

Block**2****IGNEOUS PETROLOGY - II****UNIT 4****Concept of Magma****91****UNIT 5****Crystallisation of Magma****109****UNIT 6****Felsic and Intermediate Rocks****125****UNIT 7****Mafic and Ultramafic Rocks****151****Glossary****171**

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Acknowledgement: Ms. Savita Sharma for preparation of CRC and some of the figures.
June, 2020

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ISBN:

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

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BLOCK 2: IGNEOUS PETROLOGY - II

Igneous rocks are formed from the cooling and consolidation of hot molten viscous material known as **magma**. The magma cools and solidifies either below the surface of Earth giving rise to intrusive/plutonic rock or on the Earth's surface called as extrusive/volcanic rock. Magmatic crystallisation takes place due to the significant changes in state variables such as pressure, temperature with time. During magmatic crystallisation, minerals precipitate over a range of temperature and perhaps pressure sequentially from the melt. Thus, the crystallisation can be caused by the changes in composition and pressure with decreasing temperature. The cooling and crystallisation of magma gives rise to a range of composition of igneous rocks varying in composition from ultramafic, mafic, intermediate and felsic rocks. High temperature and molten state are two significant conditions for the original material from which the igneous rocks are believed to have been formed.

In **Block 1** you had learnt the fundamental concepts about petrology. We also learnt how to classify major rock types and concept of rock cycle. Textural elements present in igneous rocks like crystallinity, granularity and fabric have also been discussed. Mineralogical classification of igneous rocks based on composition and proportion of minerals and colour index; Field, Tabular, CIPW and IUGS classification have also been explained.

Block 2 comprises four units. This block will acquaint you with the concept, physical properties, composition and crystallisation of magma. The megascopic and petrographic description of the common felsic, intermediate, mafic and ultramafic rocks will be discussed.

In **Unit 4** we will familiarise with the concept of magma and discuss the physical properties and composition of magma. Further we will also discuss Bowen's reaction series and explain the mechanisms of magmatic differentiation and assimilation.

In **Unit 5** the unicomponent and bicomponent systems are used to explain the application of phase rule on it. Further equilibrium crystallisation of magmatic system and lever principle will be discussed.

In **Unit 6** you will learn in detail about the megascopic and petrographic description of the common felsic and intermediate rocks.

In **Unit 7** you will learn about the megascopic and petrographic description of the common mafic and ultramafic rocks.

Expected Learning Outcomes

After studying this block, you should be able to:

- learn the concept, physical properties and composition of magma;
- explain the Bowen's reaction series and the mechanisms of magmatic differentiation and assimilation;
- discuss unicomponent and bicomponent systems;
- explain the application of phase rule and lever principle;
- discuss the megascopic and microscopic characters of common felsic, and intermediate rocks; and

- describe the megascopic and microscopic characters of common mafic and ultramafic rocks.

We hope that after studying this block you will be able to get familiar with the concept of magma and the megascopic and explain the petrographic description of the felsic, intermediate, mafic and ultramafic rocks.

In order to evaluate your learning while reading the self-learning material of this block, we have provided self-assessment exercises under the caption “**Self Assessment Questions (SAQ)**” at a few places and at the end “**Terminal Questions**” in all units of the block, which invariably end with answers to the questions, set in these exercises. You should attempt the exercises yourself and not be tempted to look up the answers given under the caption “Answers” beforehand. It should be noted that the check your progress is provided as study tools to help you keep on the right track as you read the units. You have been provided with the links of **audio video materials** related to this course. They are blended with the self-learning material. You are instructed to watch/listen these audio video programmes and **answer the questions** given after “terminal question”.

We advise that as you read the units, jot down important points in the space provided in the margins of each page. In fact, broad margins in the booklet are provided for you to write your notes on. Make your notes as you work through the materials. This will help you prepare for the term end examination (TEE) and also in assimilating the content.

Your feedback pertaining to this block will help us undertake maintenance and timely revision of the block. Send your feedback to us to the address given below or e-mail to kakoligogoi@ignou.ac.in or meenalmishra@ignou.ac.in:

The Course Coordinator BGYCT-135

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We hope that you would enjoy reading the self-learning material.

Wishing you success and all the best in this endeavour!!

CONCEPT OF MAGMA |

Structure

4.1	Introduction	4.7	Magmatic Differentiation and Assimilation
	Expected Learning Outcomes		Magmatic Differentiation
4.2	What is Magma?		Assimilation
4.3	Physical Properties of Magma	4.8	Summary
4.4	Composition of Magma	4.9	Activity
	Components of Magma	4.10	Terminal Questions
	Chemical Composition of Magma	4.11	References
	Mineralogical Composition of Magma	4.12	Further/Suggested Readings
	Major Types of Magmas	4.13	Answers
4.5	Origin of Magma		
4.6	Bowen's Reaction Series		
	Discontinuous Reaction Series		
	Continuous Reaction Series		
	Importance of Bowen's Reaction Series		

4.1 INTRODUCTION

We have already learnt in **Unit 1 Introduction to Petrology** of this course that the igneous rocks are formed from the cooling and consolidation of hot molten viscous material known as **magma**. If the magma cools and crystallises below the surface of Earth, it gives rise to intrusive/plutonic igneous rock. However, if it takes place above the Earth's surface it gives rise to extrusive/volcanic igneous rock. In our discussion on the rock cycle, we have learnt that the magma is also parent material for the igneous rocks which are also known as **primary rocks**. Rock cycle has provided us the understanding that magma can be derived from either the Earth's mantle or from melting of the

pre-existing rocks in extreme temperature and pressure changes. The study of igneous rocks provides the clues about the geological processes that had occurred in the geological past. In this unit we will study the concept, physical properties and chemical composition of magma, Bowen's reaction series and processes of differentiation of magma.

Expected Learning Outcomes

After reading this unit you should be able to:

- ❖ familiarise with the concept of magma;
- ❖ describe the physical properties and composition of magma;
- ❖ discuss the Bowen's reaction series; and
- ❖ explain the mechanisms of magmatic differentiation and assimilation.

4.2 WHAT IS MAGMA?

The term **magma** is derived from Greek word which means 'thick ungent'. It is a mixture of molten or semi-molten rock, volatiles and solids. Magma is often collected in a magma chamber found beneath the surface of the Earth. Magma may solidify at deep inside the Earth. It may intrude the adjacent rocks or feed a volcano. Magma when extruded on to the surface of the Earth as lava may be explosive to form pyroclastic rock.

We have read that about 700 types of igneous rocks have been reported on the earth. You must be thinking that so many different types of magma may be forming various types of rocks! Different types of igneous rocks are formed due to differentiation of magma. We will learn about processes of differentiation of magma responsible for forming different rock types later in this unit. Before proceeding further let us read about few terms related to magma.

- **Primary magma:** It refers to the initial composition of magma before it underwent any differentiation process. Primary magma must have >10% MgO by weight. Primary magma by the process of differentiation evolves into parental magma. In other words, they are modified by the process of differentiation. However, it is rare to find primary magma in nature. Primary magma is also known as primary melt.
- **Primitive magma:** This term refers to the primary magma derived from mantle. The composition of primitive magma gives an idea of the composition of the mantle which gave rise to melt. This is important in understanding the evolution of magma. Primitive magma has undergone minimal differentiation. It is also known as primitive melt.
- **Parental magma:** This refers to the magma from which the observed range of magma has been derived by the process of magmatic differentiation. In other words, parental magma is capable of producing all rocks belonging to igneous rock series by the process of differentiation. Parental magma is derived from primary magma. This is important in understanding the evolution of magma. It is also known as parental melt. A parental melt is a

magma composition which may be derived directly through melting of deep-seated primary magma.

Let us study the physical properties and origin of magma.

4.3 PHYSICAL PROPERTIES OF MAGMA

Now let us study about the physical properties of magma. The crystallisation of magma is governed by following factors:

1. **Temperature:** It is difficult to measure the temperature directly as it involves danger. The direct measurements of temperature 1200°C in flowing lava have been possible by remote control. The laboratory measurements and field observations indicate that the temperature of magma crystallises between the temperatures ranging from 1200°C to 650°C . Temperature of magmas indicate that the eruption temperature of various magmas is as follows:
 - Basaltic magma - 1000 to 1200°C
 - Andesitic magma - 800 to 1000°C
 - Rhyolitic magma - 800 to 650°C .
2. **Viscosity:** It is quantified as the resistance offered to its flow (opposite of fluidity) which controls the mobility of magma. It depends primarily on the composition and temperature of magma. The volatiles impart low viscosity to the magma. Felsic (with higher SiO_2) magma has higher viscosity as compared to mafic magma. This is because of the complexity in the crystal structure (increasing silica composition) of felsic magma. Thus, the basaltic magmas tend to be having low viscosity as compared to rhyolitic magmas. Temperature also controls viscosity of magma. Cooler magmas are more viscous than hotter magmas of the same composition. Thus, viscosity is an important property in determining the eruptive behaviour of magmas.
3. **Density:** Density of magma is 2.65 gm/cm^3 and that of mantle 3.3 gm/cm^3 . More iron rich magma has more density. Mostly basalts are richer in Fe, Ca, and Ti than rhyolites; rhyolites are richer in Na, Al, and Si than basalts. The density of basaltic magma ranges in density from 2.65 to 2.80 gm/cm^3 ; andesitic magma- 2.45 to 2.50 gm/cm^3 ; rhyolitic magma- 2.18 to 2.25 gm/cm^3 . Apart from composition, temperature and pressure are important factors in controlling density. The magma tends to expand on increase in temperature causing lowering of density. On the contrary higher pressure increases the density of the magma.
4. **Volatiles/gases:** Nearly all magmas contain dissolved volatile and gasses. According to petrologists water is predominant constituent (about 90%) of volatiles present in magma. As the pressure decreases, the magma rises towards the surface and the gas forms a separate vapour phase. Let us comprehend this with an analogy. Gas forming as separate phase is quite similar to carbonated beverages bottled at high pressure. The high pressure keeps the CO_2 dissolved in the beverage, but when the pressure is released, that is when you open the bottle the gas escapes out of the solution and forms a separate gas phase that is observable in the form of bubbles. Gas provides explosive character to magma because the volume of gas expands

as the pressure is released. As the amount of dissolved gases or the volatiles in magma increase, the explosiveness of the magma increases. After water, carbon dioxide is the most abundant volatile. In general, basaltic magmas are dry with $H_2O < 0.5\%$. While the felsic rocks like granite and rhyolite consist of H_2O content ranging from 0.5% to 0.7%.

4.4 COMPOSITION OF MAGMA

In the beginning of the nineteenth century the invention of petrological microscope led to the accumulation of petrographic data from the petrographic provinces all over the world. This firmly established that the magma is the parent material for igneous rocks. On the basis of extensive petrographic data, it was established that the magmas have some salient features mentioned below.

- The diverse mineralogical composition and texture of the igneous rocks were the result of difference in the composition of magma and its conditions of cooling.
- Magma is essentially silicate in composition and its crystallisation begins at high temperature levels. It has a range of crystallisation temperature.
- Magma has adequate fluidity because of the variable amount of volatile materials.

4.4.1 Components of Magma

We know that the magma is hot molten and mobile rock material beneath the Earth's crust. The magmas consist of complex mixtures of materials in all the three states:

- **Liquid** portion is the melt which consists mainly of mobile ions of the eight most common elements found on Earth's crust, e.g. oxygen, silica, aluminium, iron, calcium, sodium, potassium, magnesium.
- **Solid** includes silicate minerals that have already crystallised from the melt.
- **Gaseous** components are volatiles, as discussed above. Most common volatiles present are water vapour (H_2O), carbon dioxide (CO_2) and sulphur dioxide (SO_2). Other minor constituents are HCl , H_2S , HF , N_2 , Cl , F , Br .

Petrologists often use the terms 'dry magma' and 'wet magma' as we have discussed earlier. Let us distinguish. The 'dry' magmas contain no volatiles. The 'wet' magmas comprise up to 15%, dissolved volatiles. These volatiles are released in the form of gas, as the magma moves towards the Earth.

4.4.2 Chemical Composition of Magma

After having discussed the components of magma, let us discuss the chemical composition of magma. Magmas do not have a fixed composition. Petrologists describe the chemical composition of magma in terms of the weight percentage of various major oxides. The chemical composition of any magma is made up of 10 elements, including Silicon (Si), Titanium (Ti), Aluminum (Al), Iron (Fe), Magnesium (Mg), Calcium (Ca), Sodium (Na), Potassium (K), Hydrogen (H) and Oxygen (O). They together constitute more than 99% of fixed constituent. In magma all of the elements exist as electrically charged ions. The first eight

elements listed above exist as positively charged cations with charges that range from +1 to +4 and oxygen occurs as a negatively charged anion with a negative charge of -2. As both cations and anions are present there is natural tendency for the different charged ions to bond with one another to form molecules that are electrically neutral. Let us look at the average composition of magma mentioned in terms of oxide wt % (Table 4.1). SiO_2 followed by Al_2O_3 forms the major component in any magma. All the magmas contain silicon and oxygen, which combine to form the silicon-oxygen bond or silicon-oxygen tetrahedron. In a **silicon-oxygen tetrahedron** a silicon atom is surrounded by four oxygen atoms arranged in the corners of a tetrahedron. You have read about silicon-oxygen tetrahedron in block 2 of BGYCT-133 course. Silicon-oxygen tetrahedron is a fundamental component of most silicates on the Earth's crust. But magmas also contain varying proportions of other elements such as aluminum (Al), calcium (Ca), sodium (Na), potassium (K), iron (Fe), and magnesium (Mg); each of these ions also form bonds with oxygen. The magma ranges from liquid to semi liquid state therefore its molecules do not lie in an orderly crystalline lattice but are grouped in clusters or short chains.

Table 4.1: Average composition of magma in oxide weight %. (Source: Tyrell, 1973)

SiO_2 – 59%	Fe_2O_3 – 3%	Al_2O_3 – 15%
CaO – 5%	FeO – 3.5%	MgO – 3.5%
Na_2O – 3.8%	K_2O – 3%	H_2O – 1%
TiO_2 – 1%	P_2O_5 – 0.3%	CO_2 – 0.1%
MnO – 0.1%		

4.4.3 Mineralogical Composition of Magma

We have read the chemistry of magma let us study its mineralogy. As magma cools and solidifies, the elements (SiO_2 and Al_2O_3) mentioned in above subsection combine to form two major groups of silicate minerals (Table 4.2). The dark silicate minerals (mafic) are rich in iron and/or magnesium (ferromagnesium) and are comparatively low in silica. Olivine, pyroxene, amphibole and biotite mica are the common dark silicate minerals. The light silicates contain greater amounts nonferromagnesium minerals like light silicates (felsic) which include quartz, muscovite mica and feldspar group (orthoclase, microcline, and plagioclase) minerals and are richer in silica. Feldspars make up at least 40% of most igneous rocks. Felsic minerals are highest in silica and mafic minerals are lowest in silica content.

Table 4.2: Common minerals found in igneous rocks.

Compositional Groups	Minerals	Chemical Composition
FELSIC	Quartz	SiO_2
	Orthoclase feldspar	KAlSi_3O_8
	Plagioclase eldspar	KAlSi_3O_8 ; $\text{CaAl}_2\text{Si}_2\text{O}_8$
	Muscovite (mica group)	$\text{KAl}_3\text{Si}_3\text{O}_{10}(\text{OH})_2$

MAFIC	Olivine	$(\text{Mg,Fe})\text{SiO}_4$
	Pyroxene Group	$(\text{Al, Ca, Fe, Mg}) \text{SiO}_3$
	Amphibole Group	$(\text{Mg, Fe, Ca, Na})\text{Si}_8\text{O}_{22}(\text{OH})_2$
	Biotite (Mica)	$(\text{K,Mg, Fe, Ca, Al})\text{Si}_3\text{O}_{10}(\text{OH})_2$

4.4.4 Major Types of Magmas

Do you know that even a single magmatic province or an individual eruptive centre can give rise to a variety of rock types? Earlier the petrologists thought that the four different types of magma existed corresponding to each rock type, viz. felsic, mafic, intermediate, ultramafic. But now it is widely accepted that there is single parental magma which is homogenous and basaltic in composition. N.L. Bowen in 1923 established the concept of primary magma that can produce secondary magma or parental magma types. He advocated that all the different varieties of igneous rocks are supposed to have originated from a single parental magma by offering more logical interpretation for rock diversification or differentiation. We will read about magma differentiation further in this unit.

Let us consider an analogy to understand magma. Imagine four pots of molten chocolate simmering on a stove. Each pot contains a different type of chocolate, i.e. milk chocolate, bitter chocolate, dark chocolate, and resin chocolate. It is obvious that different kinds of molten chocolate yield different chocolates on solidification; each type differs from the others in taste and color. Similarly, like molten chocolate, not all molten magma is the same. Specifically, magmas differ from one another in terms of their chemical composition. Geologists distinguish following four major types of magma on the basis of silica (SiO_2) percentages (Table 4.3):

- **Felsic magma** contains a high proportion of feldspar and silica. “Fe” stands for feldspar and “Si” stands for silica.
- **Intermediate magma** gets its name simply because this type has a composition between felsic and mafic.
- **Mafic magma** contains relatively high proportion of iron oxide (FeO , or Fe_2O_3) and magnesium oxide (MgO). “Ma” stands for magnesium and “fic” stands for iron.
- **Ultramafic magma**, as the name suggests, contains even lesser amount of silica as compared to mafic magma.

As suggested by N.L. Bowen essentially, the magma is basaltic in nature. However, based on mineralogical and chemical composition, magma can be categorised as shown in Table 4.3. It is obvious from the above fact that different types of rocks are formed due to differentiation of magma. This process is called magmatic differentiation. **Magmatic differentiation** is the process by which magma is able to diversify or differentiate and produce rocks of a different composition. We will learn about magmatic differentiation in the next section of this unit.

Table 4.3: Summary of the chemical composition and physical properties of four magma types.

Magma Type	Rock Types	Chemical Composition	Temperature	Viscosity	Volatile Content
Felsic	Rhyolitic	SiO ₂ 65-75%, low in Fe, Mg, Ca and high in K, Na	650-800°C	High	High
Intermediate	Andesitic	SiO ₂ 55-65%, intermediate in Fe, Mg, Ca, Na, K	800-1000°C	Intermediate	Intermediate
Mafic	Basaltic	SiO ₂ 45-55%, high in Fe, Mg, Ca and low in K, Na	1000-1200°C	Low	Low
Ultramafic	Picritic	SiO ₂ 38-45%, Fe–Mg > 8% up to 32% MgO and lowest in K, Na	Up to 1500°C	Very low	Low

We have read about physical properties, components and composition of magma.

Before discussing about origin of magma spend some time to check your progress.

SAQ 1

- Define Primary magma.
- How the composition of magma affects viscosity?
- Mention the three components of magma.
- What is silicon-oxygen tetrahedral?

4.5 ORIGIN OF MAGMA

You have read in Unit 3 Structure and Composition of Earth of BGYCT-131 that the Earth's crust is about 35 km thick under the continents and 7 kms beneath the oceans.

The natural magmas display a wide variation in chemical composition, and that the variation is very systematic. You must be thinking why is the overall range of magma compositions the same.

Petrologists have spent countless man hours during the past century in trying to answer these questions. Based on the knowledge generated the geologists can confidently say that the overall compositional range and systematic variation in

the composition of natural magma is primarily an indication of two important processes taking place within the earth. These two processes are called partial melting and fractional crystallisation. **Partial melting** controls the composition of an initial magma when it is formed deep within the earth. **Fractional crystallisation** is a process that changes the composition of magma as it makes its way toward the surface. It is envisaged that nearly all magmas originate through partial melting of the upper mantle, under special physical conditions. Some magmas result from melting of rocks in the lower regions of the continental crust.

But question is why do mantle and/or lower crustal rocks melt.

We know that the Earth is not covered everywhere with volcanoes, there must be various regions of the earth in which various processes cause melting of rocks. The following three processes either alone or in combination with one another, can cause upper mantle (and lower continental crustal) rocks to melt:

- increase in temperature;
- decrease in pressure; and
- addition of fluids dominated by H₂O.

The magma is originated at various levels within the Earth's crust and upper mantle to depths of perhaps 250kms. Earth's crust is made up of relatively low-density materials and the mantle comprises denser rocks. Most of the magmas which form igneous rocks are generated within the upper parts of the mantle at the temperature estimated between 600°C and 1200°C. As magma cools, minerals crystallise from the melt at different temperatures.

4.6 BOWEN'S REACTION SERIES

On the basis of petrographic study geologist have identified different types of igneous rocks on large scale. The critical approach to petrography was validated with the intensive field investigations. The study of the genetic aspects of igneous rocks is known as **petrogenesis**. The petrologists became involved with genetic aspects of rocks which led them to think in terms of "evolution of igneous rocks". This eventually marked the turning point in petrology from petrographic approach to petrogenetic approach. The pioneering studies by Dr. N. L. Bowen in 1922 enunciated the Bowen's reaction series or principle which developed fundamental ideas on the magmas, their trend of evolution and origin (Fig. 4.1). This sequence of crystallisation is also known as **Bowen's reaction series** or **Bowen's reaction principle**. In this series, the minerals are so arranged that each is supposed to react with the magmatic fluid so as to produce the new mineral placed below it. Bowen's reaction series illustrates how magma may solidify as a single rock type or it may also give rise to many rock types.

You can observe in Figure 4.1 that there are two parallel series in Bowen's reaction series. On the left side is **discontinuous series** which represents transformation of structure and composition of ferromagnesian minerals with decreasing temperatures. Whereas on the right side is the **continuous series** which represents the cooling and crystallisation of the minerals of plagioclase series with decreasing temperature. Both the two series, i.e. discontinuous

series and continuous series converge and merge into single series which also forms a part of discontinuous reaction series. In the continuous reaction series as the name suggests the minerals continuously react with the magma forming the next mineral in the plagioclase series. On the contrary in the discontinuous reaction series the new minerals are formed when the magma reacts with the earlier formed minerals at a particular temperature. The minerals in the Bowen's reaction series indicates a generalised order in which each mineral crystallises from a cooling basaltic magma. Unless the early formed crystals are removed from the melt its composition can be changed further. After the early formed crystals are removed the reaction between magma and the crystals formed takes place to produce new minerals. The temperature range for Bowen's reaction series is from 1100°C to 573 °C. The crystallisation of silicate minerals begin to take place with the crystallisation of the minerals of spinel group at a temperature of about 1100° C. **Spinel** (MgAl_2O_4) is an oxide group of mineral with cubic symmetry often occurring as octahedral crystals.

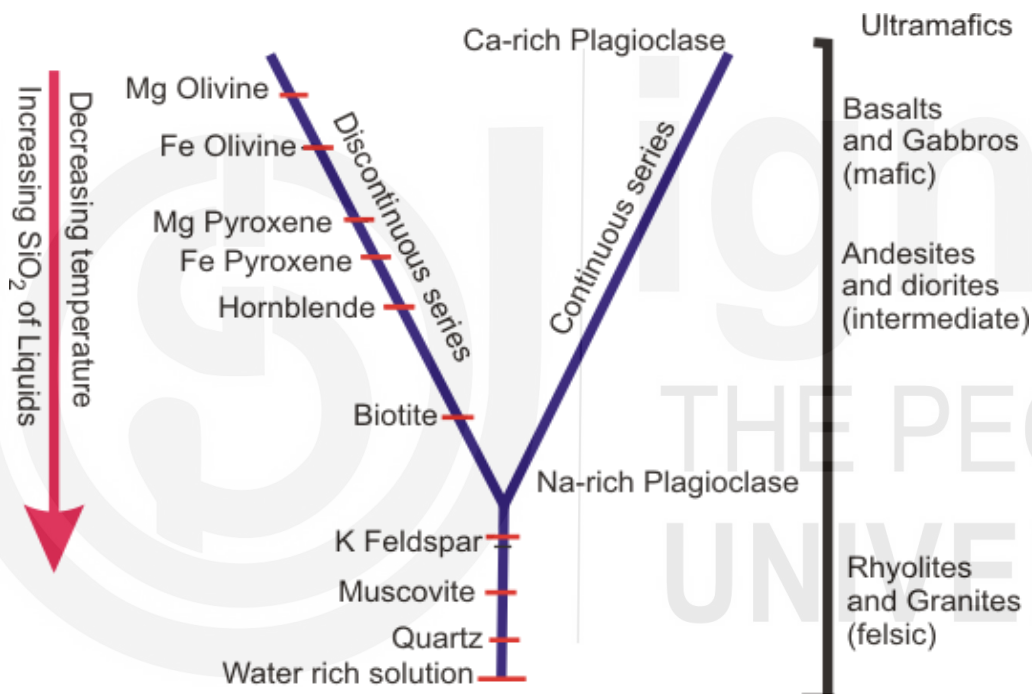


Fig. 4.1: Bowen's reaction series.

4.6.1 Discontinuous Reaction Series

You have learnt about the continuous and discontinuous series in the previous subsection. The first mineral to crystallise in the discontinuous reaction series is Mg-rich olivine followed by Fe-rich olivine. You have read in the previous subsection that as soon as olivine is formed, unless it is removed from the crystallisation site, it reacts with the magma so as to produce the next mineral in series. Thus, with the falling temperature Mg-rich olivine (mineral forsterite) is converted to Fe-olivine (mineral fayalite). This further continues till the whole of olivine is converted into Mg-pyroxene, under ideal physico-chemical conditions. As the crystallisation of magma proceeds, there is a tendency for equilibrium to be maintained between solid and liquid phases. Thus, the early formed crystals react with the liquid and changes in composition takes place in order to maintain this equilibrium. The two minerals in the series are called as '**reaction**

pair'. For example, Mg-pyroxene after reacting with the remaining magma gets converted into Fe-pyroxene and then to hornblende which further gets transformed to biotite, with the falling temperature.

4.6.2 Continuous Reaction Series

After discussing about the discontinuous series let us learn about the continuous series of the Bowen's reaction series. This is the series consisting of plagioclase minerals which begin crystallising more or less simultaneously with olivine or little later. The first formed plagioclase crystals are richest in calcium; as reaction goes on and the temperature drops, the crystals become progressively more sodic. This fact is well recorded in zoned plagioclases in which core is more calcic surrounded by successive soda rich zones.

The partial failure of reaction between olivine and melt/magma results in the enrichment of the liquid in silica and the final crystallised product may be a mixture of olivine, pyroxene and quartz. In this case, the quartz is called a **released mineral**. Rocks containing released minerals are called **dolomitic rocks**. Thus, dolomitic rocks contain released minerals due to incomplete reaction or relics of early minerals which has escaped reaction.

4.6.3 Importance of Bowen's Reaction Series

We have learnt about the Bowen's reaction series now let us read about its importance.

- It establishes the process of differentiation and diversification of magma.
- It illustrates that a magma may solidify as a single rock type or may give rise to many rock types. The primary basaltic magma may solidify as a gabbro, diorite, granodiorite to granite depending upon the degree of fractionation and the extent of the removal of the early formed minerals from further reaction with the melt.
- The silicate structure becomes more complicated from early formed minerals like olivine to the minerals like quartz.
- The early formed crystals are denser (rich in Mg and Fe) than the late formed minerals in the Bowen's reaction series.

4.7 MAGMATIC DIFFERENTIATION AND ASSIMILATION

We have known that the model of magmatic evolution based on the differentiation of primary basaltic magma, was outlined by Bowen in 1928. There are two main reasons for the origin of diverse igneous rocks:

- Magmatic Differentiation
- Assimilation

4.7.1 Magmatic Differentiation

Magmatic differentiation may be defined as a process operating within the magma (involving solid, liquid and gaseous phases) by which homogenous parent magma breaks up into fractions with diverse composition and forms different rock types.

We must remember that the process of differentiation is concerned only with variations which have clearly risen within an originally uniform body of magma. But not with the heterogeneity produced within an igneous mass by successive intrusion of different magmas or by assimilation of foreign rock material. Magmatic differentiation may be effective, when the magma is in a fluid state (only liquid or liquid + vapour system). Now Let us discuss about the important mechanisms of magmatic differentiation when:

- magma is in fluid state
- solid mineral phases are involved

A) Magma is in Fluid State

The following processes are operational when the magma is in fluid or liquid state.

- **Liquid immiscibility:** A mixture of two different components may be homogenous at a particular temperature, but with falling of temperature they become immiscible and separate as droplets or bubble from other by the difference in specific gravity. The phenomenon of liquid immiscibility explains presence of sulphides in silicate magma.
- **Liquid fractionation:** This is considered an important and effective mechanism by petrologists in the differentiation of a homogenous magma. In case of thermal gradient, the compound with which the solution is nearly saturated tends to accumulate in cooler horizons; gravitational diffusion involves separation and stratification of element in a homogenous magma under the influence of gravity.
- **Movement of volatiles:** Volatiles are excellent solvents. They are capable of making selective transfer of material from lower to higher levels, thus developing inhomogeneity in magma. We have read that with the release of pressure the volatiles tend to migrate towards areas of least pressure and distil off.

B) Solid Mineral Phases Involved

The fractional crystallisation takes place when solid mineral phases are involved in the magmatic crystallisation. Let us read the mechanism of fractional crystallisation before reading about the processes involved in it.

Fractional crystallisation: With the cooling and solidification of magma the crystallisation of the minerals begins. Crystallisation may be localised at margins, where the cooling is faster and the temperature is lower than in the central part. By the action of diffusion, the minerals formed during early crystallisation may be concentrated towards the margin of an igneous body. The core of the igneous body is more felsic as compared to the outer part which is more mafic due to crystallisation and differentiation. During crystallisation, there is a tendency for equilibrium to be maintained between the solid and liquid phases in the magma, as we have read in Bowen's reaction series. In order to maintain equilibrium between the early formed crystals react with the liquid and the changes in composition of magma takes place. In case of plagioclase, for instance the first formed crystals are those richest in calcium, as reaction proceeds with falling temperature, the crystals become progressively sodic.

Thus, Bowen's reaction principle illustrates how a primary basaltic magma may solidify as gabbro or it may give rise to rocks varying through dunite, gabbro, diorite, granodiorite, granite depending upon degree of crystal fractionation and extend to which early minerals are formed and removed from magma or melt.

Fractional crystallisation or crystallisation differentiation takes place through mechanisms like:

- Gravity settling
- Filter Pressing
- Flowage of magma
- Crystal zoning

1) **Gravity settling:** Crystal fractionation involves sinking, floating or suspension of early formed crystals within magma body. Monomineralic rocks such as dunite, pyroxenite and anorthosite are formed by this process caused by the gravitational sinking of olivine, pyroxene and calcic plagioclase respectively. The rocks formed by accumulation of crystals are described as **cumulates** (Fig. 4.2). The separation of accumulated crystals changes the composition of the melt (Fig. 4.3) which leads to the evolution and diversification of magma.

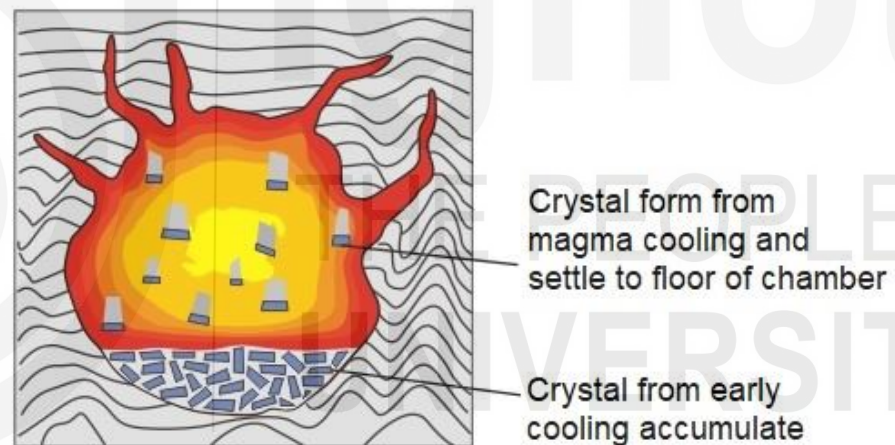


Fig. 4.2: Separation of early formed crystals from the melt under the influence of gravity in magma chamber.

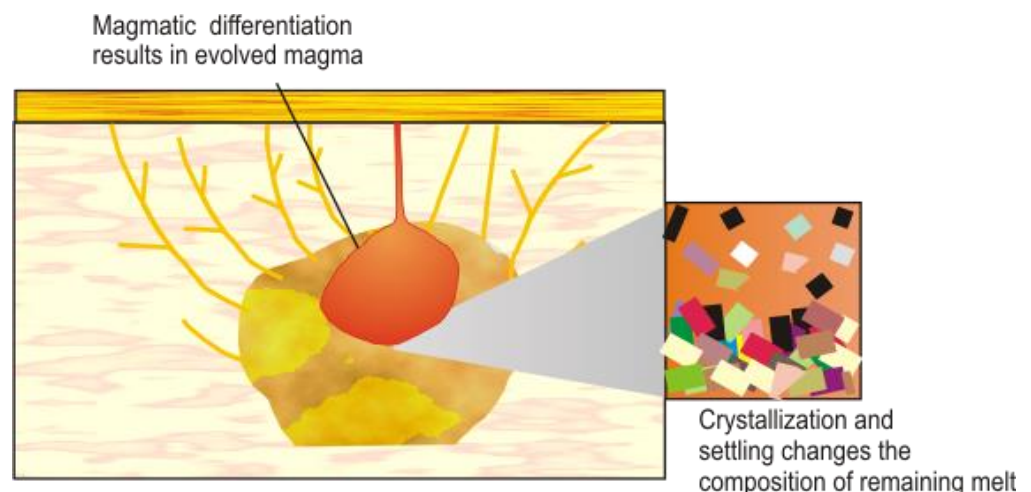


Fig. 4.3: Crystallisation and gravity settling changes the composition of the remaining melt.

- 2) **Filter Pressing:** This involves mechanical separation of coexisting magma from the crystal mesh. As the crystallisation continues a loose mesh or framework of crystals with residual liquid is formed. At this stage if the deformation of the crystallising mass occurs, the residual liquid will be squeezed out leaving behind the early formed crystals. This process of separation of solid crystals from the fluid magma is known as filter pressing.
- 3) **Flowage of magma:** You may observe that as the fluid moves along a pipe or a narrow channel, its flowage behaviour at the centre and away from the contact walls is different. This mechanism can result in preferential accumulation of early formed minerals. The rate of flow of magma changes rapidly towards the walls of an intrusion than at its centre.
- 4) **Crystal Zoning:** It is a common phenomenon in igneous rocks. If equilibrium during the crystallisation is disturbed, the successive liquids and corresponding zones will have different composition. For example, calcic plagioclase will successively be rimmed by more sodic rich species.

SAQ 2

- a) Distinguish between discontinuous and continuous series.
- b) Define magmatic differentiation.
- c) List the mechanisms for fractional crystallisation.
- d) How are the cumulates formed?

4.7.2 Assimilation

We have learnt about mechanisms of magma differentiation both in fluid state and when solid mineral phases are involved. Now let us read about another process of magmatic differentiation, i.e. assimilation.

Assimilation is the process whereby foreign rock masses are incorporated by magmas. This also includes the mingling of two liquid magmas, i.e. **magma mixing**. Assimilation is an important factor in bringing about diversity in the igneous rocks. Since these processes involve the remixing of rocks with magmas therefore, they represent the reverse of the differentiation processes resulting in heterogeneity and incomplete and nonuniform mixing.

The process of assimilation too is governed by the laws of Bowen's reaction principle. The reaction between magma and host or wall or country rock is a normal phenomenon during igneous intrusion (Fig. 4.4). In the course of this reaction the magma becomes contaminated by incorporating materials originally presenting the wall rock (Fig. 4.5).

Assimilation or incorporation of foreign rock matter in the magma occurs as:

- mechanical incorporation without chemical reaction;
- reactions involving partial solution of incorporated matter and solid phase;
- total dissolution and reaction involving disappearance of the solid phase.

The factors affecting assimilation include:

- temperature of magma at the time intrusion,
- presence or absence of notable degree of superheat,
- composition of the xenoliths or inclusions,
- concentration of volatiles in the magma, and
- conditions which facilitate or retard escape of volatiles into surrounding rocks.

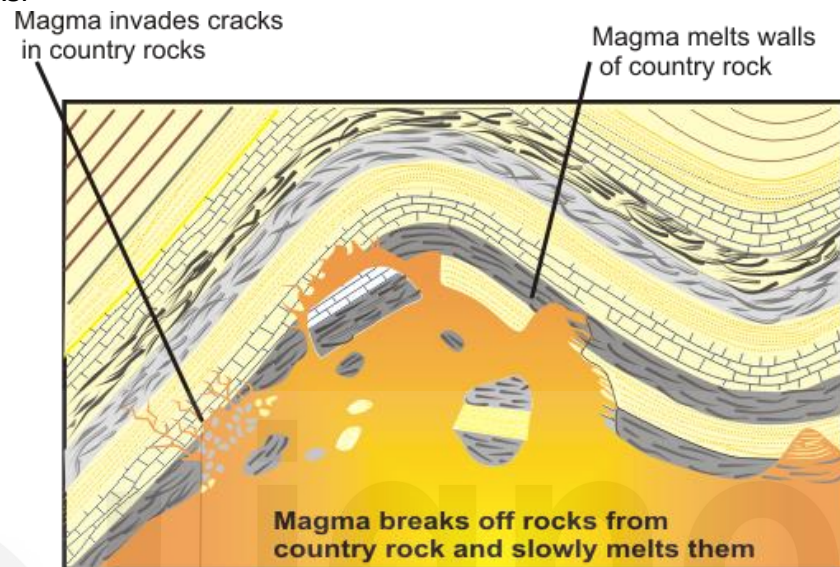


Fig. 4.4: Reaction between magmatic intrusion and wall rock.

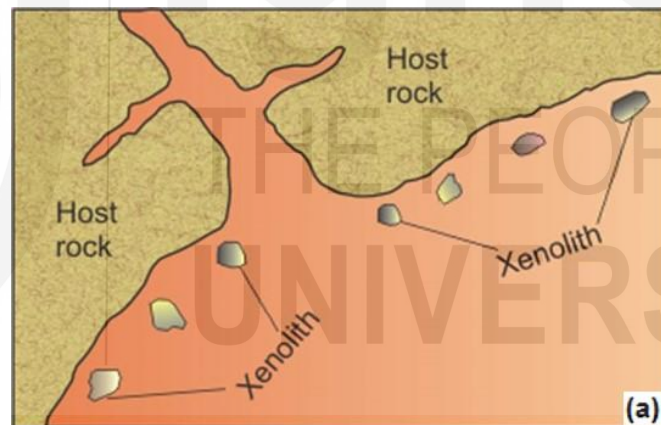
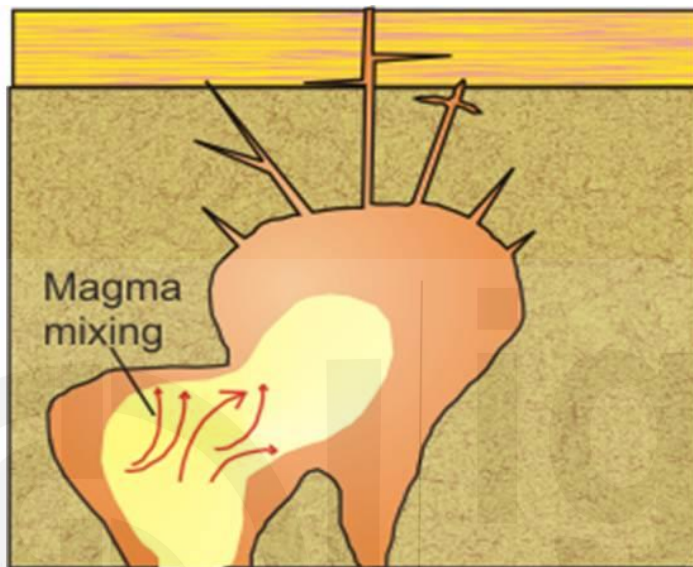


Fig. 4.5: a) Xenoliths of host rock in magmatic intrusion; and b) Xenoliths of basaltic rock in granite.

Magma mixing can take place when two or more magmas with different chemical compositions come in contact with one another beneath the surface of the Earth (Fig. 4.6). The mixing of the magmas produces compositions intermediate between the end members. If the composition of magmas are very contrasting (rhyolite and basalt), there are several factors that could prevent their mixing. The possible reasons for this may be contrast in temperature, density and viscosity. But there is evidence that magmas do sometimes mix. If there is lesser difference between the chemical compositions between two magmas probability of their mixing will be more.



(a)



(b)

Fig. 4.6: a) Sketch showing mixing or co-mingling of two magmas; and b) Field photograph indicating mixing of magma. (Photo credit: Ganga Singh Bhartiya)

4.8 SUMMARY

In this unit we have learnt about the concept and composition of magma, Bowen's reaction series and magmatic differentiation of igneous rocks. Let us summarise about what we have learnt in this unit:

- Geologists refer to melt beneath the ground surface as magma and melt that has emerged at the Earth's surface as lava.
- Magma consists of complex mixtures of solids, fluids and dissolved gases. Volatiles impart low viscosity to the magmas.
- Bowen's reaction principle illustrates differentiation and diversification of magma. It displays the crystallisation of the minerals in continuous series and discontinuous series, with decreasing temperature from 573°C to 1100°C.
- Magmatic differentiation is the process by which homogenous parent magma breaks up into fractions with diverse composition and forming different rock types through mechanisms like liquid immiscibility, liquid fractionation, movement of volatiles, fractional crystallisation, gravity settling, filter pressing, flowage of magma and crystal zoning.
- Assimilation is the process by which rock masses are incorporated by magmas. It also includes the mixing of magmas.

4.9 ACTIVITY

- Redraw Bowen's reaction series in your notebook and write the names of rocks which would crystallise with different mineral assemblage and at different temperature.

4.10 TERMINAL QUESTIONS

1. Discuss the physical properties of magma.
2. Explain Bowen's reaction series.
3. Describe various mechanisms of magmatic differentiation.
4. What is assimilation and magma mixing?

4.11 REFERENCES

- Tyrell, G. W. (1973) The principles of Petrology. John Wiley & Sons. ISBN 0470894806, 9780470894804, 349p.

4.12 FURTHER/SUGGESTED READINGS

- Mukherjee, P.K. (2000) A Text Book of Geology. The World Press, Kolkata, ISBN:81-87567-09-0, 638p.
- Singh, Parbin: Engineering and General Geology. S.K. Kataria and Sons. ISBN: 8188458511, 9788188458516, 600p.
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4.13 ANSWERS

Self Assessment Questions

- 1 a) Primary magma refers to the initial composition of magma before it underwent any differentiation process. Primary magma must have >10% MgO by weight. Primary magma by the process of differentiation

evolves into parental magma. In other words, they are modified by the process of differentiation.

- b) Viscosity depends primarily on the composition and temperature of magma. The volatiles impart low viscosity to the magma. Felsic magma has higher viscosity as compared to mafic magma. This is because of the complexity in the crystal structure of felsic magma.
 - c) Magma has three components (i) liquid portion is called melt which consists mainly of mobile ions of the eight most common elements found in the Earth's crust; (ii) solid components in the magma are silicate minerals that have crystallised from the melt; and (iii) gaseous components of the magma are called volatiles.
 - d) In a silicon–oxygen tetrahedron a silicon atom is surrounded by four oxygen atoms arranged in the corners of a tetrahedron.
- 2 a) Bowen's reaction series comprise of two parallel series – the reaction of ferromagnesian minerals called as “discontinuous series”. The “continuous series” represents the cooling and in continuity crystallisation of the minerals of plagioclase series with decreasing temperature.
- b) Magmatic differentiation may be defined as a process operating within the magma (involving solid, liquid and gaseous phases) by which homogenous parent magma breaks up into fractions with diverse composition and forms different rock types.
 - c) They are gravity settling, filter pressing, flowage of magma and crystal zoning.
 - d) Cumulates are formed by the process of gravity settling of earlier formed crystals during magmatic differentiation.

Terminal Questions

1. Your answer should include all points given in section 4.4.
2. Your answer should include all points given in section 4.6.
3. Your answer should include all points given in section 4. 7 and its subsections.
4. Your answer should include all points given in section 4.7.2.

CRYSTALLISATION OF MAGMA|

Structure

5.1 Introduction

Expected Learning Outcomes

5.2 Phase Rule

Phase Diagram

Condensed Phase Rule

5.3 Unicomponent System

Crystallisation behaviour of H₂O System

Crystallisation behaviour of SiO₂ System

5.4 Binary System

Binary System with Complete Solid
Solution of Two End Members

5.5 Lever Rule

5.6 Binary Eutectic System

5.7 Summary

5.8 Activity

5.9 Terminal Questions

5.10 References

5.11 Further/Suggested Readings

5.12 Answers

5.1 INTRODUCTION

In Unit 4, we have already learnt that the magma consists of complex mixtures of solids, fluids and dissolved gases. Essentially, they are very hot silicate melts containing large quantities of water and varying amount of highly reactive fluids and gases in the solution. You have also learnt that the volatiles impart low viscosity to the magma. The minerals in igneous rocks crystallise at a range of different temperatures. You have read in Unit 4 that the sequence in which minerals crystallise out from the magma is studied under the Bowen reaction series. In this unit, you will study about unicomponent and bicomponent or binary systems, the application of phase rule and equilibrium crystallisation.

Expected Learning Outcomes

After reading this unit you should be able to:

- ❖ define phase rule and phase diagrams;
- ❖ describe unicomponent and bicomponent/ binary systems;
- ❖ explain the application of phase rule; and
- ❖ discuss binary eutectic system.

5.2 PHASE RULE

It is important for you to understand the contribution of each chemical constituent existing in any system of the universe. The effects that occur by the addition or subtraction of constituents in the system will also be considered. This will not only help us to understand each system better, but also enable us to study more complex systems in nature. The fundamental and simple approach for this is the **Phase rule**. Before reading about the phase rule, let us get familiar with a few terms.

- **System:** It is part of the universe that one can isolate (either physically or mentally) to study it. Types of system:
 - 1) **Open System:** A system may be open, if it can transfer energy and matter to and from the surroundings.
 - 2) **Closed System:** In a closed system, only energy, such as heat, may be exchanged with the surroundings.
 - 3) **Isolated System:** Neither energy nor matter may be transferred with the surroundings.
- **Surroundings:** Surroundings can be considered the bit of the universe just outside the system.
- **Phase:** Phase is defined as a chemically and physically homogenous part of a system that is bounded by an interface with adjacent phases.
- **System Components:** Smallest number of chemical constituents needs to make up all phases in the system.
- **Variance (also known as the Degrees of Freedom, expressed as "f"):** Minimum number of variables that need to completely define the state of a system at equilibrium.

The state of a system is described completely by defining macroscopic properties of the system, which include temperature, pressure, composition, mass, volume and other interdependent properties. Gibbs phase rule was formulated by American Chemist J. Willard Gibbs and so it is named after him. It is used in the determination of the variance or degrees of freedom of a system (f). Phase rule is applicable only to the heterogeneous reversible reactions which are in equilibrium, whereas other reversible reactions are studied using "law of action."

Phase Rule governs the number of phases that can co-exist in an equilibrium in the system and is expressed as:

$$F = C - P + 2 \text{ or } F + P = C + 2$$

Where, P= Number of phases present in a system

F= Degree of Freedom

C= Components

2= Two intensive parameters usually T (temperature) and P (pressure).

As stated above, phase is physically distinct in a system (based on their composition, structure and/or state) that is mechanically separable from the rest. It may be a liquid or gas or solid.

For example:

Matter	Number of Phases
Ice	1 (solid phase)
Ice + water	2 (liquid+solid)
2 piece of ice	1 (only different pieces)

To understand a phase diagram, it is very important to know about its components. A **component** is defined as the minimum number of chemical species required to define a system and all its phases. It is generally expressed as proportion of oxides (SiO_2 , Al_2O_3 , FeO , Fe_2O_3 , H_2O , CO_2 , CaO , MgO). If we consider ice and water, they have only 1 component (H_2O) and 2 phases. To describe silica /quartz system (SiO_2), we can describe it by 3 components (Si, O or SiO_2) but only SiO_2 is good enough to define it. So, number of components is "1".

Number of components depends upon:

- 1) **the behaviour of the system** and
- 2) **the range of conditions over which it is studied.**

For example, at low temperature, calcite is treated as a single component (CaCO_3) system, but at high temperature, it is a two-component system ($\text{CaO} + \text{CO}_2$).

5.2.1 Phase Diagram

The graphical presentation giving the conditions of pressure and temperature under which the various phases are existing and transform from one phase to another is known as the **phase diagram** of the system. A phase diagram consists of areas, curves or lines and points. These diagrams display stability fields of various phases, separated by lines representing conditions under which phase changes occur. They also represent relationship between melt and solids. Phase diagrams are those which show stability fields and relationship between different phases as a function of variables such as P, T and composition (X). Thus, the results of the phase equilibrium experiment which are performed in the laboratory to study the crystallisation and melting behaviour of a magma of definite composition under same P and T conditions are graphically represented by **phase stability diagram**. These diagrams show

constitution of alloys as a function of temperature under equilibrium condition and are also known as **phase equilibrium diagrams**.

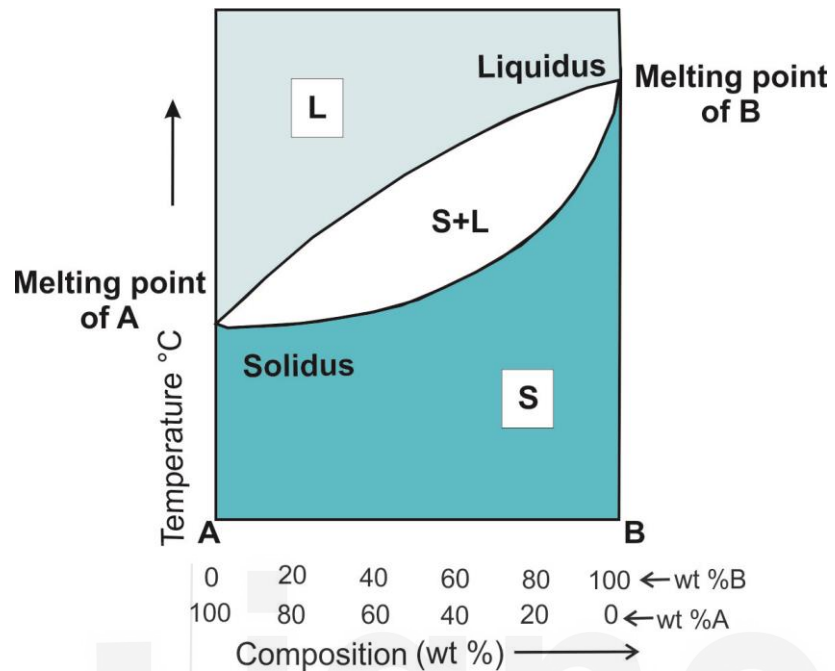


Fig. 5.1: Phase diagram showing solid-liquid-gas behaviour of a substance.

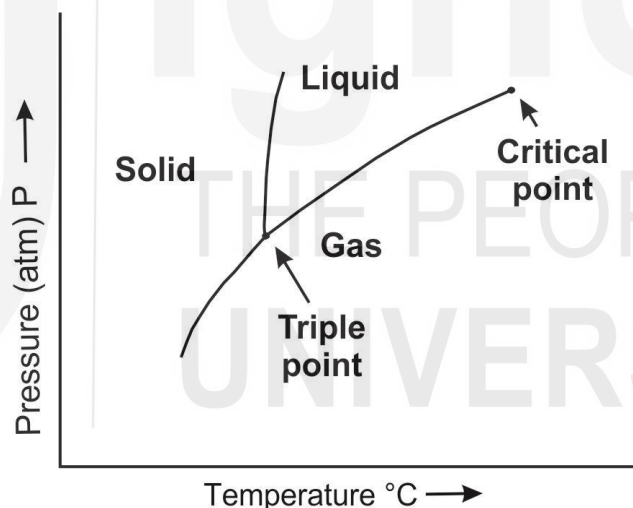


Fig. 5.2: Phase diagram of unicomponent system showing critical and triple point.

In Figure 5.1, temperature is represented as T on Y-axis and composition on the X-axis.

In general, at high temperature, the system is completely in the melt form and 100% melt field is separated from rest of the phase diagram by a boundary called liquidus. **Liquidus** line separates liquid from liquid + solid. The 100% melt exists above this line.

Likewise, low temperature stability field for 100% solid is separated from high temperature condition by a phase boundary line called solidus. **Solidus** is the line below the liquidus line, where 100% solid exists. Solidus line separates solid from liquid + solid. In the intermediate T between solidus and liquidus, the system consists of 2 types of stable phases at an equilibrium i.e., both liquid and solid crystals. Figure 5.2 shows the phase diagram of a unicomponent

system where temperature ($T^{\circ}\text{C}$) is represented on X-axis and pressure (P atm) on Y-axis. The three curves separate these phases, viz. solid, liquid and gas. **Triple point** is the point where the temperature and pressure at which the solid, liquid and vapour phases of the pure substance can exist together at equilibrium (Fig. 5.2). The end point of a phase equilibrium curve is known as **critical point**. It is defined as the point at which two phases of a substance initially become indistinguishable from one another.

You have read in Unit 3 of BGYCT-131 course that the interior of the Earth is inaccessible. Geologists observe only a tiny fraction of the rocks that compose the Earth. A large portion of information about the Earth is indirect, coming from melts of subsurface material, geophysical studies or experiments conducted at elevated temperature and pressure. Thus, it is important to note that the P and T conditions of magma generation and modification can be deduced from the real melting of melt of minerals under laboratory conditions.

5.2.2 Condensed Phase Rule

In cases, where either P or T is kept constant, one can apply the condensed phase rule with the formula:

$$F = C - P + 1$$

This is simply because the total number of variables within the system has now become 1, as only one of the two intensive properties of the system (P and T) is allowed to vary. The condensed phase rule is quite helpful in understanding isobaric T (temperature) – X (composition) or isothermal P (pressure) – X (composition) diagrams as well as experimental geochemistry where either P or T is kept constant to investigate the dependence of a system on the other intensive variable.

5.3 UNICOMPONENT SYSTEM

In the above section you have studied about phase rule and phase diagram. Now let us discuss about unicomponent system. A system having only one component is called **unicomponent system**. The least number of phases possible in any system is one. Thus, according to phase rule, a one-component system should have a maximum of two degree of freedom.

When $C=1$, $P=1$,

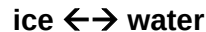
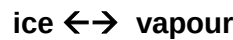
$$\begin{aligned}\text{So, } F &= C - P + 2 \\ &= 1 - 1 + 2 \\ &= 2\end{aligned}$$

Hence, a one component system requires a maximum of two variables (i.e. temperature and pressure) to be fixed in order to define the system completely. Phase diagram of one component system consist of points, curves or lines, areas, and represents a non-variant, univariant and bivariant systems respectively. SiO_2 and H_2O systems are examples of one component system. In the following section let us discuss H_2O system of unicomponent system.

5.3.1 Crystallisation Behaviour of H_2O System

Water is a one component system which is chemically a single compound involved in the system. It constitutes a three phase (ice-solid, water-liquid and

vapour-gaseous) and have the following equilibria that depends upon the conditions of temperature and pressure (variables):



If the values of vapour pressures at different temperatures are plotted against the corresponding temperatures, the phase diagram of the H₂O System (Fig. 5.3) is obtained. It consists of three stable curves and one metastable curve. Water and vapour exist together in equilibrium along the vapour pressure curve of water OB. At point D, the vapour pressure of water becomes equal to the atmospheric pressure (100 °C; boiling point of water). At temperature 374 °C and pressure 218 atm, the curve OB finishes at B where the water and vapour are indistinguishable. The system has one phase and this point is the **critical point**. Applying phase rule on this curve,

C=1, and P=2,

$$\begin{aligned} F &= C - P + 2 \\ &= 1 - 2 + 2 \\ &= 1 \end{aligned}$$

Hence, the curve represents a univariant system, i.e. only one factor either temperature or pressure is sufficient to be fixed in order to define a system. Two phases ice and vapour exist together in equilibrium along sublimation curve of ice OA (Fig. 5.3). The lower end of the curve OA extends to absolute zero (-273 °C) where no vapour exists. In Fig. 5.3 the areas AOC, COB and BOA represent following phases.

Area	Phase	Component
Area AOC	ice	H ₂ O
Area COB	water	H ₂ O
Area below BOA	vapour	H ₂ O

Thus, for every area when C=1 and P=1; Applying phase rule on areas

$$\begin{aligned} F &= C - P + 2 \\ &= 1 - 1 + 2 \\ &= 2 \end{aligned}$$

Hence, each area is a bivariant system, where it becomes necessary to specify both the temperature and the pressure to define a one phase system.

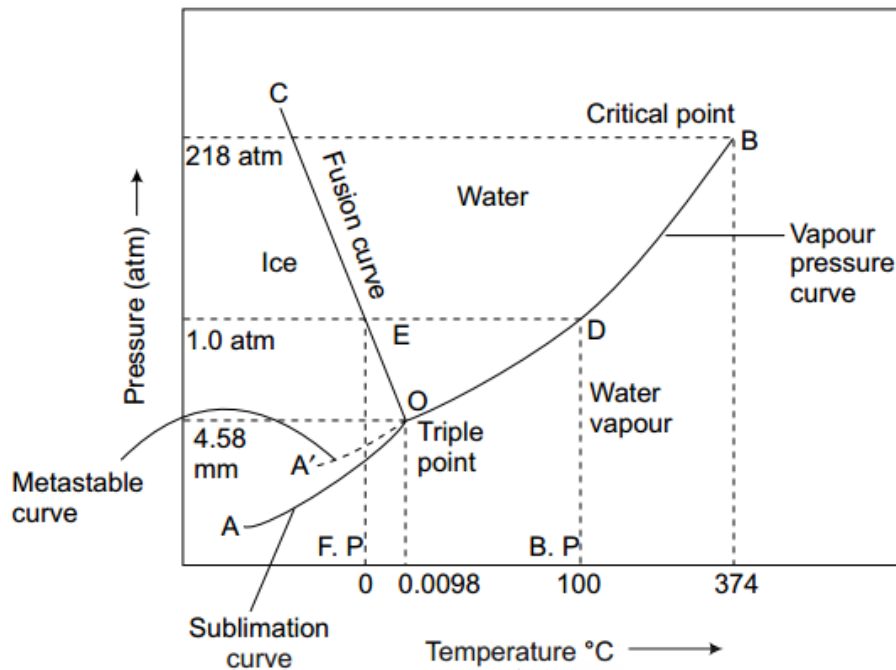


Fig. 5.3: Phase diagram of unicomponent system.

5.3.2 Crystallisation Behaviour of SiO_2 System

In one component system, e.g. silica polymorphs, where silica has number of polymorphs, each having a definite crystal structure and is stable under definite T and P range. The stability field represents the P and T conditions under which each mineral is stable and the phase boundaries define the limits of the stability field as well as the conditions under which phases in the adjoining fields are co-existing. There are various phases in the phase diagram. For any of the phases, we can freely vary P and T without affecting the nature of the phases. It is important to mention that phase rule does not provide any information on the number of phases that exist or are possibly produced in the system. A good example of unicomponent system is the SiO_2 system that consists of many phases as shown in Fig. 5.4.

At a point X, $P=3$ where high quartz, tridymite, cristobalite co-exist as the high quartz - tridymite, high quartz - cristobalite and tridymite-cristobalite phase boundaries intersect.

Here component denoted by $C=1$ (e.g. SiO_2). So, when we apply phase rule it is expressed as:

$$P+F=C+2$$

$$3+F=1+2$$

$$F=0$$

As $F=0$, X is an invariant point. i.e., at this point, 3 phases co-exist in equilibrium but, T and P are invariable, if 3 phases are co-existing.

At the phase-stability boundaries e.g. Y on the Fig. 5.4 (univariate curve)

$P=2$ (stishovite, coesite) and $C=1$,

$$F=1+2-2=1$$

$F=1$, indicating that the P and T are invariant independently. If, T increases, P must have to increase, and vice-versa, for the system to remain on the phase stability boundary, where these two phases co-exist.

For any point within a phase stability field, Z marked on the Fig. 5.4 (bivariant field),

$$P=1(\text{low quartz}) \text{ and}$$

$$C=1(\text{SiO}_2).$$

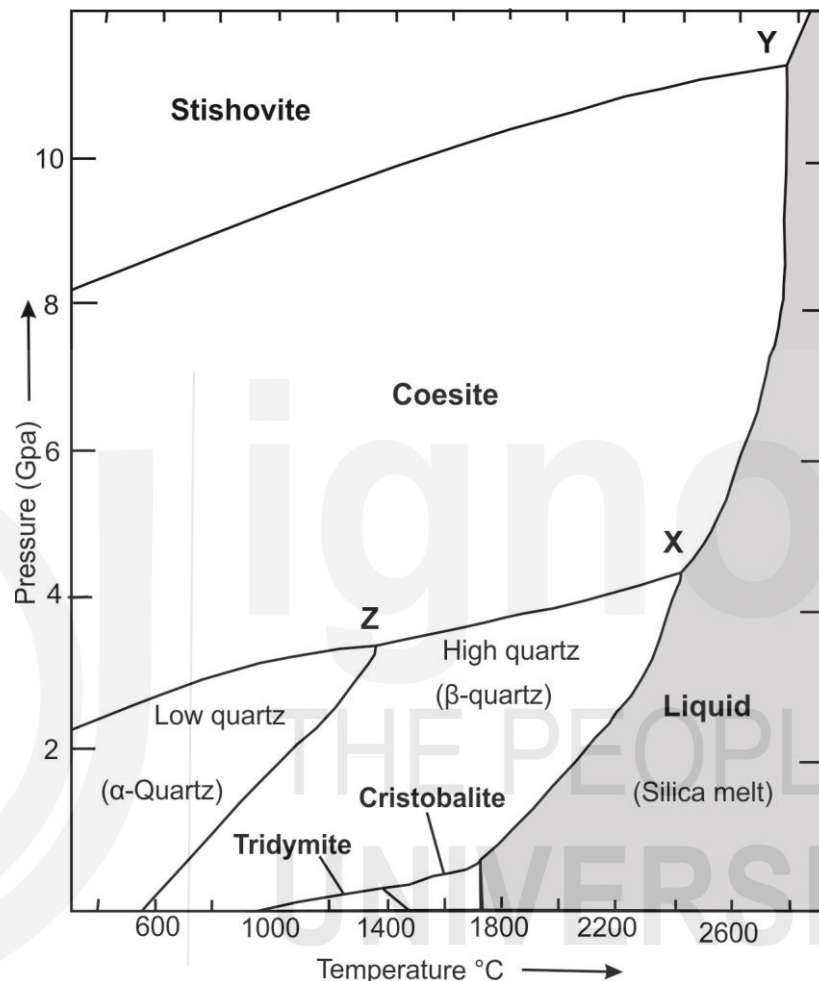


Fig. 5.4: P-T phase diagram for the SiO_2 system (unicomponent system) where following phases are present: melt SiO_2 , low quartz (α -quartz), high quartz (β -quartz), tridymite, cristobalite, coesite, stishovite.

Now $F=2$ indicating that this is a bivariant field and T and P can change independently without changing the phase stability.

In the Fig. 5.4, the shaded portion represents high T condition under which silica is in liquid phase (melt). On cooling, at X (temperature 1650°C and at pressure 0.4GPa), cristobalite begins to crystallise. On further cooling, the system will be reaching the cristobalite-tridymite phase boundary at 1470°C and here cristobalite transforms into tridymite. On continuous cooling at tridymite- high quartz phase boundary, it will transform into high quartz. With further cooling, it reaches the low-quartz/high-quartz phase boundary, where high-quartz is converted into low quartz. Two phases will coexist only at phase boundary during phase transformation. On decompression and cooling, the high-pressure varieties of SiO_2 such as, stishovite and coesite will be converted

into lower polymorphs at suitable T and P ranges. SiO_2 system explains an abundance of quartz as a rock forming mineral (as quartz is the stable polymorph of silica over a broad range of P-T conditions). The existence of coesite and stishovite associated with the meteorite impact and thermonuclear bombsites.

Learners, you have learnt about the phase rule, phase diagram and crystallisation behaviour of unicomponent system. Before discussing about the binary system, spend few minutes to perform an exercise to check your progress.

SAQ 1

- A part of universe that one can isolate either physically or mentally to study is known as _____.
- Equation 'Liquid+Solid1=Solid2' denotes _____ reaction.
- Define phase rule.
- Define triple and critical point.
- What are solidus and liquidus lines?

5.4 BICOMPONENT SYSTEM

You have studied unicomponent system in the above section. Now, let us discuss about bicomponent/binary system. Systems having two components are described as bicomponent system. The binary phase relations are mainly of three different types, such as:

- crystallisation of two end members of a solid solution,
- eutectic crystallisation of two mineral components, and
- incongruent melting of a binary eutectics with the peritectic reaction.

Generally, in nature, only three cases are possible when two components are mixed together.

- Mixed-crystals form which are miscible and form a solid solution series in indefinite proportions.
- Miscible crystals of composition 1 and composition 2 will be formed (due to eutectic reaction), which are of definite proportions.
- Two immiscible components form a crystal of intermediate composition by reaction only.

5.4.1 Binary System with Complete Solid Solution of Two End Members

Minerals with very similar mineral lattice structures mix easily on the atomic scale. This phenomenon is defined as **solid solution of one phase with the other phase**. The most common example in the igneous petrology which shows such behaviour is of olivine and plagioclase minerals. Now, let us define the term mixed crystals and solid solution series. When the two components are isomorphous and miscible in all proportions in solid state, they form

homogeneous crystals which are called as **mixed crystals**. **Solid solution** forms where both components are isomorphous and constituent ions have similar ionic radius and equal ionic charge. In this case, both the components in solid and melt phases change during equilibrium crystallisation and both the components mixed completely with each other.

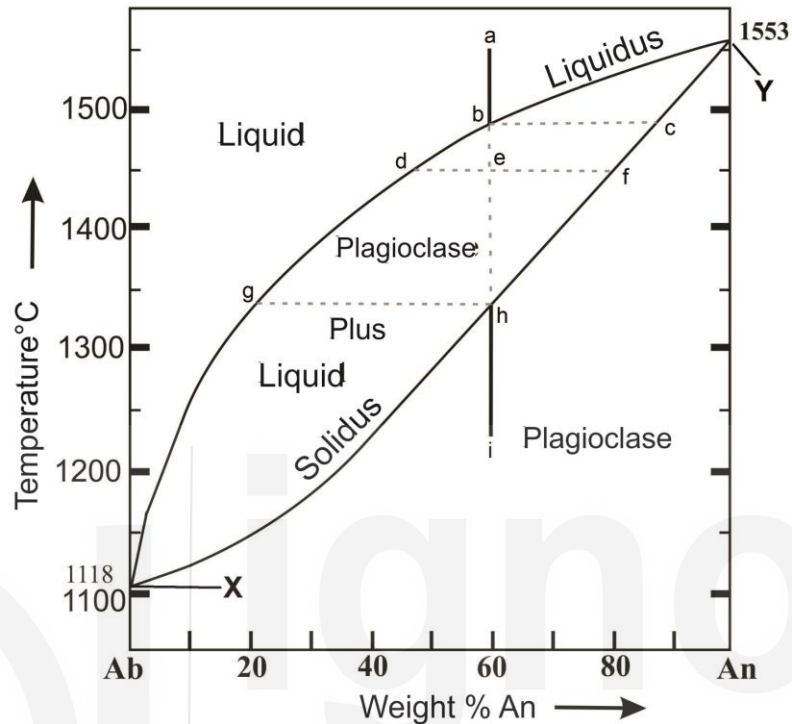


Fig. 5.5: Isobaric T-X phase diagram for Albite-Anorthite (Ab-An) system at atmospheric pressure.

Now you will learn about binary system with complete solid solution of the two end members with the help of Albite ($\text{NaAlSi}_3\text{O}_8$) - Anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$) (Ab-An) system. In Ab-An system, solid solution coupled with Na^{+1} and Si^{+4} substitution for $\text{Ca}^{+2} + \text{Al}^{+3}$ in a constant AlSi_2O_8 reference framework is involved.

In the above Fig. 5.5, pure albite (Ab) is taken on the right end and the pure anorthite (An) on the left end of the X axis. These two pure systems behave like a typical isobaric one component system. In this system, solid-melt that coexists in a single phase at a fixed temperature in equilibrium ($P=2$).

When applied in the phase rule ($F=C-P+2$), it is expressed as

$$F = 1 - 2 + 1$$

$$F = 0 \text{ (invariant point)}$$

Pure Ab and An melts at 1118 °C and 1553 °C at X and Y points respectively. Now, let us examine what happens when we add a component on either of the pure systems. In the experiment, when we add Ab component to pure An component, the melting point lowers down. In case of addition of pure Ab, melting point rises. Now, let us use the phase rule to analyse the behavior of melt of an intermediate composition.

Now, first consider a melt of a composition 'a' in Fig. 5.5 at 1600 °C ($\text{An}_{60}\text{Ab}_{40}$), we take it as the bulk composition (X_{bulk}) of the system. At about 1600 °C, liquid composition is An_{60} . In this case, the liquid composition is equal to the bulk composition as the system is entirely of liquid composition. Thus, in this case $P=1(\text{liquid})$ and $C=2$.

Applying phase rule ($F=C-P+2$), we have

$$F = (2+1-1) = 2$$

This means that for a single two component liquid at a constant pressure, $F = 2$. The two most realistic intensive variables that we can take to define the system include:

- 1) temperature, and
- 2) composition (X_{liqAn} or X_{liqAb}).

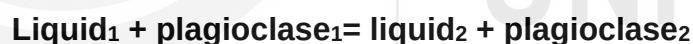
After cooling the system to point 'b' ($\text{An}_{60}\text{Ab}_{40}$) in Fig. 5.5 at about 1475 °C, plagioclase of composition 'c' (An_{87}), which is different from that of the melt begins to crystallise indicating that the initial crystal is An-rich. The line connecting **b** and **c** i.e., the composition of the co-existing phases at a definite temperature is called a 'Tie line'.

Now, with the help of a phase rule, at any point on the liquidus curve, $P=2$ (co-existing liquid and solid) and $C=2$. So,

$$F=2-2+1 = 1$$

Here, only one intensive variable is sufficient to define a system completely.

With continuous cooling, both liquid and solid vary in compositions. The liquid composition changes along the liquidus from **b** to **g** in Fig. 5.5 and the plagioclase changes from **c** to **h** indicating that with continuous cooling, both crystal and liquid become more sodic (Ab rich). In this case, the reaction is represented by:



Such reactions having at least one degree of freedom that occur by exchange of components over a range of temperature and or pressure are called continuous reaction and form a series of mixed crystals.



Watch the following video to learn more about solidus and liquidus curves.

- **Exsolution Intergrowth**

Link: <https://youtu.be/7SnfV0nJMvk>

5.5 LEVER RULE

Now let us study about lever rule. In addition to their mineralogical compositions, a phase diagram also furnishes information related to the modal proportions of phases. The technique used to find out this information is known as **lever rule**. It can be used to determine the fraction of liquid and solid phases for a given binary composition and temperature that is between the liquidus and solidus line. Using the length of a tie line at any specific

temperature, we can calculate the relative amount of phases in a system. The tie line in the two-phase regions is analogous to a lever balance on a fulcrum. This geometric approach is called “Lever rule”. Let’s consider the tie-line ‘df’ (Fig. 5.6) we can represent it as-

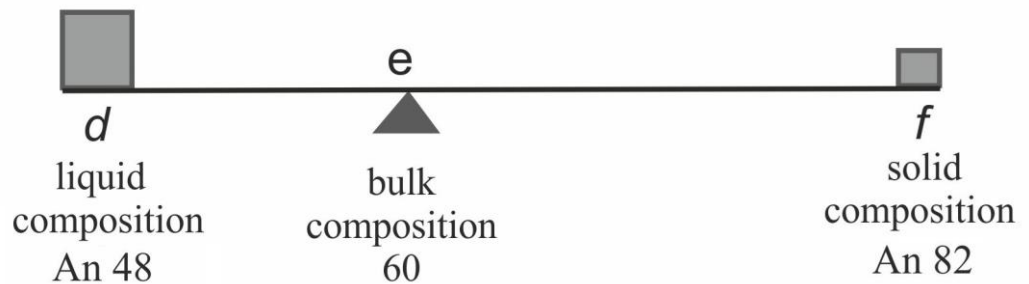


Fig. 5.6: Graphical representation of the abundance of components in a binary mixture.

According to lever’s rule:

Liquid % = length of line segment (e-f) * 100/ df

Plagioclase % = length of d-e * 100/ df

We can define lever rule as the amount of a given phase in a system is proportional to the length of segment on opposite side of the bulk composition. The closer a phase to the bulk composition, the more predominant it is. In order to understand lever rule, take help of Fig. 5.5.

Using this at 1445 °C,

ef= $An_{82} - An_{60} = 22$ and de= $An_{60} - An_{48} = 12$, thus

Liquid % = $22 \times 100 / (82 - 48) = 22 \times 100 / 34 = 64.70 \text{ wt\%}$

Solid % = $12 \times 100 / 34 = 35.29 \text{ wt\%}$

If we continue the cooling, with a constant bulk composition, ‘ef’ becomes larger, whereas ‘de’ becomes smaller which is a natural phenomenon, i.e., the % of solid increases with the decrease % in the melt.

As the temperature approaches to 1340 °C, the corresponding solid composition of melt ‘g’ (An_{22}) will be at ‘h’ which is equal to the bulk composition (An_{60}). With continuous cooling, the tiny amount of liquid (An_{22}) is consumed immediately. Here $F = 2 - 1 + 1 = 2$, so we must specify both T and a compositional variable, like in case of liquidus to specify the system.

• Petrographic Significance of Ab-An system

As solid is always rich in An-component with respect to corresponding liquid, ‘Ca’ becomes more refractory than ‘Na’. Compositional zoning can be defined by this system.

5.6 BINARY EUTECTIC SYSTEM

In a binary system, when two mineral components crystallises or melts simultaneously at a particular or fixed temperature, the temperature is called **eutectic temperature** and the process is called **eutectic crystallisation**.

Opposite to the case, when a mixture of two minerals is heated at a fixed pressure a melt of fixed composition is formed. The temperature at which two minerals are melted is called **eutectic melting temperature** and the process is called **eutectic melting**.

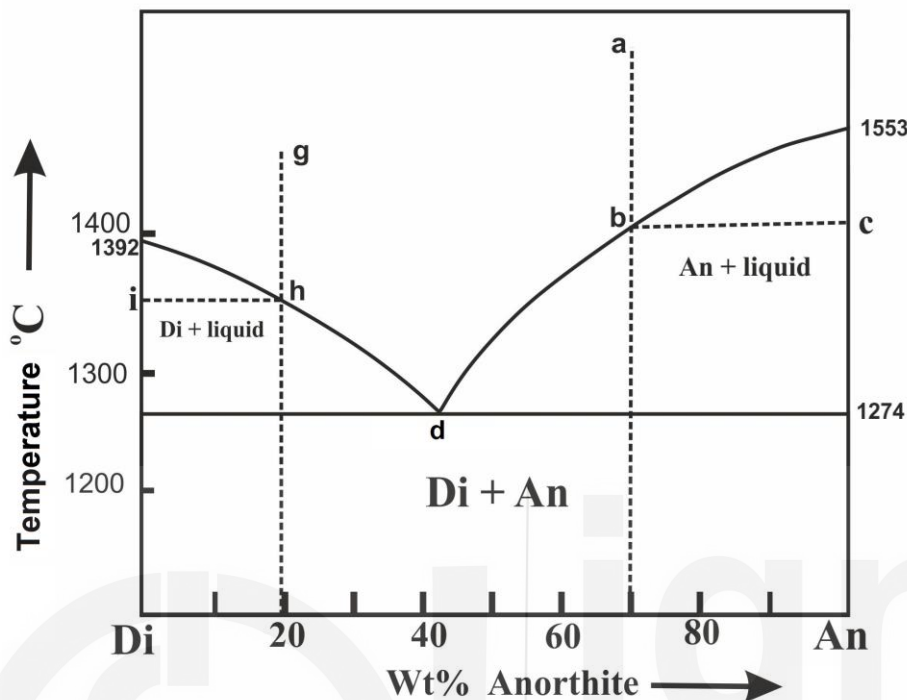


Fig. 5.7: Binary system (Diopside-Anorthite) without solid solution relation.

Fig. 5.7 represents a simple type of Diopside –Anorthite binary system without solid solution relation (as the Diopside –Anorthite possesses different mineral structure, Diopside-single chain inosilicate, Anorthite-tectosilicate). In this case, both the mineral components crystallise out simultaneously only at a particular temperature or a point called **eutectic point** in a particular fixed proportion.

- **Crystallisation behaviour on the left side of the eutectic point:** Consider a melt of 'a' ($\text{Di}_{30}\text{An}_{70}$) composition above the liquidus, $P=1$ (only liquid) and $C=2$, so applying phase rule

$$F = 2 + 1 - 1 = 2$$

Here two variables, temperature and composition (T , X_{liqAn} or X_{liqDi}) are required to define the system. With cooling, when the melt ($\text{Di}_{30}\text{An}_{70}$) touches the liquidus at a point 'b' at 1450 °C, pure Di begins to crystallise. So above liquidus, as $F = 2 + 1 - 2 = 1$, only one variable (temperature or composition) is needed to define the system. With further cooling, more and more Di crystals are formed and liquid composition will move away from b towards point d. At point d (1274 °C), anorthite joins diopside and both (Di and An) the mineral components crystallise out simultaneously at a fixed eutectic temperature and in a fixed eutectic proportion. Cooling to the point 'g' (1400 °C), crystallisation of pure 'Di' will begin and at that point, F will be $= 2 - 2 + 1 = 1$. Here, we have to fix one variable (generally 'T'). With continuous cooling, the liquid composition changes along the liquidus line from 'g' towards 'd' and pure anorthite crystals continue to form. This crystallisation of 'An' from melt is also a continuous reaction which may be represented by:

Liquid1 = solid + liquid2

With continuous cooling, at the eutectic point (1274 °C), where both the liquidus converge, there are 3 phases that coexist, and degree of freedom $F = 0$. This eutectic reaction is a type of equilibrium crystallisation.

At eutectic point, we can apply the lever's rule to determine the relative amount of solid and liquid. It has been found that with the progress of time, ratio of solid to liquid that increases.

Learners, you have learnt about the binary system with complete solid solution of two end members and binary eutectic system. Now, spend few minutes to perform an exercise to check your progress.



Watch the following video to know more about eutectic point.

- **Igneous Textures, Processes and Pathways: Volcaniclastics**

Link:

SAQ 2

- The point at which two liquidus lines meet is known as _____.
- When the two mineral components are isomorphous and miscible in all proportions in solid state, they form a homogeneous crystal and are called as _____.
- _____ is used to determine the fraction of liquid and solid phases for a given binary composition and temperature that is between the liquidus and solidus line.

5.7 SUMMARY

Let us summarise what we have learnt in this unit:

- Phase Rule governs the number of phases that can co-exist in an equilibrium in any system and expressed as $F = C - P + 2$. Where, P = number of phases present in a system; F = degree of freedom; C = components; and 2 = two intensive parameters usually T and P .
- A component is defined as the minimum number of independent chemical species required to define a system and all its phases. It is generally expressed as a proportion of oxides (SiO_2 , Al_2O_3 , FeO , Fe_2O_3 , H_2O , CO_2 , CaO , MgO). Minimum number of components depends upon: a) behaviour of the system, and b) the range of conditions over which it is studied.
- Phase diagrams show stability fields and relationship between different phases as a function of such variables as P , T and composition (X). In case, where either P or T is held constant, one can apply the condensed phase rule with the formula: $P + F = C + 1$.
- A system having only one component is called unicomponent system. For example: silica polymorphs, where silica have number of polymorphs, each having a definite crystal structure and stable under define set of T and P range.

- Two phases will co-exist only at a particular phase boundary during phase transformation.
- System having two components is described as binary system. Generally, in nature, only three cases are possible when two components are mixed. i) mixed crystal form which are miscible (solid solution) in any proportion, ii) mixed crystals of composition 1 and composition 2 formed as result of Eutectic reaction, miscible at a fixed proportion, and iii) two components will be immiscible and a crystal of intermediate composition is formed by reaction only.
- Lever rule is used to determine fraction of liquid and solid phases for a given binary composition and temperature that is between the liquidus and solidus line.
- In a binary eutectic system, a new melting point is called the eutectic point that occurs when melt of a fixed composition called eutectic composition is formed by mixture of two mineral components is heated at a fixed pressure. The temperature at which eutectic melting occurs is called the eutectic temperature.

5.8 ACTIVITY

- Redraw and discuss the phase diagram for water system and albite-anorthite (Ab-An) system as given in section 5.3.

5.9 TERMINAL QUESTIONS

1. What do you understand by phase diagram and phase rule?
2. Explain the crystallisation behaviour of SiO_2 system.
3. Explain binary system with complete solid solution.
4. Explain the principle of lever rule.

Audio/Video Material-Based Questions:

- What is eutectic point?
- Define liquidus and solidus curve.

5.10 REFERENCES

- Best, M.G. (1982) Igneous and Metamorphic Petrology: W.H. Freeman and Company, San Francisco, 630p.
- Singh Devender and Vats Satish Kumar (2010) Comprehensive engineering chemistry. I.K. International Pvt. Ltd, 356p.
- Tyrell, G. W. (1973) The principles of Petrology. John Wiley & Sons. ISBN 0470894806, 9780470894804, 349p.
- Winter J.D. (2014) Principles of Igneous and Metamorphic Petrology. Second Edition. Pearson Education Limited, Edinburgh Gate, Harlow, 728p.

5.11 FURTHER/SUGGESTED READINGS

- Best, M.G. (1982) Igneous and Metamorphic Petrology: W.H. Freeman and Company, San Francisco, 630p.
- Mukherjee, P.K. (2000) A Text Book of Geology. The World Press, Kolkata, ISBN:81-87567-09-0, 638p.
- Philpotts, Anthony R., & Ague, Jay J. (2009). Principles of igneous and metamorphic petrology, Second edition. Cambridge University Press. ISBN: 0521880068, 978-0521880060, 498p.
- Ragland, P.C. (1989) Basic Analytical Petrology: Oxford University Press, New York, 369p.

5.12 ANSWERS

Self Assessment Questions

- 1 a) System
b) Peritectic
c) **Triple point** is the point where the temperature and pressure at which the solid, liquid and vapour phases of the pure substance can exist together at equilibrium. The end point of a phase equilibrium curve is known as **critical point**.
d) The liquidus is represented by a line on a phase diagram that separates a liquid phase from a solid + liquid phase region. A system must be heated above the liquidus temperature to become completely liquid.
The solidus is represented by a line on a phase diagram that separates a solid phase from a solid + liquid phase region. The system is not completely solid until it cools below the solidus temperature.
- 2 a) Eutectic point.
b) Mixed crystal.
c) Lever rule.

Terminal questions

1. Refer to section 5.2 and subsection 5.2.1.
2. Refer to section 5.3.
3. Refer to section 5.4.
4. Refer to section 5.5

FELSIC AND INTERMEDIATE ROCKS

Structure

- | | |
|---------------------------------|---------------------------------|
| 6.1 Introduction | 6.7 Diorite |
| Expected Learning Outcome | Megascopic Characters |
| 6.2 What are Felsic Rocks? | Microscopic Characters |
| 6.3 Granite | 6.8 Syenite |
| Megascopic Characters | Megascopic Characters |
| Microscopic Characters | Microscopic Characters |
| 6.4 Rhyolite | 6.9 Summary |
| Megascopic Characters | 6.10 Activity |
| Microscopic Characters | 6.11 Terminal Questions |
| 6.5 What are Intermediate Rocks | 6.12 References |
| 6.6 Granodiorite | 6.13 Further/Suggested Readings |
| Megascopic Characters | 6.14 Answers |
| Microscopic Characters | |

6.1 INTRODUCTION

In the previous Unit 4, you have learnt the concept of magma, physical properties, and composition of magma, Bowen's reaction series, and the mechanisms of magmatic differentiation. Further in Unit 5, you have read about the unicomponent and bicomponent systems, application of phase rule and equilibrium crystallisation of magmatic systems. You have also read that the igneous rocks are grouped into four major subgroups, based on their composition, such as: ultramafic, mafic, intermediate and felsic rocks in Unit 1. These terms are used to indicate chemical composition of igneous rocks (Fig. 6.1), the silicate minerals that comprise them, and the magma types through which they were derived or formed.

Petrographic description of a rock provides detail about its mineralogical composition and texture, i.e. shape, size and inter-relationship of mineral constituents. The mineralogical composition studies cover both megascopic and microscopic observations. Megascopic description of rocks includes all the characters which are visible in hand specimens by unaided eyes. While, microscopic characters of rocks are studied using thin sections under the petrological microscope. You have read about petrological microscope in Unit 9 and diagnostic features of different minerals in thin section in Unit 10 of BGYCT-131 course. The textural relationship on the other hand is mostly observed under the microscope. Since the petrographic description and textural details of any rock contribute greatly to the understanding of the sequence of crystallisation of the various mineral constituents in a rock. This knowledge provides an idea about their genesis.

In this unit, we will discuss megascopic and petrographic description of the important felsic and intermediate rocks. The mafic and ultramafic rocks will be discussed in next unit.

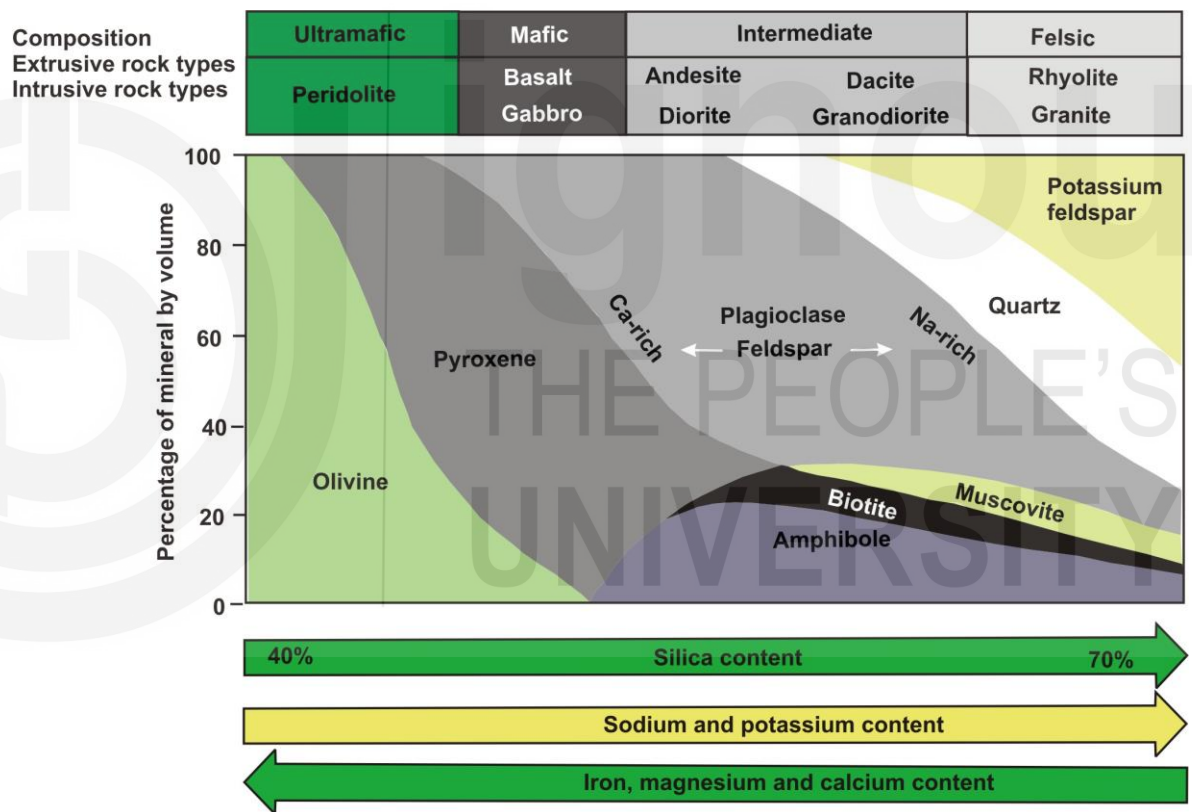


Fig. 6.1: Principal chemical and mineralogical characteristics of common igneous rock types.

Expected Learning Outcomes

After reading this unit, you should be able to:

- ❖ define felsic and intermediate igneous rocks;
- ❖ identify megascopic and microscopic characteristics of felsic rocks, e.g. granite and rhyolite; and

- ❖ learn and list megascopic and microscopic characteristics of intermediate rocks, e.g. granodiorite, diorite, syenite and phonolite.

6.2 WHAT ARE FELSIC ROCKS?

Let us discuss what are the felsic rocks.

The term **felsic**, i.e. FEL+SIC is a combination of the two words: **Feldspar** and **Silica**. The igneous rocks which have more than 65% of silica content are called **felsic igneous rocks**. These rocks are usually enriched in sodium and potassium and depleted in iron, magnesium, and calcium than the mafic rocks. The important minerals in felsic rocks are quartz, feldspathoid, soda and potash feldspar and muscovite. Felsic rocks are usually light-coloured because the minerals that comprise felsic rocks are often light-coloured. In this unit we shall discuss the most common felsic rocks, i.e. granite and rhyolite. Before discussing the important felsic rocks, let us define the following:

- **Granitoid/ Granitic Rock:** In practice, a granitic rock is used commonly for a group of plutonic rocks which include (*sensu-stricto*) granites and is classified according to the percentage of quartz, alkali feldspar and plagioclase contents present in a QAPF diagram as you have read in Unit 3. In this unit we shall discuss medium to coarse-grained rocks that are mostly felsic with a few mafic minerals present (Fig. 6.2a). Please note that the granite (*sensu-stricto*) according to modern petrologists' convention, contains both plagioclase and alkali feldspar (orthoclase and microcline).
- **Rhyolite** is an extrusive rock and is closely related to granite in composition. It is cooled much more rapidly than the granite and gives a glassy appearance. Rhyolite has much finer crystals and commonly cannot be seen by the unaided eye (Fig. 6.2b). The minerals that make up rhyolite are quartz, feldspar, mica, and hornblende.
- **Pegmatite** is very coarse-grained felsic rocks that occur as dykes or pod like segregations both within granitic plutons which are intruded into the surrounding country rock. Compositionally, most of the pegmatites are similar to granite and are composed of quartz, alkali feldspar and mica. Pegmatites are formed during the final stage of magma crystallisation. They contain exceptionally large crystals and contain minerals that are rarely found in other types of rocks (Fig. 6.2c). Pegmatite is considered to be store house of gemstones.





Fig. 6.2: a) Granite is intrusive/plutonic igneous rock; b) Rhyolite is extrusive/volcanic igneous rock, (Photo credit: Prof. Meenal Mishra); and c) Pegmatite with large crystals of tourmaline. (Source: www.gsi.gov.in)

You have studied the concept of essential and accessory minerals and also the igneous textures in Unit 2 and 3 of this course respectively. Let us recapitulate that texture is defined as the mutual relationship of different mineralogical constituents in a rock. It is determined by the size, shape and arrangement of these constituents (mineral and glass) within the rock. We shall discuss about mineralogical and microscopical characters of granite (a felsic plutonic rock) and rhyolite (a felsic volcanic rock) in the following sections.

6.3 GRANITE

Granite is one of the most common igneous rocks found on the Earth's surface and is commonly used as dimension/ building stones. Granite is a plutonic felsic rock. It is mostly light in colour and grains are large enough to be visible with the unaided eye. Let us discuss the megascopic and microscopic characteristics of granite in following subsections.

6.3.1 Megascopic Characters

Granite occurs as light coloured (leucocratic), medium to coarse-grained intrusive igneous rock (Fig. 6.3). It is essentially composed of quartz, alkali feldspar and plagioclase with minor amount of mica, amphiboles, and other accessory minerals. The predominance of alkali feldspar over plagioclase distinguishes it from granodiorite which is another felsic rock. It is important for you to note that granite is rich in alkali feldspars (orthoclase and microcline) as compared to plagioclase. Whereas granodiorite is rich in plagioclase as compared to alkali feldspars (orthoclase and microcline). You will learn about granite in section 6.6. The dominance of light-coloured minerals is responsible for its leucocratic nature of granite, although dark coloured mineral grains are visible and are dispersed throughout the rock. You may find different shades of granite such as grey, white, red or pink in colour (Fig. 6.3). These colours depend upon the bulk mineral composition of granite.

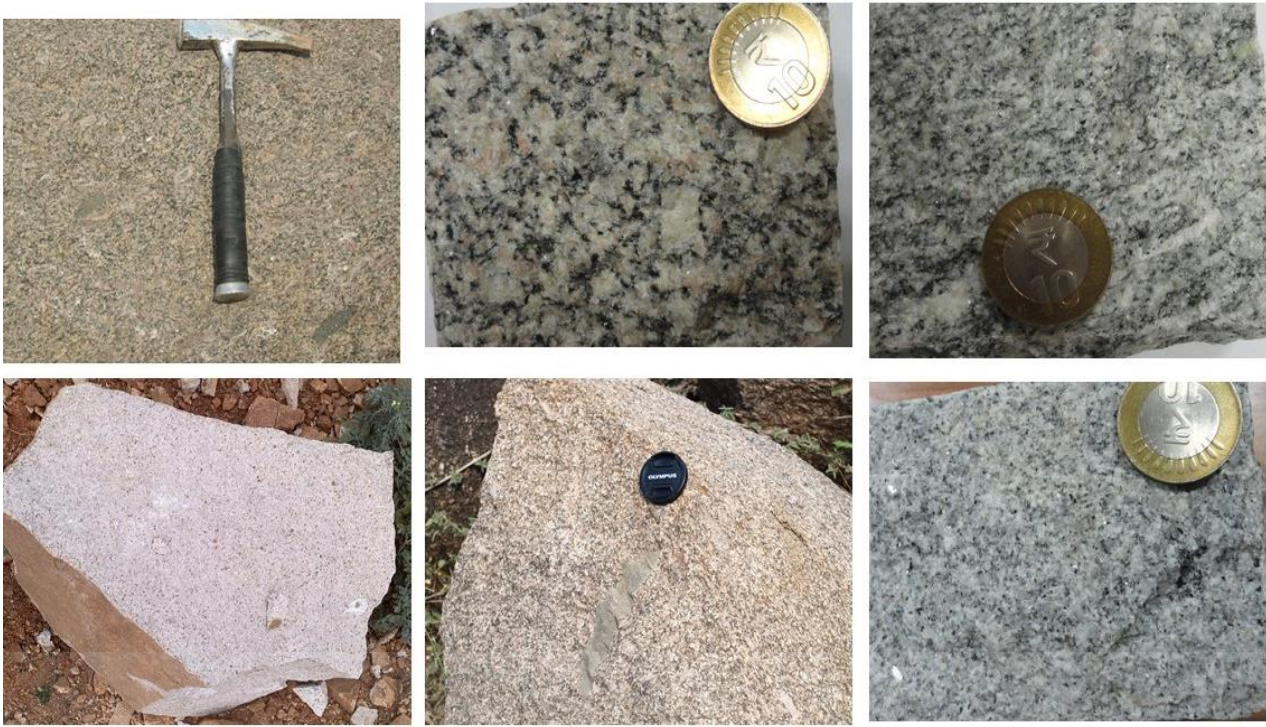


Fig. 6.3: Different colours of granite (grey, white or pink). (Photo credit: Prof. Meenal Mishra)

Granite contains more than 20% quartz, 50-80% alkali feldspars (orthoclase and/or microcline, perthite), plagioclase and mica (muscovite and biotite). In granite the amount of alkali feldspar (orthoclase and microcline) exceeds that of the plagioclase (Fig. 6.4). The mafic minerals are usually biotite, but amphibole may also occur. In a few types of granite, muscovite, garnet and cordierite are also present in variable amount.



Fig. 6.4: Field photograph showing medium-grained granite from Ladakh area. An aplitic dyke is cutting granite.

The megascopic characters of the rock are described below:

- i) **Colour:** Granite is light coloured (grey, white, pink or red) rock (Fig. 6.3). It is composed of light-coloured minerals therefore it is leucocratic rock, as you have read in Unit 3.
- ii) **Appearance:** It is medium-grained to coarse-grained grain size igneous rock.

- iii) **Mineralogical Composition:** The minerals which are found in these rocks as accessory, essential and secondary minerals are described below:
- **Essential Minerals:** Alkali feldspar (K-rich feldspar) > Na-rich plagioclase, perthite and antiperthite and quartz.
 - **Accessory Minerals:** Muscovite, biotite, hornblende, zircon, apatite, titanite (sphene), tourmaline, topaz, ilmenite and magnetite etc.
 - **Secondary minerals:** Sericite, chlorite and epidote.
- iv) **Texture:** The appearance, size and arrangement of different mineralogical constituents within the rock are as follows:
- **Physical appearance:** Granite consists of crystalline form and mostly show holocrystalline texture.
 - **Grain size:** It is generally medium to coarse-grained rock and exhibits equigranular or inequigranular (porphyritic) textures (Fig. 6.4).
 - **Mutual arrangement of the constituents/fabric:** The arrangement of the components is irregular and compact. Porphyritic texture is very commonly observed in granite. The feldspar phenocrysts (large crystals) are surrounded by fine quartz grains, feldspar and mica (Fig. 6.5).

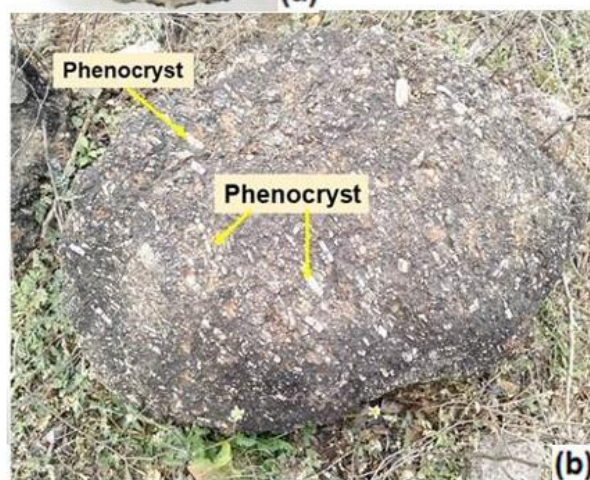
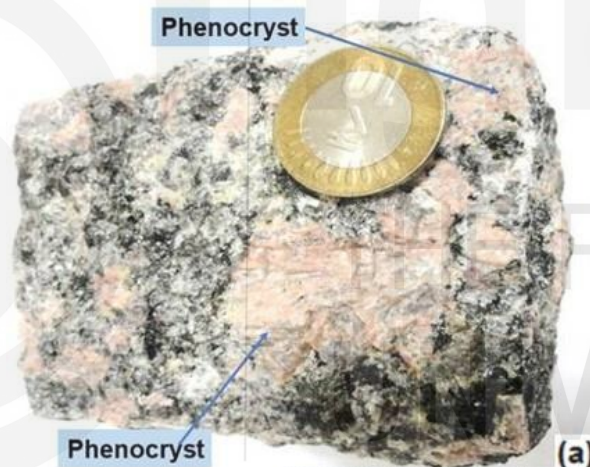


Fig. 6.5: a) Hand specimen of granite showing porphyritic texture. Phenocrysts (bigger crystals) of pink orthoclase are surrounded by smaller crystals (groundmass); and b) Boulder of porphyritic granite displaying phenocrysts of bigger crystals of lath shaped orthoclase (white) on the weathered surface. (Photo credit: Prof. Meenal Mishra)

- v) **Structure:** Granites commonly contain xenoliths (Fig. 6.6). Foliations are also rarely observed in a few granites.

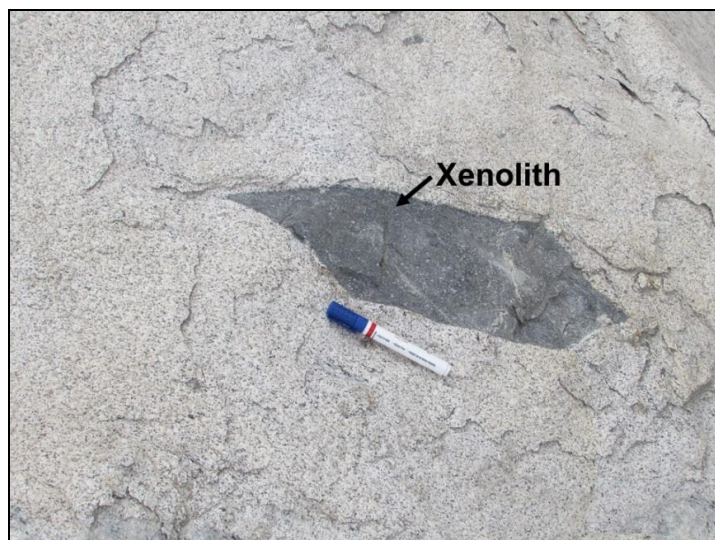


Fig. 6.6: Basaltic xenolith in granite. (Photo credit: Ihsan Ullah Lone)

6.3.2 Microscopic Characters

Microscopically granite contains mostly colourless minerals with very few coloured minerals under plane polarised light. It shows holocrystallinity. Most of the granite show equigranular texture, however a few types of granite contain coarse feldspar grains, surrounded by finer grains representing inequigranular texture. The microscopic characteristics of the granitic rock are described below:

- i) **Mineralogy:** Granite is essentially composed of quartz, alkali feldspar, plagioclase and mica in variable proportions (Fig. 6.7). The alkali feldspar is represented mostly by microcline and orthoclase and are always dominant over the plagioclase feldspar. While, studying thin sections of the granite under the microscope, you may also observe blebs or irregular lamellae of sodic feldspar within alkali feldspar. Such type of intimate intergrowth of sodic and potassic feldspars is called **perthite**. It results from subsolidus exsolution (unmixing of two minerals). You have read about exsolution texture (Fig. 6.8) in Unit 2. Let us recall. **Exsolution** textures represent chemical breakdown of an originally homogenous solid solution as it cools down. During cooling in solid state, the reverse process of solution, i.e. exsolution (unmixing) takes place and the intergrowth is produced.

Accessory minerals are those whose presence is not necessary which include: muscovite, biotite, hornblende, zircon, titanite (sphene), apatite, tourmaline and magnetite. Feldspar alters to sericite while hornblende alters to biotite and give rise to secondary chlorite. Epidote occurs rarely as secondary mineral in some of the granites.

- ii) **Texture:** The shape, size and mutual relationship between crystals are as follows:
- **Crystallinity:** The granite contains euhedral crystals of feldspar, mica, zircon, topaz and some other accessory minerals, while quartz occur in subhedral or anhedral forms. Hence, granite represents holocrystalline and hypidiomorphic texture.

- **Granularity:** Granite is medium to coarse-grained rock. It is usually granular with most of the grains of almost equal size (phaneritic), but porphyritic texture is also not rare. In case of porphyritic texture, phenocrysts of feldspar (usually euhedral or well-developed shape) are surrounded by smaller quartz and feldspar grains.
- **Mutual arrangement of the constituents/fabric:** In some granites **myrmekitic texture** is found. Myrmekite is the intergrowth of quartz in plagioclase. The intergrowths are microscopic in scale. These quartz-plagioclase (mostly sodic-albite or oligoclase) intergrowths are associated and commonly in contact with potassium feldspar texture (Fig. 6.8). In most of the granites, intergrowth of quartz and feldspar is observed giving rise to **graphic texture** (Fig. 6.9).

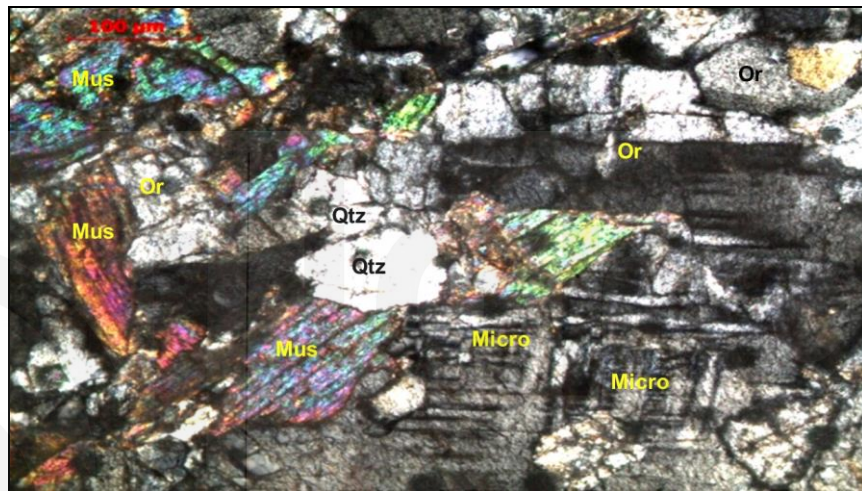


Fig. 6.7: Photomicrograph of granite showing typical mineralogy under cross nicol. Microcline (Micro) showing typical cross hatched twinning, orthoclase (Or) and quartz (Qtz) with first order grey interference colours and muscovite (Mus) with second and third order interference colours.

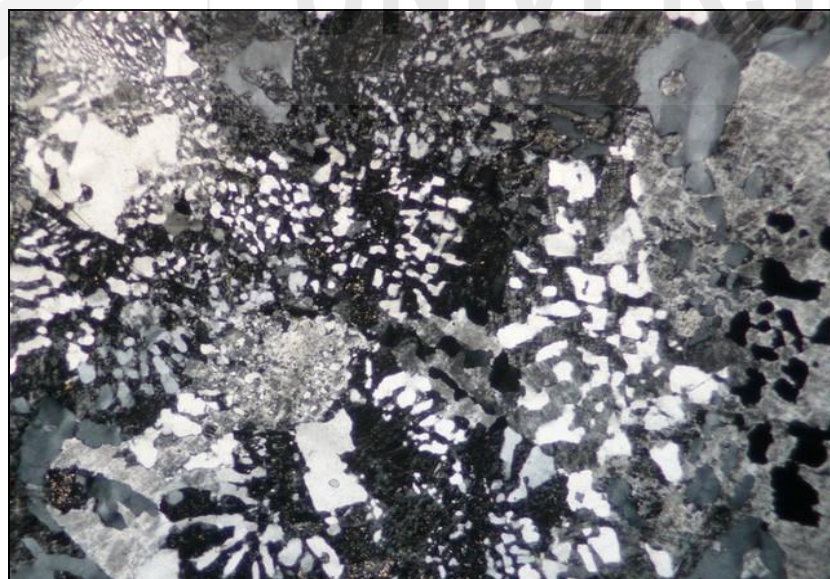


Fig. 6.8: Exsolution texture-myrmekitic texture. (Source: www.gsi.gov.in)

- iii) **Rock types:** The following types of granite are observed based on mineralogy:

- **Monzogranite:** Amount of alkali feldspar within the feldspar is 35-65% is called monzogranite. This is the most common granite type.
- **Syenogranite:** Within feldspars the alkali feldspar has an amount of 65-90%.
- **Alkali granite:** Amount of alkali feldspar within feldspar is >90%. The mafic minerals are alkali pyroxenes (aegirineaugite) and alkali amphibole.
- **Graphic granite:** Quartz and orthoclase show oriented intergrowth (Fig. 6.9) resulted from eutectic crystallisation.
- **Luxullianite (tourmaline-granite):** Tourmaline occurs in significant amount in such granites.

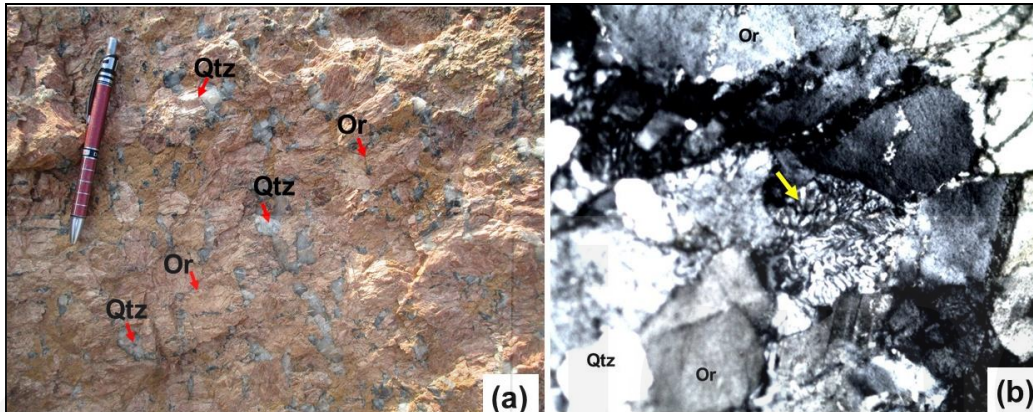


Fig. 6.9: Typical graphic texture seen in granite: a) Hand specimen of granite showing graphic intergrowth between grey quartz and pink orthoclase (Photo credit: Dr. Suresh Kumar); and b) Photomicrograph of granite showing graphic texture (marked by yellow arrow).

- iv) **Classification:** Granite is classified as felsic plutonic igneous rock.
- v) **Occurrence:** Granite is an intrusive igneous rock which is very hard and crystalline. It most commonly occurs in the form of stocks, bosses and batholiths.



Watch the following videos to know more about texture of granite.

- **Igneous Textures, Processes and Pathways: An Overview**
Link: <https://www.youtube.com/watch?v=9NU3SL7HWF4>
- **Igneous Textures, Processes and Pathways: Phaneritic Textures**
Link: https://www.youtube.com/watch?v=tw7vVvp6R_U
- **Igneous Textures, Processes and Pathways: Homogenous Textures**
Link: <https://www.youtube.com/watch?v=Zx6wQG0qiG4>
- **Rapakivi Texture**
Link: <https://youtu.be/voXGUT4HSxY>

6.4 RHYOLITE

In the above section you have read about megascopic and microscopic characteristics of granite. Now, let us discuss about another felsic rock, rhyolite. Rhyolite is a volcanic rock of felsic composition (Fig. 6.2b). It is a light-coloured

rock with high silica content (>68%). Alkali ($\text{Na}_2\text{O} + \text{K}_2\text{O}$) content reaches upto 5%. You have already read that rhyolite is extrusive equivalent of granite. These rocks are formed by acidic lavas which erupt at low temperatures (700 to 850°C) as compared to basalt and are much more viscous.

Let us now discuss the megascopic and microscopic characteristics of rhyolite in the following sections.

6.4.1 Megascopic Characters

Rhyolite is a light coloured, fine-grained igneous rock, dominated by quartz (>20%), alkali feldspar (>35%) and biotite. It is often porphyritic with feldspar (sanidine) and rarely quartz and plagioclase phenocrysts within the fine-grained or glassy groundmass. In case, quartz phenocrysts are not present, it is often difficult to identify rhyolites without chemical analysis due to their glassy groundmass. Many rhyolites consist of mainly glass, and are termed as **obsidian**, or are partially devitrified, and termed as **pitchstones**. Most of the rhyolites are banded due to small differences in composition in the glass.

You may find rhyolite with grey, bluish grey or pink in colour. Banding is quite commonly observed. It is normally related to the difference in the vesicles and crystallites in the glassy groundmass. The megascopic characters of rhyolite are:

- i) **Colour:** Generally, rhyolite (Fig. 6.10) is light coloured, such as pink, grey, bluish grey, but red rhyolites are also observed.
- ii) **Appearance:** The appearance of rhyolite is fine-grained and often banded.

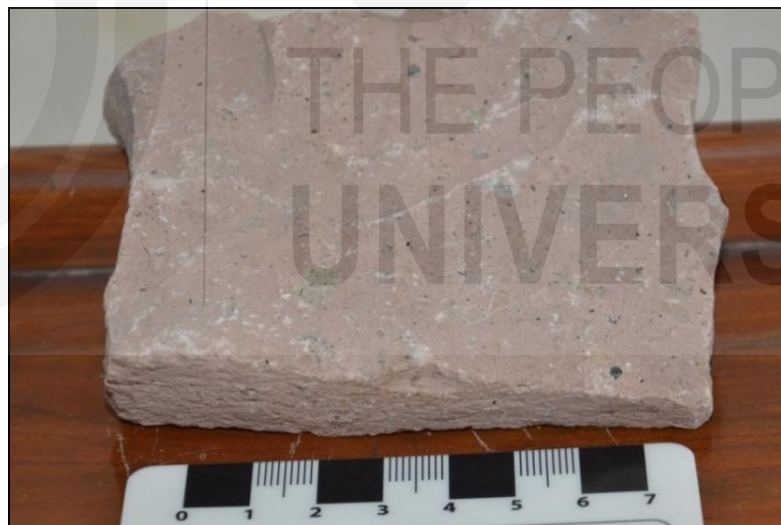


Fig. 6.10: Rhyolite with some minute vesicles.

- iii) **Mineralogical Composition:** The rock is mostly fine-grained with few crystals visible by unaided eyes. The essential, accessory and secondary minerals are described below:

- **Essential Minerals:** K-feldspar (sanidine) > Na-rich plagioclase, quartz, biotite.
- **Accessory Minerals:** Zircon, apatite, magnetite, ilmenite, pyroxene, amphibole.
- **Secondary Minerals:** Sericite, chlorite.

iv) **Texture:** The appearance and grain size present in rhyolite are discussed below:

- **Physical appearance:** The texture of rhyolite varies from glassy, aphanitic to porphyritic. The orientation of small crystals in the rock reflects the lava flow direction. Frequently, rhyolite shows altering layers that differ slightly in granularity or colour.
- **Grain size:** It is fine-grained, mostly aphanitic, but a few euhedral to subhedral crystals may also be present in the finer matrix.
- **Mutual arrangement of the constituents/fabric:** Commonly rhyolite is equigranular and fine grained but sometimes it may exhibit porphyritic texture in hand specimen.

v) **Structure:** Rhyolite rock may have vesicular (Fig. 6.10) or amygdaloidal structure. It may contain spherulites that are spherical bodies, comprising of radial aggregates of needles, usually of quartz and feldspar. You have read about these structures in Unit 3 of this course. Rhyolitic magma flows very slowly and commonly develop a flow banding in the matrix. This is due to high viscosity and low capacity of the rhyolitic lava flow. You can observe flow banding both at megascopic and microscopic levels. In the field you may observe rhyolite occurring in the form of volcanic plate and lava basin with relatively large thickness and small propagation. Flow structure (Fig. 6.11a) and columnar joints (Fig. 6.11b) are commonly found in rhyolite. You have read about flow structures and columnar joints in Unit 3 of this course.

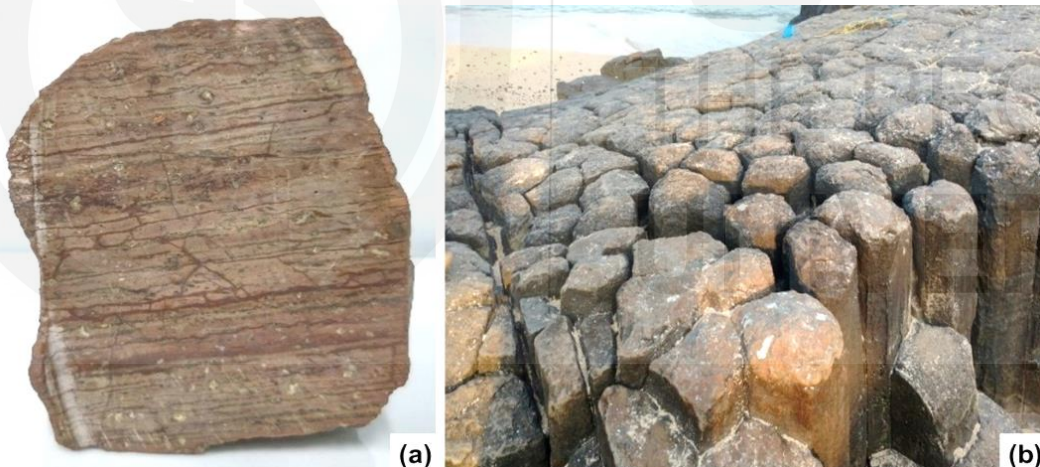


Fig. 6.11: a) Flow structures in rhyolite. Notice the dark and light bands marking flows (Photo credit: Dr. Amit Kumar); **and b) Columnar joints in rhyolite.**
(Source: www.gsi.gov.in)

6.4.2 Microscopic Characters

Rhyolite is composed of quartz, sanidine, plagioclase with minor amount of biotite, anorthoclase and magnetite when observed under the microscope. Glass is present in a variable amount. At places, the glassy portions are devitrified. Rock textures vary from holohyaline to hemicrystalline. The common texture in rhyolite is porphyritic.

i) **Mineralogy:** In general, the fine-grained groundmass is mostly made up of quartz, sanidine and plagioclase with lesser amount of orthoclase, biotite, amphibole, pyroxene and glass. Some phenocrysts of sanidine, plagioclase and

quartz are also recognised along with the amphibole and/or biotite. Quartz is more than 20% and the amount of alkali feldspars (sanidine/orthoclase) exceeds with that of the plagioclase. The mafic minerals are usually biotite and/or amphibole. Microscopically, you may find that some of the rhyolites contain equigranular quartz and feldspar and show uniform and homogenous nature. Presence of idiomorphic phenocrysts of quartz, sanidine and plagioclase set in a nearly aphanitic matrix consisting of quartz, sanidine/orthoclase, plagioclase, biotite and hornblende can be very well recognised in the porphyritic rhyolites (Fig. 6.12). One or more minerals out of zircon, apatite, xenotime, pyroxene, amphibole, magnetite, ilmenite, rutile and leucoxene may be present in rhyolites as accessory minerals. Sericitisation and chloritisation is commonly observed in rhyolite.

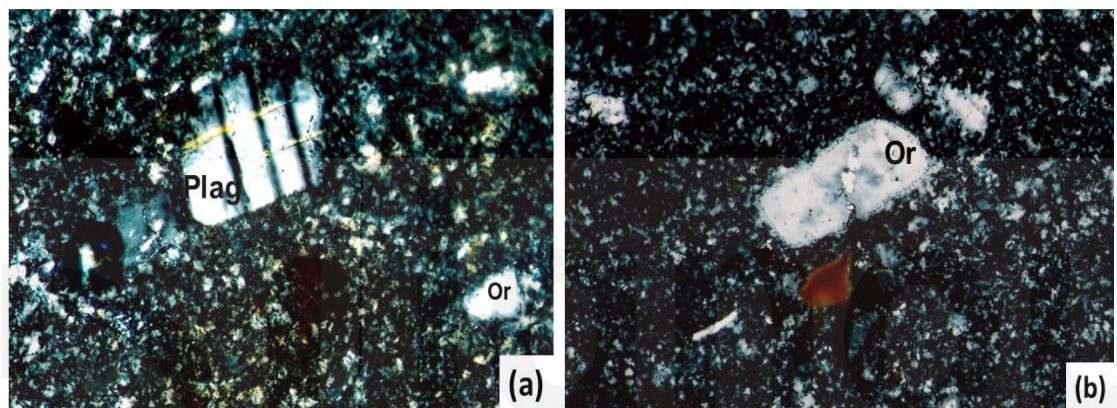


Fig. 6.12: Photomicrograph of porphyritic rhyolite showing fine grained vitrophyric matrix and phenocryst of euhedral grains of a) Plagioclase (Plag), b) Clouded orthoclase (Or) shows resorption at the margins. (Photo credit: Prof. Meenal Mishra)

- ii) **Texture:** Microscopically, the texture of rhyolite varies from cryptocrystalline to microcrystalline felsitic type to porphyritic type in accordance with their megascopic features. Spherulitic texture is also observed in devitrified glass portions. Holohyaline and hypocrySTALLINE textures characterise obsidian and pumice which contain volcanic glass.
 - **Crystallinity:** Rhyolite is mesocrystalline or hemicrystalline, very fine grained and partly glassy.
 - **Granularity:** Grain size is very fine and/or partly glassy.
 - **Mutual arrangement of the constituents/fabric:** In thin section rhyolite appears very fine-grained. It may be glassy with holohyaline texture. Rhyolite can exhibit porphyritic texture with phenocrysts of quartz, plagioclase (Fig. 6.12a) and orthoclase/ sanidine (Fig. 6.12b). Quartz phenocrysts are bipyramidal in shape. The groundmass may be fine-grained or vitrophyric. Devitrification is commonly observed in thin section. The margins of phenocrysts often show resorption.
- iii) **Rock types:** Based on mineralogy and texture following rock types are observed in rhyolite:
 - **Obsidian:** Rhyolitic glass with 1-2% water content, usually black, or rarely red in colour, having cusped fracture is called obsidian.

- **Perlite:** Rhyolitic glass with 3-5% water content, characterised by cusped fractures and globular appearance are called perlite.
- **Pumice:** It is highly vesicular glassy rhyolite (solidified magma foam) originating mostly during explosive volcanic eruption.

iv) **Classification:** Rhyolite rocks are classified as felsic volcanic rocks.

v) **Occurrence:** Rhyolites are more common and voluminous on the continents than in the oceans. They range from small domes and lava flows to much larger centres that have erupted volumes measured in hundreds of km³. Due to high silica content rhyolite melts are highly polymerised and form highly viscous lava. They also occur as breccia or volcanic plugs and dykes. Rhyolite occurs mostly at areas where thick crust is developed. It is commonly present along the subduction zones, but can also be observed in the extensional regions and in large magmatic provinces associated with the flood basalts. In India, rhyolite is extensively present within the Malani Igneous suit in Rajasthan.



Watch the following videos to know more about texture of rhyolite.

- **Igneous Textures, Processes and Pathways: An Overview**

Link: <https://www.youtube.com/watch?v=9NU3SL7HWF4>

- **Igneous Textures, Processes and Pathways: Aphanitic Textures**

Link: <https://www.youtube.com/watch?v=pboabkaFzWY&t=5s>

- **Igneous Textures, Processes and Pathways: Volcaniclastics**

Link:

In the previous sections we have studied about the megascopic and microscopic characters of felsic rocks like granite and rhyolite. Before going to the next section spend 5 minutes to check how you are progressing.

SAQ 1

- a) Name at least one plutonic and volcanic felsic igneous rock.
- b) Name the volcanic equivalent of granite?
- c) What are the essential minerals present in granite and rhyolite?
- d) Name important textures associated with granite.

6.5 WHAT ARE INTERMEDIATE ROCKS?

In the above sections you have read about felsic rocks. Now let us discuss, what are intermediate rocks?

Intermediate rocks are those igneous rocks which contain silica between 52 - 65%. Intermediate rocks are roughly even mixtures of felsic and mafic minerals that have chemical composition between those of basic and acid rocks. The most common felsic mineral in these rocks is plagioclase, while the most common mafic minerals in these rocks are hornblende, augite and/or biotite. There is little or no quartz

present in these rocks. Most common intermediate rocks are granodiorite, diorite, syenite, andesite and phonolite.

Now in the following subsections we will discuss about megascopic and microscopic characteristics of some common intermediate rocks such as granodiorite, diorite, syenite and phonolite.

6.6 Granodiorite

Granodiorite like granite is another most commonly found igneous rock on the surface of the Earth. It is also a plutonic felsic rock. It is mostly light coloured with grains large enough to be visible with the unaided eye.

You have read in the introduction part of this unit that granodiorite is a part of the granitic clan of rocks. It has some similarity with the granite. It differs from granite in having dominance of plagioclase over alkali feldspars and having low quartz and low SiO₂ contents.

6.6.1 Megascopic Characters

Granodiorite is usually medium-grained to coarse-grained and medium to light coloured intrusive felsic rock (Fig. 6.13). The large phaneritic crystal in this rock is due to slow cooling. Mineralogically, it is composed of quartz (10-30%), feldspar (plagioclase, alkali feldspar) and minor amount of biotite and amphibole. Out of the total feldspar present in the granodiorite, the Na rich plagioclase is more than K-feldspar (orthoclase). The mafic minerals are represented by amphibole, pyroxene and biotite.

- i) **Colour:** Granodiorite is of variable colours, but typically light coloured like grey, orange, pink and white. Some darker granodiorite types also occur in shades of greyish black (Fig. 6.13).
- ii) **Appearance:** It appears as holocrystalline, medium-grained to coarse-grained and light in colour.
- iii) **Mineral content:** The essential, accessory and secondary minerals are described below:
 - **Essential minerals:** Na-rich plagioclase, K-feldspar (orthoclase), quartz, biotite and amphibole. Quartz is generally colourless to smoky and identified by its glassiness, hardness, lack of cleavage, and conchoidal fracture. Feldspar dominates the granodiorite composition and is easily recognised by its appearance, colour and cleavages. Biotite is flaky, black and silver in appearance and hornblende is black/dark-green and prismatic in nature.
 - **Accessory minerals:** Muscovite, apatite, magnetite, zircon.
 - **Secondary minerals:** Sericite, chlorite, epidote.
- iv) **Texture:** The appearance, size and arrangement of different mineralogical constituents within the rock are as follows:
 - **Physical appearance:** Granodiorite consists of crystalline form and hence it shows holocrystalline texture (Fig. 6.13) with large phaneritic crystals.
 - **Grain size:** It is generally medium-grained to coarse-grained rock. They may show both equigranular and inequigranular (porphyritic) textures.

- **Mutual arrangement of the constituents/fabric:** The arrangement of the components is irregular and compact.
- v) **Structure:** The layered structure commonly occurs in many granodiorite plutons. Foliations are rarely observed in some granodiorites.

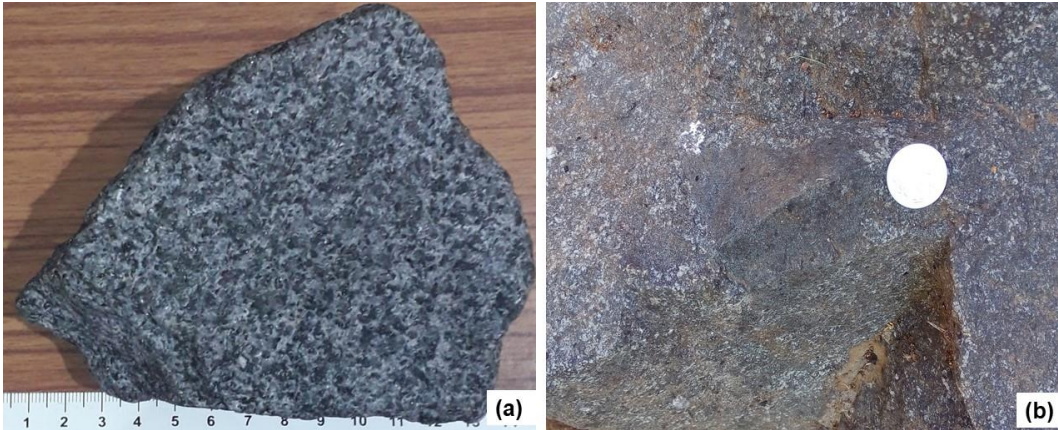


Fig. 6.13: Granodiorite showing uniform holocrystalline texture: a) Coarse-grained; and b) Medium-grained.

6.6.2 Microscopic Characters

Thin sections of the granodiorite show phaneritic texture. Under polarised light it contains many colourless minerals like plagioclase, alkali feldspar, quartz etc. with a few coloured minerals like biotite and hornblende. The microscopic characteristics of the rock are described below:

- Mineralogy:** In order of abundance, it is composed essentially of plagioclase feldspar, alkali feldspar, quartz, biotite and hornblende in variable amount. Plagioclase is almost $2/3^{\text{rd}}$ of the total feldspar present in the rock. As it is a felsic rock, the light-coloured felsic minerals (quartz and feldspar) dominate over the mafic and dark minerals like biotite, hornblende and pyroxene (Fig. 6.14a). Minor amount of muscovite and pyroxene is also present in thin section. Quartz is typically anhedral (ill-formed crystals), and occurs as fillings within the interstices between the other minerals masking its own characteristic crystal shape. Quartz sometimes shows undulose/wavy extinction. The plagioclase typically shows lamellar twinning under cross nicols. Green hornblende with typical two sets of cleavages and pleochroism and brown biotite with one set of cleavage and pleochroism are commonly seen in these rocks. You have already read the optical properties of these minerals in BGYCT-133 and BGYCL-134 courses. Some of the minerals which may occur as accessory minerals are muscovite, zircon, titanite (sphene), apatite, tourmaline, magnetite etc. In some of the rocks, feldspars have undergone alteration to sericite, while hornblende and biotite may alter into secondary chlorite. Epidote also occur rarely as secondary mineral in some of the granodiorite.
- Texture:** The shape and size of the crystals are as follows:
 - **Crystallinity:** Granodiorite is mostly granular in nature. Anhedral and subhedral minerals such as quartz, biotite and feldspar are present. You may get some euhedral grains of hornblende, zircon, sphene and plagioclase in some of the thin sections of granodiorites. The texture of granodiorite is hypidiomorphic.

- **Granularity:** The rock is mostly medium-grained to coarse-grained. It is usually granular with most of the grains are of almost equal in size (phaneritic), but porphyritic texture is also not rare (Fig. 6.14a and b). In case of porphyritic texture, feldspar phenocrysts (usually euhedral or well-developed) surrounded by smaller grains of quartz, feldspar and biotite. Zoned feldspar can also be seen in some of the granodiorite.
- **Mutual arrangement of the constituents/fabric:** Intergrowth texture is commonly observed in granodiorite. Like granite, graphic and myrmekitic textures are also observed in the granodiorite.

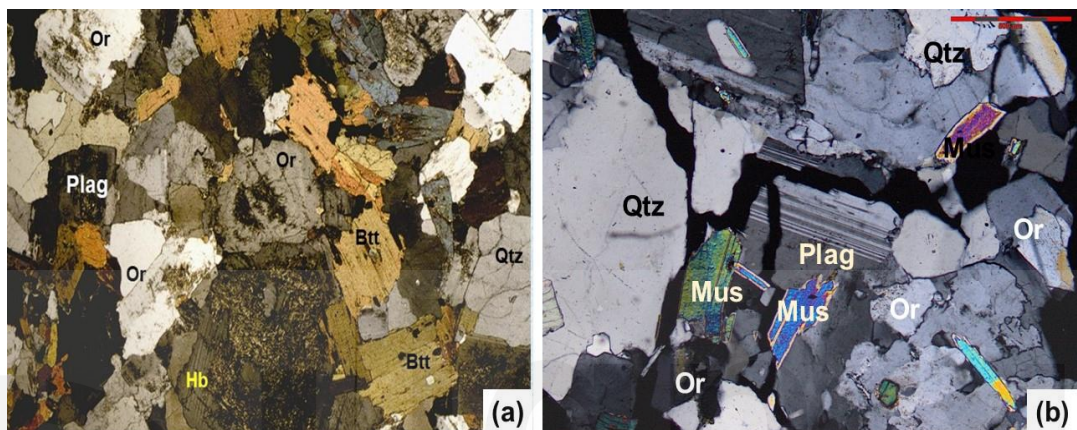


Fig. 6.14: Photomicrographs of granodiorite consisting of: a) Anhedral quartz (Qtz), orthoclase (Or), plagioclase (Plag), hornblende (Hb) and biotite (Btt); and b) Quartz, plagioclase, orthoclase and muscovite. (Photo credit: Prof. J. P. Shrivastava)

- iii) **Rock types:** The following rock type is observed:
 - **Tonalite:** It is usually coarse-grained rock with lesser amount of quartz and feldspars. They are represented almost exclusively by Na-rich plagioclase with no or very little alkali feldspar.
- iv) **Classification:** Granodiorite is classified as felsic plutonic igneous rock.
- v) **Occurrence:** Granodiorite is an intrusive rock. It is formed mostly in subduction zones (active continental margins) and collisional settings. It also occurs in small volume, shallow intrusive bodies of andesitic to dacitic volcanoes. The rock is very hard, crystalline and is visibly homogeneous in texture.



Watch the following video to know more about granodiorite.

- **Igneous Textures, Processes and Pathways: Homogenous Textures**

Link: <https://www.youtube.com/watch?v=Zx6wQG0qiG4>

6.7 DIORITE

In the above section you have read about megascopic and microscopic characteristics of granodiorite. Now, let us discuss about another intermediate rock, diorite. Diorite is a plutonic igneous rock with intermediate composition. It is crystalline in nature and usually shows granular texture. Its appearance may vary widely, but usually it is found consisting roughly of equal size crystals. Its volcanic equivalent is andesite. Diorite in wider sense may include other varieties such as

quartz diorite, quartz monzodiorite, monzodiorite etc. In strict sense of its definition based on QAPF diagram of IUGS classification, it consists of feldspar out of which more than 90% is plagioclase and less than 5% is quartz. Due to its mineralogical composition, it commonly appears as speckled black and white and hence is often referred to as "salt and pepper" rock.

6.7.1 Megascopic Characters

The megascopic characters of the rocks are described below:

- i) **Colour:** Diorite is dark to medium in colour, typical speckled black and white.
- ii) **Appearance:** Due to its mineralogical composition, it commonly appears as speckled black and white, hence it is often referred to as "salt and pepper" rock (Fig.6.15). It is a medium-grained to coarse-grained holocrystalline intrusive igneous rock.



Fig. 6.15: Diorite showing uniform salt and pepper appearance.

- iii) **Mineralogical Composition:** The essential, accessory and secondary minerals are described below:
 - **Essential Minerals:** Ca-Na plagioclase, amphibole, less biotite and pyroxene (clino- and/or orthopyroxene). Among the mafic minerals, the amphibole predominates. The feldspar in diorite is generally white. The dark minerals in diorite are primarily biotite and amphibole.
 - **Accessory Minerals:** Minor amount of quartz, alkali-feldspar, apatite, magnetite and garnet. Olivine and feldspathoids may also be seen in some diorites.
 - **Secondary minerals:** Chlorite, sericite, epidote.
- iv) **Texture:** The appearance and grain size present in diorite are as follows:
 - **Physical appearance:** Diorite is medium to dark in colour with typical equal sized black (mostly hornblende and minor pyroxenes) and white (plagioclase) crystals, holocrystalline rock.
 - **Grain size:** The grain size of diorite is medium-grained to coarse-grained.

- **Mutual arrangement of the constituents/fabric:** The mafic minerals are commonly present in good quantity along with the light coloured feldspathic minerals. The arrangement of the components is irregular and compact.

6.7.2 Microscopic Characters

Microscopically, diorite is a coarse-grained rock, consisting of Ca-Na plagioclase and one or more of the mafic minerals such as clino- and ortho-pyroxenes, hornblende and biotite. Minor amount of quartz and K-feldspar may also be present. Olivine may also be seen in some of the diorites. If quartz is more, the rock is termed as **quartzdiorite**.

- i) **Mineralogy:** The minerals present in diorite are similar to those of the gabbro except that the anorthite content of plagioclase is usually 50% and presence of minor amount of quartz. Main minerals present in this rock are plagioclase (oligoclase, andesine) and amphiboles (mainly hornblende) (Fig. 6.16). Plagioclase usually dominates over the hornblende and other mafic minerals. It frequently contains minor amount of quartz, pyroxene (usually augite, but some orthopyroxene may also be present) and biotite. In some of the diorite, olivine is also seen in smaller amount. Magnetite, apatite, sphene (titanite), ilmenite, zircon etc. are the main accessory minerals present in varying amount in diorite

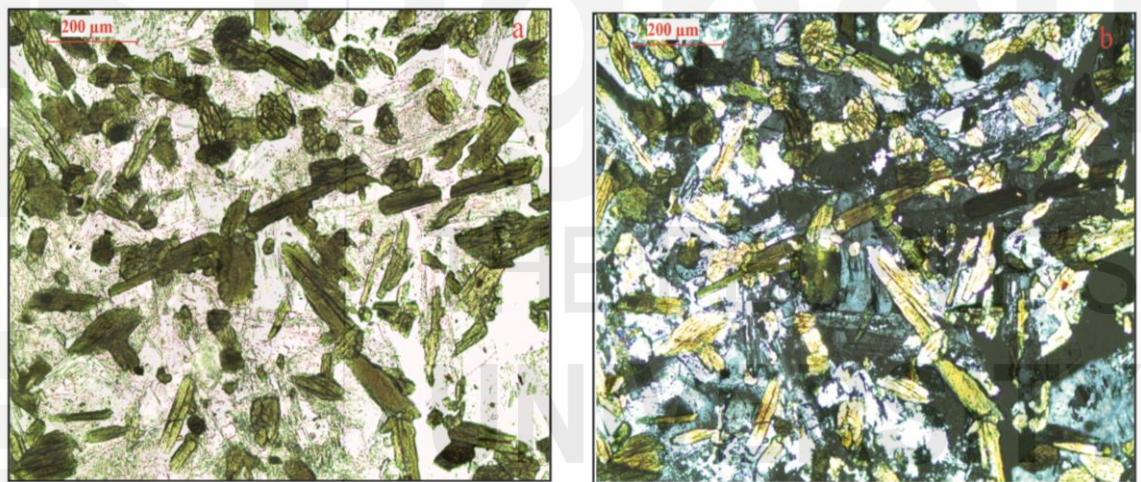


Fig. 6.16: Photomicrograph of diorite showing plagioclase and hornblende under PPL (left side) and XP (right side).

Under the microscope, the diorite contains laths of plagioclase feldspar with lamellar twinning and minor amount of subhedral quartz. The other important minerals mafic minerals are dominated by high relief hornblende and augite with their characteristic cleavage, and common biotite which exhibits some pleochroic haloes caused by zircon inclusions. Biotite occurs as pale brown to dark brown pleochroic subhedral crystals. Some of the clinopyroxenes can be easily recognised by their second order interference colours of blue and purple. The orthopyroxenes are pleochroic and show first order interference colours. In many of the diorite thin sections, you may also observe cloudy nature of plagioclase due to its alteration.

- ii) **Texture:** Microscopically the texture of diorite are as follows:

- **Crystallinity:** It is holocrystalline and hypidiomorphic. The hornblende and augite grains are subhedral. Biotite and feldspar are present as subhedral to euhedral in shape.

- **Granularity:** The texture is phaneritic and crystals are of medium size (1-2mm).
- **Mutual arrangement of the constituents/fabric:** Diorite contains phaneritic grains, often speckled represents texture of a coarse-grained rock and is occasionally porphyritic.

iii) **Rock types:** Following rock types are observed in diorite.

- **Quartzdiorite:** It is a variety of diorite containing quartz (>5%) and alkali feldspar.
- **Monzodiorite:** It is a variety of diorite containing olivine and feldspathoids.
- **Alkali diorite:** In alkali diorite it is observed that Ca-Na plagioclase > orthoclase-microcline, nepheline, sodalite, alkali amphibole, alkali pyroxene and biotite are present.

iv) **Classification:** Diorite is classified as plutonic intermediate igneous rock.

v) **Occurrence:** Diorite is usually associated with the subduction zones. Diorite may form larger plutons, but usually present in the form of sills, dykes and stocks. It occurs in both continental and oceanic crust and is not a rare rock type, but it is significantly less common than granitoids.

6.8 SYENITE

Syenite is an intrusive plutonic rock. It belongs to the alkali series of intermediate igneous rock with >65% SiO₂. The term “syenite” in a wider sense involves similar rock types like quartz syenite, alkali feldspar syenite, foid syenite and foid monzosyenite. A true syenite (*sensu stricto*), however, is having alkali feldspar (orthoclase and /or microcline) as a major mineral component with total feldspar content is >65%. Quartz is typically lacking in syenite. Compositionally, it resembles to granite with absence or very low quantity of quartz. It occurs in a wide variety of colours. Trachyte and phonolite are the two volcanic equivalents of syenite. Nepheline syenite of Kishangarh in Rajasthan is one of the exposures of a such rock type.

6.8.1 Megascopic Characters

- Colour:** Syenite is found in varied colours, but mostly it is leucocratic.
- Appearance:** Syenite is medium-grained to coarse-grained intrusive leucocratic rock, where alkali feldspar predominates (Fig. 6.17). The mafic minerals are represented by small amount of pyroxenes (usually aegirine-augite and aegirine), amphibole and biotite. Plagioclase occurs also in a small amount. Quartz or feldspathoid could be found in a minor amount. It is the intrusive equivalent of trachyte and phonolite. It is formed mostly in continental rift zones.
- Mineralogical Composition:** The essential, accessory and secondary minerals present in syenite are as follows:
 - **Essential Minerals:** Alkali feldspar, plagioclase, amphibole, biotite, pyroxene.
 - **Accessory Minerals:** Quartz or feldspathoid, ilmenite, apatite, magnetite and zircon. Foid syenites contain significant amount of relatively rare feldspathoid

minerals which are called foids in a simplified manner. Syenitic rock that contains quartz cannot contain feldspathoids and vice versa.

- **Secondary minerals:** Chlorite and sericite.

iv) **Texture:** Microscopically the texture of syenite is as follows.

- **Physical appearance:** Syenite is leucocratic, granular, holocrystalline rock.
- **Grain size:** It is medium-grained to coarse-grained rock.
- **Mutual arrangement of the constituents/fabric:** It is also granular in nature like granite and show phaneritic texture.



Fig. 6.17: Hand specimen of syenite showing pink and white orthoclase. (Source: www.gsi.gov.in)

6.8.2 Microscopic Characters

- Mineralogy:** Microscopically, the syenite is identified by the dominance of alkali feldspar, (Fig 6.18) lesser to minor amount of plagioclase (<10%) and with little or no quartz. If the quartz is present in the rock, it cannot exceed more than 5%. The alkali feldspar present in the rock may include orthoclase and perthites or very rarely microcline. Perthites are also commonly observed in syenite. Minor amount of mica, augite and hornblende may also be present. Biotite is rarely found. Common accessory minerals are apatite, ilmenite, magnetite and sulphides. Alkali syenites are rich in alkali minerals such as feldspathoids (nepheline, sodalite and leucite), alkali amphibole (riebeckite and arfvedsonite), alkali pyroxene (aegirine and aegirine-augite) and K- feldspars. It is poor/no plagioclase and quartz.
- Texture:** Microscopically the texture of syenite is as follows:
 - **Crystallinity:** The rock contains both euhedral and subhedral crystals, hence show pandiomorphic (euhedral crystals of same size) and hypidiomorphic (subhedral crystals of equal size) texture.
 - **Granularity:** It shows phaneritic texture (medium-grained to coarse-grained).
- Mutual arrangement of the constituents/fabric:** Perthitic textures are commonly observed.
- Rock types:** Following rock types are observed in syenite:

- **Quartz syenite:** It is called quartz syenite when the occurrence of quartz (Si-saturated variety) is more.
- **Nepheline syenite:** Presence of nepheline (feldspathoids) in a Si-under-saturated variety is called nepheline syenite.

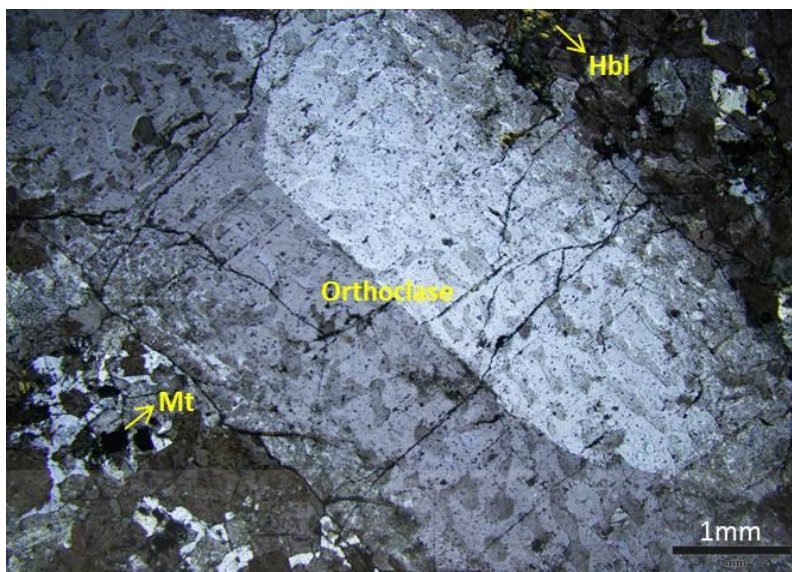


Fig 6.18: Photomicrograph of syenite showing porphyritic texture with orthoclase as phenocryst. Abbreviation: Mt- magnetite, Hbl-hornblend. (Photo credit: Mageswarii. G)

- v) **Classification:** Syenite is classified as intrusive plutonic intermediate rock.
- vi) **Occurrence:** Syenitic rocks are usually associated with other plutonic rocks. They form relatively small intrusive bodies or parts of larger intrusions. Syenitic rocks are produced by alkaline igneous activities typically resulted from partial melting of lower crust. Syenites are formed in continental rift zones and thick continental crustal areas or subduction zones.

In the previous sections we have studied about the megascopic and microscopic characters of intermediate rocks like diorite, syenite and granodiorite. Before going to the next section spend 5 minutes to check how you are progressing.

SAQ 2

- a) Name two plutonic and one volcanic intermediate rock.
- b) What are the essential minerals of granodiorite?
- c) Which rock is referred to as “salt and paper” rock?
- d) Give mineralogy of syenite.

6.9 SUMMARY

In this unit, we have discussed megascopic and petrographic characteristics of some of the important felsic and intermediate rocks. Let us summarise now.

- Granite and granodiorite are the most abundant igneous rocks present on the Earth's crust.

- Granite and granodiorite both contain quartz and feldspar as essential minerals. Granite will have more alkali feldspar than plagioclase while granodiorite will have more plagioclase than alkali feldspar.
- Rhyolite has similar mineralogy as of granite, but it is volcanic rock, hence it is fine grained.
- Diorite is a plutonic rock having dominantly plagioclase (oligoclase, andesine) and amphiboles (mainly hornblende) with a minor amount of augite, quartz and biotite.
- Syenite is an intrusive plutonic igneous rock of intermediate composition. It has high percentage of alkali feldspar (orthoclase and perthite) with little or no quartz/ feldspathoid.

6.10 ACTIVITY

Try to find out any building where granite is used either as wall tile/ floor tile or in pillar or as kitchen platform. Try to identify its minerals and name it as per its mineralogical classification. Note that granite, granodiorite, diorite, syenite, gabbro and andesite are being sold under the commercial name “Granite”.

6.11 TERMINAL QUESTIONS

1. How will you differentiate following rocks in the field?
 - a) Granite and granodiorite
 - b) Granodiorite and diorite
 - c) Granite and syenite
2. Discuss petrography of granite.
3. Describe mineralogy and textures present in the following rocks as observed under the petrological microscope.
 - a) Granodiorite
 - b) Rhyolite
 - c) Syenite
 - d) Diorite
4. Describe microscopic characteristics of a felsic composition of any volcanic rock giving suitable sketches.

Audio/Video Material Based Questions:

- Explain how felty texture is seen under the polarising microscope.
- Draw diagram of banded rhyolite as seen under the microscope.
- Discuss the texture of granodiorite as seen under the microscope.
- Mention the common texture found in aplite.
- What is alkali granite?
- Write about myrmekitic texture.

6.12 REFERENCES

- Best, M G. (1986) Igneous and Metamorphic petrology, CBS Publications. ISBN 81-239-0984-5.
- Winter, John D. (2001). An Introduction to Igneous and Metamorphic Petrology, 1st Edn. Prentice-Hall Inc., New Jersey. ISBN: 0132403420, 978- 0132403429.
- www.gsi.gov.in

(Website accessed between 20th March to 3rd April 2020)

6.13 FURTHER/SUGGESTED READINGS

- Best, M G. (1986) Igneous and Metamorphic petrology, CBS Publications.
- Ehlers, Ernest G., & Blatt, H. (1999). Petrology: Igneous, Sedimentary, and Metamorphic, 1stEdn. CBS Publications.
- McBirney, Alexander R. (2006). Igneous Petrology, 3rd Edn. Jones and Bartlett Publishers.
- Winter, John D. (2001). An Introduction to Igneous and Metamorphic Petrology, 1st Edn. Prentice-Hall Inc., New Jersey.

6.14 ANSWERS

Self Assessment Questions

- a) Granite and rhyolite.
 - b) Rhyolite.
 - c) Quartz and feldspar (alkali feldspar > plagioclase).
 - d) Equigranular, Porphyritic, Graphic.
- a) Diorite, Syenite and phonolite.
 - b) Quartz, Plagioclase and mica.
 - c) Diorite.
 - d) Essential Minerals: Alkali feldspar, plagioclase, amphibole, biotite, pyroxene.

Accessory Minerals: Quartz or feldspathoid, ilmenite, apatite, magnetite, zircon.

Secondary minerals: Chlorite and sericite.

Terminal Questions

- a) Please refer to introduction of subsections 6.3.1 and 6.6.1.
 - b) Please refer to introduction of subsection 6.6.1 and 6.7.1.
 - c) Please refer to introduction of subsections 6.3.1 and 6.8.1.
2. Please refer to introduction of subsection 6.3.2.
- a) Please refer to subsection 6.6.3.
 - b) Please refer to subsection 6.4.2.

- c) Please refer to subsection 6.8.2.
- d) Please refer to subsection 6.7.2.
- 4. You may describe rhyolite rock, refer to subsection 6.4.2



MAFIC AND ULTRAMAFIC ROCKS |

Structure

7.1 Introduction	7.6 What are Ultramafic Rocks?
Expected Learning Outcomes	
7.2 What are Mafic Rocks?	7.7 Peridotite
	Megascopic Characters
7.3 Basalt	Microscopic Characters
Megascopic Characters	7.8 Summary
Microscopic Characters	7.9 Activity
7.4 Gabbro	7.10 Terminal Questions
Megascopic Characters	7.11 References
Microscopic Characters	7.12 Further/Suggested Readings
7.5 Dolerite	7.13 Answers
Megascopic Characters	
Microscopic Characters	

7.1 INTRODUCTION

Out of the four major compositional groups of the igneous rocks, you have learnt about the felsic and intermediate igneous rocks in the previous Unit 6. In this unit, you will learn about the megascopic and microscopic characteristics of the mafic and ultramafic rocks. But, before we discuss the microscopic description of these important rocks, let us recapitulate general characteristics of the mafic and ultramafic rocks.

Mafic or basic igneous rocks have low silica contents that vary between 45% and 52% SiO_2 . They are typically composed of minerals with high iron and magnesium contents such as pyroxene and olivine. The most common rocks are gabbro, basalt and dolerite.

Ultramafic or ultrabasic igneous rocks contain <45% SiO₂, >18% MgO, high FeO, low K₂O and generally 90% mafic minerals. The common ultramafic rocks are dunite, peridotite and pyroxenite.

In this unit, we shall be discussing detailed megascopic and microscopic descriptions of the important mafic and ultramafic rocks.

Expected Learning Outcomes

After reading this unit you should be able to:

- ❖ know the terms mafic and ultramafic igneous rocks;
- ❖ identify the important rock-forming minerals in mafic and ultramafic rocks;
- ❖ discuss the textures present in mafic and ultramafic rocks; and
- ❖ discuss common structures and occurrences of mafic and ultramafic rocks.

7.2 WHAT ARE MAFIC ROCKS?

The term **mafic** is used to describe igneous rocks with 45 - 52 weight % of silica. Like felsic the term mafic is also a mnemonic as based on its mineralogy. It can be understood by breaking it in three parts as MA+F+IC. "MA" stands for "magnesium" and "F" for "*ferrum*", the Latin word for iron, and "IC" is a suffix meaning "having the character of".

You have already learnt that the chemistry of magma defines the mineralogical constituents of the rocks originated from magma. Further, it was discussed in the earlier units of this block that the mafic magmas are highly enriched in iron and magnesium and are also enriched in calcium relative to potassium and sodium. Therefore, the mafic igneous rocks are dominantly composed of iron and magnesium rich silicates, for example- olivine, pyroxenes, amphiboles, and biotite. Calcium rich plagioclase is also an important constituent in mafic rocks. The iron rich silicates form typical dark-coloured minerals; therefore, the mafic rocks are dark-coloured. The most common mafic rocks are basalt, gabbro and dolerite. The basalt is a fine-grained volcanic igneous rock. The coarse and medium grained equivalents of basalt are gabbro and dolerite, respectively. Dykes are mostly composed of dolerite rock.

In Unit 6, we have already discussed in detail about the felsic and intermediate rocks. We have read that mineralogical and textural descriptions of any igneous rocks can be dealt both at megascopic and microscopic levels. Now, we will try to understand megascopic and microscopic descriptions of important mafic rocks namely basalt, gabbro and dolerite.

7.3 BASALT

Basalt is the most abundant volcanic rock on Earth's surface and comprises of > 90% of all volcanic rocks. Much of the ocean floor is made up of basalt. It occurs in a wide variety of tectonic environments on the Earth. These tectonic environments include mid-ocean ridges, island arcs, back-arc basins, intra-plate oceanic islands and intra-continental rifts etc. Basalt is also found in other planetary bodies like the Moon and the Mars. It also constitutes an

important class of meteorites (e.g. basaltic achondrites). You have read about this in Unit 2 of BGYCT-131 course.

Basalt is an extrusive/common volcanic rock and occurs as small intrusive bodies, such as a dyke or a sill. It is fine-grained and dark in colour, chiefly composed of plagioclase, pyroxene and olivine. Basalt also contains hornblende, hypersthene, feldspathoid minerals and rarely minor amount of quartz and biotite. It also contains mantle xenoliths. Chemically, basalt contains 45-50 wt % of silica and abundant iron, magnesium and lime (calcium). But it contains little amount of soda and potash. The plutonic equivalent of basalt is called gabbro.

In Unit 4 of this course magma types have been discussed. In the unit you would read that basaltic magmas are parental to most of the more evolved magma types that develop through fractional crystallisation. Therefore, it is important to study basalt, in view of its parental role involving its relatively simple mineralogy.

Now, let us learn about the megascopic characteristics of basalt.

7.3.1 Megascopic Characters

Basalt is a fine-grained, dark coloured mafic extrusive rock. It is essentially composed of pyroxenes (mostly augite) and calcic plagioclase with or without olivine. Augite is a variety of high-Ca pyroxene and calcic plagioclase which refers to more anorthite content than albite. Augite is clinopyroxene as it crystallises in monoclinic system. However, the rock is so fine-grained and it is difficult to identify many minerals with unaided eyes, except for a few phenocrysts (Fig 7.1). The detailed megascopic characters of basalt have been described below.

- i) **Colour:** Basalt is mesocratic, dark grey to black, greenish and appears reddish black to brown in colour when altered.
- ii) **Appearance:** It is fine-grained, dark coloured, mostly aphyric rock but porphyritic basalt is also found (Fig. 7.1a and b). In the field, the morphology of the basaltic body, its structure and texture are characterised about by the mode of its eruption.
- iii) **Mineralogical Composition:** The accessory, essential and secondary minerals are described below.
 - **Essential Minerals:** Ca-rich plagioclase, clinopyroxene (augite) with or without olivine.
 - **Accessory Minerals:** Spinel (usually as inclusions in olivine and clinopyroxene), apatite, magnetite, ilmenite, glass and leucite (in alkaline basalts), K-feldspars (in Si-saturated basalts). Amphibole group minerals like hornblende are found in basalts with low-grade metamorphism.
 - **Secondary minerals:** Serpentine group of minerals, chlorite, carbonate minerals.
- iv) **Texture:** The appearance, size and arrangement of different mineralogical constituents within the rock are as follows:

- **Physical appearance:** Fine-grained rock consisting of a mosaic of crystals, normally not seen without high magnification, hence shows aphanitic texture (Fig. 7.1a).
- **Grain size:** Mostly fine to very fine-grained (cryptocrystalline or microcrystalline) and show aphyric texture, but basalt commonly may contain phenocrysts or microphenocrysts.

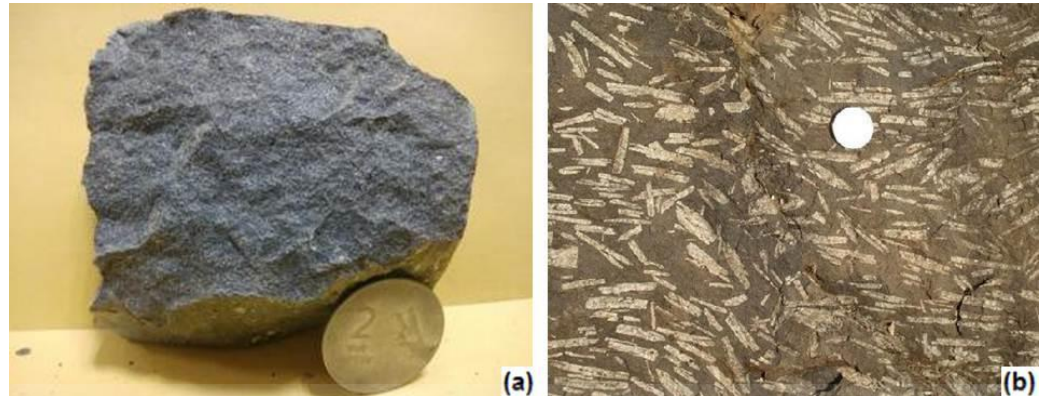


Fig. 7.1: a) Fine-grained basalt (Photo credit: Ihsan Ullah Lone); and b) Porphyritic basalt. (Source: www.gsi.gov.in)

- **Mutual arrangement of the constituents/fabric:** The arrangement of the components or crystalline and non-crystalline material is irregular and compact. Sometimes, the texture is porphyritic, containing larger crystals embedded in a fine-grained matrix. **Glomeroporphyritic** is one of the common porphyritic texture of the basalt, characterised by the phenocrysts of plagioclase and/or pyroxenes clustered together as an aggregate within the fine-grained matrix (Fig. 7.2).



Fig. 7.2: Basalt showing glomeroporphyritic texture: a) Hand specimen; and b) Photomicrograph showing cluster of plagioclase laths (glomeroporphyritic) as phenocryst in fine-grained groundmass. (Source for (b): www.gsi.gov.in)

- v) **Structure:** Basalt forms lava flows (Fig. 7.3a) or pyroclastic fields. It occurs mostly as thick and extensive lava flows because basaltic magma is one of the least viscous magma types as you have read in Unit 4 of this course. However, in case of thin and irregular lava flows, gas cavities form over rock surfaces. Such basalt with open spaces or cavities is called as vesicular basalt (Fig. 7.3b). When these gas cavities are filled up by secondary minerals (mostly silicate and carbonate minerals e.g. zeolites, calcite, quartz, or chalcedony), the rock is called as amygdaloidal basalt (Fig. 7.3c).

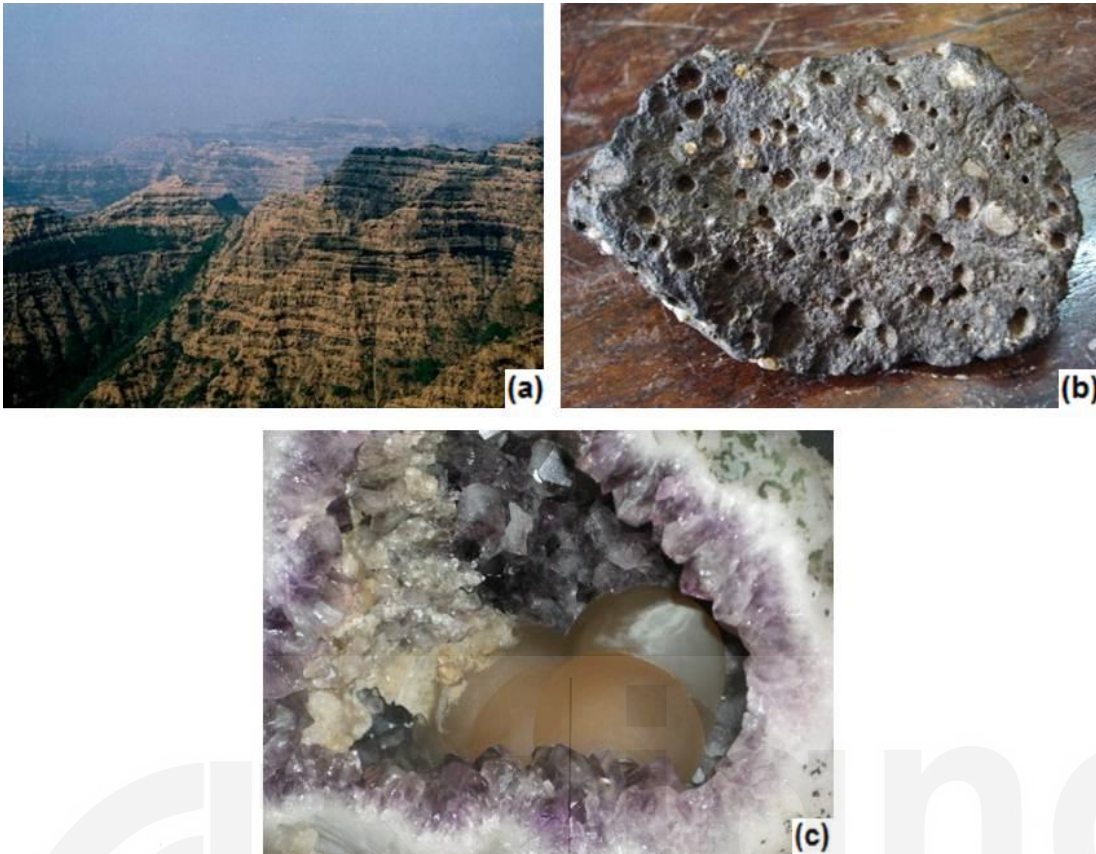


Fig. 7.3: a) Lava flows in Deccan basaltic terrain at Mahabaleshwar, notice the individual layers (Source: www.gsi.gov.in); **b) Volcanic rock showing vesicular texture (notice vesicles and some vesicles filled with quartz.** (Photo credit: Prof. Meenal Mishra); **and c) Amygdaloidal texture showing cavity filled by amethyst and calcite.** (Source: www.gsi.gov.in)

Columnar/polygonal joints (Fig. 7.4) are quite common in basaltic outcrops. Further, basalt lava flow outcrops are easily susceptible to mechanical and chemical weathering by penetration of groundwater along the polygonal joints and fractures. We have already discussed about these structures in Unit 2 of this course.



Fig. 7.4: Columnar/polygonal jointing in basalt. (Photo credit: Dr. Omkar Verma)

7.3.2 Microscopic Characters

Commonly, basalt shows aphanitic or fine-grained texture, formed as a result of rapid cooling of magma on or close to the surface of the Earth. The mineral components are so fine that they are better identifiable at higher magnification under the petrological microscope.

- i) **Mineralogy:** Mineralogically, basalt contains calcium rich plagioclase and pyroxene minerals as dominant phases. Both the minerals are present almost in equal proportion/amount. The olivine is present in a subordinate amount. Apart from these minerals, hornblende, biotite and rarely garnet is also present. Sometimes secondary quartz is also present, but in varying proportion depending on the degree of alteration (Fig. 7.5).

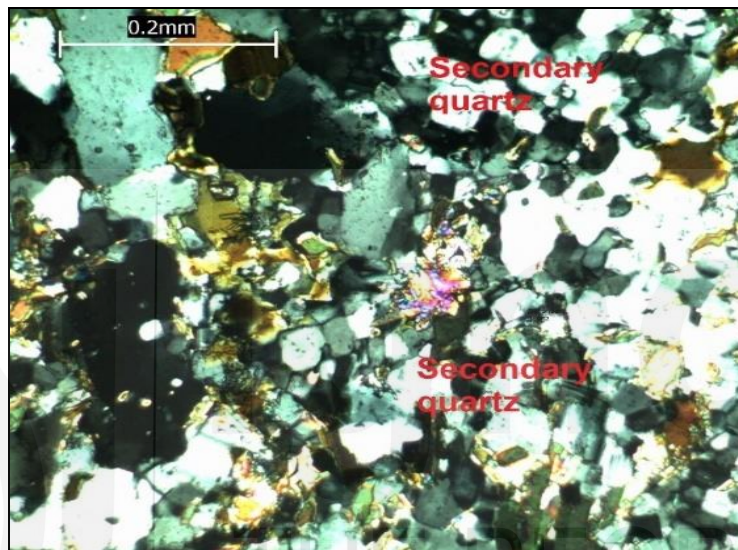


Fig. 7.5: Secondary quartz in basalt. (Photo credit: Ihsan Ullah Lone)

The calcic plagioclase is commonly referred to plagioclase (Fig. 7.6) which contains more anorthite (An) than albite (Ab) contents in molar terms and is represented by $An_{50}-An_{100}$. Labradorite is a common plagioclase present in basalt. The pyroxene is represented by augite (Fig. 7.6a and b), however enstatite or pigeonite may also occur in a few thin sections. Nepheline / leucite may or may not be present in a few basalt types. Low Ca pyroxene (enstatite or pigeonite) and quartz, however, never coexist with nepheline or leucite in basalt. Accessory minerals present in relatively minor amount, include magnetite, ulvospinel, ilmenite, apatite etc. The spinel normally occurs as inclusions in olivine and clinopyroxene. The iron-titanium oxide minerals (magnetite, ilmenite) are commonly referred to as opaque. Some altered or low-grade metamorphic minerals may also be present as secondary minerals in basalt. Olivine is altered to serpentine, pyroxene to chlorite, whereas, plagioclase is altered to sericite and saussurite (clay minerals). Saussurite may also be present as replacing glass or some other minerals.

- ii) **Texture:** The shape and size of the crystals are as follows:

- **Crystallinity:** Basalt exhibits mesocrystalline and hypidiomorphic texture. Grains are mostly anhedral grains. Euhedral phenocrysts are also commonly found in porphyritic basalt.

- **Granularity:** Basalts show, aphanitic or fine-grained texture resulted from rapid cooling of the magma at the surface or at a very shallow depth. However, a few basalt types also show larger crystals, embedded in a fine-grained matrix and giving rise to porphyritic texture.
- **Mutual arrangement of the constituents/fabric:** The term glomeroporphyritic is used to those porphyritic textures in which phenocrysts of plagioclase and/or pyroxenes are clustered together into aggregates in the groundmass due to surface tension (Fig. 7.2b). Commonly, intergranular texture is displayed by basalt, i.e. the polygonal spaces between the laths of plagioclase are occupied by augite mineral (Fig. 7.6a). Intersertal texture is also present in some basalt types, in which the polygonal spaces between the laths of plagioclase are filled by mostly glassy material (Fig. 7.6b). When the phenocryst of plagioclase and/or augite is surrounded by glassy material texture is known as vitrophyric texture. You have read about intergranular, glomeroporphyritic and intersertal, vitrophyric texture in Unit 2 of this course.

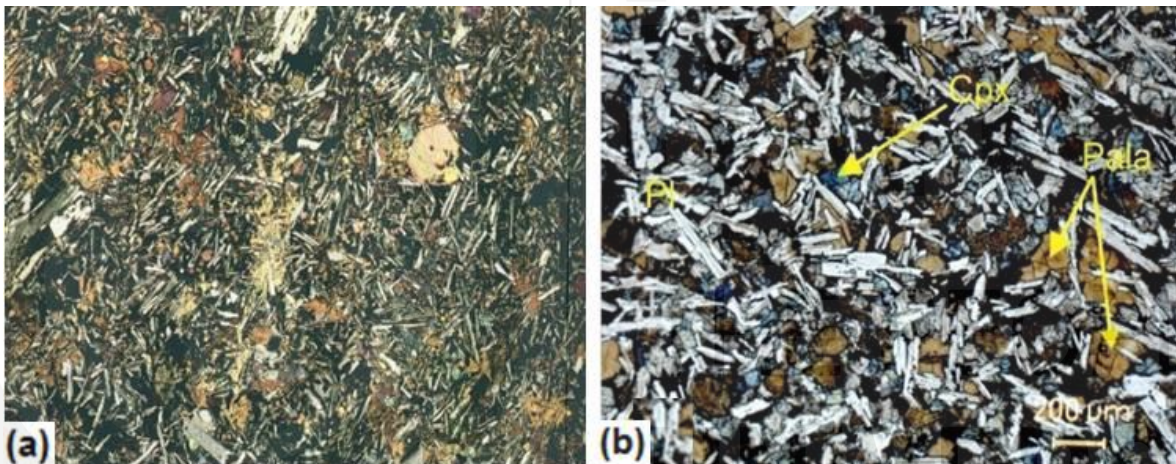


Fig. 7.6: Photomicrographs of basalt: a) Intergranular texture showing augite filled in the polygonal spaces between plagioclase laths; and b) Intersertal texture, the polygonal spaces are filled with glassy material and palagonite (Pala) between plagioclase laths (Plag). (Photo credit: Prof. J. P. Shrivastava)

iii) **Rock types:** There are two main chemical subtypes of basalt:

- **Tholeiitic basalt or tholeiite:** They are silica saturated or oversaturated basalts. Olivine-tholeiites contain olivine phenocrysts along with clinopyroxene and plagioclase. Quartz-tholeiite contain orthopyroxene (hypersthene) instead of olivine. Quartz may be present in the groundmass. Tholeiitic basalt predominates in the upper layers of oceanic crust and oceanic islands.
- **Alkali basalt:** They are silica under saturated basalt with feldspathoids (nepheline or leucite). Olivine often occurs as phenocrysts occasionally with augite. Alkali basalt is commonly found in ocean islands and in continental magmatism.

- iv) **Classification:** Basalt is classified as igneous volcanic or extrusive mafic rock.
- v) **Occurrence:** Basalt erupted in a wide variety of tectonic environments on the Earth, hence have a widespread occurrence. It is commonly present in the mid-oceanic ridges, island arcs, back-arc basins, intra-plate oceanic islands, large igneous provinces, intracontinental rifts and continental flood basalt.



Watch the following videos to know more about megascopic and microscopic characters of basalt.

- **Deccan Volcanism- An inside story**

Link: <https://www.youtube.com/watch?v=1a3glcg0oGs&t=109s>

- **Physical Features of Volcanic Terrain**

Link: <https://www.youtube.com/watch?v=Wrbw0MQzSQU&t=141s>

- **Microscopic view of basaltic rocks**

Link: <https://www.youtube.com/watch?v=2RGL3XB2x3E&t=103s>

- **Igneous Textures, Processes and Pathways: Inhomogeneous Textures**

Link: https://www.youtube.com/watch?v=XYb_tzRISKc

7.4 GABBRO

Gabbro is a dark mafic intrusive plutonic rock, equivalent to basalt in composition. It is essentially composed of calcic plagioclase and ferromagnesian minerals such as pyroxene (augite), hornblende and minor amount of olivine. Gabbro "*sensu stricto*" is a term for an intrusive rock which is chiefly composed of monoclinic pyroxene (clinopyroxene-Cpx) and plagioclase. In some cases, more than 5% of the Cpx is replaced by hypersthene. Hypersthene is orthorhombic pyroxene also known as orthopyroxene or Opx, the rock is called as gabbro-norite. When > 95% of Opx is present the gabbro, the rock is called as norite. These rocks are collectively called as gabbroic rocks.

Large gabbro intrusions exhibit internal chemical and mineralogical layering. A systematic study of these layered rocks provides details about crystallisation history of the magma, and indirectly records evolution of the magma.

Let us now understand megascopic and microscopic characteristics of gabbro.

7.4.1 Megascopic Characters

Gabbro consist of high proportion of ferromagnesian minerals. Therefore, it is a dark coloured or mesocratic mafic rock. It occurs in plutonic condition. It is mainly composed of plagioclase, pyroxenes, hornblende and opaque. It appears as a densely homogeneous rock and often displays fairly the same type of texture and composition throughout the entire gabbroic body.

- i) **Colour:** Gabbro is dark grey, greenish, greenish black, brownish in colour. It is mesocratic.

- ii) **Appearance:** It is dark coloured coarse-grained intrusive igneous rock. Gabbro is mostly dark coloured because of the high proportion of ferromagnesian minerals. They appear as a densely homogeneous rock often showing fairly the same texture and composition throughout the rock mass.
- iii) **Mineralogical Composition:** The minerals which are found in these rocks as minor proportion or are found as accessory, essential and secondary minerals are described below.
- **Essential minerals:** Ca-rich plagioclase, clinopyroxene (diopside and augite) and/or orthopyroxenes (hypersthene), olivine and amphibole (Fig. 7.7).
 - **Accessory minerals:** Apatite, magnetite, ilmenite; and may contain less amount of quartz, alkali feldspar and feldspathoids.
 - **Secondary minerals:** Chlorite, titanite, serpentine group minerals, epidote.
- iv) **Texture:** The appearance, size and arrangement of different mineralogical constituents within the rock are as follows:
- **Physical appearance:** Gabbro is holocrystalline, coarse-grained with equigranular grains and display hypidiomorphic texture (Fig 7.7).
 - **Grain size:** It is phaneritic.
 - **Mutual arrangement of the constituents/fabric:** Gabbro is a mixture of equigranular dark coloured pyroxene grains and light-coloured plagioclase laths. Gabbro exhibits typical 'salt and pepper texture'. Sometimes plagioclase laths are aligned parallel to layering.



Fig. 7.7: a) Gabbro in hand specimen equigranular texture; and b) porphyritic gabbro with phenocryst of olivine. [Photo credit: Ihsan Ullah Lone for (a) and Ganga Prasad Bhartiya for (b)]

- v) **Structure:** Gabbro is commonly layered and may show alternating light (feldspar rich) and dark (pyroxene and/or olivine rich) layers. Layered structure is called as **cumulate structure** (Fig. 7.8).



Fig. 7.8: Cumulate structure in gabbro at Sukinda complex, Odisha. (Photo credit: Ganga Prasad Bhartiya)

7.4.2 Microscopic Characters

Gabbro is a holocrystalline, hypidiomorphic rock. Therefore, several minerals present in the rock can be identified by unaided eyes or at low magnification under the petrological microscope. Now, let us study gabbro under the microscope.

- i) **Mineralogy:** The rock is chiefly composed of mixture equigranular ferromagnesian minerals and plagioclase laths. Ferromagnesian minerals show dominance of pyroxene. Mainly, two types of clinopyroxene minerals are present:

1) diopside and 2) augite.

The orthopyroxene minerals may or may not be present. If orthopyroxene mineral alone is present, it is mainly represented by hypersthene that too in a subordinate amount. The other important ferromagnesian minerals present in the gabbro are olivine and hornblende. The plagioclase feldspar in all gabbro types is chiefly of calcic in nature and is compositionally labradorite – bytownite (Fig. 7.9a and b). Proportion of olivine, pyroxene and plagioclase grains that vary from the outcrop to outcrop. The rocks have also been named on the basis of mineral compositions. Apatite, magnetite, ilmenite, quartz, alkali feldspar and feldspathoids are few accessory minerals present in gabbro. Quartz in gabbro is normally less than 5%. Considering presence of quartz or feldspathoid, and the relative proportions of alkali feldspar and plagioclase, various types of gabbros have been distinguished. Plagioclase and pyroxene undergo varying degrees of alteration, as a result, they give rise to secondary minerals such as: sericite, calcite, epidote.

- 2) **Texture:** The shape and size of the crystals are as follows:

- **Crystallinity:** Gabbro is holocrystalline and hypidiomorphi. Most of the crystals are anhedral to euhedral in shape and represent granular texture.
- **Granularity:** Gabbro is a medium to coarse-grained rock (Fig 7.9a). It is usually granular with most of the grains are of almost equal in size (phaneritic), but poikilitic texture may also be present.

- **Mutual arrangement of the constituents/fabric:** Gabbro commonly shows poikilitic texture. However, in a few cases, large, anhedral crystals of augite enclosing small, randomly oriented, euhedral plagioclase laths forming to ophitic texture.

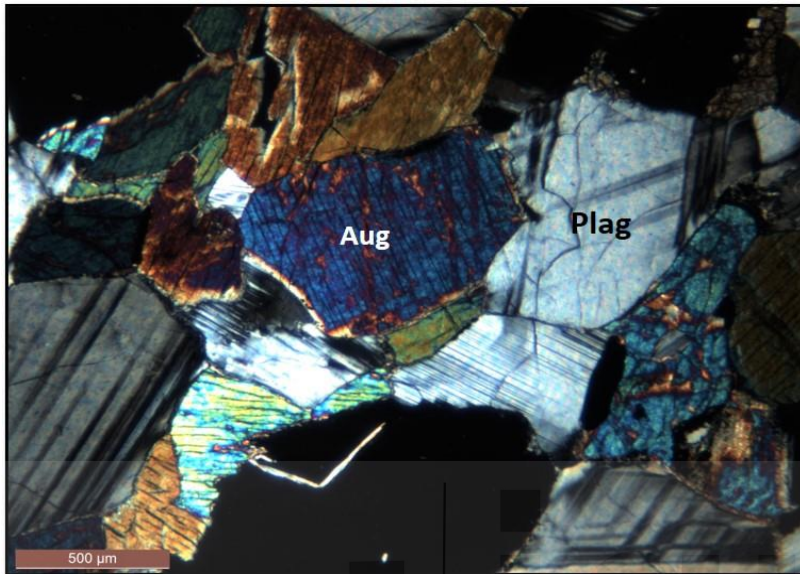


Fig. 7.9: Photomicrographs gabbro showing equigranular, hypidiomorphic texture with plagioclase (Plag) and Augite (Aug). (Photo credit: Dr. Amit Kumar)

3) **Rock types:** Rock types of gabbro are as follows.

- **Norite:** It is hypersthene and plagioclase bearing gabbro.
- **Alkali gabbro:** Apart from augite it dominantly comprises orthoclase and microcline together with alkali amphibole (Fig. 7.9b).
- **Troctolite:** It is olivine and plagioclase bearing gabbro, but, with minor amount of pyroxene.
- **Anorthosite:** It is gabbro which containing >90% Ca-rich (anorthite-rich) plagioclase.

Other varieties include monzogabbro, quartz-gabbro and quartz-monzogabbro as well as foid-gabbro. This classification is based on the relative presence of quartz or feldspathoid and proportions of alkali feldspar and plagioclase.

4) **Classification:** Gabbro is classified as mafic plutonic rock.

5) **Occurrence:** Gabbro generally occurs as batholiths and laccoliths. It is often found along mid-ocean ridges or in ancient mountains composed of compressed and uplifted oceanic crust. Gabbro is an essential part of the oceanic crust, and often found in many ophiolite sequences all over the world. Cumulate gabbros are more properly termed as pyroxene-plagioclase orthocumulate (Fig. 7.10).

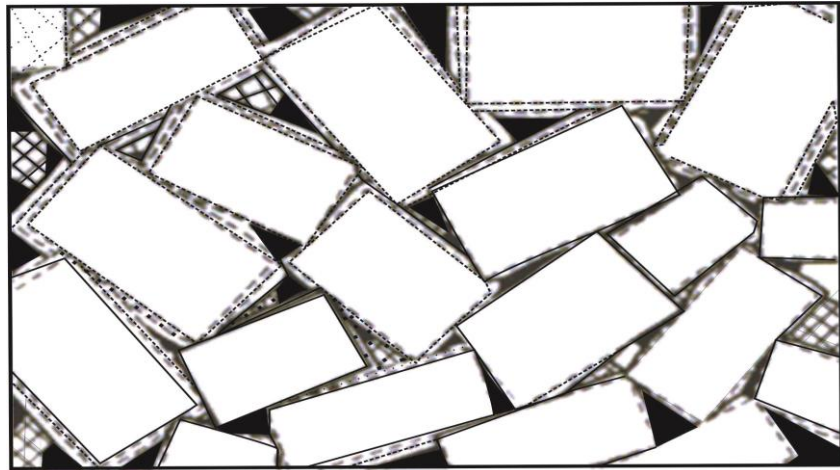


Fig. 7.10: Orthocumulate.

7.5 DOLERITE

Dolerite is a dark coloured mafic, holocrystalline, subvolcanic or hypabyssal rock. Compositionally, it is equivalent to gabbro and basalt. Texturally, it falls between gabbro and basalt, as it is finer than gabbro, but coarser than the basalt. The term microgabbro has also been used by geologists for dolerite. Another term diabase is also used as synonymous for dolerite, particularly in the North America and Europe. Ophitic and subophitic textures are common in the dolerite. Quickly cooled dolerite varieties show porphyritic texture with phenocrysts of plagioclase and pyroxene and sometimes olivine.

7.5.1 Megascopic Characters

Dolerite is a fine to medium-grained, dark coloured mafic intrusive rock (Fig 7.11). It is hard and heavy rock with specific gravity ranging between 2.9 and 3.3.

- i) **Colour:** Dolerite is dark grey, black and green in colour.
- ii) **Appearance:** It is greyish black, dark fine-grained rock contains plagioclase and pyroxene. Crystals are visible with unaided eyes. Euhedral plagioclase laths are embedded in fine matrix composed of pyroxenes and olivine.

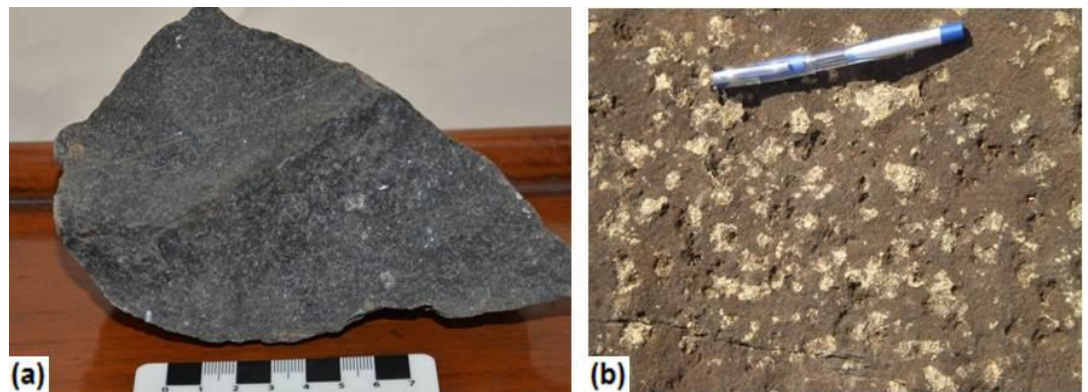


Fig. 7.11: a) Hand specimen of dolerite, and b) Porphyritic dolerite. (Source: www.gsi.gov.in)

- iii) **Mineralogical Composition:** The minerals which are found in these rocks as essential, accessory and secondary minerals are described below:

- **Essential minerals:** Plagioclase dominates over clinopyroxenes mostly augite with minor amount of olivine.
- **Accessory minerals:** Magnetite, ilmenite, hornblende, biotite and apatite.
- **Secondary minerals:** Chlorite, sericite and calcite.

iv) **Texture:** The appearance, size and arrangement of different mineralogical constituents within the rock are as follows:

- **Physical appearance:** It is greyish black to dark black in colour and fine-grained. Greyish tint is due to alteration of primary minerals such as plagioclase and pyroxene. The overall texture varies from hypidiomorphic granular, to ophitic to panidiomorphic granular.
- **Grain size:** It is phaneritic, fine-grained to granular.
- **Mutual arrangement of the constituents/fabric:** It is granular hypidiomorphic to panidiomorphic. Euhedral plagioclase laths are embedded in finer matrix of pyroxene and olivine forming subophitic to ophitic texture.

v) **Structure:** It is commonly quarried for crushed stone. Dolerite is widespread and usually it occurs as dykes, sills, and other relatively small, shallow bodies. Dolerite dykes and sills occur as shallow intrusive bodies and often exhibit fine-grained to aphanitic chilled margins which may contain tachylite (dark mafic glass).

7.5.1 Microscopic Characters

Dolerite is a medium to fine-grained holocrystalline rock shows ophitic to subophitic texture. Detailed microscopic characteristics are discussed below:

- Mineralogy:** It is essentially composed of (~ 60-65%) calcic plagioclase and > 20% pyroxenes and minor amount of olivine. Mostly, calcic plagioclase is represented by labradorite and rarely bytownite. Augite is the main clinopyroxene present in the dolerite. Other accessory minerals present include hornblende, augite, rarely biotite and opaque minerals like iron oxides and sulphides. Augite also shows uraltisation. **Uralitisation** is the process of alteration of augite to amphibole. Olivine may alter into serpentine. Other secondary minerals include as chlorite and calcite are also present.
- Texture:** The texture of dolerite varies from hypidiomorphic granular to subophitic to ophitic to panidiomorphic granular.
 - **Crystallinity:** Dolerite exhibits mesocrystalline and hypidiomorphic texture.
 - **Granularity:** It is a holocrystalline rock often shows fine-grained to aphanitic texture. Dolerite dyke may exhibit glassy texture along the chilled margin due to the formation of dark mafic glass as tachylite.
 - **Mutual arrangement of the constituents/fabric:** Dolerite shows ophitic texture (Fig 7.12a) where slender to broad plagioclase laths are embedded within anhedral to subhedral pyroxene grains. In subophitic

texture, this relationship is less developed (Fig 7.12b). Larger pyroxene grains completely enclose plagioclase; but as the quantity of the latter increases, pyroxene appears more interstitial. Generally, true ophitic texture is restricted to those doleritic rocks with a small grain size and low olivine content. In rocks of larger grain size, the texture is subophitic with high olivine content and a coarser grain size, the texture is hypidiomorphic granular. Fine-grained dolerite shows intersertal, intergranular and micro-porphyritic texture. Dolerite with poikilitic texture shows mottled luster due to the occurrence of smaller crystals of pyroxene in larger plagioclase laths.

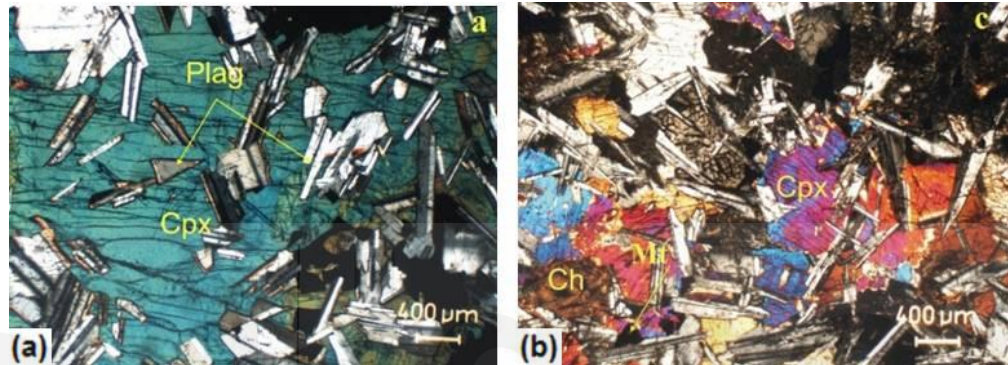


Fig. 7.12: Photomicrographs showing typical mineralogy ophitic and subophitic texture of dolerite. (Photo credit: Prof. J. P. Shrivastava)

iii) **Rock types:** Diabase and microgabbro are two synonyms for dolerite. Petrographically, it is classified as:

- **Olivine dolerite:** Dolerite having more olivine (up to 10%).
- **Tholeiitic dolerite:** It is equivalent to tholeiitic basalt. It contains enstatite (orthopyroxenes) in addition to augite (clinopyroxene) apart from Ca plagioclase. Minor interstitial quartz may also be present.
- **Alkali dolerite:** Apart from essential minerals, Ca plagioclase and augite, it also contains small amount of feldspathoids in addition to olivine. Minor amount of hornblende and biotite may be present.

iv) **Occurrence:** Dolerite usually occurs in the form of smaller relatively shallow intrusive bodies such as dykes, sills, sheet, laccolith and plugs.



Watch the following videos to know more about megascopic and microscopic characters of gabbro and dolerite.

- **Physical Features of Volcanic Terrain**

Link: <https://www.youtube.com/watch?v=Wrbw0MQzSQU&t=141s>

- **Microscopic view of Basaltic Rocks**

Link: <https://www.youtube.com/watch?v=2RGL3XB2x3E&t=103s>

- **Igneous Textures, Processes and Pathways: Homogenous Textures**

Link: <https://www.youtube.com/watch?v=Zx6wQG0qiG4>

In the previous sections we have studied about the megascopic and microscopic characters of mafic rocks like basalt, gabbro and dolerite. Before going to the next section spend 5 minutes to check how you are progressing.

SAQ 1

- a) Name a mafic volcanic and plutonic rock.
- b) List the essential minerals present in basalt.
- c) Name the essential minerals present in gabbro.
- d) Define ophitic texture?

7.6 WHAT ARE ULTRAMAFIC ROCKS?

Ultramafic rocks are not very much abundant on the Earth's surface. Commonly, they are intrusive in nature and rarely occur as extrusive rock. Ultramafic rocks occur in three distinct geological settings such as:

- a) Intrusive ultramafic rocks occur mostly as large layered intrusive complex and act as host rocks for major ore deposits of chromium, nickel, platinum group of elements and massive sulfides.
- b) They are found as mantle xenoliths (small pieces) derived from the peridotite mantle of the Earth and transported as representative specimens to the surface or shallower depths by volcanic or tectonic processes.
- c) They also occur as lavas of the ultramafic compositions erupted on the surface and are called as komatites. Komatites were found during the Archean age. They possess typical spinifex texture.

You have read in classification of igneous rocks that the ultramafic rocks contain < 45% SiO₂ content. They are also referred to as ultrabasic rocks. Chemically these rocks contain < 45% SiO₂, > 18% MgO, high FeO and low K₂O. Ultramafic igneous rocks are melanocratic (dark coloured) and contain >90% ferromagnesian minerals (magnesium and iron bearing mafic minerals) with almost no plagioclase. The common ultramafic rocks are peridotite, dunite and pyroxenite. Dunite and pyroxenite are monomineralic rocks (i.e. made up more than 90% of one mineral only). Dunite is mainly composed of olivine, while pyroxenite is mainly composed of pyroxene. On the basis of modal percentage of main ferromagnesian minerals constituents (olivine, pyroxene and hornblende). Ultramafic group of rocks have been further classified. For example, rocks with >40% olivine form a subgroup known as **peridotite**. Monomineralic ultramafic rocks with >90% olivine is called **dunite**, >90% pyroxene is classified as **pyroxenite** and >90% amphibole is known as **hornblendite**.

In the following section, we will discuss the megascopic and microscopic characters of the peridotite.

7.7 PERIDOTITE

Generally, peridotite refers to those ultramafic rocks which are coarse-grained dense, dark green to black having high specific gravity. Peridotite derives its

name from the “**peridot**” gemstone which is a gem variety of the pale green olivine.

Peridotite represents a group of ultramafic rocks, which contains > 40% magnesium rich olivine (forsterite), pyroxenes (both clino- and orthopyroxenes) and hornblende. The nomenclature of peridotite depends on the varying proportions of olivine and pyroxene. Accessory phases include garnet, spinel, plagioclase, ilmenite, chromite and magnetite. Peridotite occurs as xenoliths within a wide range of mantle derived magma types and also within the sequences of ophiolites.

7.7.1 Megascopic Characters

- i) **Colour:** Typical peridotite specimen is bright green in colour with a few black specks (Fig. 7.13). But it may exhibit a wide range of colours from blackish green, yellow, brown to red.



Fig. 7.13: Hand specimen of peridotite.

- ii) **Appearance:** Peridotite is very dense, coarse-grained, olivine rich ultramafic plutonic rock. It is massive/ homogeneous and holocrystalline, but layers are also present in case of layered peridotite. It is identified by typical green colour with black specks.
- iii) **Mineralogical Composition:** Megascopically, peridotite consist of olive-green olivine, black orthopyroxenes and grass-green clinopyroxenes grains that are visible with unaided eyes. It contains following minerals:
- **Essential Minerals:** Olivine > 40%, orthopyroxene and clinopyroxene.
 - **Accessory Minerals:** Spinel or garnet, rarely amphibole, phlogopite, and apatite.
 - **Secondary minerals:** Serpentine group of minerals.
- iv) **Texture:** The appearance, size and arrangement of different mineralogical constituents within the rock are as follows.
- **Physical appearance:** Peridotite is usually holocrystalline, coarse-grained and olive-green coloured rock.
 - **Grain size:** The grains are phaneritic, coarse-grained.

- **Mutual arrangement of the constituents/fabric:** Peridotite is a granular rock. There are three main varieties of texture found in the peridotite:
 - a) Where well-defined olivine crystals are surrounded by pyroxene and other minerals. The olivine crystals crystallise out first and owing to their high specific gravity, they settle down in the magma chamber.
 - b) In few peridotites, equal sized crystals with straight grain boundaries meet at angle of 120° forming triple junction. They result from the slow cooling.
 - c) The long olivine crystals in peridotite with ragged curvilinear boundaries, resulted from internal deformation.
- v) **Structure:** Mostly, peridotite occurs in massive form, but it is also present in the form of layers. The layered peridotites form the base of gabbro intrusions. It is a cumulate rock, formed by settling of olivine crystals in the bottom of the magma chamber. Some peridotite that are rich in amphibole show concentric layered structure and form parts of zoned ultramafic complexes.

7.7.2 Microscopic Characters

Microscopically, peridotite is one of the most colourful rocks when viewed under the cross nicol conditions. It contains lot of olivine grains which show second to third order blue-red interference colours.

- i) **Mineralogy:** You have read above that olivine and pyroxene (and/or amphibole) are the main components of the peridotite. It constitutes >40% of the pair olivine + pyroxene (or amphibole) (Fig. 7.14). The mafic minerals form more than 90% of the bulk. Other notable minerals that are present includes chromite, garnet and plagioclase. Under the microscope, various minerals can be identified easily. The orthopyroxenes are usually grey, while olivine shows second-third order bright blue-red interference colours. Clinopyroxenes show light green colour, pleochroism and spinel shows brown colour under plane polarised light.
- ii) **Texture:** The shape and size of the crystals are as follows.
 - **Crystallinity:** It shows mesocrystalline, hypidiomorphic and granular texture. Few subhedral to euhedral crystals of olivine are observed in some peridotites.
 - **Granularity:** It is coarse-grained phaneritic.
 - **Mutual arrangement of the constituents/fabric:** Poikilitic texture is common in peridotite. In this type of texture oval shaped olivine crystals are embedded in clinopyroxene crystals. Some of the peridotite also exhibit cumulate textures and display preferred crystal orientation (Fig. 7.14).

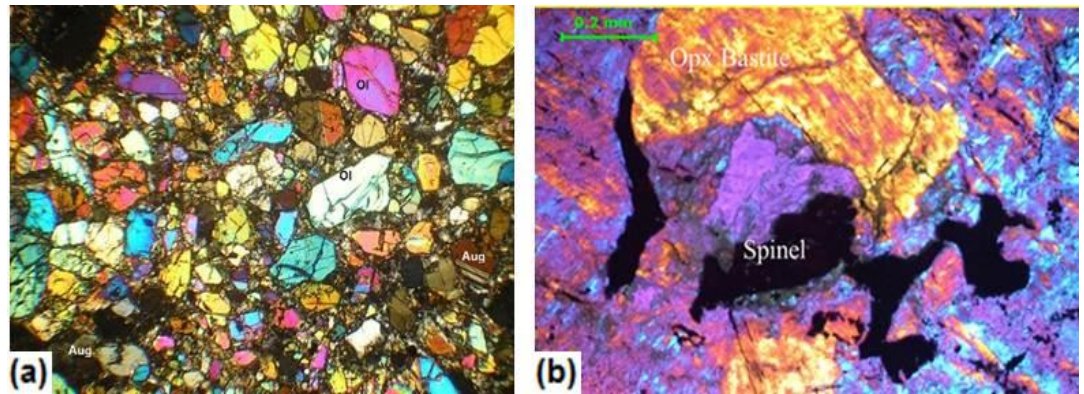


Fig. 7.14: Photomicrograph of peridotite: a) Peridotite with olivine (Ol) and augite (Aug) (Source: <http://petrography.geology.uiowa.edu>); **and b) Altered peridotite showing irregular interlocking crystals of pseudomorph of olivine and orthopyroxene (bright colours).** (Photo credit: Irfan Bhat)

iii) **Rock types:** The following rock types are observed:

- **Dunite** is a monomineralic ultramafic rock where olivine > 90%.
- **Harzburgite** is a rock having olivine > 40%, orthopyroxene (commonly enstatite), clinopyroxene < 5% (commonly diopside).
- **Lherzolite** has olivine > 40%, clinopyroxene and orthopyroxene.
- **Wehrlite** is composed of > 40% olivine and clinopyroxenes and < 5% orthopyroxene.

iv) **Occurrence:** Peridotite is a common component of oceanic lithosphere and which is derived from upper mantle. Peridotites are also formed as cumulates in layered intrusions. Peridotite is found in layered igneous complexes.

In the previous sections we have studied about the megascopic and microscopic characters of ultramafic rocks like peridotite. Before going to the next section spend 5 minutes to check how you are progressing.

SAQ 2

- Name the essential minerals of peridotite.
- Name a monomineralic ultramafic rock.
- What is lherzolite?
- Which ultramafic rock exhibits spinifex texture?

7.8 SUMMARY

In this unit, we have discussed megascopic and microscopic characters of some of the important mafic and ultramafic rocks. Let us summarise now.

- Mafic igneous rocks contain 45–52 wt% silica, while ultramafic rocks contain < 45% silica.
- Basalt is a dark coloured, fine-grained mafic extrusive rock. Essentially, it is composed of pyroxenes (mostly augite) and calcic plagioclase with or

without olivine. However, the rock is so fine-grained that it is difficult to identify minerals with unaided eyes except a few phenocrysts. Basalts show intergranular, intersertal and glomeroporphyritic textures.

- Gabbro is a dark mafic intrusive rock. Gabbro is intrusive equivalent to basalt. This plutonic rock is composed of calcic plagioclase and ferromagnesian minerals such as pyroxenes, hornblende and minor amount of olivine.
- Dolerite is a fine to medium-grained, dark coloured intrusive mafic rock consisting of calcic plagioclase, clinopyroxenes and minor amount of olivine, characteristically shows subophitic to ophitic texture.
- Peridotite is a group of ultramafic rocks, which contains >40% (by volume) magnesium rich olivine, pyroxenes (both clino- and ortho- pyroxene) and hornblende. The rocks are chiefly composed of a single mineral or in combination of various proportions of olivine and pyroxenes.

7.9 ACTIVITY

- Prepare a list of ultramafic and mafic rock types found in India.

7.10 TERMINAL QUESTIONS

1. What are the mafic and ultramafic rocks?
2. Describe mineralogy of basalt.
3. Discuss microscopic characters of peridotite group of rocks.
4. Write note on the gabbro giving its mineralogical composition, texture and occurrences.

Audio/Video Material Based Questions:

- Explain the following textures present in basalt:
 - a) Intersertal
 - b) Porphyritic
 - c) Intergranular
 - d) Vitrophyric
- Write the texture and mineralogical composition of dolerite.
- Name a monomineralic rock.
- List the microstructures found in basaltic rock.
- How is spinifex texture formed?

7.11 REFERENCES

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- <http://petrography.geology.uiowa.edu>
- www.gsi.gov.in

(Website accessed on 25th March 2020)

7.12 FURTHER /SUGGESTED READINGS

- Best, M G. (1986) Igneous and Metamorphic Petrology, CBS Publications.
- Ehlers, Ernest G., & Blatt, H. (1999). Petrology: Igneous, Sedimentary, and Metamorphic, 1st Edn. CBS Publications.
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7.13 ANSWERS

Self Assessment Questions

- 1 a) Basalt, Gabbro
b) Ca-rich Plagioclase, clinopyroxene (augite) with or without olivine.
c) Ca-rich plagioclase, clinopyroxene (diopside and augite) and/or orthopyroxenes (hypersthene), olivine and amphibole.
d) Bigger crystal of augite encloses smaller laths of plagioclase.
- 2 a) Olivine>40%, ortho- and clino-pyroxenes.
b) Dunite.
c) Peridotitic rock having olivine>40%, clinopyroxene and orthopyroxene.
d) Komatiite.

Terminal Questions

1. Please refer to sections 7.2 and 7.6.
2. Please refer to sections 7.3.
3. Please refer to sections 7.7.3.
4. Please refer to sections 7.4.

GLOSSARY

Acid rocks	: Rocks consisting of silica rich minerals like quartz, alkali feldspar and muscovite in large amount. They comprise more than 65% silica.
Accessory minerals	: They are present in minor amounts and their presence or absence does not affect the definition or nomenclature of the rock.
Alteration	: The process of physical and chemical changes which rock or mineral undergoes after its formation.
Amygdaloidal	: Term describing volcanic rocks that contain numerous amygdules.
Andesite	: General name of intermediate rock that is extrusive.
Anorthite	: The end member of plagioclase feldspar series having the composition of calcium aluminum silicate $\text{CaAl}_2\text{Si}_2\text{O}_8$.
Assimilation	: Bedrock around the magma chamber being incorporated into the magma, sometimes changing the composition of the magma.
Back-arc basin	: The regional depression above a subduction zone, between an island arc and the continental mainland, commonly underlain by oceanic crust.
Basic rock	: Igneous rock in which the minerals with less silica and sufficient alkali, like amphibole, pyroxene, biotite and olivine are comparably abundantly present.
Basalt	: Igneous rock, fine-grained, almost black in colour, formed from a non-viscous type of lava.
Biotite	: It is a member of mica Group. Biotite varies in colour from dark brown to dark green. It is a common rock forming mineral having parallel cleavage and crystallises in monoclinic system.
Bombs - volcanic	: Lumps of rock and/or lava thrown out of a volcano during an eruption.
Bowen's Reaction Series	: A series of mineral formation temperatures that can explain the minerals that forms in specific igneous rocks. For example, pyroxene will form with olivine and amphibole, but not quartz.

Chilled margin	: Edge or margin of dyke or other intrusive body, where magma has cooled quickly in contact with a cold wall or country rock; crystals in the chilled margin are much smaller than of the dyke.
Crossed nicol	: In this condition two nicol prisms are kept perpendicular to each other.
Crystallisation	: The process by which crystalline phases are separated from liquid, viscous or dispersed state.
Diorite	: General name of an intermediate rock that is intrusive and has the same amount of felsic minerals and mafic minerals.
Explosive eruption	: Volcanic eruption where viscous, gas-rich magmas burst out as explosions of pyroclastic material ("bombs", pumice and "ash").
Fayalite	: It is a mineral belonging to olivine group having the composition of Fe_2SiO_4 . It is found both in crystalline and massive form.
Felsic	: Term used for rocks containing one or more minerals with sufficient silica like feldspar, feldspathoid and silica.
Felsite	: Light-coloured, fine-grained extrusive or shallow-intrusive igneous rock with or without phenocrysts and composed chiefly of feldspar and quartz.
Ferromagnesian	: It refers to a mineral rich in iron and magnesium.
Gabbro	: Dark-coloured, coarse-grained, igneous rock; cooled slowly in large intrusions (same chemical composition as basalt).
Glassy	: Term used for glass like texture developed in volcanic rocks.
Granite	: General name of a felsic rock that is intrusive consisting of more felsic minerals than mafic minerals.
Granodiorite	: Intrusive igneous rock related to granite, but contains a greater proportion of plagioclase feldspar and mafic minerals; roughly intermediate in composition between a granite and a diorite.

Intermediate	: It is the term used for those igneous rocks between basic and felsic rock groups. They consist of silica between 52 and 65%.
Island arc	: A curved belt of volcanic islands that form above a subduction zone.
Mantle	: Layer of hot, molten, dense rock deep beneath the surface (from about 25 to 2500 km down).
Megascopic	: Big enough to be seen by lens.
Microscopic	: This term is used in connection to microscope and objects which have very small size.
Oligoclase	: A kind of feldspar with composition between albite and anorthite but its chemical composition is closer to albite.
Olivine	: An orthosilicate with chemical composition $(\text{Mg, Fe})_2\text{SiO}_4$. Its hardness ranges between 6.5-7 and specific gravity is between 3.27-3.37. Colour of olivine is typical olive green, grayish green or brown. It is an important rock-forming of specifically mafic and ultramafic rocks.
Pleochroic haloes	: Minerals like biotite and tourmaline have inclusions of radioactive minerals (like zircon) that are surrounded by dark-coloured concentric haloes.
Rhyolite	: Fine-grained, igneous rock formed from a very viscous type of lava produced by some volcanoes.
Rift Valley	: A large valley between two sets of opposite-facing Normal faults, resulting from tension forces in the rocks, e.g. E. African Rift.
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.
Texture	: The physical appearance of rock as it appears from size, shape and fabric of constituent particles.
Volcanic	: It is concerned with characters of volcanic, related to them, situated on them and originated from them.

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