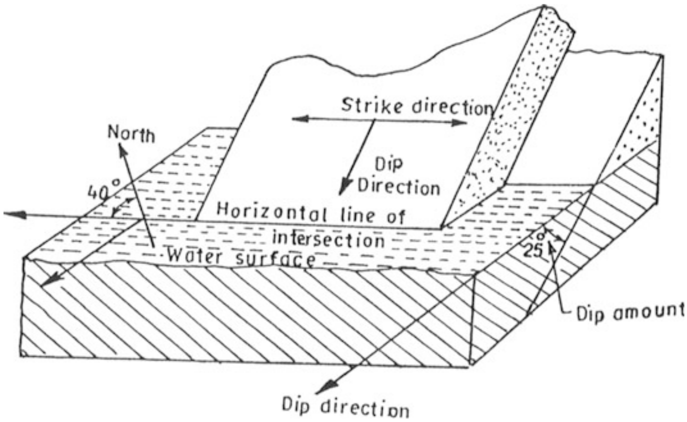

Fig. 2.1 Strike and dip relationship

and these are called the true dip direction or simply dip direction. The amount of inclination along this direction is called the true dip amount or simply dip amount Fig. 2.2. Close observation reveals that this dip amount gradually decreases on either side of the true dip direction towards the strike direction. Along the strike direction the inclination of lie bed (i.e. dip amount) is zero, i.e. the bedding plane will be horizontal. All directions which lie in between the strike direction and the true dip direction are known as apparent dip directions and the inclinations along them are called apparent dip amounts. Apparent dip amount is higher towards the true dip direction and lesser towards the strike direction. The strike direction and true dip directions are always mutually perpendicular (Fig. 2.1).

In the field, exploration geologist uses clinometer compass and the Brunton compass for the purpose.

2.4.4.2 Folds

When a set of horizontal layers are subjected to compressive forces, they bend either upwards or downwards. The bends noticed in rocks are called folds. Folds are described variously as wavy, arch-like, curved, undulating, or warping appearances found in rocks. They are also called flexures or buckling phenomenon of rocks. Generally, they occur in series. In nature, folds found in rocks have a range of magnitude in terms of their length and breadth. At one extreme, they may be very small such as few cm in length. At the other extreme, they may be a few km across and several km long. The radius of curvature of a fold is small compared to its wavelength and amplitude. In terms of their nature too, folds may occur as single local bend (monoclines) or may occur repeatedly and intricately folded according to the tectonic history of the region.

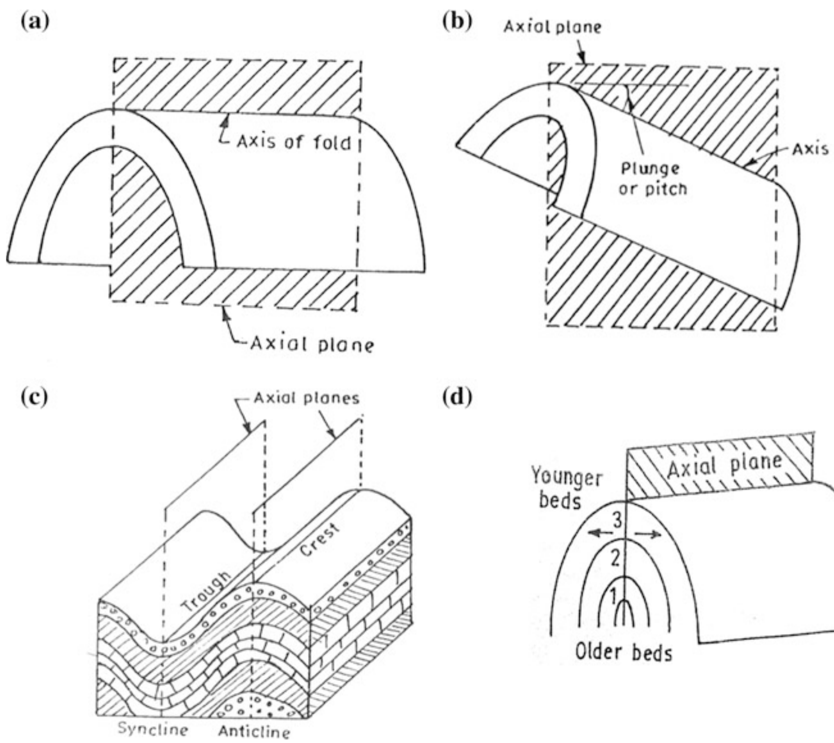

Fig. 2.2 Patterns and parts of folds

Limbs, crest, trough, axial plane, axis, wavelength and plunge, which are the important parts of a fold, are shown in Fig. 2.2a–d.

Limbs or Flanks

These are the sides of a fold. There are two limbs for every fold and one limb common to the adjacent folds as shown in Fig. 2.2.

Crest and Trough: The curved portions of the fold at the top and bottom are called crest and trough, respectively. In general, these are smoothly bent, but in chevron folds, these are sharp and angular. Some geologists refer to crests and troughs as hinges.

Axial Plane and Axis: This is an imaginary plane which divides a fold into two equal (or nearly equal) halves. It passes through either the crest or the trough. Depending upon the nature of the fold, the axial plane may be vertical, horizontal or inclined. In case of symmetrical folds, the axial plane divides the fold into exactly two equal halves. But in asymmetrical folds, the two halves will be only nearly equal. Like a bedding plane, the axial plane also can be expressed by strike and dip refers to the trace of the intersection between the axial plane and the crest or trough of the fold. Depending on the nature of the fold, it may be inclined or horizontal or vertical. When it is inclined, the angle between the axis and the horizontal plane is called the plunge or pitch. In general, an axis is undulating and its height changes along the trend of the fold.

Classifications and Types of Folds

Based on different principles, the folds are variously classified, on the basis of (I) symmetrical character, (II) upward or downward bend, (III) occurrence of plunge, (IV) uniformity of bed thickness and (v) behaviour of the fold pattern with depth.

Anticline and Syncline: When the beds are bent upwards, the resulting fold is an anticline. In anticlines, the older beds occur towards inside. In a simple case, the limbs of anticline slope in opposite directions with reference to its axial plane. But when the anticline is refolded, the inclined character of limbs gets complicated.

Syncline is just opposite to anticline in its nature, i.e. when the beds are bent downwards the resulting fold is called syncline. This fold is convex downwards. In this, the younger beds occur towards the concave side and, in a simple type of syncline, its limbs dip towards each other with reference to the axial plane. When the axial plane divides a fold into two equal halves in such a way that one-half is the mirror image of another, then such a fold (whether anticline or syncline) is called a symmetrical fold. If the two halves are not mirror images, then the fold is called an asymmetrical fold.

Plunging and Non-Plunging Folds: The plunge of a fold is axis to the horizontal plane. Based on this, the folds are grouped as plunging folds or non-plunging folds. In geological maps, when strike lines are drawn for both the limbs, for a

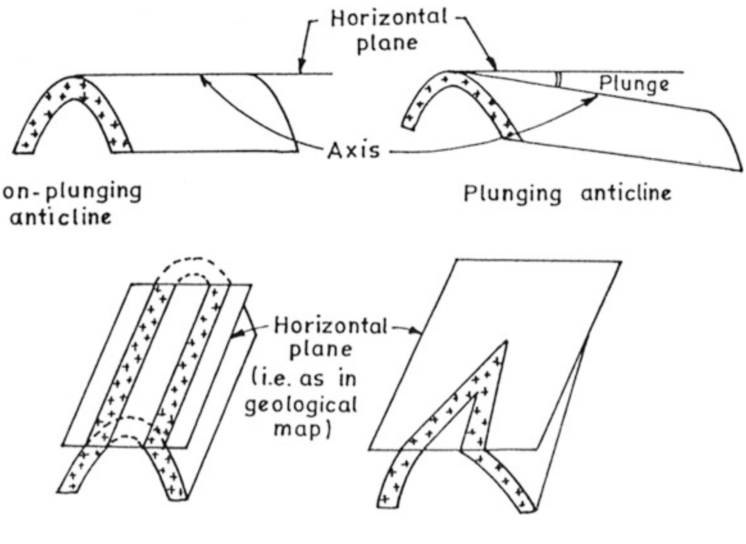

Fig. 2.3 Plunging and non-plunging anticlines

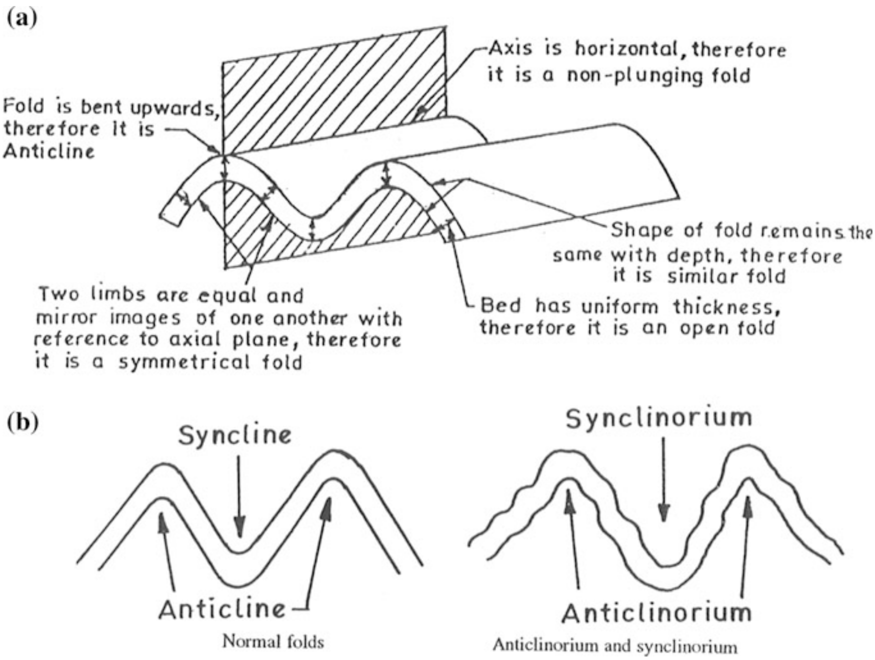

Fig. 2.4 **a** Non-plunging, similar, symmetrical and open anticline and; **b** concept of anticlinorium–synclinorium

non-plunging fold, they will be mutually parallel and for a plunging fold, they will be either converging or diverging but not parallel. On a horizontal plane, the outcrops of non-plunging and plunging folds appear as shown in Fig. 2.3. Reader needs to refer to books on structural geology for details.

Geanticlines and geosynclines: The anticlines and synclines with a normal shape but a very large magnitude are called "geanticlines" (giant anticlines) and "geosynclines". Geosynclines are of special importance from the physiography point of view because these are the places accompanied by long periods of sedimentation and are the potential places which can become great mountain ranges in future such as the Himalayas, the Alps, the Appalachian and the Cordillera, a few examples sites of mountain ranges. When the limbs of folds are not plain but characterized by the appearance of other minor folds on them, the major folds are called anticlinoriums and synclinoriums (Fig. 2.4a, b).

Criteria for Recognition of Folded Strates

In order to study folds systematically to enable easy interpretation, the following sequence of observation and terminology is recommended:

(a) Axes—Location, plunge, smoothly rounded or sharp, straight of curved, thickening or thinning along axes.
(b) Strike and dip of axial planes, fracture systems.
(c) Flanke (limbs), width, variation in strike and dip, smooth or irregular, thickening or thinning of beds, fracture system and evidence of slippage along bedding planes.
(d) Dating—Evidence of more than one period of movement.
(e) Topographic expression—drainage pattern.

Recognition of folding is not always easy. Only in rare cases all the limbs will be directly observable. Systematic study helps in identifying complex folds. There are, however, a few keys which help in recognizing folds.

(i) **Repetition of beds**: One bed may be seen in a traverse repeated at several places. By plotting and interpretation and eliminating the possibility of faults, the fold can be reconstructed.
(ii) **Topography**: In certain types of terrain, folds are easily inferred by topography. This is particularly true in the case of aerial photography. Folds can also be studied by geophysical methods and drilling.

In the area where folding has been simple, the study and recognition of fold are not difficult in a terrain of complex folds; particularly where bed is over turned, it is difficult to collate the strata. It is also difficult to determine the chronological sequence of beds. Some criteria for recognizing the top and bottom of the bed are essential. A few criteria adopted are discussed below.

When beds are overturned, primary features are used in recognizing the top and bottom. These are cross bedding, ripple marks, graded bedding and mud cracks. In rocks, the vesicular tops and flow structures can be used for correct orientation of such minor features to be confirmed by field observation. In ripple marks, the crests are at the top. In cross bedding, the laminae are parallel to the bedding at the bottom, but form sharp angles at the top. In graded bedding coarser grains are always at the bottom.

2.4.4.3 Faults

Structurally, faults fractures along with relative (i.e. parallel) displacement of adjacent blocks have taken place. If such relative displacement does not take place on either side of fracture plane, it is called a joint. Thus both joints and faults are fractures in rocks but with a difference in the kind of displacement. Joints may be described as a set of aligned parallel cracks or openings in geological formations.

Magnitude and Nature of the Faulty Plane: Faults also have considerable range in their magnitude. Some occur for short lengths (a few centimetres), while others can be traced for very long distances (to several kilometres). The degree of displacement differs widely. In some, the displacement may be less than a centimetre while in others it may be of many metres or even kilometres (as in the case of nappes of the Himalayas). The magnitude of faulting depends on the intensity and the nature of shearing stresses (kinds of tectonic forces) involved. The relative displacement caused during faulting may be horizontal, vertical or inclined, and may be parallel or rotational with reference to the fault plane.

Rarely, the displacement during faulting occurs along a single fault plane. In many cases, faulting takes place along a number of parallel fractures. That is the total displacement is distributed over this zone. Such a zone which contains a number of closely spaced subparallel fractures along which the relative displacement has been taken place is called the shear zone or fault zone: Due to frictional resistance, the brittle rock masses get crushed to different degrees in the fault zone (producing fault breccias). Sometimes, this crushing may produce an even fine clay-like material called "gouge".

Fault Plane: This is the plane along which the adjacent blocks were relatively displaced. It is the fracture surface on either side of which the rocks had moved past one another. Its intersection with the horizontal plane gives the strike direction of the fault. The direction along which the fault plane has the maximum slope (i.e. the direction which is perpendicular to the strike direction) is its true dip direction. The amount of inclination of the fault plane with reference to the horizontal plane along the true dip direction is called its (true) dip amount. Sometimes, the term "hade" is used to refer to the angle between the inclined fault plane and a vertical plane. Naturally, both dip and hade together make up 90°.

The fault plane may be plain and straight or may be curved or even irregular. It may be horizontal, inclined or vertical. Like a bedding plane, a fault plane too is described by its attitude by its strike direction, dip direction and dip amount.

Parts of a Fault

The different parts of a fault are shown in Fig. 2.5.

Foot Wall and Hanging Wall: When the fault plane is inclined as shown in the figure, the faulted block which lies below the fault plane is called the "footwall" and the other block which rests above the fault plane is called the "hanging wall". In the case of vertical faults, naturally, the faulted blocks cannot be described as footwall or banging wall.

Slip: The displacement that occurs during faulting is called the slip. The total displacement is known as the net slip. This may be along the strike direction (strike slip) or the dip direction (dip slip) or along both as shown in Fig. 2.5.

Heave and Throw: The horizontal component of displacement is called "heave" and the vertical component of displacement is called "throw". In the figure, the points A and B were together side by side before faulting. After faulting, they are displaced and hence found separately in different positions. In this, AC which is the horizontal component of displacement is heave and CB which is the vertical component of displacement is throw of a fault (Fig. 2.6). In vertical faults, there is only throw, but no heave. In horizontal faults, there is only heave, but no throw.

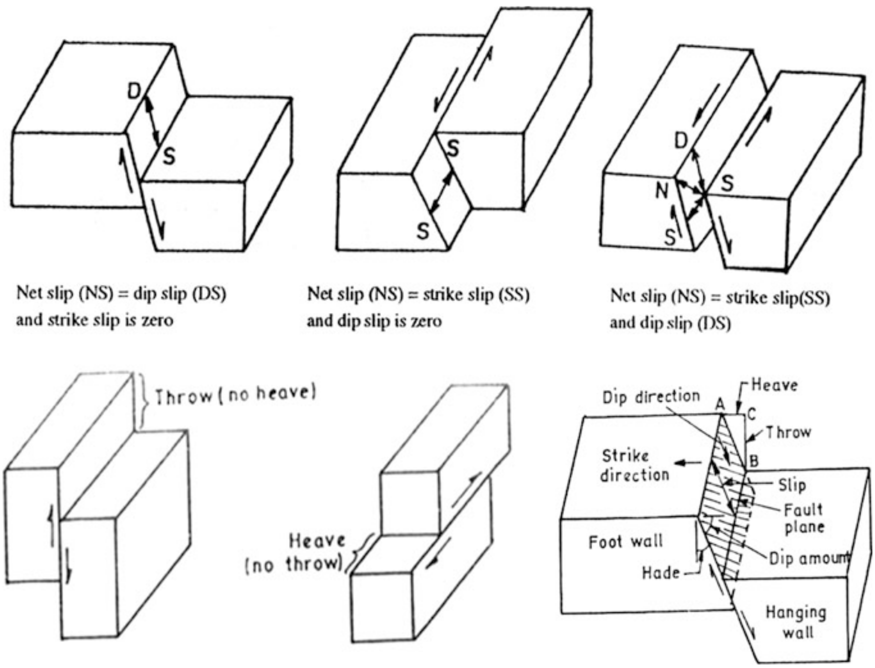

Fig. 2.5 Understanding of parts of a fault

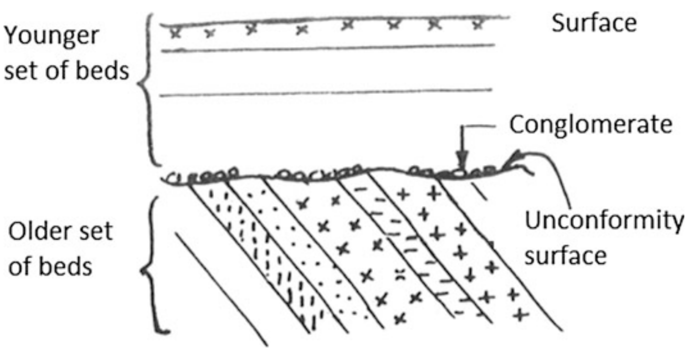

Fig. 2.6 Parts of an unconformity

Absolute and Relative Displacement: Faults are studied only after they have occurred and hence the actual or absolute type of displacement suffered by rocks (i.e. which faulted block had actually gone up or gone down and to what extent) is not known. The relative position of blocks as seen in the fields is possible through five different kinds of relative displacements as shown in Fig. 2.6. In view of the absence of knowledge of absolute movements during faulting, the figures of faulting are shown with symbols representing relative displacement (half arrows).

Recognition of Faults During Exploration Field Work

In several cases faults are recognizable, but when difficult, careful observation of certain features of faults is essential for deciphering the fault. Six criteria are as follows:

(a) Discontinuity of structures: Features like dykes, sills, veins, prominent fractures and folds may be seen ending abruptly against a place in an exposure. This may be due to faulting.
(b) Repetition and omission of strata: In a traverse line, strata may disappear altogether in a sharp contact or may be repeated sequentially in association with sharp contacts. Both may indicate faulting.
(c) Features characteristic of fault planes: In some cases, it is possible to recognize the fault plane by virtue of characteristic features such as (i) slickensides, (ii) mullion structure, (iii) drag, (iv) gauge, (v) breccias, (vi) mylonite and (vii) horses (caught up blocks).

    (i) Slickensides: Striations in the fault planes caused by movement and can be easily recognized by the glistening surfaces and striations.
    (ii) Mullion structures: Large grooves or furrows with a definite crest and bottom.
    (iii) Drag: The end of the beds affected by fault is dragged up and down.
    (iv) Gouge: Fine-grained clay-like powdery rock.
    (v) Breccia: Mixture of angular and subangular rock pieces of varying sizes in a finely crushed matrix.
    (vi) Mylonite: Microbreccias with streaked or platy structure, which is typically dark and fine grained; the coherence of a microbreccia is maintained during deformations.
    (vii) Hores: Small blocks of rocks caught up in a wide fault plane.

(d) Silicification and mineralization: Silicification may occur along the zones of fracture. Similarly, mineralization may also occur.
(e) Sudden change in the sedimentary facies: The phenomenon of a coarse-grained sandstone abutting against a shale of the same age and other similar instances is indicative of faulting during sedimentation.
(f) Physiographic evidences: The following physiographic evidences are suggestive of faults: (i) offset ridges, (ii) scarps, (iii) triangular facet and (iv) truncation of structures by a ridge front.

(i) Offset ridge: Where a resistant sedimentary stratum may show discontinuity. This is called an offset ridge; (ii) Scarp: A steep straight slope of any height; (iii) Triangular facet: On scarp faces, some 'V' notches may form due to erosion during movement. The sum total is a structure known as a triangular facet; (iv) Truncation of the structure by ridge front: Sudden termination of structures, particularly against a mountain front, is suggestive of faulting.

Other field evidences are springs in a linear arrangement, such as trees in a line and lakes in a line, all of which may coincide with the alignment of the fault. The sudden steep in a stream bed, abrupt ending of a stream, also may indicate faulting.

The criteria recommended here are indicative of faulting. Besides, some of them also indicate other structures like folds, unconformity. Careful study and a series of eliminations at each stage are needed before a particular set of criteria can be correlated to a fault. Usually, a combination of criteria is applied before any conclusion is drawn.

Common Difficulty Related to Faults in Mineral Exploration

When a tectonic disturbance takes place in an area, it may give rise to new structures either by the partial or total destruction of old structures or by superimposition of a new set of rocks over the relief of existing structures. Faults, folds, shears and joint are geological deformation caused by stress and strain. In a normal sequence of events, folds are formed first, whether synclines or anticlines; and if the forces causing the folding are still intense, then the rocks yield to these forces forming faults and shears. In an area which is geologically un-disturbed, it is possible to establish the sequence of events. But, in an area that has experienced disturbances belongs to repeatedly, it is difficult to establish which generation an individual structure to and its effect on other structures.

The effect of folds on faults is widely understood. However, it can be attributed that the effect of faults on folds is still a subject of discussion. Many examples have been given cited to show the influence of faults on folds, though on a regional scale.

Just like folds, faults also present problems to the exploration geologist. Some fault planes act as passages for the mineralizing solutions, and the deposits are formed in the fault plane itself. Faults may cut off mineralizing solutions in a favourable host rock or even act as a connection to a favourable host rock. Faults may block off the already existing deposits. As in folds, in faults also, it is important to establish the exact relationship existing between faults and mineralizing solutions. If the fault is pre-mineral, every change in the fault plane is influencing the mineralization. On the other hand, if the fault is post-mineral, the deposit may be merely displaced. The following criteria are sometimes useful in distinguishing the pre-mineral faults from the post-mineralization faults:

(a) Pre-mineralization faults:

   (i) Mineralization will be on the fault plane. Ore may be in breccia and vugs and
   (ii) Localizing effect of the fault will be on ore. Ore bodies tend to be in the fault.

(b) Post-mineralization fault:

(i) Ore will be slicken sided or brecciated. Drags will be clearly visible in many cases and
(ii) Observable offsetting of veins or orebody.

The presence or absence of a fault in a region influences an exploration strategy particularly in the selection of methods. Ore bodies may come close to the surface in certain faults making it an attractive target proved easily by shallow drill holes. It can also affect the economic workability of an ore body adversely by throwing it down to great depths.

In some cases, the determination of down-thrown or up-thrown block is critical. The criteria for recognition are discussed below:

(i) Correlation of wall rocks—If the sequence of the rocks which have been faulted is known, it is easy to find out the displaced block.
(ii) Drag—As explained earlier, the drag is always against the direction of movement.
(iii) Slicken sides—The groove of a slickenside will be smooth in the direction of movement, and rough against it.
(iv) Throw of minor and sympathetic fault—Since minor and sympathetic faults form in harmony with the main faults, their direction of throw will indicate the direction of the throw of the main fault.

2.4.4.4 Joints

As already mentioned under faults, joints are fractures found in all types of rocks. They are cracks or openings formed due to various reasons. Naturally, the presence of joints divides the rock into parts or blocks. These separated blocks may move only perpendicular to the plane of fracture, but do not move past one another as in the case of faults. Though the joints may be described as cracks in rocks, they may differ mutually. The difference between them is somewhat similar to that of fracture and cleavage (both of which refer to the nature of the broken surface) found in minerals. Joints, like cleavage of minerals, occur oriented in a definite direction and as a set (as a number of parallel planes). The cracks, like the fracture of minerals, are random or irregular in their mode of occurrence. Thus, joints occur, generally, parallel and oriented fractures in rocks. Such a group of fractures is called "joint set". Every set of joints (i.e. joint planes) shall have their own strike and dip. As mentioned earlier, the folded and faulted sedimentary rocks when associated with tension and shearing joints, the limestones and sandstones are characterized by a set of parallel fractures which enables these rocks to be split into thin sheets of uniform thickness. These rocks are called flaggy sandstones and flaggy limestones. In some sedimentary rocks, two sets of joints which are mutually perpendicular (and parallel to strike and dip directions) occur at right angles to the bedding planes. Joints are common as parallel to the bedding planes of sediments; in sandstones and limestones, joints occur several metres apart but in shales they occur closely.

Joints in Metamorphic Rocks: Though joints are found very commonly in metamorphic rocks also, they do not have any definite pattern of occurrence in any specific kind of rocks.

In this context, it is appropriate to know a little about rock cleavage or fracture cleavage. When shear between beds occurs either due to folding or faulting, a complimentary system of fractures often develops. In the weak beds, these fractures are generally closely spaced. Because of these fractures, the rock can split into thin sheets. Such a phenomenon is called rock cleavage or fracture cleavage.

2.4.4.5 Unconformity

Unconformity is one of the common geological structures found in rocks. It is somewhat different from other structures like folds, faults and joints in which the rocks are distorted, deformed or dislocated at a particular place. Still, unconformity is a product of diastrophism and involves tectonic activity in the form of upliftment and subsidence of land mass.

When sedimentary rocks are formed continuously or regularly (at a stretch) one after another without any major break, they are said to be a set of conformable beds, and this phenomenon is called conformity. All beds belonging to a conformable set shall possess the same strike direction, dip direction and dip amount. On the other hand, if a major break occurs in sedimentation (if sedimentation does not take place for a long interval) in between two sets of conformable beds, it is called an unconformity. So, an unconformity refers to a period of nondeposition and appears as a plane of contact between two sets of conformable beds.

There are different types of unconformities. Figure 2.6 shows a very common kind of unconformity and its parts. Generally, other unconformities through similar may differ in detail. All types have two sets of formations belonging to two different ages, i.e. one set is older and the other set younger having a depositional break in between. They have an unconformity surface; a few may have conglomerates along unconformity surfaces.

Formation of an Unconformity

The formation of an unconformity involves three stages as follows: In (i) the first stage, under favourable conditions, a conformable set of beds is formed; (ii) in the second stage, a break in sedimentation (deposition of sediments stops) occurs. This happens generally due to the upliftment of that region to the level above that of the water level (of river, lake, where deposition had been occurring). After some time, when subsidence occurs in that region and favourable conditions for sedimentation recur, (iii) the third stage begins. Here, renewed sedimentation produces another set of conformable beds. The set of beds, i.e. those which have been formed during the third stage, is younger compared to the other set of beds formed earlier (i.e. those which have been formed during the first stage).

The aforementioned indicates that an unconformity is a plane (or a slightly undulating surface) which represents a break in sedimentation. An unconformity also represents a period of nondeposition of sediments and separates two sets of conformable beds which belong to different ages.

(a) **Hiatus**

An unconformity which represents a long geological period (during which break in sedimentation had occurred) is known as a “hiatus”. In India, examples of such a hiatus are seen in the Peninsular region, where, after the formation of Precambrian strata (i.e. the Cuddapah system and the Vindhyan system), there was no deposition of sediments for a long geological time (this time gap covers the Cambrian period of 150 million years, the Ordovician period of 90 million years, the Silurian period of 35 million years, the Devonian period of 50 million years and a part of the Carboniferrous period which is 60 million years, i.e. total approximately 385 million years). After that, the sedimentation began the Gondwana group of sediments that were deposited.

(b) **Conglomerates and Bauxite along an Unconformity**

The two important points about unconformity formation are as follows: (i) When the first set of beds is uplifted and a break in sedimentation takes place, geological action (weathering and erosion followed by transportation and deposition) may or may not occur during the unconformity period. If it occurs, the exposed beds are disintegrated and the rock fragments roll and get rounded or subrounded during their transport. Later, such pebbles and gravels get deposited under favourable conditions. When sedimentation resumes (younger series of beds begin to form), the pebbles of older beds get cemented and a conglomerate is formed. Thus, conglomerates occur in association with some unconformities.

During the unconformity period, if considerable leaching of earlier rocks occurs, these rocks may get changed over to laterites or bauxites. Thus, bauxite deposits occur sometimes along unconformities. (ii) The second important point is that the first formed conformable set of beds mayor may not get tilted (or folded) either during their upliftment or subsidence, depending upon the way the relevant tectonic forces had acted. If they were in a tilted disposition at the time of formation of the second (i.e. younger) set of beds, then beds of both these sets will be mutually inclined; otherwise, they will be mutually parallel.

Types of Unconformity

Based on factors such as the types of rocks, relative attitudes of sets involved and their extent of occurrence, the different types of unconformities are named.

Nonconformity: When the underlying older formations are represented by igneous or metamorphic rocks (unstratified rocks) and the overlying younger formations are sedimentary (stratified) rocks, the unconformity is called "nonconformity".

Angular Unconformity: When the younger and older sets of strata are not mutually parallel, then the unconformity is called "angular unconformity". In such a case, beds of one set (usually belonging to the older set) occur with a greater tilt or folding.

Disconformity: When the beds of the younger and older sets are mutually parallel and the contact plane of two sets is only an erosion surface, the unconformity is called "disconformity." Here, the lower set of beds would have undergone denudation prior to deposition of the overlying strata commenced.

Paraconformity: When the two sets of beds are parallel and the contact is a simple bedding plane, the unconformity is called "disconformity." In such cases, the unconformity is inferred by features like sudden change in fossil content or in lithological nature (such as the occurrence of coarse detrital sediments overlying fine sediments).

Regional and Local Unconformity: When an unconformity extends over a great area, it is called regional unconformity, but when it occurs over a relatively small or limited area it is called local unconformity.

Different unconformities are shown in Fig. 2.7 along with conformity structures for comparison. The MNO plane refers to the unconformity plane in these figures.

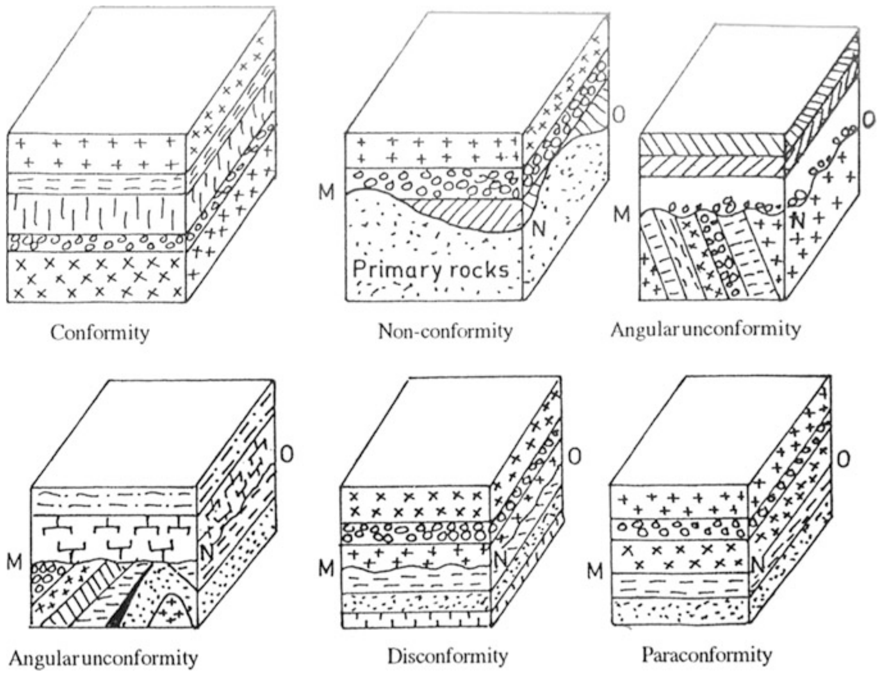

Fig. 2.7 Different types of unconformities

Recognition of Unconformity in the Field

Observations that help in locating an unconformity are as follows: (i) Difference in attitudes of two adjacent sets of beds (disconformity is an exception); (ii) Remarkable difference in nature, age and types of fossils in adjacent sets of beds; (iii) Occurrence of conglomerates along the unconformity plane; (iv) Occurrence of residual soil/laterite/bauxite along the unconformity surface; (v) Considerable difference in the degree of metamorphism of two adjacent sets of beds; and (vi) Stratigraphic correlation and lithological peculiarities.

The following enhancements help in locating an unconformity:

(a) ***Difference in the degree of induration***: the rocks on either side of an unconformity are likely to show different degrees of induration; the older rock showing greater induration.
(b) ***Differences in the grades of metamorphism***: the younger rocks are likely to be less metamorphosed than the older ones on either side of an unconformity.
(c) ***Differences in folding***: in some cases, the younger rocks will show less intense folding than the older on the two sides of an unconformity.
(d) ***Relation to intrusive***: in some cases, the presence or absence of an intrusive may determine the presence of an unconformity.

Unconformities are studied best in a single sharp exposure. Aerial photographs and satellite images are very useful in the study of unconformities.

Unconformity in Mineral Exploration—Localization of Ores

Since unconformity separates rocks of differing ages, it acts as barrier in mineral deposits associated with either of the two sets of rocks. Some difficulties posed by unconformities are similar to those faults, but the solutions seen in the case are different. Thus dying out of deposits at the plane of unconformity is common but, unlike in faults, their continuity also ends at the plane of unconformity. The plane of unconformity possesses of residually and mechanically concentrated mineral deposits such as bauxite, clay (in conglomerates) and gold. The plane of unconformities here acts as a channel for mineralizing solutions.

One problem is that the planes may be irregular and undulating, and the resulting mineral deposits are likely to be very irregular. This can be resolved by a systematic geological mapping followed by drilling in trace the continuity of the plane of unconformity itself. Proving of any deposit will come only at a later stage.

Most of the rock and geological structures described earlier offer controls in localizing mineral deposits. Some of the common structures which have a direct bearing on localization ore are (i) bedding planes, (ii) cleavages, (iii) joint planes and (iv) faults and folds.

Amongst these, the role played by fault and shear zones is important. The pre-ore faults in particular offer a ready passage to mineral and ore carrying fluids.

Faults and shear zones are widened when the ore or mineral fluids penetrate and move along the planes of weakness. Examples of shear zones acting as ore paths are very typically seen in deposits of barites (Pulivendala) in Andhra Pradesh, fluorite (Chandi Dongri), Copper (Khetri in Rajasthan) and lead–zinc (Zawar in Rajasthan). In all cases, the shear and fault zones have acted as field guides.

The localizing influence of fold is typically seen in the iron and manganese ore deposits. The synclinal troughs have usually shown a better concentration in many iron and iron and manganese deposits than anticlinal crests. The manganese deposits of Madhya Pradesh and Maharashtra show evidence of structural influences, particularly the influence of synclines. The influence of bedding planes, cleavage and schistosity is demonstrated by the mica deposits in Nellore and Hazaribagh where the mica-bearing pegmatites have intruded along the planes of schistosity and cleavage. This relationship has been used as a field guide.

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