Indira Gandhi National Open University
School of Sciences

BGYCT – 133 CRYSTALLOGRAPHY, MINERALOGY AND ECONOMIC GEOLOGY

Block

2

MINERALOGY

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Acknowledgement: Ms. Savita Sharma for assistance in preparation of CRC and some of the figures and Prof. V.K. Verma for carefully reading the earlier draft.

December, 2019

ISBN: 978-93-89969-67-2

Printed and published on behalf of Indira Gandhi National Open University, New Delhi by the Registrar, MPDD, IGNOU.

Printed by : Chandra Prabhu Offset Printing Works Pvt. Ltd., C-40, Sector-8, Noida-201301 (U.P.)

BGYCT-133: CRYSTALLOGRAPHY, MINERALOGY AND ECONOMIC GEOLOGY

BLOCK 2: MINERALOGY

You have studied about crystals, their symmetry and crystal systems in Block-1 of this course. Crystals are minerals in a crystallised form and minerals are the building blocks of rocks. Minerals have fascinated human since prehistoric period and have been used as tools, ornamental stones and colouring agents. The curiosity of learning more about the minerals has evolved as a branch of geology dealing with the study of minerals, their physical and optical properties, mode of occurrence and formation, called mineralogy.

Minerals are studied to unravel Earth's geological history. Also, study of minerals occurring in a particular geological environment is of significance as it helps geologists to locate potential mineral deposits. Hence, it is important to learn about minerals here prior to studying rocks in the next course to identify different kinds of rocks and know how they are formed.

In this block, you will learn about minerals, physical properties useful in their identification, their chemical and structural classification, major rock forming mineral groups, and physical properties of common rock-forming mineral groups.

Unit 4 Minerals: The Building Blocks of Rocks introduces you to minerals and their importance. It also discusses about physical properties of minerals that are used to identify them. You will also have a brief idea about gemstones in this unit.

As its title suggests, in **Unit 5 Classification of Minerals**, you would get introduced to the basis of mineral classification and their evolution. It first discusses about chemical classification of minerals and structural classification of silicates. Classification of common rock forming mineral groups such as olivine, garnet, pyroxene, amphibole, mica, feldspar, feldspathoid, and quartz are also discussed.

Rock-forming minerals are essential components of rocks occurring in the Earth's crust which are discussed in the next two units.

Physical properties of common rock-forming silicate minerals such as muscovite, biotite, augite, hypersthene, olivine, garnet, hornblende and kyanite are discussed in **Unit 6 Rock-Forming Minerals-I**. Physical properties of common rock-forming silicate minerals such as quartz, feldspar (orthoclase, plagioclase, microcline), nepheline, chlorite, epidote and calcite are discussed in **Unit 7 Rock-Forming Minerals-II**.

Expected Learning Outcomes

After studying this block, you should be able to:

- get acquainted with minerals, its characters, importance and physical properties;
- discuss chemical classification of minerals and structural classification of silicates;
- explain classification of common rock-forming mineral groups, and
- describe physical properties of common rock-forming minerals.

Your familiarity with the diagnostic properties of these common rock-forming minerals would help you to identify them on the basis of their physical properties. In the next block you would learn about optical properties of the minerals.

We wish you all success in this endeavour!

UNIT 4

MINERALS : THE BUILDING BLOCKS OF ROCKS

Structure

4.1 INTRODUCTION

You have been introduced to crystals and their symmetry in the Block 1 of this Course, which are minerals in a crystallised form. Now you know that crystals of different minerals have characteristic form or habit that is the reflection of their atomic structure. An external expression of the atomic lattices of a mineral is the development of crystal faces.

You will be introduced to rocks in the course BGYCT-135. A rock is composed of some combination of minerals hence minerals are the building blocks of rocks. Geologists study rocks and minerals to understand processes and events that occurred in the geological past at some specific part of the Earth. The specific rocks and minerals occurring in a particular geological environment also help geologists to locate potential mineral/ore deposits of economically important resources. Hence, it is important to learn about minerals prior to studying rocks to identify different kinds of rocks and understand how they are formed.

In this unit, you will learn about minerals and their importance to human beings and discuss about characters and physical properties of minerals. We will also get a brief idea about gemstones.

Expected Learning Outcomes

After reading this unit you should be able to:

- define a mineral;
- state significance of minerals to human beings;
- list characters of a mineral; and
- prepare a list physical properties of minerals and describe them.

4.2 MINERAL

You must have played with sand in river or in a beach, which contains various mineral grains. These grains of different colours are actually different minerals. Different colours of these minerals come from the elements present in them.

In the first Unit of Course BGYCT-131, you have learnt that mineralogy is the branch of geology that deals with the study of minerals, their structure, composition, occurrence and association. Let us now understand what a mineral is.

4.2.1 Definition and Characters

Geologists define mineral as **a naturally occurring inorganic solid crystalline substance having definite chemical composition and distinctive physical property.**

The above definition of mineral contains six different parts which are six characters of a mineral. We will examine these characters here in Table 4.1. Any substance that does not fulfil this criteria is not called as mineral. There are exceptions of petroleum and coal. Petroleum is not solid and does not have any specific chemical composition. Coal is not formed by inorganic process. These two are called minerals because of their economic significance.

You will learn about formation of minerals in detail in Block-4 Economic Geology of this course.

Table 4.1: Characters of a mineral and their description.

Character	Description
Naturally occurring	Formed in nature by some natural process. Substances produced artificially in a laboratory are called synthetic minerals (e.g. zeolite)
Solid	Only the solids qualify to be called as a mineral. It excludes gases and liquid materials with the exception of the native mercury. H_2O as ice in a glacier is a mineral but as water it is not. Similarly, gas as a hydrate in ocean floor is considered a mineral but not otherwise
Formed by inorganic process	Although, only the inorganic substances qualify to be called as a mineral, it is now recognised that minerals may also be formed by organisms e.g. calcium carbonate (i.e. calcite and aragonite) of corals and shells, and such substances are called biogenic minerals.
Crystalline substance	Only the solid substances which are commonly crystalline (but not always) i.e. having an orderly internal lattice structure [or geometric framework of its atoms (or ions)] can be called as a mineral. Substances that meet the other criteria but lack internal orderly structure are called **mineraloids**
Definite chemical composition	Minerals have a definite (i.e. same) chemical composition that can be expressed by a specific chemical formula (i.e. either fixed or ranges within particular limits) and is homogeneous (i.e. compositionally same) throughout its volume. Chemical composition of quartz is expressed as SiO_2 as it contains silicon and oxygen in a ratio of 1:2. Although the formula remains definite, but the composition may vary within limit for some minerals, e.g. chemical composition of dolomite mineral is $CaMg(CO_3)_2$ as it contains Ca, Mg and CO_3 in a ratio of 1:1:2. However, its general chemical composition may be written as $Ca(Mg,Fe,Mn)(CO_3)_2$ for the iron and manganese containing varieties
Distinctive physical property	Characteristic set of physical properties of a mineral is a result of all the above five characters. All minerals have some distinctive physical properties (such as colour, hardness, nature of breakage, etc.) that are used to identify and distinguish them from other minerals.

4.2.2 Uses

As we have read in BGYCT-131, minerals are important to us from edible salt (i.e. halite mineral) to ceramic mugs or glass tumbler to the utensils (made up of metals such as steel or aluminium or copper) are all derived from different minerals. The bricks and cement we use to construct our houses and the paints and tiles are all have minerals as a major component. You will be amazed to know that different components of the automobiles, computers, mobiles, battery, filament of light bulbs, etc. are made up of various minerals. Even toothpaste, automobile fuels, pencil leads, mirror glass, cosmetics, jewellery and the gems we wear are minerals. So, now you have understood how significant minerals are to us. In fact, we cannot imagine our lives without minerals because they have become integral part of our lives.

Listen to the following audio to know more about minerals and their uses.

- **Minerals and their uses**

  Link: http://egyankosh.ac.in//handle/123456789/53487

4.3 PHYSICAL PROPERTIES OF MINERALS

According to the International Mineralogical Association (https://www.ima-mineralogy.org), there are more than 5530 minerals known so far in the Earth's crust. You must be wondering how do we distinguish one mineral from another? Geologists identify these minerals based on their certain characteristic physical properties. Characteristic composition, texture and physical properties of principal rock-forming minerals have been identified. In this section, we shall learn about the physical properties of common rock forming minerals based on which minerals one identified. These minerals have a wide range of physical properties i.e. their ability to absorb or reflect light, conductivity to heat, electricity, etc.

As we see in the Fig. 4.1, the granite rock is composed of quartz, hornblende and feldspar. These minerals have their own physical appearances and characteristics.

Fig. 4.1: Two varieties of granite rocks and their major minerals components.

Although, it is difficult to determine chemical composition and crystalline structure of a mineral without the use of proper instruments, these two characteristics determine physical properties of a mineral. Physical properties of a mineral are the result of:

- how the atoms and molecules are arranged, and also
- the strength of the bonding between the atoms.

These physical properties can be observed or measured without changing its chemical composition such as how they:

- appear,
- bend, break or deform, and

- feel.

It may appear that physical properties of many minerals are common but when we examine all the physical properties, we find that each mineral has a unique set of physical characters which are helpful to identify them. For our convenience we may group physical properties of minerals under the following:

- Properties depending upon interaction of light such as colour, streak, lustre, transparency and luminescence
- Properties depending upon atomic structure and state of aggregation such as form, habit, cleavage, fracture, hardness and tenacity
- Properties depending upon specific gravity
- Properties depending upon certain senses such as feel, taste and odour
- Properties depending upon forces such as heat, magnetism, electricity, radioactivity and reaction to acid.

We shall discuss about these physical properties in detail in this section.

4.3.1 Depending upon Light

There are several physical properties of minerals that depend upon interaction of light with it. These properties are colour, streak, lustre, transparency and luminescence. Let us discuss these properties here.

a) Colour

Minerals have a typical colour, which is generally the first noticeable and important physical property for their identification. Colour of a mineral is a result of reflection and/or absorption of light from its surface. Some minerals reflect light, while others absorb. There are other minerals which reflect and absorb varying amount of light in different wavelengths. The colour shown by a mineral depends upon the absorption of light in certain wavelength and reflection of others. When a mineral reflects all of the white light it appears white but when it absorbs all and reflects none, it appears black. So, if a mineral reflects light of green wavelength and absorbs light of other wavelengths then it appears green to our eyes.

Some minerals appear colourless (such as pure quartz) or white (such as calcite, barite, aragonite, etc.) or light coloured (fluorite, orthoclase, etc.), some in bright colours (jasper, malachite, azurite, etc.), whereas many others appear in dark colour (hornblende, tourmaline, etc.). Although, colour of a mineral is the most noticeable physical property, it is not a reliable property for their identification (except for sulphur and pyrite minerals) as colour varies for most of the minerals.

The variation in the colour of minerals is due to the following:

- **Amount of trace element present within them -** Minerals belonging to a single group show different colours e.g. quartz group of minerals with the composition SiO_2. While pure quartz is colourless inclusions of trace elements may produce quartz of many different colours. For example, although a quartz is generally colourless or white but presence of trace

elements makes it to appear as pale brown (smoky), pale pink (rose quartz), pale yellow (citrine), purple (amethyst), black (morion) (Fig 4.2). Similarly, beryl has two varieties namely, emerald (green) and aquamarine (blue). The two colours exhibited by beryl are because of slight variation in trace elemental concentrations.

- **Nature and arrangement of constituent atoms -** Minerals having the Al, Ba, Ca, K, Na, Sr and Zr atoms as the main components which are either colourless or light in colour whereas minerals having Co, Cr, Cu, Fe, Mn, Ni, Ti and Vi are usually dark in colour.
- **Bonding between the atoms** - One of the best examples is of diamond (colourless) and graphite (black). Although, both of them are composed of carbon atoms, owing to difference in the bonding between carbon atoms, remarkable difference in the colour is observed.
- **Valency of ion -** Minerals with Fe^{2+} are usually green whereas minerals with Fe^{3+} are yellow, red or brown. The minerals, in which both the Fe^{2+} and Fe^{3+} ions are present, appear black.
- **Thickness of the mineral pieces being observed -** Thicker slices of many minerals appear darker whereas their thinner pieces appear light in colour.
- **Disturbance of Crystallinity –** A very few minerals show colour variation within a single crystal, either arranged in regular fashion or different colour bands (as tourmaline) or in patches within a mineral (fluorite).

Fig. 4.2: Different colours of quartz to change in the trace elemental concentrations.

There are different terms which are used to describe minerals that display certain characteristics related to interaction of light such as idiochromatic and allochromatic:

- **Idiochromatic mineral** - Mineral which has characteristic colour related to their composition e.g. malachite, azurite, Lapis Lazuli.
- **Allochromatic mineral** - Mineral which shows a range of colours that are dependent on the presence of impurities or inclusions e.g. quartz, beryl, garnet.

A few minerals display a character called **play of colours**. When these minerals are rotated or observed from different directions, they display a changing series of prismatic colours, similar to a rainbow e.g. diamond, quartz and other colourless minerals.

b) Streak

You have read that although colour is an important property but not the reliable physical property for identification of minerals because it varies due to different factors. Colour of a mineral in its fine powdered form is called **streak**, which is usually a constant physical property irrespective of the presence of trace elements. Streak of a mineral could be very different than the colour of that mineral. Although, colour of large mineral pieces may vary because of characteristic reflection of light by the trace elements, it would have little influence on the reflection from very small mineral particles.

Colour of minerals may vary for all its varieties but their streaks are generally constant or similar. Hence, streak is a reliable physical property for identification of minerals. Remember that you do not need to crush a mineral piece to see its streak rather you can determine it by rubbing the mineral on a piece of unglazed porcelain plate called **streak plate** (Fig. 4.3a). However, you should note that since the streak plate cannot be used with minerals of hardness greater than seven because streak plate has a hardness of about seven.

Streak of non-metallic minerals is generally light in colour or white because their mineral particles reflect most of the light (Fig. 4.3b), whereas metallic minerals have dark coloured streak because their mineral particles absorb most of the light (Fig. 4.3c). Fluorite may be of different colours but its streak is white. Black hematite gives reddish brown streak, whereas gray galena has lead gray and brassy yellow pyrite has greenish/brownish black streak. Hence, streak is very useful property, especially for identification of metallic minerals.

(a) **(b)** **(c)**

Fig. 4.3: Streak of light and dark coloured minerals: a) Streak plate; b) White streak of calcite (a non-metallic mineral); and c) Cherry red streak of hematite (a metallic mineral).

Let us spend five minutes to check our progress prior to learning about next physical property.

SAQ 1

a) List the characters of a mineral?

b) What are the reasons for the variation in the colour of minerals?

c) What is the difference between colour and streak of minerals?

c) Luster

Luster refers to the appearance of mineral surfaces to the combination of scattered and reflected light. It may vary in intensity from splendent (i.e. distinctly reflective as a mirror e.g. quartz) to shining (i.e. indistinctly reflective e.g. hornblende, augite), glistening (i.e. shiny by reflection with a sparkle, e.g. diamond) and glimmering (feebly reflective and intermittent flicker) and also in type from glassy to resinous to silky to waxy. Lustre is always observed and determined on the freshly broken surfaces of a mineral because minerals may chemically weather to a dull lustre with time such as a copper coin or an iron piece.

Generally, two types of lustre are recognised i.e. metallic and non-metallic. Let us now understand about the two general types of luster:

- **Metallic luster** - Minerals reflecting light and looking shiny, like metal objects are said to have metallic lustre. These minerals are opaque to light and usually have reflective surfaces with sheen such as steel, gold, silver, brass or copper metals. These minerals usually give black or very dark coloured streak. Common examples of minerals having metallic luster are galena, pyrite (Fig. 4.4a) and chalcopyrite.
- **Non-metallic luster** - If surface of a mineral is not shining then it is said to have non-metallic lustre. In general, such type of minerals are, light coloured and transmit light. For dark coloured minerals, their thin edges/slices would transmit light. These minerals usually give colourless or very light coloured streak. There are different kinds of non-metallic luster, which are discussed in Table 4.2.

(a)

(b)

(c) (d) (e)

Fig. 4.4: Different types of luster: a) Metallic luster in pyrite; b) Adamantine luster; c) Vitreous luster in quartz; d) Pearly luster in biotite; and e) Earthy lustre of bauxite. (Photo credit: a-Nishit Shukla)

Table 4.2: Different kinds of non-metallic lusters and their examples.

Non-metallic luster	Description	Example
Adamantine	It is a luster displayed by minerals such as diamond and garnet. Usually, it is due to mineral's high refractive index	Diamond, Zircon, Garnet, Cassiterite, Cerussite (Fig. 4.4b)
Vitreous	This type of lustre is like that of a polished glass and is common. It is displayed by silicates and carbonates, sulphates and the halides and other non-metallic minerals such as quartz, feldspars, pyroxenes, etc. It is further classified as sub-vitreous when it is less developed, e.g. hornblende and augite	Vitreous - Quartz (Fig. 4.4c), Emerald, Tourmaline Sub-vitreous - Hornblende, Calcite and Augite
Resinous	It is the luster of a resin and glue. Minerals displaying this kind of luster are usually yellow or brown in colour	Sphalerite, Opal, Amber, Sulphur
Silky	It gives silk or satin like luster. It is caused by reflection of light from a fine fibrous parallel aggregate	Asbestos, Satinspar (gypsum), Serpentine, Malachite
Waxy	Minerals with this type of luster appear like a paraffin or wax e.g. candle	Chalcedony
Pearly	This type of luster has milky shimmer and resembles to iridescent pearl	Talc, Selenite, Apophyllite, Brucite, Biotite (Fig. 4.4d)
Greasy	This type of luster resembles to luster of a grease and thin layer of oil covered materials	Nepheline, some milky quartz
Earthy (dull)	When there is no reflection at all, (e.g. in chalk and clay). This type of luster lacks in the reflection and appears dull such as dry soil is characteristic of aggregates of very fine-grained material	Chalk, Goethite, Limonite, Glauconite (Fig. 4.4e)

(Compiled and tabulated from Gribble, 1991; and Klein and Dutrow, 2017)

Minerals with an intermediate luster (i.e. luster is slightly less than the metallic minerals) are said to be sub-metallic e.g. chromite and cuprite. However, it is treated as metallic for the purpose of mineral identification.

d) Diaphaneity

Besides a mineral's colour, you may also record clarity of that mineral. Clarity of a mineral depends upon its diaphaneity or degree of transparency i.e. their ability to allow the light to pass (in other words, transmit) through it. Diaphaneity of a mineral also depends upon thickness of the mineral piece. You can determine diaphaneity of minerals by observing it.
Based on diaphaneity, minerals can be grouped under the following:

- **Transparent** – When light passes through a mineral and objects are seen clearly like a clear glass, e.g. clear quartz (Fig. 4.5a).
- **Subtransparent** – When objects can be indistinctly seen through a mineral.
- **Translucent** – When the mineral cannot be seen through clearly and rather appears foggy because of diffusion of light and internal absorption, e.g. quartz, calcite. It is partly due to thickness and purity of the mineral e.g. pure quartz is transparent, but some varieties and thicker pieces with the presence of large numbers of bubbles are translucent (Fig. 4.5b). Another example is of hematite which is usually opaque, but very small sized pure crystals are translucent.
- **Opaque** – When the mineral is impervious to light. It means no light passes through mineral. You cannot see through the mineral, e.g. quartz (Fig. 4.5c), tourmaline, hornblende and metallic minerals such as hematite, which is always opaque even in thin sections.

(a) **(b)** **(c)**

Fig. 4.5: Different varieties of quartz mineral: a) Transparent; b) Translucent; and c) Opaque.

e) Luminescence

Some minerals emit light at low temperature and are visible in dark. Luminescence is the emission of light by a mineral that is not the direct result of incandescence (i.e. the mineral has not been heated). There are two types of luminescence:

- **Fluorescent minerals:** Luminescent during exposure to UV light, X-rays or cathode rays, e.g. scheelite (yellowish green glow) and scapolite (yellowish orange glow).
- **Phosphorescent minerals:** Luminescent continuously even after the existing rays are cut off, e.g. diamond and ruby.

4.3.2 Depending upon Atomic Structure and State of Aggregation

Atomic structure and state of aggregation determine several physical properties of minerals such as form, habit, cleavage, fracture, hardness and tenacity. We shall discuss about these characters here.

a) Crystal Forms

We all have seen some beautiful crystals of a mineral in a variety of shapes. We also know that crystals grow and take their shape from their tiny building blocks, called as **unit cells**. Each unit cell has an identical atomic arrangement/ structure. The characteristic geometric shape of a crystal that is formed by intersecting flat outer surfaces (i.e. crystal faces) is called its **form**. Minerals grow into a definite crystal form only under favourable environmental conditions such as:

- availability of constituents in the mineral solution for growth,
- enough space for the crystals to grow, and
- non-obstruction by other solids.

Form of a mineral denotes whether the mineral is crystallised or non-crystallised. Gribble, (1991) describes following terms associated with the form or crystal characters of a mineral:

- **Crystallised**: It refers to minerals with well developed crystals, e.g. rhombohedral calcite.
- **Crystalline**: It refers to a confused aggregate of imperfect crystal grains interfering with each other during the growth.
- **Cryptocrystalline**: It refers to mineral with traces of crystalline structure such as poorly developed crystal faces. Such structures can only be observed using microscope.
- **Amorphous**: It refers to the complete absence of crystalline structure, e.g. obsidian. It occurs rarely.

In the Block 1 of this course, you have read about the seven crystal systems (Table 4.3) in which minerals crystallise.

Table 4.3: Crystal systems and the minerals which crystallise in these systems

Crystal systems	Minerals
Cubic	Galena, garnet, pyrite, halite magnetite, flourite, leucite,
Tetragonal	Rutile, cassiterite, zircon
Hexagonal	Apatite, beryl
Trigonal	Calcite, quartz, tourmaline
Orthorhombic	Sulphur, barite, olivine, topaz
Monoclinic	Gypsum, augite, hornblende, orthoclase
Triclinic	Axinite, rhodonite

On the basis of degree of development of crystal faces and forms, crystals are grouped into following three groups:

- **Euhedral crystals** – Although, it is rare, but when crystals grow unhindered, they have well developed and clearly defined crystal faces thus crystal forms are recognised.
- **Subhedral crystals** – Such crystal types are more common because most of the time crystals grow together resulting in crystals with deformed crystal faces and imperfect crystal forms. Such types of crystals are imperfect. Subhedral crystals have enough faces developed thus their forms are recognised.
- **Anhedral crystals** - When minerals have no crystal faces developed they are called anhedral crystals.

Based on matching of their crystal faces, crystals are classified into following forms (Farndon and Parker, 2009):

- **Isometric forms** - When crystals have various numbers of matching faces e.g. tetrahedron (4 faces), octahedron (8 faces) (Fig. 4.6a&b).
- **Non-isometric forms** - When crystals have non-matching faces e.g. rhombohedron, dipyramid (Fig. 4.6c&d).

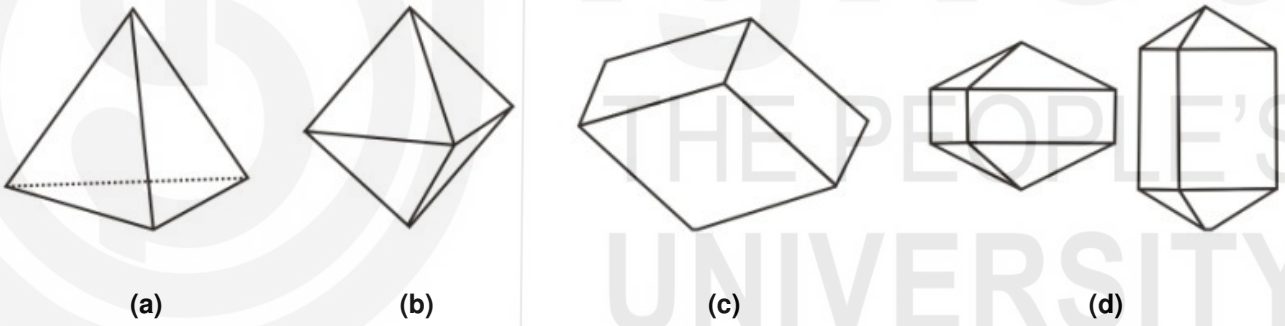
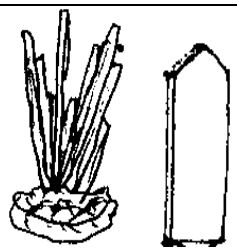
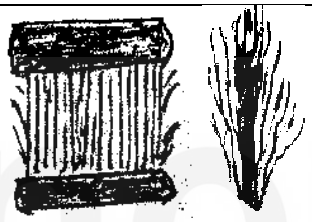
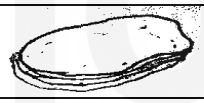
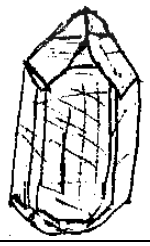


Fig. 4.6: Crystal forms: Isometric forms: a) tetrahedron; b) octahedron - Non-isometric forms; c) rhombohedron; and d) dipyramid.

b) Mineral Habits

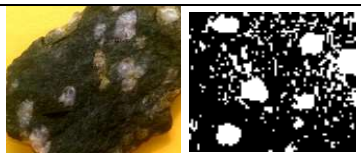
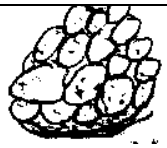
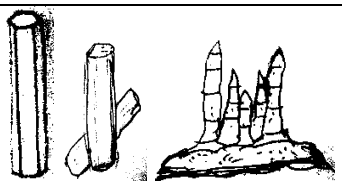
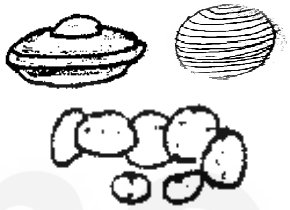
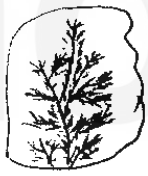
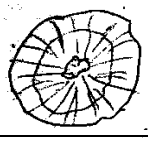
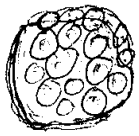
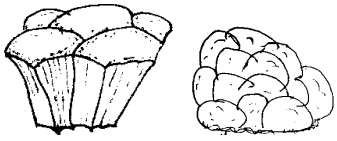
Habit of a mineral is its general shape and pattern in totality. Individual crystal and aggregate tends to form under a given set of environmental conditions. Such type of character is helpful in identification of minerals. Habit can be either individual or group of crystals (aggregates). We shall discuss about these two types and their habits. Individual crystals may have several habits (patterns and shapes) as given in Table 4.4. Similarly, combination of two or more crystals (i.e. crystal aggregates) produces habit as given in Table 4.5. You may note that when there is no distinctive pattern of a mass of crystals as observed in specimen (due to tight intergrowth), it is called **massive**.

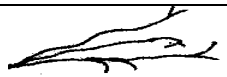
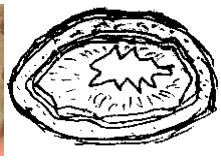
Table 4.4: Habits of individual crystals.

Habit	Crystal Characteristics	Illustration
Acicular	Fine needle like crystals, e.g. natrolite	
Bladed	Resembles to a blade of a knife, e.g. kyanite	
Fibrous	Consists of clumps of strings, or hair like fibres or thread like structure, e.g. satin-spar (gypsum), and asbestos	
Foliated or foliaceous	Consists of thin and separable plates or lamellae or leaves, e.g. mica minerals	
Lamellar	Consists of separable plates or leaves, e.g. wollastonite	
Prismatic	Elongated crystals in one direction, like net, e.g. pyroxene, amphiboles	
Reticulated or rutilated	Network of small crystals developed in a cross mesh pattern, e.g. inclusion of rutile needles in quartz	
Scaly	In small plates, e.g. tridymite	
Tabular	Broad, flat and thin crystals e.g. feldspar	

(Text compiled and tabulated from Gribble, 1991 and Klein and Dutrow, 2017)

Table 4.5: Habits of crystal aggregates.

Habit	Characteristics of Crystal Aggregates	Illustration
Amygdaloidal	Almond shaped aggregates, e.g. zeolites in basalt cavities	
Botryoidal	Spherical aggregation, like bunch of grapes, e.g. azurite, chalcedony	
Columnar and Stalactitic	Aggregates making slender columns usually parallel, e.g. calcite forming stalactite, stalagmite; beryl, tourmaline	
Concretionary and nodular	Spherical, ellipsoidal or irregular masses, e.g. flint	
Dendritic and arborescent	Generally found in minerals deposited in crevasses or narrow planes. It resembles to tree branches or a river system, e.g. psylomelane	
Granular	Evenly sized coarse and fine grained aggregates, e.g. chromite and olivine. Resembles to a lump of sugar, hence also called saccharoidal	
Lenticular	Lense like, flattened balls or pettets, e.g. many concretionary and nodular minerals	
Mammiliated	Mutually intersecting spheroidal surface but larger than botryoidal, e.g. malachite	
Radiating or divergent	Fibres arranged around a central point, e.g. barite and in many concretions	
Oolitic	Consisting of small spheroids or ellipsoids that resembles to tiny fish eggs, e.g. oolitic hematite, chamosite	
Pisolitic	Similar to oolitic but comparatively larger spheroids, e.g. bauxite	
Reniform	Mineral aggregates in which radiating crystals terminate in rounded masses with kidney shaped surface, larger than botryoidal, e.g. kidney iron ore (hematite)	

Stellate	Fibers radiating from a centre producing star like shape, e.g. wavellite	
Wiry or filiform	Like many hair like or thread like filaments or a twisted wire, e.g. native copper and silver	
Geodic or drusy	It is a cavity in rock that is lined with mineral but not completely filled e.g. agate	 

(Text compiled and tabulated from Gribble, 1991 and Klein and Dutrow, 2017)

c) Cleavage and Parting

Form and habit depend upon the state of aggregation. Now we shall learn about the physical properties that depend upon the internal atomic structure.

When you hit a mineral, it tends to break (cleave) along its weakest points/ lines/ planes. When hammered, most of the minerals tend to break in a systematic way along planes of weakness. When a mineral breaks along a definite plane surface it is said to possess a cleavage. So, cleavage is the tendency of a mineral to break/split in a systematic way. Cleavage plane is determined by internal atomic structure of the mineral i.e. by the type and strength of the chemical bonds between the atoms. The cleavages (i.e. planes of weakness) represent parallel layers between rows or sets of planar atoms, where the atomic bonds are weaker than the adjacent layers of the atoms. Since, cleavage is closely related to crystalline form and atomic structure; cleavage planes are parallel to either a particular face or to a set of faces representing a crystal form.

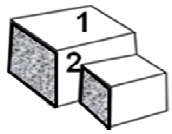
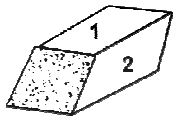
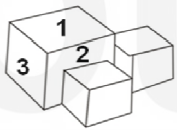
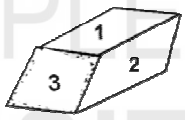
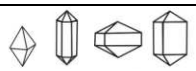
Different minerals break in different ways and show different types of cleavages. Hence, cleavage is used as a diagnostic physical property for identification of minerals. Many a times, cleavage planes in mineral specimens are identified easily. Sometimes, the cleavage planes are not visible, however the mineral still cleave along the weak planes because the cleavage surface may be microscopic.

Cleavage is defined using following two sets of criteria:

- **Ease in obtaining:** If we can easily obtain cleavage and distinguish cleavage planes then the cleavage is considered as an **excellent** or **perfect**. If the mineral has obvious cleavage planes but we can obtain them with some difficulty then it is called **good**. If we can obtain cleavage with difficulty and some of the planes are difficult to distinguish, then the cleavage is called as **imperfect**.
- **Direction of the cleavage surfaces:** We have learnt that cleavage planes are parallel surfaces of weak chemical bonding between lattices. Each set of parallel cleavage planes is called a cleavage direction. There could be more than one set of cleavage planes present in a crystal with each different set of cleavage planes having an orientation relative to the crystalline structure. Some minerals have one direction of cleavage whereas others may have two, three, four or six. In such cases, the cleavage types are termed (based on the shape formed by the cleavage surfaces) as cubic, rhombohedral, octahedral, dodecahedral, basal or prismatic.

These two sets of criteria are defined specifically by the angles of the cleavage lines as indicated in the Table 4.6. Some examples are shown in Fig. 4.6.

Table 4.6: Different types of cleavages.

Cleavage Types	Cleavage Directions	Description	Illustration
Basal	One direction parallel to basal plane of the mineral	Cleavage occurs along planes between sheets or multiple sheets (layers) of atoms because there are weak bonds along the sheets. Cleavage is parallel to basal plane of the mineral, e.g. mica minerals, which split apart like pages of a book	
Prismatic	Two directions parallel to the prismatic faces intersecting at or near 90°	Cleavages occur between the stacked chains of Si-O atoms. Mineral cleaves by breaking off thin, vertical, prismatic crystals off of the original prism, e.g. orthoclase (90°), plagioiclase (at 86° & 94°) and pyroxene (augite) (at 87° & 93°)	
Prismatic	Two directions parallel to the prismatic faces but not inter-secting at 90°	Cleavages occur parallel to the prism zones of the minerals, e.g. amphibole (hornblende) (at 56° & 124°)	
Cubic	Three directions parallel to the faces of the cube at 90° to one another	Minerals with this cleavage break into small cubes and shapes made of cubes. Cleavages are parallel to all three pairs of cube faces and cleavage directions are at 90° to one another, e.g. rock salt (halite), galena	
Rhombo-hedral	Three directions parallel to the faces of the rhombohedron but not at 90° to one another	Minerals with this cleavage split along three cleavage planes giving them 'diamond' shape called a rhombohedron, e.g. calcite	
Octahedral	Four directions parallel to the faces of the octahedron	Minerals with this cleavage break into shapes made of octahedron and parts of octahedron, e.g. diamond and fluorite. Four main cleavage intersect at 71° and 109° to form octahedron, which split along hexagon shaped surfaces; may have secondary cleavage at 60° and 120°	
Pyramidal	Four directions parallel to the pyramidal faces	Type of cleavage that occurs parallel to the faces of a pyramid, e.g. scheelite	
Dodeca-hedral	Six directions parallel to the faces of the dodecahedron intersecting at 60° and 120°	Minerals with this cleavage break into shapes made up of dodecahedron and parts of dodecahedron, e.g. Sphalerite	

(Simplified from Boger et al, 2015)

Fig. 4.7: a) One direction of cleavage in muscovite; b) Three planes giving rise to rhombohedral cleavage in calcite; c) Two planes of cleavages in orthoclase at right angles to each other; and d) Two planes of cleavages in hornblende at an angle of 24° and 156°.

Parting is similar to a very poor cleavage but it refers to breaking along planes of structural weakness due to crystal defects. It is generally not very recognisable.

You may have some confusion between cleavage and crystal form. While both of them give rise to flat planes, the reasons are different. Some minerals may have both the cleavage and crystal form such as in calcite, fluorite, halite, but some may have only cleavage e.g. muscovite and a few may have only the crystal form e.g. quartz. You can distinguish them by remembering that minerals with cleavage will always break in the same direction or set of directions, forming flat planes or stair-step pattern on their surfaces, whereas minerals with crystal form will not break in any particular direction and form irregular surface after breakage.

d) Striations

Some minerals such as quartz, tourmaline, feldspar, garnet and pyrite have hairline grooves or furrows on the cleavage planes or crystal faces which is also useful for their identification (Fig. 4.8). They are very fine parallel lines or furrows on cleavage planes or crystal faces and called as **striations**, which form due to crystal structure and growth patterns. Plagioclase feldspars (i.e. albite and labradorite) commonly exhibit striations on one cleavage plane as the

calcium content of the feldspar increases. You can clearly identify striations in a mineral by slightly rotating it back and forth in the light and observing change in the reflection due to striations.

(a) (b)

(c)

Fig. 4.8: Striations in a) Tourmaline; b) and c) Quartz.

Let us spend 5 minutes to check our progress before we proceed to the next physical property.

SAQ 2

a) What is a crystal form?

b) What are the habits of individual crystal and crystal aggregates.

c) What is a cleavage?

d) What is a striation?

e) Fracture

Cleavage is a plane of weakness along which the minerals break. The broken surface may be smooth and flat or uneven. When you break a mineral in random direction(s) other than the cleavage plane(s), the broken surface would have a typical characteristic feature, which is known as fracture. It describes characteristics of a broken surface. Unlike, the cleavage planes which are smooth and flat, fracture surface is generally rough or uneven.

There are different terms which are used to describe various types of fractures as given in Table 4.7 and as shown in Fig. 4.9:

Table 4.7: Different terms used to describe various types of fractures.

Type of fracture	Description	Illustration
Conchoidal	Fracture surface is a curved (concave or convex) parting surface having shell-like lines or arcuate ridges. It is similar to the smooth curved surface produced when a glass is broken. It is developed in the minerals that are homogeneous and equally strong in all directions e.g. pure quartz, natural glass (obsidian), opal	
Uneven/ irregular	Fracture surface is rough and irregular with minute elevations and depressions, e.g. milky quartz, anhydrite and most minerals	
Even	Fracture surface is flattish (not cleavage), e.g. chert, magnesite	
Hackly	Fracture surface is jagged with sharp points or edges e.g. cast iron, native copper, kyanite. You should be careful while handling such minerals because the sharp points or edges may cut on your fingure	
Splintery	Fracture surface is similar to the broken wooden surface. It is produced by intersecting good cleavages or partings e.g. hornblende. It occurs in finely acicular minerals and in minerals with relatively higher hardness in one direction than the other two directions e.g. chrysotile, serpentine, kyanite	
Fibrous	Fracture surface is thin and elongated and separates into soft fibers, like cloth, e.g. asbestos. It is produced by crystal forms or intersecting cleavages	
Earthy	Fracture surface is similar to the broken children's clay. It is generally found in massive and loosely consolidated minerals e.g. limonite	

(Text compiled and tabulated from Gribble, 1991; and Klein and Dutrow, 2017)

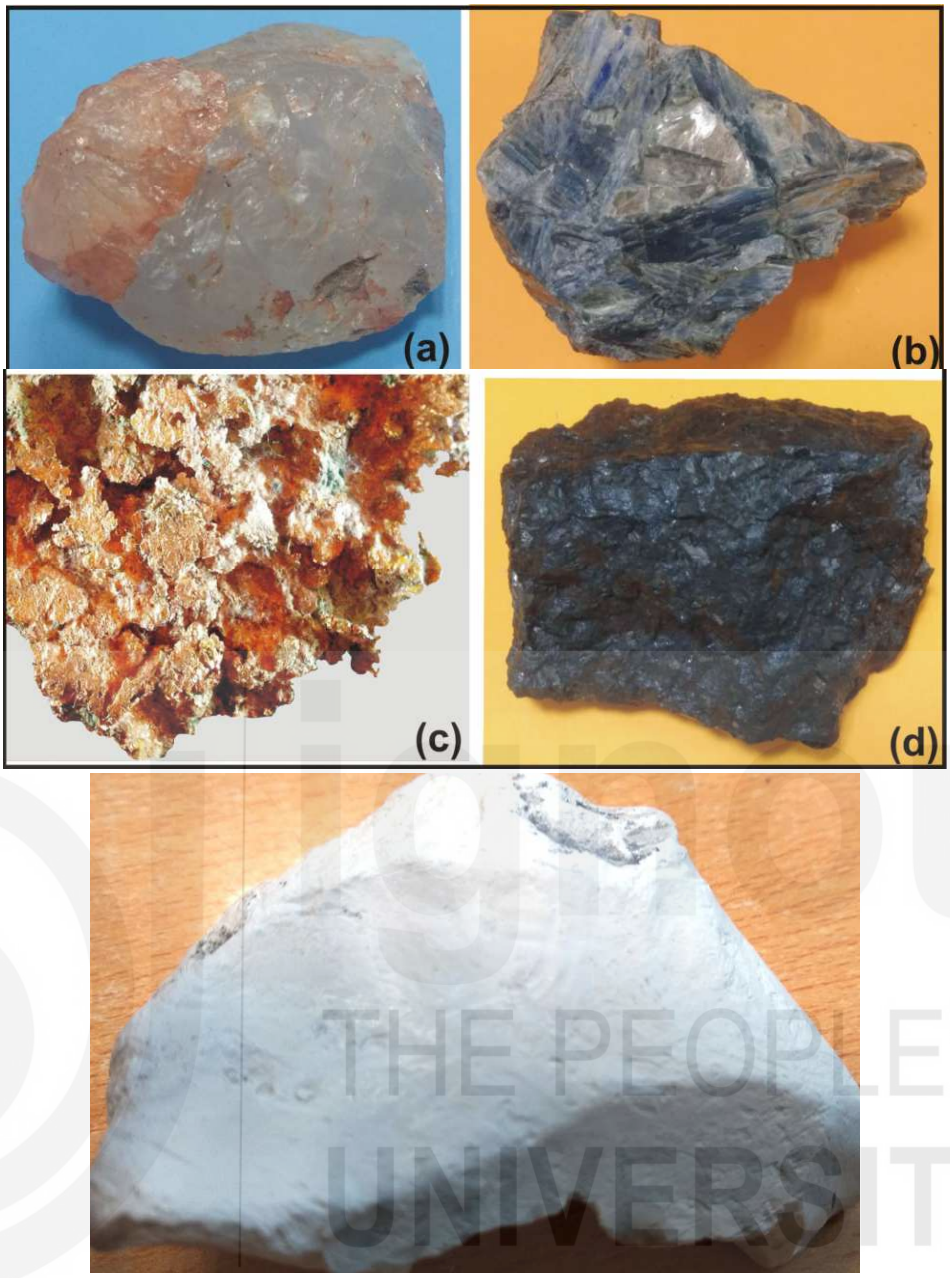


Fig. 4.9: Fractured surface of minerals: a) Conchoidal fracture in quartz; b) Splintery fracture in kyanite; c) Hackly fracture in native copper; d) Uneven fracture in hematite; and e) Earthy fracture in kaolinite.

You can clearly recognise cleavage planes and fracture surfaces. You now know that cleavage planes are parallel, smooth and flat, whereas fracture surface(s) is generally rough or uneven and never occur in parallel sets. Further, when you rotate a broken piece of a mineral crystal in bright light, there would be periodic reflective flashes of light from its cleavage planes, whereas no such reflective flashes of light occur if there is no cleavage.

f) Hardness

Hardness is one of the most important diagnostic properties of minerals. It is the resistance offered by a smooth surface of a mineral against its scratching so it might also be said to be its “scratchability”. Hardness of minerals depends upon atomic structure and density of ions in the mineral.

Friedrich Mohs, a German mineralogist developed a relative scale of mineral hardness in 1812 by arranging minerals in the order of their increasing relative hardness. The quantitative scale is known as the **Mohs' scale of hardness**, which is a set of 10 minerals of known arbitrary hardness (Table 4.8 and Fig. 4.10). The softest mineral (talc) has hardness of 1 and the hardest mineral (diamond) has hardness of 10. Higher numbered (i.e. the harder) minerals can scratch the lower-numbered (i.e. the softer) minerals because the forces that hold the crystals together can be broken by the harder mineral. The scale provides a standard to which all other minerals can be compared. However, you should note that this is a simplified relative hardness scale and the increase in hardness of the minerals from 1 to 9 is approximately linear but hardness of mineral at 10 (i.e. diamond) has been estimated as four times higher than the mineral at 9 (i.e. corundum).

Table 4.8: Mohs' scale of hardness of minerals and hardness of common objects.

Hardness	Mineral	Minerals with similar hardness	Common objects that can be used to measure relative hardness of minerals
1	Talc	Graphite, clays	
2	Gypsum	Sulphur, halite, muscovite, chlorite	Finger nail (2.2) May vary from person to person Copper coin (2.9)
3	Calcite	Barite, biotite, native copper, gold, silver	Brass (wood screw, washer) (3.5)
4	Fluorite	Siderite, dolomite, aragonite, malachite	Wire (iron) nail (4.5)
5	Apatite	Limonite, serpentine, kyanite (along length)	Steel nail, Steel Knife blade (5-6.5) depending on the steel quality Glass plate (~5.5)
6	Orthoclase feldspar	Leucite, nepheline, sodalite, amphibole, pyroxene, epidote, pyrite, rutile, hematite	Steel file (~6.5)
7	Quartz	Garnet, kyanite (across length), olivine, casseterite, andalusite	Streak plate (~7)
8	Topaz	Beryl	Emery sandpaper
9	Corundum		Knife sharpener
10	Diamond		

(Compiled and tabulated from Gribble, 1991; and Klein and Dutrow, 2017)

You can determine hardness of a mineral by comparing its hardness with other minerals or common objects. In general, minerals are grouped into two classes:

- **Soft minerals** (those with hardness 5.5 or less) that are softer than the glass plate (i.e. they can be scratched by glass), and
- **Hard minerals** (those with hardness >5.5) that are harder than the glass plate (i.e. they can scratch the glass).

Soft minerals can be easily scratched by a knife blade or steel nail and do not scratch glass. Hard minerals cannot be scratched by a knife blade or steel nail and easily scratch glass.

You should take precautions while testing hardness. You need to carefully note the kind of noise a mineral makes when it is scratched on another mineral and also the powder produced as a result of scratch. Further, some minerals may display different hardnesses in different scratch directions. A significant difference in the hardness is noticeable in kyanite and calcite. Kyanite shows hardness of 5 parallel to the length, but 7 across the length.

Fig. 4.10: Minerals in the Mohs' hardness scale: first row from left are talc, gypsum, calcite, fluorite and apatite; second row from left are orthoclase feldspar, quartz, topaz, corundum and diamond.

d) Tenacity

The way a mineral offers resistance (or deforms) when it is subjected to crushing, bending, breaking or tearing, is known as tenacity. In other words, it is cohesiveness of the mineral. Tenacity varies from one mineral to another; hence it is used as a useful physical property for mineral identification. The terms used to describe tenacity are given in Table 4.9.

Table 4.9: Terms used to describe tenacity of minerals and their examples.

Term	Description	Example
Brittle	Such minerals are broken or crushed easily into powder with hammer	Galena, hematite, sulphur, iron pyrite, apatite, fluorite
Malleable	Such minerals can be hammered out into thin flat sheets	Native gold, silver, copper
Elastic	Such minerals or their thin plates or laminae can bent and return to their original position after removal of the pressure	Mica
Flexible	Such minerals bent, but do not return to their original position even after removal of the pressure	Talc, chlorite, selenite
Sectile	Such minerals can be cut with a knife	Graphite, steatite, gypsum
Ductile	Such minerals can be drawn into thin wires	Gold, silver, copper

(Tabulated from Gribble, 1991)

4.3.3 Based on Specific Gravity

Specific Gravity (SG) determines relative density of minerals. It is a constant feature for each of the minerals. It depends upon the chemical composition of a mineral and also the packing of atoms in its crystal structure. Usually, the minerals composed of higher atomic weight elements usually have higher specific gravity such as minerals rich in Mg and Fe. Tighter the packing of atoms and heavier is the mineral e.g. diamond and graphite have same chemical composition, but diamond has higher specific gravity of 3.5 due to closely packed structure. Therefore, two minerals of the same size may have different weights. However, specific gravity may slightly vary within a mineral because of impurities present in its structure. Most of the minerals with a metallic luster are heavy. Galena is known for its high specific gravity.

The specific gravity of a mineral determines how heavy it is by its relative weight to water. The specific gravity is expressed upon how much greater the weight of the mineral is to an equal amount of water. The specific gravity of a body is the ratio of weight of the body to that of the equal volume of water at 40^{o} C. Water has a specific gravity of 1.0. Minerals with a specific gravity value < 2 are considered light, between 2 and 4.5 average, and > 4.5 heavy. If a mineral has a specific gravity of 3.5, it is 3.5 times heavier than the water.

There are several methods employed for determination of specific gravity of different kinds of minerals. Selection of a method depends usually upon the size and character of the specimen. Commonly used methods are listed in Table 4.10.

The specific gravity is very useful in the identification of minerals. You should note that to determine specific gravity, selection of mineral specimens is important. Ideally, pure specimens, which are homogeneous and devoid of any crack or cavity, are considered suitable for the purpose. However, such specimens are not easily found hence generally, specimens having a volume of about one cubic centimetre are used.

4.3.4 Based on Senses

Sensory tests such as feel, taste and odour may be diagnostic in identification of some minerals. We shall learn about them here.

a) Feel

How a mineral feels in our hand can be used to identify some minerals along with other physical properties to identify them. This property of minerals can be sensed by handling of minerals by bare hands. Some minerals have their own characteristics feel such as:

- **Soapy** – Some minerals such as talc gives sense of soapy feeling.
- **Greasy** - Some minerals such as graphite gives feel of a grease when touched.
- **Smooth and rough** – Some minerals feel smooth to touch and some others rough to touch such as chromite.

Table 4.10: Commonly used methods of determining specific gravity.

Method	Description	Useful for/to
Hefting	It is a simple method to judge specific gravity of one mineral relative to another. This is done by holding equal sized pieces of two minerals in different hands and feeling the difference in weight between the two. The mineral feeling heavier has a relatively higher specific gravity than the other	To differentiate metallic minerals from non-metallic minerals
By measuring displaced water	It is used for approximate and faster determination of specific gravity. It is obtained by half filling a graduated cylinder with water, placing the previously weighed specimen into the cylinder, and noting the increase in the volume. SG is determined by weight (in grammes) of mineral in air divided by the increase in volume (in millilitres)	Large number of pieces of the same mineral
Chemical balance	Specimen is suspended by a thread from one arm of the balance and immersed in a beaker of water. SG is determined by dividing the mineral's weight in air by the difference between its weights in air and water	Fragments of minerals about the size of a walnut
Walkers's steelyard	The apparatus consists of a long graduated beam which is pivoted near one end and counterbalanced by a heavy weight suspended from the short arm	Large specimens
Jolly's spring balance	It is similar to the chemical balance method. However, instead of determining the absolute weight of the specimen, values proportional to the weights in air and in water are determined. Specimen is suspended by a thread from one arm of the balance and immersed in a beaker of water. SG is then determined by dividing the mineral's weight in air by the difference in weights in air and in water	Very small specimens
Pycno-meter or specific gravity bottle	A small glass bottle containing a known volume of water is used which is fitted with a stopper having a fine opening. Specific gravity is determined by dividing weight of the mineral by the weight of distilled water displaced by it in the bottle used	Porous or friable minerals, mineral grains gemstones and liquids
Heavy liquids	Determined by comparing specimens to liquids of known specific gravity, which are of relatively high densities, hence called heavy liquids e.g. bromoform or tetrabromoethane (SG-2.89) and methylene iodide (SG-3.3). Heavier minerals sink and the lighter ones float in the liquid. SG of a liquid can be adjusted to a value at which a mineral will neither float nor sink. By knowing SG of the liquid we can determine SG of the mineral. Diffusion column is used for small samples, Berman Torsion microbalance for very small samples, and Westphal balance for small amount of liquids	For separation of mineral mixtures into their pure components

(Compiled and tabulated from Gribble, 1991; and Klein and Dutrow, 2017)

b) Taste

Minerals soluble in water can be identified by their taste. However, testing this property in classroom/laboratory could be dangerous because some minerals are poisonous. So, **you should not put minerals in your mouth or on the tongue**. Gribble (1991) has used following terms for minerals based on taste:

- **Saline** – Some minerals such as halite (NaCl) taste salty which is common salt.
- **Alkaline** – Potash and soda taste alkaline.
- **Cooling** – Nitre or potassium chlorate give cooling taste.
- **Astringent or puckering** – Green vitriol (hydrated iron sulphate) gives astringent taste and alum gives sweetish astringent taste.
- **Bitter** – Some minerals such as sylvite (KCl) and epsom salt (hydrated magnesium sulphate) tastes salty and bitter.
- **Sour** – Sulphuric acid tastes sour.

c) Odour

Most minerals do not have any odour, however when they are rubbed, struck, heated or breathed upon they leave some odour which could be a diagnostic property for those minerals. Gribble (1991) has used several terms to describe those odours as given in Table 4.11.

Table 4.11: Terms used to describe odours of minerals.

Odour	Description	Example
Alliaceous (Garlic)	Some minerals like arsenic compounds give odour that of garlic upon heating and grinding	Arsenopyrite
Horse raddish	Some minerals such as selenium compounds give odour of decaying horse-radish upon heating	Selenium minerals
Sulphurous	When iron pyrite is struck or some sulphides are heated they give rise to odour of burning sulphur	Pyrite when struck, chalcocite upon heating
Fetid (rotten eggs)	Some minerals such as certain varieties of quartz or limestone give odour of rotten eggs when heated or rubbed	Sphalerite when scratched, heating, rubbing of geodes of agate, quartz
Argillaceos or clayey (Musty)	When some minerals are breathed upon they give odour of clay	Clay minerals

4.3.5 Depending upon Forces

Physical properties based on forces such as heat, magnetism, electricity and radioactivity can also be used in identification of some minerals. We will learn about these physical properties in this subsection.

a) Heat

It has been recognised that minerals behave differently on heating. Some minerals melt at lower temperatures, whereas other minerals melt at much higher temperatures at the atmospheric pressure. So they have their specific

fusibility i.e. the temperature or amount of heat that is required to melt or liquefy a mineral. Wolfgang Xavier Franz Ritter von Kobell, a German mineralogist suggested a **scale of fusibility** which is used in mineralogy to define the approximate relative fusibility (temperature of fusion) of different minerals. The scale consists of following six minerals arranged according to approximate temperature of fusion (Gribble 1991).

- Stibnite (525° C)
- Natrolite (965° C)
- Almandine garnet (1,200° C)
- Actinolite (1,296° C)
- Orthoclase (1,300° C); and
- Bronzite (1380° C).

b) Magnetism

Some minerals display the property of magnetism (i.e. attraction or repulsion of magnetic materials to the mineral) and for these minerals, it could be a diagnostic property. Generally, the iron bearing minerals display magnetism; however it is not the case always. Also the degree of magnetism displayed by a mineral does not necessarily depend on the iron content.

Minerals may vary from nonmagnetic to weakly magnetic to strongly magnetic. Although, it can be difficult for you to determine different types of magnetism, but it is worth knowing that there are distinctions made.

Based on the type of magnetism displayed by minerals they can be grouped under the following:

- **Diamagnetic (non-magnetic)** – Minerals having no attraction for magnetic field e.g. quartz, calcite and most minerals.
- **Paramagnetic** – Minerals that are drawn to a magnetic field as long as the magnetic field is present. Paramagnetic minerals can be further classified as:
    - **Strongly magnetic/ferromagnetic** – These minerals are most magnetically active, e.g. magnetite, native iron.
    - **Moderately magnetic:** These minerals are not so magnetically active, e.g. Ilmenite, siderite, hematite, chromite**.**
    - **Weakly magnetic:** These minerals are least magnetically active, e.g. tourmaline, monazite, some hematite.

You have read in the course BGYCT-131 that past magnetic events are useful in reconstructing geological history. Magnetic minerals record the direction of the Earth's magnetic field through time and hence are very important. You may also note that the magnetic property of minerals is utilised to separate ore minerals from waste materials.

c) Electricity

Some minerals exhibit distinct electrical property i.e. the capacity to conduct electricity which is useful for their identification. Mostly, the minerals with metallic luster such as native metals (e.g. native copper, silver, gold) and sulphides except sphalerite (which has non-metallic luster) are good conductors

of electricity. Depending upon their capacity for conducting electricity, minerals can be categorised as non-conductor, semiconductor and conductor.

It has been observed that some minerals develop an electrical charge either

- when they are subjected to stress i.e. **piezoelectric**, e.g. quartz, or
- when they are heated i.e. **pyroelectric**, e.g. tourmaline.

c) Radioactivity

Uranium and thorium minerals (e.g. uraninite, pitchblende, thorianite, autunite) contain elements which continuously undergo radioactive decay reaction. In the process, radioactive isotopes of U and Th (such as U^{238}, U^{235} and Th^{232}) form various daughter elements and large energy is released in the form of alpha and beta particles and gamma radiation. This released radiation can be measured using instruments called Geiger - Muller counters, scintillometers and radon detectors.

d) Solubility in Acid or Reaction to Acid

Another diagnostic property of some minerals is that they undergo a change when a drop of dilute hydrochloric acid (HCL) is applied on their fresh surfaces from a dropper bottle. This test is particularly useful for identification of carbonate minerals such as calcite, aragonite, strontianite, etc. which show bubbles or effervescence. However, other carbonate minerals such as dolomite, rodochrosite, magnesite and siderite show effervescence in hot HCL.

There are some varieties of minerals known as gems, which are considered as precious due to their certain characteristics and rarity. We shall have a brief idea about them in the next section.

4.4 GEMSTONES

Most of the mineral crystals are dull and quite small but a few of them are rich in colours and sparkle. When such beautiful stones are hard enough to cut and fashion into jewellery, they are called **gemstones**. In other words, gems are minerals with an ornamental value, and are distinguished from non-gems by their beauty, durability, and usually, rarity. Of the number of minerals known, only about 130 mineral species are considered as gem minerals, and the gem minerals which are frequently used as gems are less than 50. The rarest and most valuable of all the gems are diamond, emerald (green beryl), ruby (red corundum) and sapphire (blue corundum). Gem minerals are often present in several varieties, and so one mineral can account for several different gemstones; for example, ruby and sapphire are both corundum and composed of Al_2O_3. Some of the less rare ones, such as pearl (aragonite), turquoise, lapis lazuli (lazurite), garnet, topaz, tourmaline, peridot (gem olivine), acquamarine (blue beryl), chrysoberyl, opal (chalacedony), jadeite are known as semi-precious stones.

Gemstones are very rare because they form under rare geological conditions for example:

- In volcanic pipes such as diamonds in kimberlite and lamproite (rock) pipes

- In pegmatite rock, which in the last stages of magma intrusions concentrate rare minerals to form gems such as beryl, rubies, sapphires, tourmalines, topazes and many others
- Due to intense metamorphism may create gems such as garnets, emeralds, jades, lapis lazuli, etc.

Gemstones are valued based on their beauty, durability and rarity and are often assessed in terms of following four Cs:

- **Clarity -** We have read about clarity in the previous section. It is considered as the most valued property for gems. Gems, which are flawless transparent crystals, are considered as the perfect gems that sparkle brilliantly due to internal reflection e.g. diamond,
- **Colour** - We have also learned about the colour as the first noticeable property of minerals. In the case of gems which are opaque, but have vivid colours are also prized e.g. jade, turquoise, lapis lazuli, etc. As you have studied, presence of trace elements brings wide range of colours in gems. While colourless diamond is most valued in comparisons to coloured diamonds, coloured varieties of beryl (i.e. emerald) is more valued than the colourless beryl.
- **Cut** - Besides the colour and clarity, cut is also important for gems because gems are cut to bring all its sparkle and colour. Hence it is important for gems to be tough enough to be used in jewellery.
- **Carat** - Size of the gems is also prized e.g. larger stones are the most valued. The word carat is believed to have been derived from the carob tree, seed of which were used in past to weigh gems. These seeds are known for their constant weight. It forms the basis of a standard weight called carat i.e. about a fifth of a gram.

There are several famous gems in the world. In India, one of the most famous gems in India is the Kohinoor.

4.5 SUMMARY

Let us now summarise what we have learnt in this unit.
In this unit, we have learnt that

- A mineral is a naturally occurring inorganic solid crystalline substance having definite chemical composition and distinctive physical property.
- Minerals form through the processes of crystallisation, evaporation/ precipitation, alteration and metamorphism
- Minerals are very significant to us. Right from the edible table salt to the utensils, toothpaste, building materials, computers and cosmetics we use, are all either the minerals or the products derived from them
- Minerals have certain physical properties based on which we can identify them
- Physical properties of minerals are their characteristics that we can observe such as i) shape and pattern of the crystals and their growth individually and in aggregates (form, habit), ii) its interaction with light and appearance of its fresh surface (color, luster, clarity, transparency, luminescence), iii) its resistance to scratching (hardness), iv) nature of bending, breakage or deformation under stress (cleavage, fracture, tenacity), v) density of packing of atoms (specific gravity), vi) response of our senses to them (feel, taste, odour), and vii) its response to forces (heat, magnetism, electricity, radioactivity), and
- gems are rare minerals which are formed under unusual geological conditions.

4.6 TERMINAL QUESTIONS

1. List the basis of grouping physical properties of minerals?
2. What are the physical properties of minerals which are used to identify them?
3. List any five types of lusters of non-metallic minerals.
4. How many sets of cleavages are found in minerals?
5. List any five types of fractures of minerals.
6. List any four types of habits of both individual crystal and crystal aggregates.

Audio/video material based questions

- Can you categorise minerals based on their usage?
- List the house-hold objects in which minerals are used.
- What is the significance of minerals in our life?

4.7 REFERENCES

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4.8 FURTHER/SUGGESTED READINGS

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4.9 ANSWERS

Self Assessment Questions

1 a) Naturally occurring, solid, formed by inorganic process, crystalline substance, definite chemical composition and distinctive physical property.

b) Amount of trace element present within them, nature and arrangement of constituent ions, bonding between the atoms, valency of ion, thickness of the mineral pieces being observed, disturbance of crystallinity.

c) Colour of the minerals is a result of reflection and/or absorption of light from its surface whereas streak is the colour of its fine powder.

2 a) Crystal form is the characteristic geometric shape of a crystal that is formed by intersecting flat outer surfaces.

b) The general shape and pattern in totality that its individual mineral crystals and aggregates tend to produce under a given set of environmental conditions of their formation is known as habit of the mineral.

c) Cleavage is the tendency of a mineral to break/split in a systematic way which is determined by internal atomic structure of the mineral.

d) Striations are the very fine parallel lines or furrows on cleavage planes or crystal faces.

Terminal Questions

1. The basis of grouping physical properties of minerals are i) shape and pattern of the crystals and their growth individually and in aggregates, ii) their interaction with light and appearance of its fresh surface, iii) resistance to scratching, iv) nature of bending, breakage or deformation under stress, v) density of packing of atoms, vi) response of our senses to them, and vii) their response to forces.
2. The physical properties of minerals which are used to identify them are form, habit, color, luster, clarity, transparency, luminescence, hardness, iv) cleavage, fracture, tenacity, specific gravity, feel, taste, odour, heat, magnetism, electricity, radioactivity and reaction to acid.
3. Adamantine, vitreous, resinous, silky, waxy, pearly, greasy and earthy (dull).
4. One, two, three, four and six.
5. Concoidal, uneven, even, hackly, splintery, fibrous and earthy.
6. Individual crystals: acicular, bladed, fibrous, foliated or foliaceous, lamellar, prismatic, reticulated, scaly and tabular. Crystal aggregates: amygdaloidal, botryoidal, columnar and stalactitic, concretionary and nodular, dendritic and arborescent, granular, lenticular, mammiliated, radiating or divergent, oolitic, pisolitic, reniform, stellate, wiry or filiform and geodic.

UNIT 5

CLASSIFICATION OF MINERALS

Structure

5.1 INTRODUCTION

You have been introduced to minerals and their physical properties in Unit 4 of this Block, and to crystals (i.e. minerals in crystallised form) in Block1 of this course. You have also read in the Unit that minerals have definite chemical composition and their crystals have characteristic form or habit, governed by their atomic structure.

In this unit, you will learn about classification of minerals which are based primarily on their chemical composition and internal crystal structure. We will first introduce chemical classification of minerals and then about structural classification of silicates. We will then discuss about classification and characteristics of common rock forming mineral groups.

You will be introduced to megascopic properties of commonly occurring rock forming minerals in the next two units of this block i.e. Units 6 and 7.

Expected Learning Outcomes

After reading this unit you should be able to:

- identify basis of mineral classification and major developments in classification schemes;
- describe chemical classification of minerals;
- discuss structural classification of silicates; and
- list out the commonly occurring rock forming mineral groups and their important characteristics.

5.2 BASIS AND DEVELOPMENTS OF MINERAL CLASSIFICATION SCHEMES

As we have read earlier, there are ~5530 minerals known so far and many are discovered every year. We have also read that each mineral has unique chemical composition however, despite the distinct chemical identity; there are many minerals which appear quite similar to other minerals. Some minerals are also known to have similar crystal form or to shape to another mineral. It is not an easy task to study these many thousands of minerals individually, so to make sense of them and for convenience to study them, scientists have attempted to organise/classify such a large set of minerals into certain groups.

There are different ways by which minerals have been classified such as on the basis of their:

- physical properties,
- chemical properties,
- chemical composition, and
- internal crystal structure.

The two parameters which are most important for mineral classification are the (i) chemical composition and (ii) internal crystal structure because these two control physical and chemical properties of minerals.

Based on the nature and basis of classification, the several classification schemes proposed can be grouped under the following:

- physical classification scheme
- hybrid (physical-chemical) classification scheme
- chemical classification scheme
- hybrid (chemical-structural) classification scheme, and
- structural classification scheme

Earlier attempts of mineral classification are considered as mostly nonscientific. The great German mineralogist and considered as 'Father of Mineralogy' Georgius Agricola's best known work ‘Agricola's De re metallica’ (On minerals, 1556) published after his death is believed to be the first scientific attempt of mineral classification.

Initial classifications of minerals were primarily based on their physical properties, which were being improved based on more accurate observations of physical properties. With the developments in extensive studies of chemical properties of natural materials, hybrid classification of minerals was proposed in the beginning of the 19th century that was based on both physical and chemical properties. With the advancements in knowledge, the hybrid classification was later replaced by chemical classification.

In that phase, majority of the mineralogists preferred to classify minerals into families based on their chemical composition. Two and a half centuries later Swedish chemist and mineralogist Jöns Berzelius (1779-1848) developed the basics of the classification system used today. The first classification based on chemical composition was given by J.J. Berzelius in 1824. In the **Berzelian system**, minerals are categorised based on the main anion group present in their chemical structure. Since, minerals of a certain class possess the same main anion group, all the minerals are chemically similar. The mineral classes are further subdivided based on physical features, presence of type of cations, presence or absence of water or hydroxyl anions, or internal structure of a mineral. In this system, minerals are classified into native elements; sulfides and sulfosalts; oxides and hydroxides; halides; carbonates, nitrates and borates; sulfates; phosphates; and silicates.

Berzelius's classification system was refined later in the nineteenth century by the American mineralogist James Dwight Dana and later simplified by the American geologists Brian Mason and L.G. Berry. Yale University Professor J.D. Dana proposed a chemical composition based mineral classification system in 1854, which formed the basis of the current classification system. The classification system known as the **Dana system** is most commonly used. In this system, minerals are classified into eight main mineral groups based on chemical composition. These classes are: native elements, silicates, oxides, sulfides, sulfates, halides, carbonates, phosphates, and mineraloids.

Although, the Dana system of classification has been revised and extended, it still remains the core of the mineral classification. It was latter realised that chemical composition alone is not sufficient to determine identity of a mineral and classify it. With the discovery of X-rays by British physicist Lawrence Bragg it became possible to use X-rays to determine atomic arrangement in crystalline substance. Bragg and Norwegian mineralogist Victor Goldschmidt classified silicate mineral groups based on their internal atomic structure. In 1941, Professor Hugo Strunz proposed chemical-structural classification of minerals in which he combined crystallography with chemical composition for mineral classification. The classification is known as **Strunz classification**. He arranged minerals into ten groups: elements; sulphides and sulphosalts; halides; oxides; carbonates; borates; suplhates; phosphates, arsenates and vanadates; silicates; and organic compounds. In his classification system, within each group, minerals are grouped into families based on their internal atomic structure and then each family is subdivided into group of minerals having similar internal structure (i.e. iso-structural minerals).

The Strunz classification system has undergone several refinements and the latest edition is known as **Nickel-Strunz classification** in which the previous version has been refined in the light of recent developments in crystal-structure determinations. In this classification system, minerals are grouped under ten major compositional classes: elements; sulfides; halides; oxides; nitrates, carbonates; borates; sulfates; phosphates; silicates; and organic compounds. These classes are further subdivided into divisions, families and groups on the basis of chemical composition and crystal structure (http://webmineral.com/help/StrunzClass.shtml).

Classification of minerals is similar to the classification of fauna and flora as we have read in school. It follows a similar hierarchical orders of mineral classification as given in Table 5.1:

Table 5.1: Hierarchical orders of mineral classification.

Unit	Basis	Example
Class	Dominant anions and anionic groups present in minerals. Minerals with highest ratio of metal to nonmetal is given first followed by those containing progressively less metal	Sulphide class – Cu_2S, AgS_2, FeS_2, etc., and Carbonate class – $MgCO_3$, $FeCO_3$, $ZnCO_3$, etc.
Sub-class (Family)	Structural type, or	Fayalite and pyrope, in which each SiO_4 tetrahedron is isolated and not connected to another
	Chemical composition	Two subclasses of carbonate class, such as hydrous and anhydrous
Group	Chemical/ structural similarity to greater degree	Hematite and spinel groups are included within the oxide class, or olivine and garnet groups included within nesosilicate class
Series	Same structure but different chemistry; Solid solution relationship,	Ablite and anorthite minerals constitute plagioclase series
Species	Individual mineral types	
Varieties	Chemical varieties by adjectival modifiers reflecting unusual amount of chemical constituents	

You may please note that the hierarchical units may not be applicable in some cases and cannot be generalised.

We have now got an idea of the basis of mineral classification and development of the classification schemes. In the next two sections, we shall learn in fewer details about the chemical classification of minerals and structural classification of silicate minerals. So now let us first learn about the chemical classification of minerals.

5.3 CHEMICAL CLASSIFICATION OF MINERALS

As you have learnt in Unit 4, minerals have definite chemical composition and range widely from pure metals and salts to complex constituents. So, minerals have been classified mainly on the basis of anion groups.
A majority of the mineralogists preferred to classify minerals into families based on their chemical composition. The chemical classifications generally begin with the elements and then further subdivides based on anion groups present. The first chemical classification proposed by Berzelius was based on electronegativity of the elements, in which mineral classes were recognised by the common occurrence of anions and radicals. This classification was extended by J.D. Dana. Although, there have been several updates in the classification system. The classification scheme given by Professor James Dana is the most commonly used.

We have learnt in this and the previous sections that in chemical classification scheme, minerals are divided into classes based on the dominant anion (e.g. oxygen O^{-2}) or anionic groups (e.g. carbonate CO_3^{-2}). This criterion is considered a valid basis for the broad framework of classification because:

- minerals having the same dominant anion or anionic groups are similar than the minerals containing the same dominant cation
- minerals with the same anion tend to occur together or in the similar geological environment e.g. sulfides in vein or replacement type
- this scheme is consistent with the periodic classification of elements.

In general terms, the classification system accepted by mineralogists today is as follows in which minerals have been divided into following eight basic classes.

1) **Native Elements**: This is the category of the pure metals. Most of the minerals are made up of combinations of chemical elements. e.g., element like the Copper (Cu) is found in a naturally pure form. There are about 40 elements, which are known to occur in a native state in the nature as relatively pure minerals. The finding of elements in a native state is related to structure of their atoms having inconvertible electronic shells. Although, occurrence of gold (Au), argentum (Ag), platinum (Pt) in native state are rare but most carbon (C), sulphur (S) and copper (Cu) are commonly found.

2) **Silicates**: Silicates are made from the metals which combine with the silicon and oxygen atoms. This is the largest group of minerals and most abundant in the Earth's crust than the sum of all the mineral groups. Silicate minerals are composed largely of silicon and oxygen, with the addition of ions such as aluminium, magnesium, iron, and calcium. Some important rock-forming silicates include feldspar, quartz, olivine, pyroxene, amphibole, garnet, and mica. We shall discuss about the silicate minerals in detail in the next section. It includes important rock-forming silicates such as feldspar, quartz, olivine, pyroxene, amphibole, garnet, and mica.

3) **Oxides**: Oxides form from the combination of a metal with oxygen. The oxide class includes the oxide and the hydroxide minerals. This group ranges from dull ores like bauxite to gems like rubies and sapphires. The

most widespread minerals of this group are oxides of silicon, aluminium, iron, manganese and titanium. Oxides are considered extremely important as they form many of the ores from which valuable metals can be extracted. Oxide minerals commonly occur either as precipitates at or near the Earth's surface, or as oxidation products or as accessory minerals in igneous rocks found in the crust and mantle. Some of the common oxides are hematite (iron oxide), magnetite (iron oxide), chromite (iron chromium oxide), rutile (titanium dioxide), and ice (hydrogen oxide). This class also includes the oxide and the hydroxide minerals.

4) **Sulfides**: Sulfides are made up of compounds of sulfur usually with a metal. They tend to be heavy and brittle. Several important metal ores come from this group like pyrite. Sulphide minerals generally have metallic luster, high density and low hardness. Many of the sulfide minerals are economically important for metals. Sulphides of copper, lead, zinc, argentum, antimony, etc. are common such as pyrite (iron sulfide), chalcopyrite (copper iron sulfide), pentlandite (nickel iron sulfide), and galena (lead sulfide). It also includes selenides, tellurides, arsenides, antimonides, bismuthinides, and sulfosalts (sulfur and a second anion such as arsenic).

5) **Sulfates:** Sulfates contain the sulfate anion, $(SO_4)^{2-}$. They are large group of minerals, which are made up of compounds of sulfur combined with metals and oxygen. Sulfate minerals tend to be soft, and translucent like barite (barium sulfate). They commonly form in evaporitic setting, in hydrothermal veins as gangue minerals along with the sulfide ores and also as secondary oxidation products of the original sulfide minerals. Some of the common examples of sulfate minerals are anhydrite (calcium sulfate), barite (barium sulfate), gypsum (hydrated calcium sulfate) and celestine (strontium sulfate). This class also includes chromate, molybdate, selenate, sulfite, tellurate, and tungstate minerals.

6) **Halide** group of minerals form from halogen elements like chlorine, bromine, fluorine, and iodine combined with metallic elements. They are very soft and easily soluble in water e.g. sodium chloride commonly known as table salt. Halides minerals form natural salts and include fluoride, chloride, bromide and iodide minerals such as fluorite (calcium fluoride), sylvite (potassium chloride), and sal ammoniac (ammonium chloride), etc. Similar to the sulfates, halides are also commonly found in evaporitic settings such as playa lakes and landlocked seas such as the Dead Sea and Great Salt Lake or in artificial salt pans. This class includes fluoride, chloride, and iodide minerals.

7) **Carbonate** group of minerals are made up of carbon, oxygen and a metallic element. They contain $(CO_3)^{2-}$ anions. The common minerals are calcite and aragonite (both calcium carbonate), dolomite (magnesium/calcium carbonate) and siderite (iron carbonate). Carbonates minerals are commonly formed in marine settings, where shells settle and accumulate on the sea floor, and in the evaporitic settings (e.g. the Great Salt Lake, Utah) and also in karst regions. It also includes the nitrate and borate minerals.

8) The **phosphate** group of minerals are made up of minerals having PO_4 complex ions acting as a non-metal with a metallic element. The most common example is apatite found in teeth and bones of many animals. This class includes phosphate, arsenate, vanadate, and antimonate minerals.

A summary of the chemical classification of minerals is given in Table 5.2.

Table 5.2: Summary of the chemical classification of minerals.

Chemical Class / Mineral Group	Anion or Anionic Complex	Description	Representative Minerals
Native elements	-	Naturally pure; only one kind of element is present	S-sulfur, Au-gold, Hg-silver, Cu-copper, C-diamond, C-graphite
Sulfides	S^{-2}	A metal bonds directly with sulfur as the nonmetal	FeS_2-pyrite, PbS-galena, ZnS-sphalerite, $CuFeS_2$-chalcopyrite
Oxides	O^{-2}	A metal bonds directly with oxygen as the nonmetal	hematite, magnetite, chromite
Halides	Cl^{-1}, F^{-1}	A metal bonds with a halogen (Cl, F, Br or I) as a nonmetal	NaCL-halite, CaF_2-fluorite
Sulfates	$(SO_4)^{-2}$	A metal bonds with the SO_4 complex ion acting as a nonmetal	$CaSO_4$-anhydrite, $CaSO_4.2H_2O$-gypsum, $BaSO_4$-barite
Carbonates	$(CO_3)^{-2}$	A metal bonds with the CO_3 complex ion acting as a nonmetal	$CaCO_3$-calcite, $CaMg(CO_3)_2$-dolomite
Phosphates	$(PO_4)^{-3}$	A metal bonds with the PO_4 complex ion acting as a nonmetal	$Ca_5(PO_4)_3(F,OH,Cl)$-Apatite
Silicates	$(SiO_4)^{-2}$	A metal bonds with the SiO_4 complex ion acting as a nonmetal	SiO_2-quartz, $(Na,Al,C)Si_3O_8$-feldspar

In this section, we have learnt about chemical classification of minerals. Let us now learn about the structural classification of silicate minerals. But before that let us spend five minutes to check our progress.

SAQ 1

a) What are the bases of mineral classification?

b) List the categories of mineral classification schemes.

c) List the eight basic classes of minerals identified under chemical classification?

5.4 STRUCTURAL CLASSIFICATION OF SILICATES

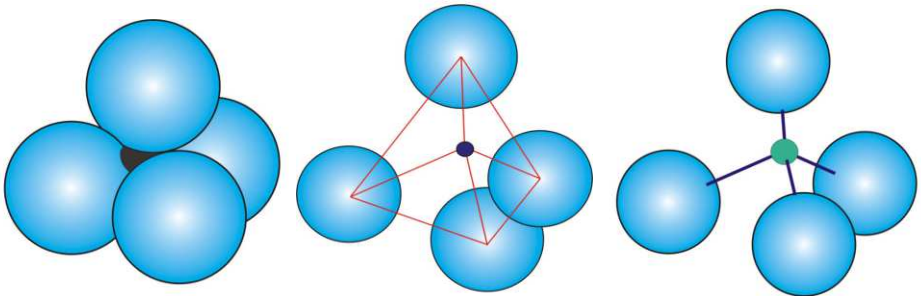
With developments in crystal structure analysis, it was proposed that mineral classification should be based on crystal structure because it controls physical and chemical properties of minerals and also their paragenesis to some extent. However, except for a few chemical classes of minerals, the scheme is yet to be developed extensively.

The crystal structure based classification scheme was developed initially by Bragg, who proposed classification of silicates based on the extent or degree in which the SiO_4 tetrahedral polymerise. Later on Zoltai, Leibau, Pabst and Hawthrorne classified aluminium hexafluorides according to the ways in which the AlF_6 octahedral polymerise. Christ and Clark (1977) worked on classification of borates according to the ways in which the BO_3 triangles and BO_4 tetrahedral polymerise. These classifications were based on the polymerisations of the principal anionic groups and ignored interrelationships among structures involving different anionic groups, but it was realised that such type of approach is of little use for mineral groups such as phosphates. The phosphate group of minerals was classified based on polymerisation of divalent and trivalent cation octahedra. Hawthrone (1979) and Moore (1980) pointed out that such approaches focused merely on one part of the structure and some of the classes such as borates and silicates are actually chemical rather than structural. Hawthorne (1985) suggested that structures may be ordered or classified according to the degree of polymerisation of those coordination polyhedra with higher bond-valences. This led to the developments of chemical-structural classifications. It is believed that a true structural classification scheme is based on structure of the minerals and must be applicable to all the minerals irrespective of their chemical composition.

Let us discuss in detail about the structural classification of silicate minerals. Silicates are the most abundant minerals in Earth's crust. They are composed of oxygen (O) and silicon (Si) atoms, which are the most abundantly elements found in combination with the cations of the other elements. Silicates have been further classified based on their structure. The basic unit of the silicate structure is the four sided pyramidal form which is known as **SiO_4 tetradedron** (Figure 5.1a&b). The silicate atom is tetravalent and is always surrounded by four oxygen atoms at the corners of a regular tetrahedron. Each side of the tetrahedron forms a triangle (Figure 5.1c). Each silicon-oxygen tetrahedron is an anion which has four negative charges. To make an electrically neutral, the negative charges must be balanced by four positive charges which may happen in the following two ways:

- The ion can bond with cations such as sodium (Na^+), potassium (K^+), calcium (Ca^+), magnesium (Mg^{2+}) and iron (Fe^{2+}), or
- The ion can share oxygens with other silicon-oxygen tetrahedra.

All the silicate minerals are made up of silicon-oxygen tetrahedral as a basic unit, linked in combinations of the above two ways.

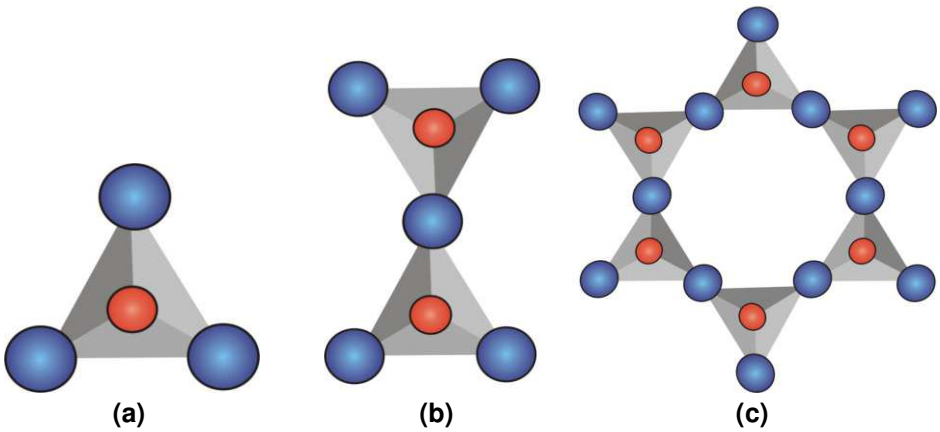


(a) (b) (c)

Fig. 5.1: a) A model of the silicate tetrahedra which has one silicon atom shared by four oxygen atoms; b) A detailed view of the same tetrahedron; and c) triangles on each side of the tetrahedron.

Silicate minerals are classified based on how the silica tetrahedra are linked together. The silica tetrahedra are built into the following different structures:

1. **Nesosilicates** or **orthosilicates** or **island silicates** (Independent/Isolated tetrahedra groups) [$(SiO_4)^{-4}$]: These minerals contain independent tetrahedral that are linked by the bonding of each oxygen atom of the tetrahedron to a cation. The cation in turn bond to the oxygen of other tetrahedral (Fig. 5.2a). Thus the tetrahedra are isolated from one another by cations on all sides. The ratio of oxygen to silica is 4:1. Examples of such silicate minerals are olivine group, garnet group, zircon, etc.
2. **Sorosilicates** (Double Tetrahedral group) [$(Si_2O_7)^{-6}$]: In this type of silicates, two tetrahedra are linked together by a single oxygen atom or in other words, two tetrahedra share one oxygen atom (Fig. 5.2b). The ratio of oxygen to silica is 2:7 or 3.5:1. Example of this type of silicate structure is epidote group, and the melilite group.
3. **Cyclosilicates** or **ring silicates** [$(Si_6O_{18})^{-12}$] or [$(Si_3O_9)^{-6}$]: In this type of silicates, tetrahedrals share two oxygens atoms and linked together to form a ring (Fig. 5.2c). The ratio of oxygen to silica is 3:1. It forms following three types of closed rings:
   (i) each of 3 tetrahedral sharing an oxygen atom such as in mineral benitoite
   (ii) each of 4 tetrahedral sharing an oxygen atom such as in mineral axinite
   (iii) each of 6 tetrahedral sharing an oxygen atom such as in mineral beryl.

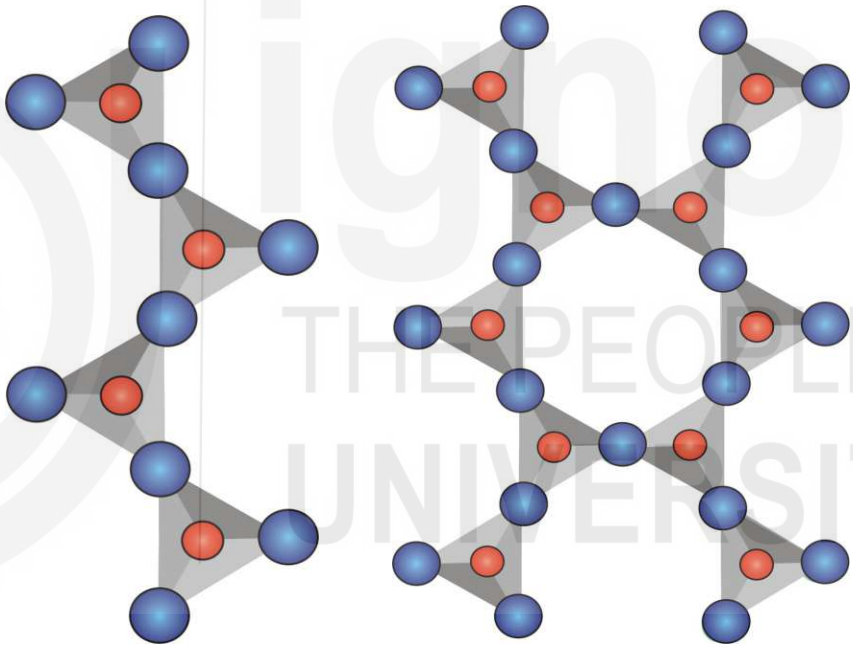


(a) (b) (c)

Fig. 5.2: Crystal structures: a) nesosilicate; b) sorosilicates; and c) cyclosilicate minerals.

4. **Inosilicates** or **chain silicates**: There are following two major sub-groups of the in silicate group:

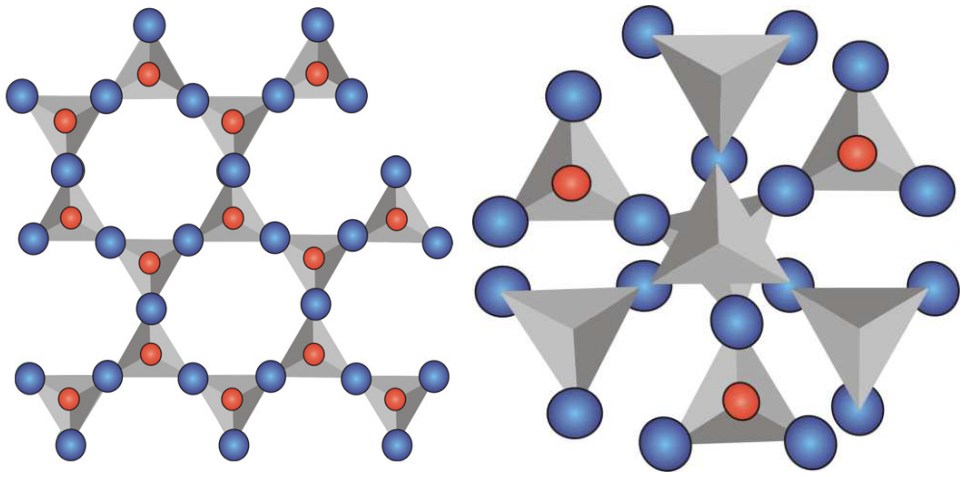
   - **Single Chain silicates** $(SiO_3)^{-2}$: This type of structure also forms by sharing oxygen atoms but in this case, two oxygen atoms from each tetrahedral bond to adjacent tetrahedra but in an open-ended chain instead of a closed ring. Single chains are linked to other chains by cations (Fig. 5.3a). The ratio of oxygen to silica is 3:1. Examples of such silicates are the pyroxene group of minerals.
   - **Double Chain silicates** $(Si_4O_{11})^{-6}$: It is a continuous double chain structure of tetrahedras alternatively sharing two and three oxygen atoms. In this case, two single chains combine to form a double chain linked to each other by shared oxygen atoms. Adjacent double chains linked together by cations and forms the structure which is typically found in the amphibole group of minerals (Fig. 5.3b). A common mineral, hornblende has a complex composition, include calcium, sodium, magnesium, iron and aluminium as bridging atoms. The ratio of oxygen to silica is 2.75:1.



(a) (b)

Fig. 5.3: Crystal structures of a) single chain; and b) double chain silicate.

5. **Phyllosilicates or sheet silicates** $[(Si_2O_5)^{-2}]$: Sheet silicate structures are those in which each tetrahedron shares three of its oxygen atoms with adjacent tetrahedra to build stacked sheets of tetrahedra. Cations may be present in the interlayered tetrahedral sheets (Fig. 5.4a). The ratio of oxygen to silica is 2.5:1. The micas and clay minerals are the most abundant sheet silicates. The minerals with sheet structures can be separated into extremely thin sheets.
6. **Tectosilicates** or **framework silicates** $[(SiO_2)^0]$: Three dimensional framework form when each tetrahedra shares all its oxygens with other tetrahedra (Fig. 5.4b). In this silicate structure, the ratio of oxygen to silica is 2:1. This is the most important groups and includes minerals of feldspars, quartz, the feldspathoids and the zeolite group.

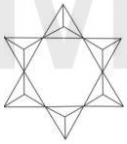
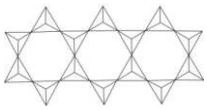
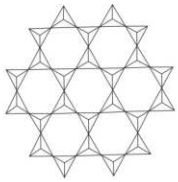
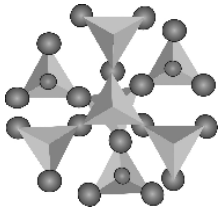


(a) (b)

Fig. 5.4: Crystal structures: a) phyllosilicate minerals; and b) tectosilicate minerals.

A summary of the structural classification of silicates is given in Table 5.3.

Table 5.3: Summary of the structural classification of silicates.

Structure class	Structure type	Formula	Oxygen to silica ratio	Illustration	Example
Nesosilicates or **orthosilicates** or **island silicates**	Independent/ Isolated tetrahedral group	$(SiO_4)^{-4}$	4:1		olivine group, garnet group, zircon,
Sorosilicates	Double Tetrahedral group	$(Si_2O_7)^{-6}$	2:7 or 3.5:1		epidote group, melilite group
Cyclosilicates or **ring silicates**	Closed ring structure	$(Si_6O_{18})^{-12}$ or $(Si_3O_9)^{-6}$	3:1		benitoite, axinite, beryl
Inosilicates or Chain silicate	Single Chain	$(SiO_3)^{-2}$	3:1		pyroxene group
	Double Chain	$(Si_4O_{11})^{-6}$	2.75:1		amphibole group
Phyllosilicates or Sheet silicate	Sheet	$(Si_2O_5)^{-2}$	2.5:1		micas and clay minerals
Tectosilicates or Framework silicate	Framework	$(SiO_2)^0$	2:1		feldspars, quartz, feldspathoids, zeolite group

We shall now discuss about classification of rock forming minerals groups.

5.5 ROCK-FORMING MINERALS

We have learnt about chemical and structural classification of minerals. As we have learnt that there are more than 5530 minerals but only about 25 minerals are the most common minerals and most abundant on the Earth's crust. We shall now learn here about the common rock forming minerals.

As the name suggests, rock-forming minerals are the minerals which form bulk of the crustal rocks. In other words, they are the major components of commonly occurring crustal rocks. Different types of rocks have their own characteristic rock-forming minerals. Some of these minerals which form the essential components of the rock are called essential minerals and the other minerals which are present in trivial amount are called as accessory minerals. Accessory minerals may or may not be present in the rocks. The native elements and halides are not found as commonly as rock forming minerals. The most common rock-forming minerals are the silicate group of minerals.

Silicate minerals are the most important rock-forming minerals and are considered as building blocks of the common rock-forming minerals. According to an estimate about 27% of all known minerals and about 40% of common rock forming minerals are silicates. Silicate minerals make up ~ 90% of rocks in the Earth's crust. Besides the silicate group of minerals, the carbonates, oxides, sulfides and sulfates are also common rock-forming minerals.

As discussed earlier, silicates are the most abundant minerals in Earth's crust and are composed of oxygen and silicon elements in combinations with the cations of other elements.

The silicate minerals can be further subdivided in terms of their composition. In general, light coloured silicate minerals such as quartz, muscovite mica and feldspar are devoid of iron (Fe) and magnesium (Mg), hence we call such silicate minerals as "non-ferromagnesian silicates" whereas, the other silicate minerals and mineral groups such as olivine, pyroxene, amphibole and biotite mica are enriched in iron (Fe) and/or magnesium (Mg), which are called "ferromagnesian silicates".

The common rock-forming silicate mineral groups are listed here:

- Olivine group
- Garnet group
- Pyroxene group
- Amphibole group
- Mica group
- Feldspar group
- Feldspathoids and
- Silica group

Of the above lists of rock-forming minerals groups such as olivine, pyroxene, amphibole, mica, feldspar, feldspathoid and quartz are the important component of igneous rocks. Carbonate minerals such as calcite and dolomite and other minerals such as anhydrite and clay minerals are the important

component of sedimentary rocks. Garnet and other rock forming minerals such as kyanite, andalusite, sillimanite, staurolite, chlorite, serpentine, wollastonite and glaucophane form important component of metamorphic rocks. There are other accessory rock-forming minerals such as zircon, apatite, magnetite, ilmenite, sphene, fluorite and a few sulphide minerals, however in this unit we shall restrict ourselves to the above listed common rock forming silicate and carbonate minerals only.

The silicate minerals we shall discuss later will be from the groups Saehan quartz/ silica (quartz), feldspar (orthoclase, microcline, plagioclase), mica (muscovite, biotite), pyroxene (augite, hypersthene), amphibole (hornblende), feldspathoid (nepheline), olivine and garnet. The calcite is the common rock-forming mineral from carbonate group. We shall discuss about it in the following subsections:

5.5.1 Olivine Group

Olivine is the name of a group of common rock-forming minerals. It mostly occurs in dark-coloured mafic and ultramafic igneous rocks. It is a magnesium iron silicate with the following chemical composition:

$(XY)_2SiO_4$

where,

X is Fe, and

Y is Mg

Olivine is usually green in colour and have compositions that ranges between Mg_2SiO_4 (Fosterite - Mg rich) and Fe_2SiO_4 (Fayalite - Fe rich). The ratio of magnesium and iron varies between the two end members of olivine group. Olivine is not a separate mineral and the term is used instead of "forsterite" or "fayalite".

5.5.2 Garnet Group

Minerals of garnet group are generally used as gemstones and abrasives. Garnet has the following generalised chemical composition:

$X_3Y_2(SiO_4)_3$

where,

X can be Ca, Mg, Fe^{2+} or Mn^{2+}, and

Y can be Al, Fe^{3+}, Mn^{3+}, V^{3+} or Cr^{3+}.

There are two subgroups of garnets: pyralspites and ugrandites. Pyralspites (pyrope, almandine, spessartine) are reddish brown and occur in aluminium-rich metamorphic rocks or igneous rocks. Ugrandites (uvarovite, grossular, andradite) are brownish-black and occur mostly in calc-silicate rocks.

5.5.3 Pyroxene Group

Pyroxene group of minerals are the most significant and abundant group of rock-forming ferromagnesian silicates. They are found in almost every varieties of igneous and metamorphic rocks. Pyroxene crystallises in both the

orthorhombic and monoclinic crystal systems and generally occur as stubby prismatic crystals. They are chemically analogous to the amphibole group minerals except that the hydroxyl group is absent in the pyroxene structure. Due to the absence of hydroxyls, pyroxene group of minerals have slightly higher densities otherwise they have physical properties similar to amphiboles.

The chemical composition of minerals of the pyroxene group has the following general formula:

XYZ_2O_6

where,

X= Na^+, Ca^{2+}, Mn^{2+}, Fe^{2+}, Mg^{2+}, Li^+;

Y= Mn^{2+}, Fe^{2+}, Mg^{2+}, Fe^{3+}, Al^{3+}, Cr^{3+}, Ti^{4+}; and

Z= Si^{4+}, Al^{3+}.

The range of possible chemical substitutions in pyroxene is constrained by the sizes of the available sites in the structure and the charge of the substituting cations. The most common pyroxene mineral is **augite**. Augite is generally dark green to black in colour and forms short, stubby crystals.

5.5.4 Amphibole Group

Amphiboles are common minerals in metamorphic rocks (amphibolite, glaucophane schist) and some igneous rocks (especially diorite). Amphiboles are hydrous minerals, therefore, amphiboles are not stable in anhydrous and high-temperature conditions where they tend to transform to pyroxenes. The F and Cl get substituted for (OH). There are three main groups of amphiboles: (a) Ca-poor (Ca+Na=~0), (b) Ca-rich (Ca>Na), and (c) the alkali amphiboles. The most common amphibole is **hornblende**. Hornblende, the calcium rich amphibole (Ca>Na), is quite similar to augite. Both are dark minerals; however, hornblende crystals are generally longer, thinner and shinier than the augite. While basal sections of pyroxenes are eight sided and square shaped, that of amphiboles are six-sided and diamond shaped. Some examples of minerals of this group are tremolite, actinolite, asbestos, etc.

The chemical composition of minerals of the amphibole group has the following general formula:

$AX_2Y_5Z_8O_{22}(OH,F)_2$

where,

A = Na (often no Na in Ca-rich); Na or K (in alkali amphiboles)

X = Mg or Fe^{2+} (in Ca-poor); Ca (in Ca-rich); Na (or Na and Ca), (in alkali amphiboles)

Y = Mg, Fe^{2+}, Fe^{3+}, Al, etc. (in Ca poor); MG, Fe, Al, etc. (in Ca-rich and alkali amphiboles); and

Z = Si or Al.

They occur in metamorphic rocks derived from mafic igneous rocks with dark-coloured ferromagnesian minerals. They are important constituents in a variety of plutonic and volcanic igneous rocks ranging in composition from

granitic to gabbroic. Amphiboles decompose to anhydrous minerals (mainly pyroxenes) at elevated temperatures.

5.5.5 Mica Group

Micas comprise about 4% of the crust. Mica is easily distinguished by its characteristic of peeling into many thin flat smooth sheets or flakes. This is similar to the cleavage in feldspar except that in the case of mica the cleavage planes are in only one direction and no right angle face joins occur.

General formula for the mica group of minerals is given here:

$X_2Y_{4-6}Z_8O_{20}(OH,F)_4$

where,

X= K or Na

Y= Mg, Fe^{2+}, Fe^{3+} or Al, and

Z= Si or Al

Mica may be white and pearly (**muscovite**) or dark and shiny (**biotite**). Muscovite is a very common mica found in many rock types having chemical composition $KAl_2(AlSi_3O_{10})(OH)_2$.

5.5.6 Feldspar Group

Feldspar is the most abundant minerals in the crust. It is a common, light-coloured rock-forming mineral. Instead of being glassy like quartz, it is generally dull to opaque with a porcelain-like appearance. Colour varies from red, pink, and white (**orthoclase**) to green, grey and white (**plagioclase**). Feldspar is also hard but can be scratched by quartz. In igneous rocks, feldspar forms well developed crystals which are roughly rectangular in shape, and they cleave or break along flat faces. Feldspar grains, in contrast to quartz, often have straight edges and flat rectangular faces. Some of the faces and edges meet at right angles.

There are two subgroups: alkali feldspars and plagioclase feldspars. Alkali feldspars is usually potassium-rich. Hence, they are often named K-feldspars (orthoclase, microcline, and sanidine belongs to this group). Plagioclase feldspar forms a solid solution between Na- and Ca-rich end-members.

5.5.7 Feldspathoid Group

Feldspathoid minerals have certain similarities with the feldspars usually in terms of their chemistry and structure. They usually form (instead of feldspars) when enough silica is not available. Feldspathoids are relatively rare minerals in comparison to feldspars. Some of the members belonging to this group are nepheline, kalsilite, leucite, sodalite, etc.

5.5.8 Silica Group

Minerals that belong to this group share the same chemical composition i.e. SiO_2. The most important mineral in this group is quartz. Quartz is a glassy looking, transparent or translucent mineral which varies in colour from white and grey to smoky. When there are individual crystals they are generally clear,

while in larger masses quartz looks milky white. Quartz is hard - it can easily scratch a steel knife blade. In many rocks, quartz grains are irregular in shape because crystal faces are rare and quartz does not have a cleavage.
(i.e., it does not break on regular flat surfaces)

5.5.9 Carbonate

Carbonates are an important group of minerals that are most widespread in sedimentary environments, evaporite deposits, and hydrothermal veins. These are environments where carbon dioxide is generally available to form the fundamental building block of carbonate minerals - the carbonate ion. Calcite is a very common mineral, especially in sedimentary environments. Dolomite occurs mostly in rocks which were originally limestone formations $CaMg(CO_3)_2$.

The common rock-forming mineral groups with their idealised formula and silicate structure is summarised in Table 5.4.

Table 5.4: Summary of the common rock forming mineral groups.

Mineral Group		Formula	Number of cleavage plane	Silicate Structure
Olivine		$(Mg, Fe)_2 SiO_4$	Absent	Nesosilicate
Garnet		$(CA,Mg,Fe, or Mn)_3 (Fe,Mn,V or Cr)_2 (SiO_4)_3$	Absent	Nesosilicate
Pyroxene (Augite)		$(Ca, Na) (Mg, Fe, Al) (Si, Al)_2 O_6$	2 at 87º and 93º	Inosilicate-single chain
Amphibole (Hornblende)		$(Na or K) (Mg,Fe,Ca,Na,)_2 (Mg,Fe,Al)_5 (Si or Al)_8 O_{22} (OH, F)_2$	2 at 60º and 120º	Inosilicate-double chain
Mica	Biotite	$K(Mg,Fe)_{2-3} Al_{1-2} Si_{2-3} O_{10} (OH,F)_2$	1	Phylosilicate
	Muscovite	$KAl_2 (AlSi_3O_{10}) (OH)_2$	1	Phylosilicate
Feldspars	Orthoclase	$KAlSi_3O_8$	2 at 90º	Tectosilicate
	Plagioclase	$NaAlSi_3O_8$ to $CaAl_2Si_2O_8$	2 at 90º	
Feldspathoids (Nephelene)		$Na_3KAl_4Si_4O_{16}$	3	Tectosilicate
Silica (Quartz)		SiO_2	Absent	Tectosilicate

Minerals belonging to these rock-forming mineral groups are discussed in detail in the Units 6 and 7 in which we shall also learn physical properties of those minerals.

Let us spend 5 minutes to check our progress.

SAQ 2

a) What is the structural classification of silicates?

b) What is SiO_4 tetrahedron?

c) List the classes of silicate minerals identified based on the structures of silica tetrahedra.

Watch this video to know more about minerals

- **Microscopic Study of Basaltic Rocks**

  Link: https://www.youtube.com/watch?v=2RGL3XB2x3E&t=2s

5.6 SUMMARY

Let us now summarise what we have learnt in this unit.

In this unit, we have learnt that

- on the basis of chemical composition, minerals are divided into eight basic classes i.e. native elements, silicates, oxides, sulfides, sulfates, halides, carbonates and phosphates
- on the basis of structure, silicates are classified into nesosilicates, sorosilicates, cyclosilicates, inosilicates, phyllosilicates and tectosilicates
- the common rock-forming mineral groups are olivine, garnet, pyroxene, amphibole, mica, feldspar, feldspathoid and silica.

5.7 TERMINAL QUESTIONS

1. How has the classification of minerals developed with time?
2. Discuss the chemical classes of minerals.
3. Discuss the types of silicate structures.
4. What are the common rock forming minerals?

Audio/video material based question

- What are the rock forming minerals of basalt?
- What are accessory minerals?

5.8 REFERENCES

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5.9 FURTHER/SUGGESTED READINGS

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5.10 ANSWERS

Self Assessment Questions

1 a) Minerals have been classified on the basis of physical properties, chemical properties, chemical composition, and internal crystal structure.

b) Different mineral classification schemes are: physical, hybrid (Physical-chemical), chemical, hybrid (Chemical-structural), and structural classification scheme.

c) The eight chemical class (/mineral groups) identified based on their chemical composition are: native elements, sulfides, oxides, halides, sulfates, carbonates, phosphates and silicates.

2 a) With developments in crystal structure analysis, minerals were classified based on crystal structure because it controls physical and chemical properties of minerals and also their paragenesis. Common example is the classification of silicate minerals based on silicate structures.

b) SiO_4 tetradedron is the four sided pyramidal form which is the basic unit of silicate structure.

c) The six types of silicate structures identified are: nesosilicates or orthosilicates or island silicates, sorosilicates, cyclosilicates or ring silicates, inosilicates (both single and double chain), phyllosilicates and tectosilicates.

Terminal Questions

1. Your answer should include the points discussed under the section 5.2 including the schemes from Berzelian and Dana systems to Strunz classification and Nickel-Strunz classification.

2. Your answer should include the points discussed in section 5.3 and summarised in the Table 5.2.
3. Your answer should include the six types of structures discussed in section 5.4 and summarised in the Table 5.3.
4. Your answer should include the mineral groups discussed in section 5.5 and summarised in the Table 5.4.

UNIT 6

ROCK-FORMING MINERALS-I

Structure

6.1 INTRODUCTION

We have learnt about minerals, their physical properties and classification in Units 4 and 5 of this block. Now in this unit we shall discuss about physical properties of common rock-forming minerals. Minerals form essential component of our daily life. Let us realise it after following this example. We begin use of minerals right from the morning with the ringing of alarm, washing our face, brushing our teeth, getting dressed and eating breakfast. Now, we hope you have realised that you have used dozens of minerals with the beginning of the day. Mostly, everything we are using throughout day is associated with minerals. Minerals are utilised in manufacturing products we use, in the construction of our buildings, homes, roads, machines and industries. They are used as fertilisers in growing crops, producing energy for our homes and offices, adding flavour to our foods and constitute important ingredient of many medicines. In the United States alone, each individual (including children) uses about 10 tons of minerals and rocks per year (Fletcher, 2011).

Human beings have learnt the use of minerals since the Stone Age. They gradually evolved new and different ways to use minerals and Earth materials to improve their living conditions. Therefore, identification of minerals is crucial and critical part of mineralogy. Each mineral has a specific name. The names of the minerals are derived from Latin, Greek, German or English. Some of the minerals are named after the diagnostic properties they possess, e.g. olivine is named after its olive green colour. Others may be named after their discoverer or in honour of a famous person, e.g. mineral sillimanite is named in honour of a famous nineteenth century mineralogist Benjamin Silliman. Some minerals indicate the place where the mineral was first discovered, e.g. illite was first identified in rocks from Illinois. The minerals are also named after the element they contain like mineral chromite contains chromium.

The physical properties of minerals you have studied in Unit 4 will be used to describe physical properties of common rock-forming minerals in this and the next units, i.e. Unit 6 and Unit 7.

Expected Learning Outcomes

After reading this unit you should be able to:

- list the common rock-forming minerals; and
- identify them on the basis of their physical properties.

6.2 ROCK-FORMING MINERALS

Let us learn about rock-forming minerals.

Rock-forming minerals are essential components of rocks, commonly occurring in the Earth's crust. About 25 minerals are usually considered to play an important role in the composition of the crustal rocks. About 96 percent of the minerals found in the Earth’s crust are silicates. They are regarded as building blocks of the common rock-forming minerals. Silicate minerals are essentially composed of silicon and oxygen and usually one or more other elements. Each group of rocks characteristically has its own rock- forming minerals. Let us discuss.

- Magmatic or igneous rocks, formed from the cooling and crystallisation of the magma. The common rock- forming minerals found in these rocks are quartz, feldspars, augite, hornblende, muscovite, biotite, olivine and feldspathoids.
- Sedimentary rocks are formed by disintegration and decomposition of the pre-existing rocks- igneous, metamorphic or even earlier formed sedimentary rocks. The common rock-forming minerals found in these rocks are quartz, feldspar, muscovite, calcite, dolomite, anhydrite and clay minerals.
- Metamorphic rocks are formed when a pre-existing rock or protolith; undergoes a solid-state change in response to the modification of its environment, i.e. temperature and/or pressure). These rocks comprise minerals like kyanite, andalusite, sillimanite, staurolite, chlorite, serpentine, garnet, wollastonite and glaucophane.

Accessory rock-forming minerals include zircon, apatite, magnetite, ilmenite, sphene, fluorite and a few sulphide minerals. Now, let us discuss about physical properties of common rock forming silicate minerals like muscovite, biotite, augite, hypersthene, olivine, garnet, hornblende and kyanite.

6.3 DIAGNOSTIC PROPERTIES OF MINERALS

We have learnt about various physical properties such as colour, streak, lustre, hardness, specific gravity, crystal habit, cleavage, and fracture used in the identification of minerals in unit 4 Minerals. About 5530 plus minerals have been discovered so far. Out of which only a few hundred are considered to be common. About 50 to 100 new minerals are reported every year. Mineralogists are the people with specialisation in the study of minerals. Each mineral possesses distinguishing or diagnostic physical properties that can be used to identify the minerals. The mineralogists' make use of the diagnostic physical properties of minerals for their identification. We shall learn to use diagnostic properties to identify minerals. In this unit, we will develop a systematic approach in making use of the physical properties of minerals as identifying tools. This approach shall enable us in identifying most of the common minerals or at the least narrow down the possibilities.

Each mineral has peculiar diagnostic property which helps us to distinguish it from others. For example, diagnostic property of muscovite is its transparency, lamellar form and pearly lustre. Therefore, these physical properties will be very important in identification of muscovite. We must remember that mineral identification is a skill which improves rapidly with repetition, practice and experience. We should wisely and systematically follow the process of identification and should not try to memorise them The reason is that the same mineral can exhibit different colours and different minerals can show same colour. Secondly, we should not find the name of the mineral first and then identify its properties. Remember! this is not the right way of mineral identification. Rather we should concentrate on determining the diagnostic properties of the minerals. We should use physical properties of minerals for guidance and identification, using tables and determine the mineral name.

6.4 MUSCOVITE

We have discussed in unit 5 that muscovite and biotite are the two important minerals of mica group. Muscovite belongs to sheet silicates or phyllosilicates and crystallises in monoclinic system. It characteristically posses a brilliant shine that glitters and sparkles. It is the most common mineral of the mica group and is also known as K-rich mica or common mica. In the 1700s muscovite was mined from pegmatites in the area around Moscow, Russia. It has the ability to split into thin transparent sheets which are sometimes up to several feet across. Therefore, during the medieval period muscovite was used as window panes (as a cheaper alternative to glass in windows). These panes were called 'muscovy glass' in England and mineral got its name as "muscovite". The earliest names given to muscovite were- Muscovy Glass, Cat Silver and Lapis Specularis (stone mirror). The name 'Muscovite' was used by Johann Gottfried Schmeisser in 1794 in his book titled "System of Mineralogy".

Muscovite is easily identified because of its perfect one set of cleavages which allows it to split into thin, flexible, elastic, colourless, transparent sheets with a pearly lustre. It readily cleaves into thin transparent sheets. Muscovite has pearly to vitreous lustre. If muscovite is held in the light it can be seen as transparent and nearly colourless, but mostly have a slight brown, yellow, green or rose-colour tint.

Fig. 6.1: Notice the pearly lustre of muscovite.

Let us summarise physical properties of the muscovite in Table 6.1.

Table 6.1 Physical properties of muscovite.

Physical property	**Description**
Silicate structure	Phyllosilicate
Colour	Thick specimens often appear as black, brown or silver in colour; however, when split into thin sheets muscovite is colourless, sometimes with a tint of brown, yellow, green
Transparency	Transparent to translucent when held up in bright light
Streak	Colourless or white often sheds tiny flakes
Lustre	Pearly
Hardness	2.5 to 3
Specific gravity	2.8 to 2.9
Form and habit	Occurs typically in lamellar masses or small flakes/ foliated. Crystals are commonly tabular. Also occurs in granular and massive form.
Cleavage	One set of perfect cleavages. Thin cleavage flakes are elastic or flexible
Fracture	Conchoidal to uneven
Crystal system	Monoclinic
Chemical composition	$KAl_2(Si_3AlO_{10})(OH)_2$
Diagnostic properties	Colourless, brown or silver; one direction cleavage; sheet like form; pearly lustre

Occurrence: Muscovite mineral has a magmatic origin. It is common in felsic rocks like granite, granodiorite and pegmatites. In pegmatite muscovite is often found in large crystals with a pseudohexagonal outline. These crystals

are called "books" because they can be split into paper-thin sheets. Muscovite rarely occurs in igneous rocks of intermediate, mafic and ultramafic composition. Muscovite forms during the metamorphism of argillaceous rocks. It also occurs in phyllite, mica schist or micaceous gneiss. Tiny flakes of muscovite sometimes survive long enough to be incorporated into sediments and immature sedimentary rocks.

Uses: Due to its high dielectric and heat-resisting properties, sheet mica is used as an insulating material in the manufacture of electrical apparatus. Ground mica is used in paint as lubricant and plastic industry. Ground mica is used in the manufacture of molded rubber products such as tyres and as refractory roofing material. The pearly lustre of ground mica makes it an important ingredient in the cosmetic products. Sheet structure of muscovite makes it an excellent insulator that makes it suitable for manufacturing specialised parts for electrical equipment.

6.5 BIOTITE

We have read that the biotite is a phyllosilicate or sheet silicate, belonging to mica group in unit 5. It is black in colour also known as black mica. Silicate of Fe, Al and Mg with OH group as ligand form sheets in biotite that are weakly bound together by potassium ions. Biotite mineral is named in honour of Jean Baptiste Biot (1774-1862), a French physicist, mathematician, and astronomer who carried extensive research on the optical properties of mica minerals.

A generalised chemical composition of biotite is:

$K(Mg,Fe)_{2-3}Al_{1-2}Si_{2-3}O_{10}(OH,F)_2$

Biotite is very easy to identify. As discussed above, it is black mica with perfect cleavage and a pearly lustre on the cleavage faces. When biotite is separated into thin sheets, the sheets are flexible, but, break upon severe bending. When held up to the light the sheets are transparent to translucent with a brown, gray or greenish colour.

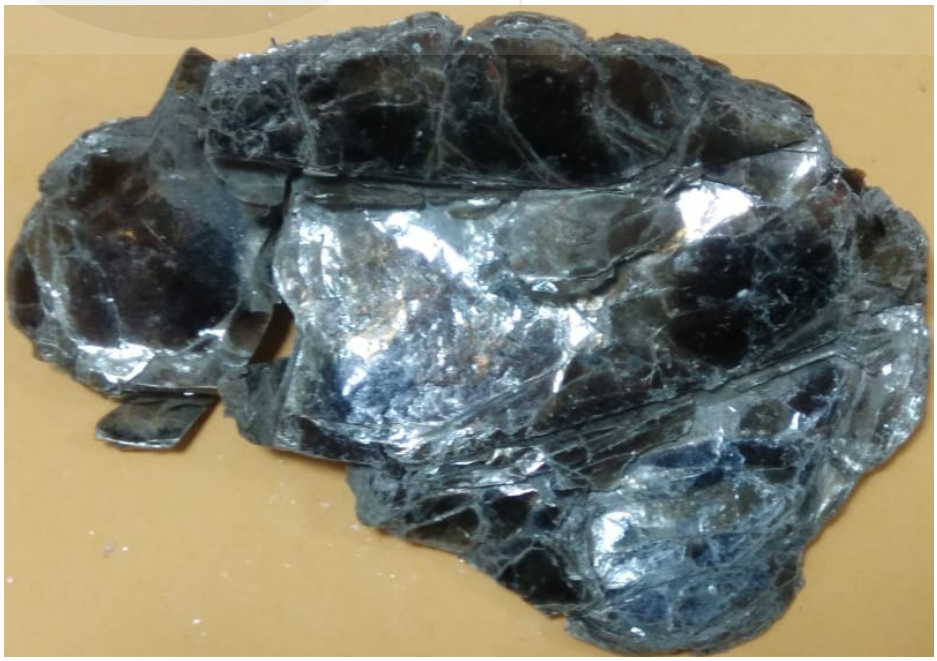


Fig. 6.2: Hand specimen of biotite.

Let us summarise physical properties of biotite in Table 6.2.

Table 6.2 Physical properties of biotite.

Physical property	Description
Silicate structure	Phyllosilicate
Colour	Black, dark green, dark brown
Transparency	Thin sheets are transparent to translucent, books are opaque
Streak	Colourless or white sometimes greyish, flakes often produced
Lustre	Splendent
Hardness	2.5 to 3
Specific gravity	2.7 to 3.4
Cleavage	One set perfect cleavage. Thin cleavage flakes are both elastic or flexible
Fracture	Conchoidal to uneven
Crystal system	Monoclinic
Chemical composition	$K(Mg,Fe)_{2-3}Al_{1-2}Si_{2-3}O_{10}(OH,F)_2$
Diagnostic properties	Dark colour; one set of cleavages; lamellar form; splendid lustre
Special property	Thin cleavage flakes may exhibit asterism

Occurrence: Biotite is found in a variety of geological environments; igneous rocks (i.e. granite, pegmatite, lamprophyre, etc.) metamorphic rocks (i.e. biotite schist, gneiss) and sedimentary rocks (clastic rocks particularly arenaceous rocks). As it is not very resistant to weathering, thus, transforms into clay minerals. It is sometimes found in sediments and sandstones.

Uses: Biotite has limited commercial uses as compared to muscovite. Ground mica is used as filler and extender in paints, as an additive to drilling muds, as an inert filler and mold-release agent in rubber products, and as a non-stick surface coating on asphalt shingles and rolled roofing. Biotite is helpful in precise dating of rocks, by either potassium-argon dating or argon-argon dating.

6.6 AUGITE

Augite has a single chain structure of inosilicate. It is a clinopyroxene. It crystallises in monoclinic system. Augite is an important rock-forming mineral, and large crystals are fairly common. It is the most widespread member of the pyroxene group about which you have studied n unit 5..

The name ‘augite’ given by Abraham G. Werner in 1792 is derived from the Greek word ‘*augites*’ meaning "brightness", which is in reference to its bright lustre along the cleavage. The transparent variety of augite with dendritic patterns is known as *shajar*. Augite usually occurs as large

lustrous crystals. The composition of augite is silicate of calcium, sodium, magnesium, iron, and aluminum.

Augite is dark green, brown or brown black in colour. It has hardness 5-6. It typically occurs as prismatic and stubby crystals (Fig. 6.3). It has two distinctive planes of cleavages with intersecting angles at 87° and 93°.

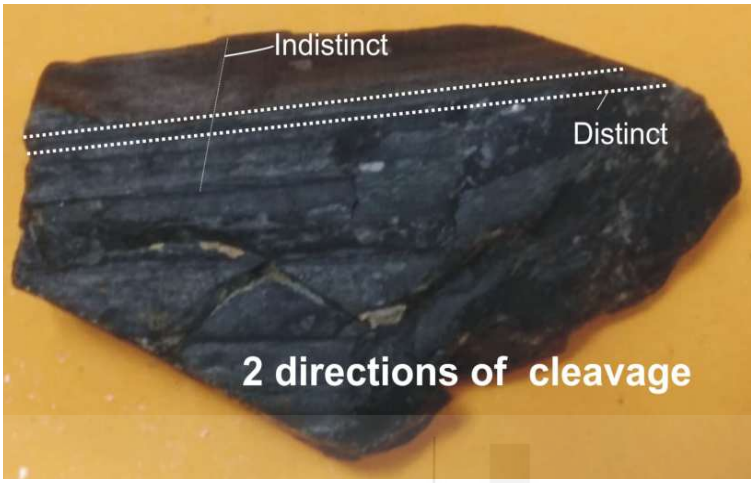


Fig. 6.3: Augite mineral in hand specimen.

Let us summarise physical properties of augite in Table 6.3.

Table 6.3 Physical properties of augite.

Physical property	Description
Silicate structure	Inosilicate (single chain)
Colour	Green, grayish-green, greenish brown, dark brown, black
Transparency	Translucent to opaque in thin section
Streak	Light green to colourless
Lustre	Vitreous
Hardness	5 to 6
Specific gravity	3.2-3.3
Form and habit	Occurs as prismatic crystals with a rectangular or octagonal cross section. Stubby crystals with a flattened pyramidal termination also common. Other forms are columnar, granular, massive, lamellar, fibrous, and disordered aggregates of rectangular crystals. Prismatic crystals show square or eight sided cross section.
Cleavage	Two sets of perfect prismatic cleavages at angles of 87º and 93º (characteristic of minerals in the pyroxene group). Partings also common
Fracture	Uneven to splintery
Crystal system	Monoclinic
Chemical composition	(Ca, Na) (Mg, Fe, Al) $(Si, Al)_2 O_6$
Diagnostic properties	Prismatic form; dark colour; two sets of cleavage with cleavage angle 87º and 93º

Occurrence: Augite is important rock forming mineral found in ultramafic igneous rocks such as peridotite and harzburgite and mafic igneous rocks like basalt, gabbro, etc. It can appear in diorite, granodiorite and andesites. Iron-rich compositions can also appear in syenite and alkali granite. In metamorphic rocks augite is present in amphibolite, hornblende gneiss, granulite. Augite weathers very fast, seldom it occurs in sedimentary rocks as heavy mineral.

Uses: *Shajar* variety of augite is used as gems and ornamental stones. Banda city in Uttar Pradesh state is noted for trade of *shajar* stone.

6.7 HYPERSTHENE

Hypersthene is also a common rock-forming inosilicate mineral of pyroxene group. It is an important iron rich orthopyroxene crystallizing in orthorhombic system. The name hypersthene comes from Greek words '*hyper*' and '*stenos*' means 'over strength' or 'above power' because of its greater hardness than amphibole.

Hypersthene is often blackish brown, greenish black or reddish in colour, waxy to sub metallic lustre and hardness ranges from 5 to 6. It commonly occurs as prismatic, columnar, tabular or richly faceted crystal. Hypersthene displays a typical characteristic of 'schillerisation' meaning display of colour in natural light. The chemical formula of hypersthene is $(Mg,Fe)_2Si_2O_6$.

Fig. 6.4: Hypersthene in hand specimen (source: www.esci.umn.edu/courses/1001/minerals/images/pyroxene.jpg)

Occurrence: Hypersthene is commonly found in both plutonic (hypersthene gabbro) and volcanic (andesite) rocks and also in metamorphosed igneous rocks. It is also an important constituent of ultramafic rocks like pyroxenites and harzburgite. Hypersthene is also found in stony meteorites.

Uses: Hypersthene is collected by gemstone collectors and faceted into gems.

Let us summarise physical properties of hypersthene in Table 6.4.

Table 6.4 Physical properties of hypersthenes.

Physical property	Description
Silicate structure	Inosilicate (single chain)
Colour	Gray, green, dark yellow, yellow-brown, greenish-brown, brown, black
Transparency	Translucent to opaque in thin section
Streak	Light brown to grayish-white
Lustre	Waxy, sub metallic
Hardness	5 - 6
Specific gravity	3.2-3.3
Form and habit	Occurs as aggregates of rectangular crystals, as single prismatic and stubby crystals
Cleavage	Two set of perfect prismatic at cleavages angles of 87º and 93º (characteristic of minerals in pyroxene group). Partings also common
Fracture	Uneven, brittle
Crystal system	Orthorhombic
Chemical composition	$(Mg,Fe)Si_2O_6$
Diagnostic properties	Prismatic form; two sets of cleavages with angle of 87º and 93º; dark colour; waxy or submetallic lustre
Special property	Schillerisation is characteristic of hypersthene

We have discussed rock-forming minerals like olivine, garnet, augite and hypersthene. Before proceeding further, spend five minutes to check your progress.

SAQ 1

a) List the common rock-forming minerals in igneous, sedimentary and metamorphic rocks.

b) Mention diagnostic physical properties of muscovite and biotite.

c) Mention diagnostic physical properties of augite.

d) What is the lustre of hypersthenes?

6.8 HORNBLENDE

We have discussed the physical properties of single chain inosilicates like augite and hypersthene. Now, let us learn about physical properties of hornblende.

Hornblende has a double chain inosilicate structure belonging to amphibole group and crystallises in the monoclinic system. It is named after the German word *horn*, referring to its colour, and *blenden*, meaning 'deceiver', referring to its habit of being confused with ore metals due to its dark colour and lustre. Its typical dark coloured and opacity are usually caused by iron in its structure.

Hornblende is a mixture of calcium-iron-magnesium silicate, aluminium-iron-magnesium silicate, and an iron-magnesium silicate.

The general formula can be given as:

$(Ca,Na)_{2-3}(Mg,Fe,Al)_5(Al,Si)_8O_{22}(OH,F)_2$.

Thus, it is a complex basic silicate of sodium, calcium, magnesium, and aluminum. The crystals are commonly prismatic and elongated, but, sometimes occur as fibrous or acicular. The hardness is 5-6. The typical two sets of perfect prismatic cleavages at angles of 124º and 56º is present in hornblende.

Fig. 6.5 Notice prismatic form of hornblende in hand specimen.

Occurrence: Hornblende is an important and widely distributed rock-forming mineral. It occurs in igneous (granite, syenite, diorite, gabbro, basalt, andesite) and metamorphic rocks (gneiss, and schist). Hornblende mineral forms black streaks in granite. Hornblende even constitutes its own monomineralic rock type known as hornblendite (dark rock formed mostly from hornblende).

Uses: Hornblende is usually found as a gangue material, especially when it is confused with ore minerals due to its shiny lustre. Good crystals are rarely found in nature.

Let us summarise physical properties of hornblende in Table 6.5.

Table 6.5 Physical properties of hornblende.

Physical property	Description
Silicate structure	Inosilicate (double chain)
Colour	Black, dark green, dark brown, dark gray
Transparency	Opaque may be slightly translucent on thin cross-sections under strong back-lighting
Streak	Pale green
Lustre	Vitreous, submetallic, dull
Hardness	5 to 6
Specific gravity	2.9 - 3.4
Form and habit	Occurs as prismatic or tabular crystals with a diamond-shape in cross-sections. Also as dense groups of platy or grainy crystals. Sometimes as columnar, radiating, acicular, fibrous and massive. Rarely found as individual crystals.
Cleavage	Two sets of perfect prismatic cleavages at angles of 124º and 56º
Fracture	Uneven, splintery
Crystal system	Monoclinic
Chemical composition	$(Ca\ Na)_{2\text{-}3}\ (Mg\ Fe\ Al)_5\ Si_6\ (Si\ Al)_2\ O_{22}\ (OH)_2$
Diagnostic properties	Dark green brown colour; crystal aggregates; cleavage angle is 124º and 56º

6.9 OLIVINE

Olivine is a nesosilicate and crystallises in orthorhombic system. It is magnesium iron silicate with the chemical composition $(MgFe)_2SiO_4$. Olivine is usually olive green as it is named or yellow green in colour (Fig. 6.1). It occurs as granular masses. It has vitreous lustre and hardness ranging from 6.5-7 depending on varying properties of Mg and Fe.

The earliest name given to olivine was chrysolit (chrysolite) by Johan Gottschalk Wallerius in 1747. Mineral olivine derives its name from its commonly found olive green colour. The name olivine was used either as a mineral or as a group since then. Many people are familiar with translucent green olivine because it is very popular as gemstone known as peridot (péridot, the French word for olivine). The yellowish green transparent olivine is called chrysolite.

Fig. 6.6 Hand specimen of olivine mineral.

Let us summarise physical properties of olivine in Table 6.6.

Table 6.6 Physical properties of olivine

Physical property	Description
Silicate structure	Nesosilicate
Colour	Usually olive green, but can be yellow-green to bright green, iron-rich specimens are brownish-green to brown
Transparency	Transparent to translucent
Streak	Colourless or white gray
Lustre	Vitreous
Hardness	6.5-7
Specific gravity	3.2 - 4.4
Form and habit	Occurs as typically granular masses or sometimes foliated. Crystals are uncommon.
Cleavage	Absent
Fracture	Conchoidal
Crystal system	Orthorhombic
Chemical composition	$(Mg\ Fe)_2\ SiO_4$ Magnesium iron silicate. Olivine ranges from the magnesium end member (fosterite) to the iron end member (fayalite) compositions
Diagnostic properties	Olive green colour, granular form, and cleavage absent
Special property	Soluble in dilute hydrochloric acid

Occurrence: Olivine is a common rock-forming mineral, varying in amount from that of an accessory to that of a main constituent. Olivine mineral is magmatic in origin. It is found principally in Mg-rich igneous rocks, such as in mafic (basalt, gabbro, diabase) and ultramafic igneous rocks (peridotite, harzburgite). Dunite is a monomeralic rock which is entirely (>90%) composed of olivine garins. Olivine is an uncommon mineral in sedimentary rocks because it is easily altered by weathering. Olivine may also occur in meteorites.

Uses: Olivine has several industrial uses, e.g. in bricks and refractory bricks. Mostly olivine is used in metallurgical processes as a slag conditioner. It is

also used as a flux for steel production, and is an important ore of magnesium. The transparent varieties of olivine like peridot and chrysolite are used as gemstone.

6.10 GARNET

You have learnt about garnet group in Unit 5. The name garnet is used for (a) a group of similar minerals and (b) also to a mineral so called in the group. Minerals of garnet group have been used as gemstones and abrasives since the Bronze Age. We will discuss physical properties of garnet. The word 'garnet' is taken from the 14th-century Middle English word gernet, which means 'dark red'. The word 'garnet' is derived from the Latin word *granatus*, which means 'grain, seed') which possibly refers to dark red grains of pomegranate.

Garnet belongs to nesosilicate and crystallises in isometric system.

As discussed above garnet has varying composition, thus, the generalised chemical composition of $A_3B_2(SiO_4)_3$ is given below.

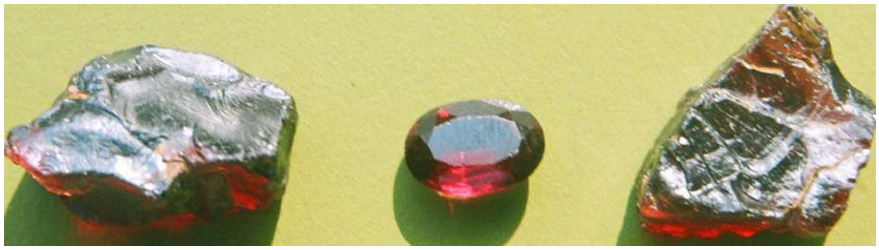
Where,

A can be Ca, Mg, Fe^{2+} or Mn^{2+} and

B can be Al, Fe^{3+}, Mn^{3+}, V^{3+} or Cr^{3+}

Garnet exhibits many colours including red, orange, yellow, green, purple, brown, blue, black, pink and it may be colourless also (Fig. 6.2). Lustre is vitreous to resinous. Its hardness varies from 7-8. Light transmission properties can range from the gemstone-quality, i.e. transparent to the opaque varieties which are used for industrial purposes such as abrasives. Garnet possesses vitreous or resinous lustre.

(a)



(b)

Fig. 6.7: a) Rhombohedral form of garnet; and b) Reddish brown colour natural garnet with its faceted counterparts from Bastar, Chhattisgarh. (Photo credit: Dr. Sandeep Vansutre)

Let us summarise physical properties of garnet in Table 6.7.

Table 6.7 Physical properties of garnet.

Physical property	Description
Silicate structure	Nesosilicate
Colour	Often in red, reddish brown, black, orange and pink colours. Also found colourless, emerald green, white, grey, pink, pale brown and pale green variety
Transparency	Transparent to translucent
Streak	White or gray
Lustre	Vitreous to resinous
Hardness	7-8
Specific gravity	3.6 to 4.5
Form and habit	Typically occurs as perfect crystal of rhombododecahedron form. It occurs as granular masses or sometimes foliated.
Cleavage	Absent
Fracture	Conchoidal to uneven
Crystal system	Isometric
Chemical composition	$A_3B_2(SiO_4)_3$ where, A can be Ca, Mg, Fe^{2+} or Mn^{2+}, B can be Al, Fe^{3+}, Mn^{3+}, V^{3+} or Cr^{3+}
Diagnostic properties	Rhombododecahedron form; reddish brown colour; rhombododecahedron crystal habit; 7-8 hardness; lack of cleavage

Occurrence: Garnet is found both in metamorphic and igneous rocks, formed under high temperatures and pressures conditions. Garnet is used by metamorphic petrologists to measure the temperature and pressure under which a particular garnet-bearing rock is formed. Garnet being resistant to both mechanical and chemical weathering occurs as detrital grains in sedimentary rocks in the heavy mineral fraction. Almandine variety of garnet is common in metamorphic rocks. Garnet minerals like pyrope, uvarovite is usually found in ultrabasic rocks such as kimberlite and peridotite.

Uses: Garnet is used as a gemstone for thousands of years. It has some value as an abrasive because it is fairly hard and breaks down into irregular grains.

We have discussed rock-forming minerals like olivine, garnet, augite and hypersthene. Before proceeding further, spend five minutes to check your progress.

SAQ 2

a) Mention the cleavage angle exhibited by hornblende.

b) Mention the generalised chemical formula of garnet.

c) List the uses of garnet.

d) What is the chemical composition of olivine?

e) Which peculiar type of hardness found in kyanite?

6.11 KYANITE

Kyanite, andalusite, and sillimanite are naturally occurring anhydrous aluminum silicate minerals. All three of them have same chemical formula, Al_2SiO_5, but, differing crystal structures. They are known as polymorphs, i.e exist in different forms. Kyanite is the high pressure polymorph, andalusite is the low pressure polymorph and sillimanite forms at high temperature.

We will learn about kyanite. Kyanite is a member of the aluminosilicate series. It is a nesosilicate. Kyanite is one of the most attractive blue mineral in nature. It is a commonly found in Al-rich metamorphic pegmatites and sedimentary rocks as an accessory mineral.

The mineral kyanite was named by Abraham Gottlieb Werner in 1789. It derives its name from the Greek word *kuanos* also referred to as 'kyanos', as deep blue. Kyanite typically exhibits inky blue colour, often intense shades of blue also seen. Less commonly it is colourless, white, gray, green, orange, or black. Kyanite most often occurs typically as long and slender bladed crystals (Fig. 6.8). It is also found in crystal groups which are radiating, reticulated and flattened tabular crystals. The lustre of kyanite varies from vitreous to greasy.

Kyanite displays as unusual variable hardness which becomes its diagnostic characteristic. It varies depending upon crystallographic direction. It varies from 4.5 to 5 if it is examined parallel to the length of a crystal; 6.5 to 7 if examined across the short dimension of a crystal. Due to the variable hardness of mineral, it is commonly called 'disthene' which means 'two strengths'. Kyanite is also known as rhaeticite and cyanite. The French spelling, '*Cyanite*', was commonly used by mineralogists of the 19th and early 20th centuries.

Colour of the kyanite and its well-developed crystalline structure makes it recognisable for the expert collectors.

Fig. 6.8: Notice the inky blue colour and bladed form of kyanite.

Let us summarise physical properties of kyanite in Table 6.8.

Table 6.8 Physical properties of kyanite.

Physical property	Description
Silicate structure	Nesosilicate
Colour	Commonly light to inky blue, dark blue, indigo-blue, shades of blue and less commonly colourless, white, gray, green, orange, or black
Transparency	Transparent to translucent
Streak	White, colourless
Lustre	Vitreous, greasy
Hardness	Kyanite often occurs in long, bladed crystals having hardness of 4.5 to 5 along the length of the crystals and 6.5 to 7 across the width of the crystals (at right angles).
Specific gravity	3.5 to 3.7
Form and habit	Occurs as long and slender bladed crystals. Also found in crystal groups which can be radiating, reticulated and flattened tabular crystals.
Cleavage	Perfect in two directions, faces sometimes striated
Fracture	Uneven to hackly
Crystal system	Triclinic
Chemical composition	Al_2SiO_5
Diagnostic properties	Blue to indigo colour, hardness 4-7 (variable) two set cleavage, bladed crystals
Special property	Reacts turbulently even in contact with weakly in dilute HCl

Occurrence: Kyanite occurs mainly in metamorphic rocks. It is found in the schists and gneisses. It occurs as detrital grains in heavy mineral fraction in sedimentary rocks.

Uses: Kyanite is used ~~to~~ in the manufacture of ~~a~~ wide range of products, like ceramics, refractory bricks, insulators and abrasives. It is also used in the automotive and railroad industries where heat resistance is important. Kyanite has properties that make it well suited for the manufacture of high refractory-strength porcelain, e.g. white porcelain insulator on a spark plug. It is heat resistant and its hardness makes it an excellent material for use in the manufacture of grinding wheels and cutting wheels. Kyanite is used as gemstone. Petrologists use kyanite as one of the index minerals used to estimate the temperature, depth, and pressure at which a rock has undergone metamorphism.

Table 6.9: Summary of the physical properties of rock-forming minerals

Physical property	Muscovite	Biotite	Augite	Hypersthene	Hornblende	Olivine	Garnet	Kyanite
Colour	Brown or silver	Black, dark green, dark brown	Green, grayish-green, greenish brown, dark brown, black	Gray, green, dark yellow, yellow-brown, greenish-brown, brown, black	Black, dark green, dark brown, dark gray	Usually olive green, but can be yellow-green to bright green	Often in red, red brown, black, orange, pink	Commonly inky blue, indigo-blue, shades of blue
Transparency	Transparent to translucent when held up to bright light	Transparent to translucent	Translucent to opaque in thin section	Translucent to opaque in thin section	Opaque, may be slightly translucent on thin sections	Transparent to translucent	Opaque, gem varieties are transparent	Transparent to translucent
Streak	White often sheds tiny flakes	White to gray, flakes often produced	Light green to colourless	Light brown to grayish-white	Pale green	White or gray	White or gray	White, colourless
Lustre	Pearly	Pearly	Vitreous	Waxy, sub metallic	Vitreous, submetallic	Vitreous	Vitreous to resinous	Vitreous, greasy
Hardness	2.5 to 3	2.5 to 3	5 to 6	5 - 6	5 to 6	6.5-7	7-8	Variable-4.5 to 5 along the length and 6.5 to 7 across the width
Specific gravity	2.8 - 2.9	2.7 - 3.4	3.2-3.3	3.2-3.3	2.9 - 3.4	3.2 - 4.4	3.6 to 4.5	3.5 to 3.7
Form and habit	Lamellar masses or small flakes/ foliated, tabular and massive	Lamellar masses or small flakes/ foliated, tabular and massive	Prismatic, stubby crystals	Aggregates of rectangular crystals, single prismatic	Prismatic, tabular crystal, columnar, radiating, acicular, fibrous and massive.	Crystals are uncommon. It occurs as typically granular masses or sometimes foliated.	Typically occur as perfect crystal, rhombododecahedron form	Bladed crystals, radiating, reticulated and flattened tabular crystals.
Cleavage	One set of perfect cleavage. Thin cleavage flakes are both elastic and flexible	One set of perfect cleavage. Thin cleavage flakes are both elastic or flexible	Two sets of perfect prismatic cleavages at angles of 87º and 93º	Two sets of perfect prismatic cleavages at angles of 87º and 93º	Two sets perfect prismatic cleavages at angles of 124º and 56º	Absent	Absent	Perfect in two sets
Fracture	Conchoidal to uneven	Conchoidal to uneven	Uneven to splintery	Uneven, brittle	Uneven, splintery	Conchoidal	Conchoidal to uneven	Uneven to hackly
Crystal system	Monoclinic	Monoclinic	Monoclinic	Orthorhombic	Monoclinic	Orthorhombic	Isometric	Triclinic
Chemical composition	$KAl_2(Si_3AlO_{10})(OH)_2$	$K(Mg,Fe)_{2-3}Al_{1-2}Si_{2-3}O_{10}(OH,F)_2$	(Ca, Na) (Mg, Fe, Al) $(Si, Al)_2O_6$	$(Mg,Fe)Si_2O$	$(Ca\ Na)_{2-3}(Mg\ Fe\ Al)_5Si_6\ (Si\ Al)_2O_{22}\ (OH)_2$	$(Mg\ Fe)_2SiO_4$	$A_3B_2(SiO_4)_3$	Al_2SiO_5
Diagnostic properties	Colour, cleavage, transparency, sheet like form, lustre	Dark colour, cleavage, transparency, form, lustre	Prismatic form, dark colour, cleavage.	Prismatic form, cleavage, dark colour, lustre	Colour, crystal aggregates, and cleavage angle of amphiboles	Colour, form and cleavage	Form, colour, isometric crystal habit, hardness, lack of cleavage	colour, cleavage, bladed crystals

Watch this video to know more about minerals

- **Microscopic Study of Basaltic Rocks**

  Link: https://www.youtube.com/watch?v=2RGL3XB2x3E&t=2s

6.12 SUMMARY

In this unit we have learnt about megascopic characters of common rock-forming minerals. Let us summarise them now:

- Minerals comprise an important part of our everyday life. Each mineral has a specific name. Some minerals are named after their discoverer or the place of discovery or in honour of a famous person.
- Each mineral has peculiar diagnostic property which helps us to distinguish it from others. We should use physical properties of minerals for guidance and identification using tables and determine the mineral name.
- Rock-forming minerals are essential components of rocks that occur commonly in the Earth's crust. The common rock- forming minerals in magmatic rocks are quartz, feldspars, pyroxenes, amphiboles, micas, olivine and feldspathoids.
- The rock- forming minerals like calcite, dolomite, anhydrite and clay minerals constitute ~~the~~ important component of the sedimentary rocks.
- The metamorphic rocks comprise rock forming minerals like kyanite, andalusite, sillimanite, staurolite, chlorite, serpentine, garnet, wollastonite and glaucophane.
- The physical properties of the rock-forming minerals dealt in this unit have been summarised in Table 6.9. You are advised to refer to these mineral identification tables.

6.13 ACTIVITY

- Make a list of minerals used or consumed by you directly or indirectly in a day. For example, from brushing your teeth and using cosmetics.

6.14 TERMINAL QUESTIONS

1. Discuss physical properties of a clinopyroxene (Cpx) and orthopyroxene (Opx) minerals.
2. Describe physical properties, occurrence and uses of muscovite.
3. Briefly write physical properties of hornblende.
4. Write physical properties of kyanite.

Audio/video material based question

- List the physical properties of rock-forming minerals of basalt?

6.15 REFERENCES

- Fletcher, C. (2011) Physical Geology, The Science of Earth, John Wiley & Sons.
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6.16 FURTHER / SUGGESTED READINGS

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6.17 ANSWERS

Self Assessment Questions

1 a) **Igneous rocks** - quartz, feldspars, augite, hornblende, muscovite, biotite, olivine and feldspathoids.

Sedimentary rocks - quartz. feldspar, muscovite, calcite, dolomite, anhydrite and clay minerals.

Metamorphic rocks - kyanite, andalusite, sillimanite, staurolite, chlorite, serpentine, garnet, wollastonite and glaucophane.

b) Muscovite - brownish transparent colour, one set of perfect cleavages, transparency, sheet like form, pearly to vitreous lustre. Biotite-dark colour, one set of cleavages, transparency, sheet like form, vitreous lustre.

c) Prismatic form, dark colour which may be green of greenish black, two sets of cleavages 87° and 93°.

d) Waxy and sub-metallic.

2 a) Two sets of perfect prismatic cleavages at angles of 124º and 56º .

$A_3B_2(SiO_4)_3$, where, A can be Ca, Mg, Fe^{2+} or Mn^{2+}, and B can be Al, Fe^{3+}, Mn^{3+}, V^{3+} or Cr^{3+}.

b) Garnet is used as an abrasive because it is fairly hard and breaks down into irregular grains. Garnet crystals are crushed to provide garnet 'sand' and good crystals can be cut into attractive gemstones.

c) Magnesium iron silicate $(Mg\ Fe)_2\ SiO_4$. Olivine ranges from magnesium end member to the iron end member.

d) Hardness varies depending upon crystallographic direction. It varies from 4.5 to 5 parallel to the length of a crystal; 6.5 to 7 across the short dimension of a crystal.

Terminal Questions

1. The clinopyroxene (Cpx) mineral is augite, i.e. it crystallises in monoclinic system. Orthopyroxene (Opx) mineral is hypersthene as it crystallises in orthorhombic system. Please refer section 6.6 for augite and 6.7 for hypersthene.
2. Please refer to section 6.4 for muscovite
3. Please refer to section 6.8 for hornblende.
4. Please refer to section 6.11 for kyanite mineral.

UNIT 7

ROCK-FORMING MINERALS-II

Structure

7.1 INTRODUCTION

We have studied physical properties of rock-forming minerals like muscovite, biotite, augite, hypersthene, hornblende, olivine, garnet and kyanite in the previous unit. In this unit, we shall further discuss the physical properties of some other common rock-forming minerals like quartz, feldspar (orthoclase, plagioclase, microcline), nepheline, chlorite, epidote and calcite.

Expected Learning Outcomes

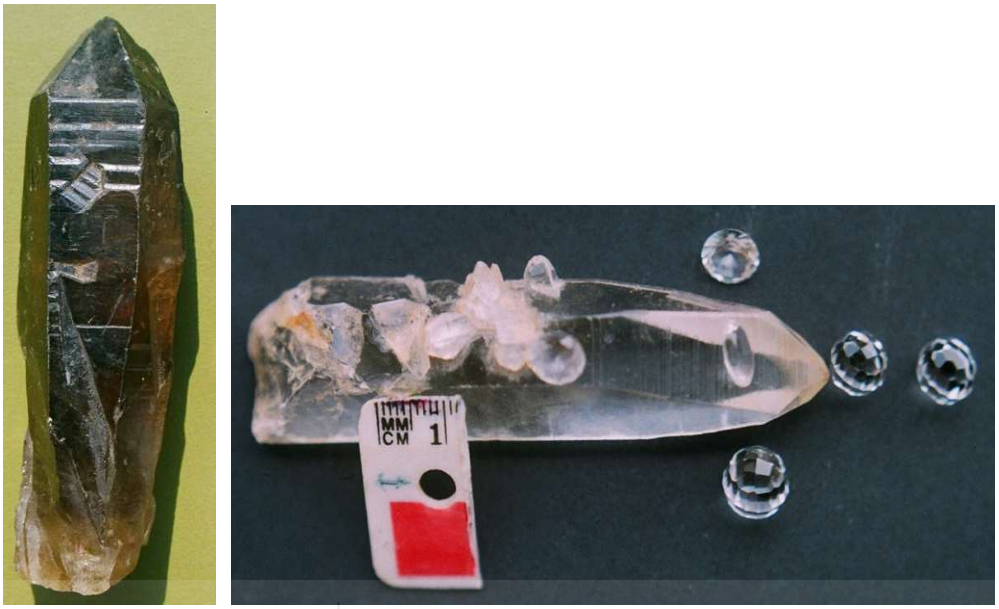
After reading this unit you should be able to:

- list the common rock-forming minerals, and
- identify them on the basis of their physical properties.

7.2 QUARTZ

Quartz is a member of the silica or quartz group having chemical composition of SiO_2. It is the second most abundant mineral on the Earth continental crust after feldspar. Quartz is a tectosilicate and possesses framework silicate structure. It crystallises in the trigonal system.

The root words of ‘quartz’ signify ‘ice cold’ and ‘to contract’ (or solidify) which is derived from Greek word *kritallos* that means permanently solidified ice. The earliest printed use of "quertz" was anonymously published in 1505, but attributed to a physician in Freiberg. Germany, Ulrich Rühlein von Kalbe. By 1530, Agricola used the spelling "quartz" as well as "quertze", but Agricola also referred to "crystallum", "silicum", "silex", and silice".



(a) (b)

Fig. 1: (a) Smoky quartz crystal, notice the striations on crystal faces, and (b) Transparent quartz crystal. (Photo credit: Dr. Sandeep Vansutre)

Now let us summarise physical properties of mineral quartz in Table 7.1.

Table 7.1: Physical properties of quartz.

Physical property	Description
Silicate structure	Tectosilicate
Colour	Occurs in virtually every colour-white, gray, purple, yellow, brown, black, pink, green and red.
Transparency	Transparent to translucent, sometimes opaque
Streak	Colourless (harder than the streak plate)
Lustre	Vitreous
Hardness	7 (on Moh's scale), cannot be scratched with the knife
Specific gravity	2.6 to 2.7
Form and structure	Crystals commonly prismatic with prism faces horizontally striated (Fig. 1a), It can be massive, granular, acicular
Cleavage	Absent
Fracture	Conchoidal fracture
Crystal system	Trigonal
Chemical composition	Composition of all pure quartz is close to 100% SiO_2
Diagnostic properties	Conchoidal fracture; glassy luster; hardness is 7 and absence of cleavage
Special property	Piezoelectric and pyroelectric

Occurrence: Quartz is a common mineral occurring in a great variety of geological environments. It is present in many igneous and metamorphic rocks and is major constituent of granite, gneisses and pegmatite. Quartz is basic

material of sandstone. Quartz is highly resistant to both mechanical and chemical weathering.

Uses: Silica sands are used in the glass-making industry. Quartz is used as building stones, in ceramic industry, as abrasive, toothpaste and in scouring soaps. One of the most common piezoelectric uses of quartz today is as a crystal oscillator. The quartz clock is a familiar device using the mineral.

7.3 ORTHOCLASE

We have studied in unit 5 that feldspar group consists of important minerals like orthoclase, plagioclase and microcline. In this section we will further discuss about ~~the~~ physical properties of these minerals.

Orthoclase is one of the ten well-defined minerals of the Mohs scale of mineral hardness. Orthoclase most commonly known as K feldspar is a tectosilicate. Rene Just Haüy in 1801 named "orthose" from the Greek word~~s~~ *orthos* - "right" and *kalo* - "I cleave" in reference to good cleavage at right angles of the mineral orthoclase. The name was changed to orthoklase by Johann Friedrich August Breithaupt in 1823. Microcline and sanidine are polymorphs of orthoclase. These three minerals form the K-feldspar group.

Orthoclase crystallises in monoclinic system. Typically, orthoclase is flesh red in colour (Fig. 7.2), but, it can be white or grey. Crystal habit is blocky or tabular. Two sets of cleavages which are present at right angles. Orthoclase hardness is 6. It shows pearly lustre on cleavage faces whereas vitreous lustre on fractured faces to dull, if weathered.

Fig. 7.2: Flesh coloured orthoclase. Two sets of cleavage are clearly visible.

Occurrence: Orthoclase is one of the most common minerals occurring in diverse environments, i.e. igneous, metamorphic and sedimentary. Orthoclase is found in many silicic igneous rocks including granite~~s~~, granodiorite, syenite in particular in shallow intrusions and other felsic igneous rocks. Orthoclase is also found in sedimentary environments. Sanidine, the high temperature K feldspar is more common in volcanic rocks. NASA's Curiosity Rover discovery of orthoclase in Martian sandstones suggested that some Martian rocks may have experienced complex geological processing.

Let us summarise physical properties of orthoclase in Table 7.2.

Table 7.2: Physical properties of orthoclase.

Physical property	Description
Silicate structure	Tectosilicate
Crystal system	Monoclinic system
Colour	Flesh red (Fig. 7.2), colourless, white gray, rarely yellow or green
Transparency	Translucent to opaque (rarely transparent)
Streak	Colourless to white
Lustre	Pearly on cleavage faces and vitreous on fractured faces
Hardness	6 on Moh's scale of hardness
Specific gravity	2.6
Form and structure	Tabular crystals, somewhat flattened crystal, massive
Cleavage	Two sets of cleavages intersect at 90º
Fracture	Conchoidal, hackly
Crystal system	Monoclinic
Chemical composition	$KAlSi_3O_8$
Diagnostic properties	Tabular habit; flesh red colour but can be white; 6 hardness; two sets of cleavages at 90°; pearly on cleavage faces and vitreous on fractured faces

Uses: Orthoclase is a common raw material for the manufacture of few glasses and ceramics such as porcelain and as a constituent of scouring powder. The gem variety of orthoclase is called moonstone because of its transparent and translucent appearance. Most moonstones are translucent and white, although grey and peach-coloured varieties also occur in nature. Finely ground potash feldspar is used as a fertilizer. Feldspar is used in ceramic industry as a glaze for chinaware, porcelain and earthenware. Orthoclase is also utilised in wall tiles and ceramic flooring tiles, as it improves their strength and durability of the tiles. The chemical industries use orthoclase as a flux component.

7.4 MICROCLINE

We have read about physical properties of orthoclase which has chemical composition of K Feldspar. Microcline is another mineral with same chemical composition. It is an important igneous rock-forming tectosilicate. It is also K-rich alkali feldspar. Microcline typically contains minor amounts of sodium. Microcline forms during slow cooling of orthoclase and is more stable at lower temperatures than orthoclase. It is more abundantly found in deep seated plutonic rocks.

Johann Friedrich August Breithaupt in 1830 named bluish green feldspar from Norway as microcline. The name of the mineral is derived from the Greek word '*micro*' -little and '*cline*'-to incline, in reference to the small departure from monoclinic symmetry. The word 'microcline' is derived from the Greek word

which means 'small slope'. As discussed above microcline has the same chemical composition as orthoclase but is classified in the triclinic crystal system. Microcline is usually sea green to bright green in colour (Fig. 7.3) with tabular to massive form. It displays 2 sets of cleavages which intersect at 90°.

Fig. 7.3: Sea green coloured Microcline.

Microcline is identical to orthoclase in many physical properties. Let us summarise physical properties of microcline in Table 7.3.

Table 7.3: Physical properties of microcline.

Physical property	Description
Silicate structure	Tectosilicate
Colour	White, grey, greyish yellow, yellowish, tan, salmon-pink, bluish green, green
Transparency	Translucent to opaque
Streak	White
Lustre	Vitreous
Hardness	6-6.5
Specific gravity	2.55 to 2.63
Form and structure	Tabular crystals, somewhat flattened crystal, massive
Cleavage	Two sets of cleavages intersect at 90^0
Fracture	Conchoidal, uneven
Crystal system	Triclinic
Chemical composition	$KAlSi_3O_8$
Diagnostic properties	Green colour; cleavage is at right angles; tabular to massive form

Microcline forms largest known crystal in pegmatite in Karelia, USSR, where, a single crystal weight is 2000 tons. Green microcline is known as amazonite.

Difference between orthoclase and microcline are minor in hand specimens. Microcline tends to be deeper-coloured and is not always, a blue-green (amazonite). It shows striations on cleavage surfaces.

Occurrence: Microcline commonly occurs in plutonic igneous rocks such as granite and syenite that cooled slowly at considerable depths. Microcline is also found in sedimentary environment.

Uses: Microcline is used in the manufacture of porcelain. It is very finely ground and mixed with kaolin and quartz. It acts as binding cement on heating. Fused feldspar is also a main constituent in the glaze on porcelain. It is very well used to supply alumina in the manufacture of glass. The blue-green feldspar amazonite is the only gem variety of microcline.

7.5 PLAGIOCLASE

Plagioclase feldspars occupy a range of compositions between albite $NaAlSi_3O_8$ and anorthite $CaAl_2Si_2O_8$. Plagioclase contains both sodium (Na) and calcium (Ca) ions that freely substitute for one another in the silicate crystal structure. Sodic and calcic end-members are represented by albite (Ab) and anorthite (An), respectively. The plagioclase series follows with the percent anorthite content (written in parentheses):

We have discussed about plagioclase earlier also in unit 5. Plagioclase is a major constituent mineral in the crustal rocks of the Earth's. It is an important diagnostic tool in petrology for the study of composition, origin and evolution of igneous rocks. Plagioclase within the feldspar group is a tectosilicate mineral. The mineral name plagioclase is derived from the Greek word which means ‘oblique fracture’, in reference to its two sets of cleavages that intersect at right angles to each other. This was first shown by the German mineralogist Johann Friedrich Christian Hessel in 1826. The series forms solid solution that ranges from albite to anorthite end members with varying compositions of $NaAlSi_3O_8$ ~~to~~ and $CaAl_2Si_2O_8$, respectively. Sodium and calcium atoms had undergone atomic substitution for each other in the crystal lattices. Plagioclase series is a group of related feldspar minerals that essentially represents the same formula, but, vary in their percentage of sodium and calcium ions. In many cases, it becomes very hard to tell whether particular plagioclase feldspar is calcic or sodic. If it cannot be identified, it is simply called plagioclase or plagioclase feldspar.

Fig. 7.4: Hand specimen of plagioclase.

A good way to distinguish between varieties of feldspars is to look for striations found on many cleavage planes of plagioclase feldspar, but this is not present on potash feldspar.

Let us summarise physical properties of plagioclase in Table 7.4.

Table 7.4: Physical properties of plagioclase.

Physical property	Description
Silicate structure	Tectosilicate
Colour	White, colourless, cream, gray, yellow, orange, pink, green, blue, red, brown, black
Transparency	Transparent to translucent and opaque
Streak	Colourless or white
Lustre	Vitreous to pearly
Hardness	6-6.5
Specific gravity	2.6 - 2.8
Form and structure	Granular, massive, columnar, rosette, and rounded. Crystals are usually flat and bladed, and often striated. It also occurs as long tall prismatic and short, stubby tabular crystals
Cleavage	Two sets of cleavages intersect at 90º
Fracture	Conchoidal to uneven
Crystal system	Triclinic
Chemical composition	$NaAlSi_3O_8$ to $CaAl_2Si_2O_8$
Diagnostic properties	Its pale grey or white colour; together with two visible cleavages allows plagioclase to be distinguished easily from quartz. It is often difficult to distinguish from alkali feldspar when anhedral, however, the later is often pink.
Special property	Striations on crystal faces

Occurrence: Plagioclase feldspars are important rock-forming minerals and occur in numerous mineral environments. Plagioclase is widespread in igneous rocks occurring in all except some highly acidic, alkaline and ultramafic rocks. They are commonly found in granite, syenite, rhyolites and trachyte. Albite is common is pegmatites. Plagioclase is also important constituent of gabbro, dolerite basalt and many ultramafic rocks such as peridotite and harzburgite. It is important constituent of anorthosite. It also occurs in a wide range of metamorphic rocks and in immature sediments. Plagioclase is also a major constituent of rock in the highlands of the Earth's Moon.

Uses: The mineral plagioclase is chiefly used in the manufacture of glass, pottery, ceramic glass and, enamels, vitreous enamels for coating meal-ware and in special electrical porcelain. It is used as a bonding agent or flux for abrasive wheels, as base for scouring soap and in the manufacture of artificial teeth.

7.6 NEPHELINE

We have studied that nepheline is the most common feldspathoid in Unit 5. Nepheline is a rock-forming mineral. It is mostly found in alkali rich rocks like nepheline syenite. Nepheline, also called as nephelite and its name is derived from the Greek meaning ‘cloud’. Greasy lustre of nepheline is the diagnostic character (Fig. 7.5). The massive nepheline variety having greasy lustre is called "eleolite" which is derived from the gGreek word for ‘oil’. It is a silica-undersaturated sodium potassium aluminosilicate ($Na_3KAl_4Si_4O_{16}$). It occurs in intrusive and extrusive rocks with low silica contents. M. H. Klaproth in 1809

named it from Greek words for 'oil' and 'stone' based on its typical blue colour and greasy lustre. It is usually massive and seldom well-crystallised. Nepheline is often sold in rock shops due to a lack of good crystals or attractive specimens.

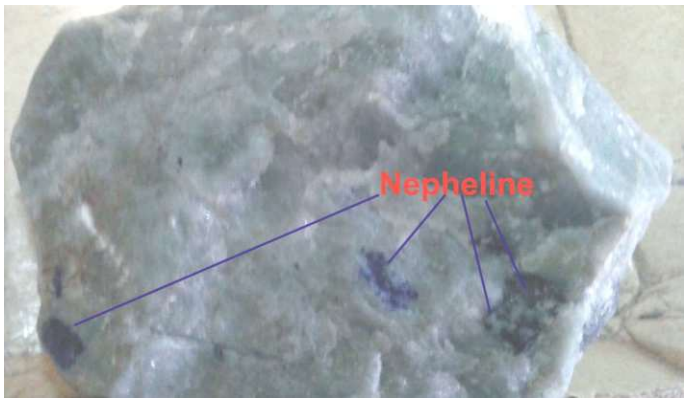


Fig. 7.5: Hand specimen of nepheline.

Let us summarise physical properties of nepheline in Table 7.5.

Table 7.5: Physical properties of nepheline.

Physical property	Description
Silicate structure	Tectosilicate
Colour	White, gray or bluish
Transparency	Transparent to opaque
Streak	Colourless, white and reddish with white
Lustre	Greasy to waxy
Hardness	5.5 - 6
Specific gravity	2.60-2.65
Form and structure	Often massive or granular, rarely prismatic to columnar crystals are found with a simple hexagonal cross section
Cleavage	Poor, in three directions, prismatic, but rarely seen. One set cleavage is distinct
Fracture	Subconchoidal to uneven
Crystal system	Hexagonal
Chemical composition	$Na_3KAl_4Si_4O_{16}$
Diagnostic properties	Coarsely crystallised with greasy luster, Grayish, bluish colour
Special property	Nepheline is reactive to acids although it does not bubble like many of the carbonates

Occurrence: Nepheline is found in silica deficient and alkali rich both in plutonic and volcanic rocks like nepheline syenite, phonolite, nepheline syenite pegmatite.

Uses: Nepheline serves as an ore of aluminium. It is sometimes used as a source of soda, silica, and alumina in the manufacture of glass and ceramics. Rare alkaline metals and gallium can be extracted from nepheline.

We have discussed rock-forming minerals like quartz, orthoclase, microcline and plagioclase. Before proceeding further, spend five minutes to check your progress.

SAQ 1

a) List the diagnostic physical properties shown by quartz.

b) Distinguish between orthoclase and microcline on the basis of physical properties.

c) List the minerals of plagioclase series.

d) Write physical properties of nepheline.

e) What are the uses of quartz?

7.7 CHLORITE

The chlorite minerals have a foliated appearance and are sheet silicates. The most common minerals of chlorite group are clinochlore, clinozoisite, pennantite, and chamosite.

The name chlorite is derived from the Greek word *chloros*, meaning 'green', in reference to its color. Chlorite is typically green in color with perfect one set of cleavages. It is oily to soapy in feel. Chlorite is so soft that it can be scratched by a finger nail. It has a foliated appearance.

Chlorite is represented by a generalised chemical composition/formula:

$(X,Y)4\text{-}6(Si,Al)_4O_{10}(OH,O)_8$

Where, 'X' and 'Y' represent: Fe^{+2}, Fe^{+3}, Mg^{+2}, Mn^{+2}, Ni^{+2}, Zn^{+2}, Al^{+3}, Li^{+1}, or Ti^{+4} ions.

Variable chemical composition of chlorite gives a range of hardness and specific gravity.

Fig. 7.6: Hand specimen of chlorite.

Let us summarise physical properties of chlorite in Table 7.6.

Table 7.6: Physical properties of chlorite.

Physical property	Description
Silicate structure	Phyllosilicate
Colour	Shades of green. Rarely yellow, white, pink, black
Transparency	Transparent, translucent, opaque
Streak	Greenish to greenish gray
Lustre	Vitreous, pearly, dull
Hardness	2 to 3
Specific gravity	2.6 to 3.3
Form and structure	Foliated masses, scaly aggregates, disseminated flakes
Cleavage	Perfect in one direction
Fracture	Uneven
Crystal system	Monoclinic
Chemical composition	$(X,Y)_{4-6}(Si,Al)_4O_{10}(OH,O)_8$ Where, 'X' and 'Y' in the formula represent Fe^{+2}, Fe^{+3}, Mg^{+2}, Mn^{+2}, Ni^{+2}, Zn^{+2}, Al^{+3}, Li^{+1}, or Ti^{+4} ions.
Diagnostic properties	Color; hardness; foliated appearance; feels slightly greasy
Special property	Oily to soapy feel

Occurrence: They are found in igneous, metamorphic and sedimentary rocks. Chlorite minerals are found in rocks which had undergone deep burial, hydrothermal activity, or contact metamorphism. 'Chlorite' is the name assigned to a group of common sheet silicate minerals formed during early stages of metamorphism. They are also found as retrograde minerals in igneous and metamorphic rocks that have been weathered. Chlorite is abundantly found in rocks like phyllite, chlorite schist, and greenschist.

Uses: Chlorite is a mineral with a low potential for industrial use. It is used as filler and as a constituent of clay. Chlorite is usually intimately inter-mixed with other minerals, and the cost of separation would be high. As a result, chlorite is not mined and processed for any specific use. Its major use is in the form of a coincidental constituent in crushed stone.

7.8 EPIDOTE

Epidote is a silicate mineral found in low-to-slightly medium grade metamorphic rocks. Epidote group of minerals are known since the 18th century, but at that time the greenish to dark coloured varieties of epidote were termed as actinolite. Haüy defined mineral species and introduced the name "epidote" in 1801, whereas Werner in 1805 used the term pistacite. It refers to its green color. Epidote is derived from the Greek word *epidosis* which means 'addition' in allusion to one side of the ideal prism being longer than the other.

Epidote crystallises in monoclinic system and granular or prismatic in habit. It is green, grey, brown or almost black in color, but represents characteristic shade of yellowish-green or pistachio-green. The chemical composition of epidote is:

$Ca_2(Al,Fe)Al_2O(SiO_4)(Si_2O_7)(OH)$

Epidote characters such as colour and specific gravity vary with the amount of Fe content present in it.

Fig. 7.7 Hand specimen of epidote.

Let us summarise physical properties of epidote in Table 7.6.

Table 7.7: Physical properties of epidote

Physical property	Description
Silicate structure	Sorosilicate
Colour	Usually yellowish green to pistachio green, sometimes brownish green to black
Transparency	Transparent to translucent to nearly opaque
Streak	Colorless
Lustre	Vitreous to resinous
Hardness	6 to 7
Specific gravity	3.3 to 3.5
Form and structure	Crystals are uncommon. It occurs as typically granular masses or sometimes foliated.
Cleavage	Perfect in one direction
Fracture	Conchoidal to uneven
Crystal system	Monoclinic
Chemical composition	$Ca_2(Al_2,Fe)(SiO_4)(Si_2O_7)O(OH)$
Diagnostic properties	Pistachio green color; granular form; cleavage; specific gravity

Occurrence: Epidote is abundantly found as one of the rock-forming minerals, but of secondary origin. It is also a product of contact metamorphism, hydrothermal alteration of various minerals (feldspars, micas, pyroxenes, amphiboles, garnets, and others) composing of igneous rocks.

Uses: Epidote has no significant use as an industrial mineral and has only minor use as a gemstone. It is considered to be a semiprecious stone. High-quality transparent epidote crystals ~~of~~ are used as gemstones. The Unakite is a popular rock, used to make beads, ornamental objects. The bright pink and pistachio green colors are very unusual and attract attention of gemstone hunters.

7.9 CALCITE

The Earth's crust also comprises of common carbonate group of minerals such as calcite ($CaCO_3$) and dolomite ($MgCO_3$). These minerals possess trigonal symmetry and are structurally and chemically related groups. Typically, the carbonates are transparent, light coloured minerals with a white streak, average density, and soft with good to perfect cleavage. They are soluble in acidic solutions. Carbonates usually originate in sedimentary oxidising conditions.

Let us discuss the physical properties of mineral calcite.

Calcite is a rock-forming mineral with a chemical formula of $CaCO_3$. It is commonly found in sedimentary, metamorphic and igneous rocks. Some geologists consider it as a 'ubiquitous mineral' - one that is found everywhere. Calcite is the principal constituent of limestone (sedimentary rock) and marble (metamorphic rock). These rocks are extremely common and make up appreciable portion of the Earth's crust. They serve as one of the largest carbon sequestration repositories on our planet.

Calcite gets its name from the Greek word '*chalix'* meaning lime. Calcite forms limestone-which is massive, fossiliferous and oolitic. The calcite crystals are found in various shapes. It crystallises in 300 different forms. Calcite is the primary mineral of stalactites and stalagmites formed in caves.

Calcite commonly exists in prismatic, rhombohedral forms with perfect rhombohedral cleavages (Fig. 7.8). It has perfect cleavage parallel to the unit rhoombohedron and conchoidal fracture. Calcite is colourless or white, sometime grey, yellow, blue, red, brown, or with black tints. Calcite hardness is 3 on Moh's scale. Lustre is vitreous to dull. Properties of calcite make it one of the most widely used minerals.

(a) (b)

Fig. 7.8: Hand specimen of calcite: a) transparent; and b) translucent varieties.

Let us summarise the physical properties of calcite in Table 7.8.

Table 7.8: Physical properties of calcite.

Physical property	Description
Colour	Colour variable, but, generally white or colourless or with light shades of yellow, orange, blue, pink, red, brown, green, black and gray
Transparency	Transparent to translucent
Streak	white
Lustre	vitreous
Hardness	3
Specific gravity	2.7
Form and structure	Crystals are uncommon. Occurs as granular masses or sometimes foliated or tabular in nature
Cleavage	3 sets of perfect cleavages, rhombohedral
Fracture	Conchoidal to uneven
Crystal system	Hexagonal, calcite type or Ditrigonal-sclenohedral class
Chemical composition	$CaCO_3$
Diagnostic properties	Perfect parallel to the unit rhoombohedron 3 sets of cleavages; hardness 3
Special property	Reacts turbulently even in contact with dilute HCl

Let us discuss few varieties of calcite.

Nail head spar and dog tooth spar are common habit of calcite. Dog tooth spar is compact finely fibrous variety. Iceland spar is a valuable variety of calcite used in optical instruments like polarising microscopes. It is commonly used in construction of Nicol prisms used in polarising microscopes.

Occurrence: Calcite occurs widely in nature, found in sedimentary rocks like limestone, chalk and marble. Limestone is of chemical or biogenic in origin. Marble is a metamorphosed limestone. Calcite is principal constituent of carbonate shells. Calcite occurs as infilling in the vesicles of volcanic rocks. Calcite rarely forms in the igneous rocks (carbonatites) as primary mineral, but it occurs as secondary infillings.

Uses: The variety of calcite like iceland spar is used in optical instruments (polarising microscopes).

Calcite: A Carbon Dioxide Repository

Carbon dioxide is one of the most important greenhouse gases, accountable for global warming of the atmosphere as its variation in the concentration affects the global carbon cycle as well as temperature of the Earth. The process of limestone formation involves natural sequestration, where, CO_2 is immobilised and stored in the form of carbonate rocks (such as limestone and

dolomite) for a longer periods of time. This process has been operational for several millions of years and producing enormous amount of stored carbon dioxide. When these rocks have undergone weathering, used to neutralise acids, and heated to form cement or metamorphosed severely. During metamorphism, some of their carbon dioxide is released and returned back to the atmosphere. All these processes of limestone formation and destruction have impact on the Earth's climate.

We have discussed rock-forming minerals like nepheline, chlorite, epidote and calcite. Before proceeding further, spend five minutes to check your progress.

SAQ 2

a) List few minerals of chlorite group.

b) Write about occurrence of chlorite.

c) What is the diagnostic colour of epidote.

d) Write about occurrence of epidote.

e) Hardness of calcite is _____ on Moh's scale.

Watch this video to know more about minerals

- **Microscopic Study of Basaltic Rocks**
  Link: https://www.youtube.com/watch?v=2RGL3XB2x3E&t=2s

7.10 SUMMARY

In this unit, we have learnt about megascopic characters of common rock-forming minerals such as quartz, feldspar group of minerals, nepheline, chlorite, epidote and calcite. Let us now summarise:

The physical properties of the rock-forming minerals dealt in this unit have been summarised in Table 7.9. You are advised to refer to mineral identification table.

7.11 ACTIVITY

- Make a list of minerals used or consumed by you directly or indirectly in a day.

7.12 TERMINAL QUESTIONS

1. Discuss physical properties of orthoclase, microcline and plagioclase
2. Describe the physical properties and occurrence of quartz.
3. Discuss the physical properties of carbonate mineral.
4. Write physical properties of nepheline.

Table 7.9: Summary of the physical properties of rock forming minerals

Physical property	Quartz	Orthoclase	Microcline	Plagioclase	Nepheline	Chlorite	Epidote	Calcite
Colour	Occurs almost in all colours-white, gray, purple, yellow, brown	Flesh red, colourless, white gray, rarely yellow or green	White, grey, sea green, yellow, bluish green,	White, cream, gray, blue, red, brown, black	White, gray or bluish	Shades of green. Rarely yellow, white, pink, black	Yellowish green to pistachio green, sometimes brownish green to black	Colour is extremely variable but generally white or colourless
Transparency	Transparent to translucent sometimes opaque	Translucent to opaque	Translucent to opaque	Transparent to translucent and opaque	Transparent to opaque	Transparent, translucent, opaque	Transparent to translucent to nearly opaque	Transparent to translucent
Streak	Colourless	White	White	white	Colourless, white	Greenish to greenish gray	Colorless	white
Lustre	Vitreous	Pearly on cleavage faces and vitreous on fractured faces	Vitreous	Vitreous to pearly	Greasy to waxy	Vitreous, pearly, dull	Vitreous to resinous	vitreous
Hardness	7 (on Moh's scale), cannot be scratched with knife	6 on Moh's scale of hardness	6-6.5	6-6.5	5.5 - 6	2 to 3	6 to 7	3
Specific gravity	2.6 to 2.7	2.6	2.55 to 2.63	2.6 - 2.8	2.60-2.65	2.6 to 3.3	3.3 to 3.5	2.7
Form and structure	Crystals commonly prismatic, massive, granular, acicular	Tabular crystals, some what flattened crystal, massive	Tabular flattened crystals, massive	Massive, columnar, prismatic and short, stubby tabular crystals	Massive, granular, rarely prismatic to columnar	Foliated masses, scaly aggregates, disseminated flakes	Granular masses, sometimes foliated.	Granular massese or tabular
Cleavage	Absent	Two set cleavage at 90^0	Two set cleavage at 90^0	Two set cleavage at 90^0	Poor, in three directions	Perfect in one direction	Perfect in one direction	Perfect 3 sets, rhombohedral
Fracture	Conchoidal fracture	Conchoidal, hackly	Conchoidal, uneven	Conchoidal to uneven	Subconchoidal to uneven	Uneven	Conchoidal to uneven	Conchoidal to uneven
Crystal system	Hexagonal	Monoclinic	Triclinic	Triclinic	Hexagonal	Monoclinic	Monoclinic	Trigonal
Chemical composition	SiO_2	$KAlSi_3O_8$	$KAlSi_3O_8$	$NaAlSi_3O_8$ to $CaAl_2Si_2O_8$	$Na_3KAl_4Si_4O_{16}$	$(X,Y)_{4-6}(Si,Al)_4O_{10}(OH,O)_8$ 'X' and 'Y' are Fe^{+2}, Fe^{+3}, Mg^{+2}, Mn^{+2}, Ni^{+2}, Zn^{+2}, Al^{+3}, Li^{+1}, or Ti^{+4}.	$Ca_2(Al_2,Fe)(SiO_4)(Si_2O_7)O(OH)$	$CaCO_3$
Diagnostic properties	Conchoidal fracture, glassy lustre, hardness and absence of cleavage	Colour, form, lustre, cleavage	Colour, cleavage is at right angles	Colour, 2 set cleavage, form	Crystallised with greasy luster, Grayish, bluish colour	Color, hardness, foliated appearance, feels slightly greasy	Pistachio green color, granular form, cleavage, specific gravity	Rhombohedral form, 3 set cleavage, hardness 3, colour

Audio/video material based question

- What are accessory minerals?

7.13 REFERENCES

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7.14 FURTHER/SUGGESTED READINGS

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- Deer, W.A., Howie, R.A. and Zussman, J. (1992) An Introduction to Rock - Forming Minerals, Longman Scientific & Technical.
- Gribble, C.D. (1991) Rutley's Elements of Mineralogy, 27th Edition, CBS Publishers and Distributors, Delhi.
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7.15 ANSWERS

Self Assessment Questions

1 a) Conchoidal fracture, vitreous lustre, 7 hardness and absence of cleavage.

b) Orthoclase is flesh red in colour and show vitreous to pearly lustre having tabular form. Microcline is sea-green in colour, vitreous lustre and tabular to massive form.

c) Albite, Oligoclase, Andesine, Labradorite, Bytownite, Anorthite.

d) Please refer to Table 7.5.

e) Silica sands are used in glass making industry. Quartz is used as building stones, in ceramic industry, as abrasives, toothpaste and in scouring soaps. One of the most common piezoelectric uses of quartz today is as a crystal oscillator. The quartz clock is a familiar device using the mineral.

2 a) Clinochlore, clinozoisite, pennantite, and chamosite.

b) They are found in rocks which have undergone deep burial, hydrothermal activity, or contact metamorphism. They are also found

as retrograde metamorphosed minerals in igneous and metamorphic rocks that have been weathered.

c) Pistachio green

d) Epidote is an abundant rock-forming mineral, but of secondary origin. It is also a product of contact metamorphism, hydrothermal alteration of various minerals (feldspars, micas, pyroxenes, amphiboles, garnets, and others) composing igneous rocks.

e) 3.

Terminal Questions

1. Please refer to sections 7.3, 7.4 and 7.5.
2. Please refer to section 7.2.
3. Please refer to section 7.9.
4. Please refer to section 7.6.

GLOSSARY

Accessary minerals : These minerals are present in less quantities in a rock. Their presence and absence do not affect the definition and classification of a rock.

Amorphous : This term is used for those rocks, minerals and materials which have no form and definite crystal structure.

Anhydrite : This mineral is composed of anhydrous $CaSO_4$ and crystallises in orthorhombic system. It's colour is white sometimes with greyish, bluish and reddish tinge.

Augite : Augite has a single chain structure of inosilicate. It is clinopyroxene as it crystallizes in monoclinic system. It is an important rock-forming mineral.

Books of mica Muscovite occurs as "books" because they can be split into paper-thin sheets.

Calcareous : This term is used for those rocks which are composed of calcium carbonate.

Conchoidal : This term is used to describe nature of the fracture.

Chlorite Chlorite minerals have a foliated appearance and are sheet silicates. The most common minerals of chlorite group are clinochlore, clinozoisite, pennantite, and chamosite.

Dolomite : It is a mineral composed of calcium magnesium carbonate varying from white to pink colour. Its crystals are rhomboherdral in shape.

Euhedral : It is concerned with a form which is partially comprises of its own crystal faces in crystallography.

Fayalite : It is a mineral of olivine group with composition Fe_2SiO_4

Flint : It is a lusterless, and coloured fine grained microcrystalline silica displaying conchoidal fracture.

Glassy : It is the term used for glassy texture developed in volcanic rocks.

Halite : Common or rock salt found as amorphous, crystalline or granular. On crystallizing it is found as cube.

Heavy minerals : Minerals with relatively more density than bromoform (2.9).

Hypersthene Hypersthene is also a common rock-forming inosilicate mineral of pyroxene group. It is an important iron rich

orthopyroxene crystallizing in orthorhombic system.

Jasper : It is commonly red or brown coloured microcrystalline quartz.

Kaolin : It is white or nearly white coloured clayey rock formed due to decomposition of feldspar containing rocks. It is used to make porcelain rich paste.

Kyanite : Kyanite is a member of the aluminosilicate series. It is a nesosilicate. Kyanite is one of the most attractive blue mineral in nature. It is a commonly found in Al-rich metamorphic pegmatites and sedimentary rocks.

Muscovite : Muscovite is easily identified because of its perfect one set cleavage which allows it to be split into thin, flexible, elastic, colourless, transparent sheets with a pearly to vitreous lustre.

Peridot : Translucent green variety of olivine is very popular as gemstone known as peridot (péridot, the French word for olivine). The yellowish green transparent olivine is called chrysolite

Plagioclase : Plagioclase contains both sodium (Na) and calcium (Ca) ions that freely substitute for one another in the silicate crystal structure. Sodic end member is represented by Ab (albite) whereas calcic end member is represented by An (anorthite).

Polymorph : Kyanite, andalusite, and sillimanite are naturally occurring anhydrous aluminum silicate minerals. All three of them have same chemical formula, Al_2SiO_5, but differing crystal structures. They are known as polymorphs, i.e exist in different forms. Kyanite is the high pressure polymorph, andalusite is the low pressure polymorph and sillimanite forms at high temperature.

Quartz : Quartz is a member of the silica or quartz group which has the chemical composition SiO_2. It is the second most abundant mineral on the Earth continental crust after feldspar. Quartz has tectosilicate or framework silicate structure. It crystallises in trigonal system.

Rock-forming minerals : Rock-forming minerals are essential components of rocks commonly occurring in the Earth's crust.The common rock- forming minerals in magmatic rocks are quartz, feldspars, pyroxenes, amphiboles, micas, olivine and feldspathoids.

The rock- forming minerals like calcite, dolomite, anhydrite and clay minerals constitute the important component of sedimentary rocks.

The metamorphic rocks comprise rock forming minerals like kyanite, andalusite, sillimanite, staurolite, chlorite, serpentine, garnet, wollastonite and glaucophane.

Shajar : Shajar is transparent variety of augite with dendritic patterns is known as.

Schiller structure : Hypersthene displays a typical characteristic of 'schillerisation' meaning display of colour in natural light.

Streak plate : Piece of non glassy porcelain used to examine streak of a mineral.

Striations : Minor parallel lines present on the surface or cleavage faces of a mineral.

Subhedral : It is concerned with a form which is partially comprises of its own crystal faces in crystallography.