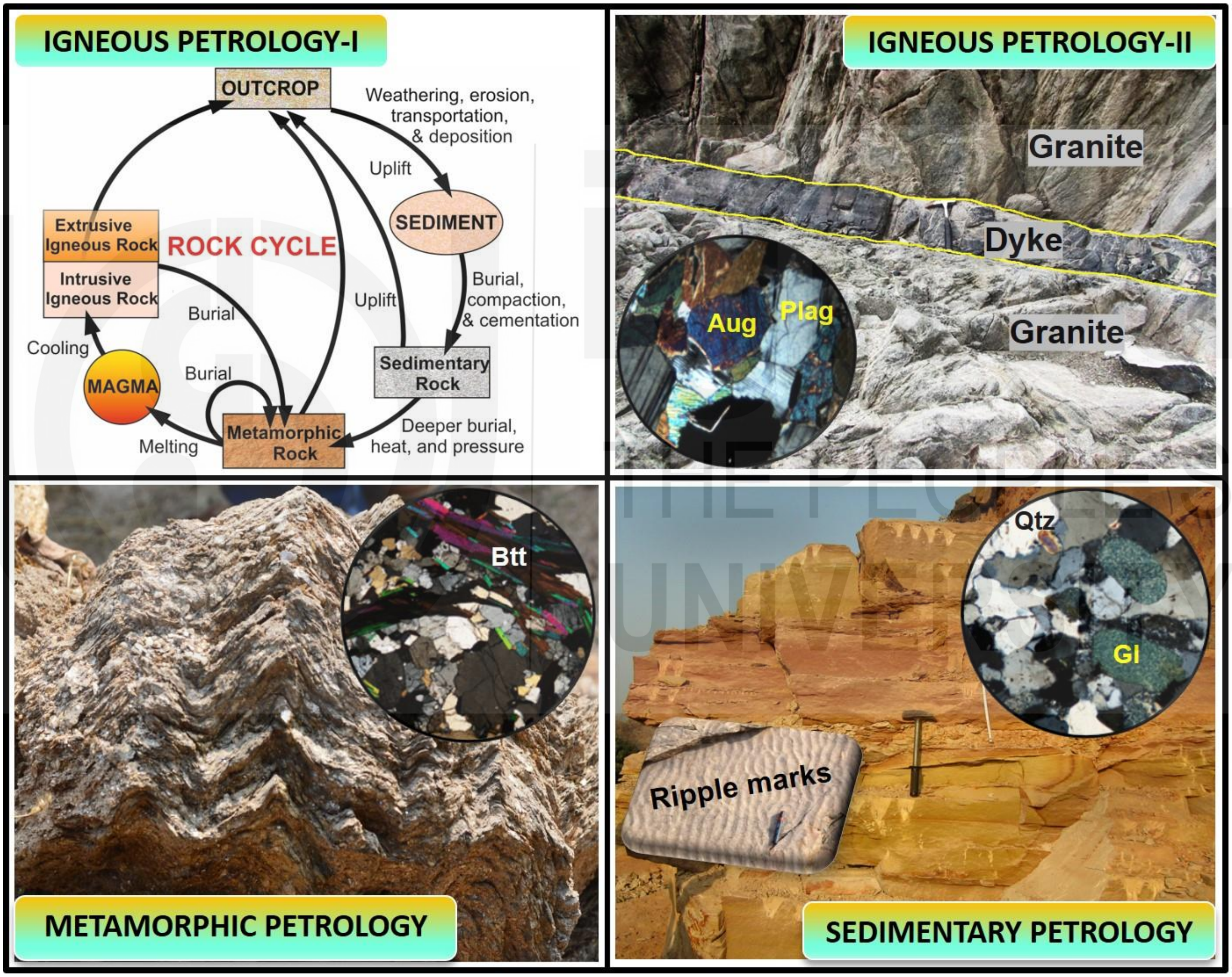
Indira Gandhi National Open University
School of Sciences

BGYCT – 135
PETROLOGY



Igneous Petrology

Vol. 1

"शिक्षा मानव को बन्धनों से मुक्त करती है और आज के युग में तो यह लोकतंत्र की भावना का आधार भी है। जन्म तथा अन्य कारणों से उत्पन्न जाति एवं वर्गगत विषमताओं को दूर करते हुए मनुष्य को इन सबसे ऊपर उठाती है।"

— इन्दिरा गांधी

"Education is a liberating force, and in our age it is also a democratising force, cutting across the barriers of caste and class, smoothing out inequalities imposed by birth and other circumstances."

– Indira Gandhi

Indira Gandhi National Open University
School of Sciences

BGYCT - 135
PETROLOGY

Volume

1

IGNEOUS PETROLOGY

Course Design Committee

Prof. Vijayshri
Former Director
School of Sciences
IGNOU, New Delhi

Prof. V. K. Verma (Retd.)
Department of Geology
University of Delhi,
Delhi

Late Prof. Pramendra Dev
School of Studies in Earth Sciences
Vikram University
Ujjain, MP

Prof. P. Madhusudhana Reddy (Retd)
Department of Geology
Dr. B.R. Ambedkar Open University
Hyderabad

Late Prof. G. Vallinayagam
Department of Geology
Kurukshetra University
Kurukshetra, Haryana

Prof. J. P. Shrivastava (Retd.)
Centre of Advanced Study in Geology
University of Delhi, Delhi

Prof. M. A. Malik (Retd.)
Department of Geology
University of Jammu
Jammu, J & K

Prof. D. C. Srivastava
Department of Earth Science
Indian Institute of Technology Roorkee
Roorkee, Uttarkhand

Prof. L. S. Chamyal
Department of Geology
M.S.University of Baroda
Vadodara, Gujarat

Prof. H. B. Srivastava
Centre of Advanced Study in Geology
Banaras Hindu University
Varanasi, UP

Prof. Arun Kumar
Department of Earth Sciences
Manipur University
Imphal, Manipur

Prof. (Mrs.) Madhumita Das
Department of Geology
Utkal University
Bhubaneshwar, Odisha

Prof. K. R. Hari
School of Studies in Geology &
Water Resources Management
Pt. Ravishankar Shukla University
Raipur, Chhattisgarh

Prof. S.J. Sangode
Department of Geology
Savitribai Phule Pune University
Pune, Maharashtra

Dr. K. Anbarasu
Department of Geology
National College
Tiruchirapalli, Tamilnadu

Faculty of Geology Discipline
School of Sciences, IGNOU

Prof. Meenal Mishra

Prof. Benidhar Deshmukh

Dr. M. Prashanth

Dr. Kakoli Gogoi

Dr. Omkar Verma

Volume Preparation Team

Course Contributors

Prof. Meenal Mishra (Units 1,2,3 & 4)
School of Sciences
IGNOU, New Delhi

Prof. K. R. Hari (Unit 5)
School of Studies in Geology &
Water Resources Management
Pt. Ravishankar Shukla University
Raipur, Chhattisgarh

Prof. Pankaj K. Srivastava (Units 6 & 7)
Department of Geology
University of Jammu, Jammu

Content and Language Editor

Prof. J. P. Shrivastava (Retd.)
Centre of Advanced Study in Geology
University of Delhi, Delhi

Transformation: Dr. Kakoli Gogoi

Course Coordinators: Dr. Kakoli Gogoi and Prof. Meenal Mishra

Audio Visual Materials

Dr. Amitosh Dubey
Producer, EMPC, IGNOU

Prof. Meenal Mishra
Content Coordinator

Production

Mr. Rajiv Girdhar
A.R. (P), MPDD, IGNOU

Mr. Sunil Kumar
A.R. (P), SOS, IGNOU

Mr. Hemant Kumar
S.O. (P), MPDD, IGNOU

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BGYCT-135: PETROLOGY

List of audio/video materials related to this course

1. **Igneous Textures, Processes and Pathways: An Overview**

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

2. **Igneous Textures, Processes and Pathways: Aphanitic Textures**

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

3. **Igneous Textures, Processes and Pathways: Phaneritic Textures**

   Link: https://www.youtube.com/watch?v=tw7vVvp6R_U

4. **Igneous Textures, Processes and Pathways: Homogenous Textures**

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

5. **Igneous Textures, Processes and Pathways: Inhomogeneous Textures**

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

6. **Geology around us-Part I**

   Link: http://egyankosh.ac.in//handle/123456789/63948

7. **Geology around us-Part II**

   Links: https://youtu.be/BtmJ8lOfxek

   http://egyankosh.ac.in//handle/123456789/65950

8. **Deccan Volcanism- An inside story**

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

9. **Physical Features of Volcanic Terrain**

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

10. **Microscopic view of basaltic rocks**

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

11. **Exsolution Intergrowth**

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

12. **Rapakivi Texture**

    Link: https://youtu.be/voXGUT4HSxY

13. **Textures Related Zoning in Igneous Rocks**

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

14. **Sedimentary structure of clastic rocks**

    Link: https://www.youtube.com/watch?v=llg5aAbaL0s&t=44s

15. **Sedimentary Structure of non-clastic rocks**

    Link: https://www.youtube.com/watch?v=3iL__lYkFRM

16. **Soil: Product of Weathering**

    Link: https://www.youtube.com/watch?v=y-SENU4Abv8

17. **Weathering its types and significance**

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

18. **Contact Metamorphic and Contact Metasomatic Deposits**

    Link: https://youtu.be/8uoDoJwNHCc

Development of audio/video programmes is a continuous process. For recent materials pertaining to the course you may visit YouTube page of the School of Sciences, IGNOU.

Alternatively, you can visit eGyankosh website at http://egyankosh.ac.in/handle/123456789/36575

BGYCT-135: PETROLOGY

Petrology (derived from the Greek word *petra* meaning 'rock', and *logos* meaning 'discourse or explanation'), is the branch of geology dealing with the mineral composition, texture. origin, occurrence, structure and history of rocks. Rocks are aggregates of minerals and building units of the Earth's crust. The rocks have been divided into three basic types based on their mode of formation: (1) Igneous rocks, (2) Sedimentary rocks, and (3) Metamorphic rocks. Petrological studies include theoretical knowledge of petrology, laboratory investigation and field work.

Igneous rocks are formed by the consolidation of hot molten rock materials called magma. Igneous rocks are also called magmatic or primary rocks. The magma solidifying within the Earth's crust forms intrusive or plutonic igneous rocks like granite, dolerite, lamprophyre, etc. The magma which is forced upwards through the crust of the Earth along the planes of weakness due to loose temperature and thus it solidifies to form extrusive or volcanic igneous rocks such as basalt, rhyolite, dunite etc.

Sedimentary rocks result from the consolidation of loose sediments derived by mechanical and chemical weathering. These rocks are also termed as secondary rocks because they are derived from pre-existing rocks. Sedimentary rocks can also form from the chemical precipitation from solution or from an organic rock, consisting of secretions or remains of plants and animals at a normal temperature and pressure.

Metamorphic rocks result from changes in pre-existing igneous, sedimentary and metamorphic rocks brought about by changes in heat, pressure and chemical action to which the rocks are subjected. The process by which rocks within the crust are changed under the influence of temperature, pressure and chemical action is called metamorphism

This course provides an extensive understanding of the fundamental concepts of petrology by means of two distinct volumes. Each volume comprises of two blocks. **Volume 1** comprises blocks 1 and 2 which deals with igneous petrology. **Volume 2** consists of blocks 3 and 4 pertaining to sedimentary and metamorphic petrology respectively.

Block 1 deals with igneous petrology, which will give you a brief idea about rock cycle and petrology. In this block you will study about texture, structure and forms of igneous rocks. You will also read about the mineralogical and chemical classification of igneous rocks.

Block 2 introduces you to the concept of magma, its composition, origin and crystallisation of magma. It also describes Bowen's reaction series, magmatic differentiation and assimilation. You will also study in detail about megascopic and petrographic description of felsic, intermediate, mafic and ultramafic rocks.

Block 3 provides the fundamental concepts about of processes of formation, textures and structure of sedimentary rocks. It will also study about classification of sedimentary rocks on the basis of texture, composition, classification, origin and occurrence.

Block 4 discusses metamorphism and products of metamorphism, type, zones and grade of metamorphism. Textures and structures of metamorphic rocks, factors affecting textures and types of textures, classification of metamorphic rocks. You will also study about megascopic and microscopic characters of some common metamorphic rocks.

Expected Learning Outcomes

After studying this course, you should be able to:

- define rock and rock cycle;
- outline mineralogy, textures, structures of igneous, sedimentary and metamorphic rocks;
- discuss megascopic and petrographic description of common felsic, intermediate, mafic and ultramafic rocks;
- describe the concept of sediment and processes of formation of sedimentary rocks;
- classify sedimentary rocks on the basis of texture, composition, classification, origin and occurrence;
- explain metamorphism, facies, grades and types of metamorphism; and
- classify metamorphic rocks.

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

Best wishes for the endeavour!!!

VOLUME 1: IGNEOUS PETROLOGY

The course **BGYCT-135 Petrology** consists of four blocks, which have been packaged in two volumes.

Volume 1 contains Block 1 and Block 2 which deals with igneous petrology. The first block, **Block 1 Igneous Petrology-I** comprises of three units. This block deals with introduction to petrology, rock cycle, uses of rocks, texture, structure, forms and classification of igneous rocks.

The second block, **Block 2 Igneous Petrology-II** comprises four units. The block will acquaint you with the concept of magma, its composition, origin and crystallisation. It will explain Bowen's reaction series, magmatic differentiation and assimilation. This block will also familiarise with megascopic and petrographic description of common felsic and intermediate rocks like granite, granodiorite, rhyolite, syenite, phonolite, diorite. You will also study the megascopic and petrographic description of common mafic and ultramafic rocks like basalt, gabbro, dolerite, peridotite.

Expected Learning Outcomes

After studying this volume, you should be able to:

- classify rock and explain rock cycle;
- list textures, structures and forms of igneous rocks;
- define concept of magma;
- explain Bowen's reaction series;
- describe unicomponent and binary system;
- explain the application of phase rule and;
- discuss megascopic and petrographic description of common felsic, intermediate, mafic and ultramafic rocks;

Wishing you success in this endeavour!!

Indira Gandhi National Open University
School of Sciences

BGYCT – 135
PETROLOGY

Block

1

IGNEOUS PETROLOGY - I

Course Design Committee

Prof. Vijayshri
Former Director
School of Sciences
IGNOU, New Delhi

Prof. V. K. Verma (Retd.)
Department of Geology
University of Delhi,
Delhi

Late Prof. Pramendra Dev
School of Studies in Earth Sciences
Vikram University
Ujjain, MP

Prof. P. Madhusudhana Reddy (Retd.)
Department of Geology
Dr. B.R. Ambedkar Open University
Hyderabad

Late Prof. G. Vallinayagam
Department of Geology
Kurukshetra University
Kurukshetra, Haryana

Prof. J. P. Shrivastava (Retd.)
Centre of Advanced Study in Geology
University of Delhi, Delhi

Prof. M. A. Malik (Retd.)
Department of Geology
University of Jammu
Jammu, J & K

Prof. D. C. Srivastava
Department of Earth Science
Indian Institute of Technology Roorkee
Roorkee, Uttarkhand

Prof. L. S. Chamyal
Department of Geology
M.S.University of Baroda
Vadodara, Gujarat

Prof. H. B. Srivastava
Centre of Advanced Study in Geology
Banaras Hindu University
Varanasi, UP

Prof. Arun Kumar
Department of Earth Sciences
Manipur University
Imphal, Manipur

Prof. (Mrs.) Madhumita Das
Department of Geology
Utkal University
Bhubaneshwar, Odisha

Prof. K. R. Hari
School of Studies in Geology &
Water Resources Management
Pt. Ravishankar Shukla University
Raipur, Chhattisgarh

Prof. S.J. Sangode
Department of Geology
Savitribai Phule Pune University
Pune, Maharashtra

Dr. K. Anbarasu
Department of Geology
National College
Tiruchirapalli, Tamilnadu

Faculty of Geology Discipline
School of Sciences, IGNOU

Prof. Meenal Mishra

Prof. Benidhar Deshmukh

Dr. M. Prashanth

Dr. Kakoli Gogoi

Dr. Omkar Verma

Block Preparation Team

Course Contributor

Prof. Meenal Mishra (Units 1, 2 & 3)
School of Sciences
IGNOU, New Delhi

Content and Language Editor

Prof. J. P. Shrivastava (Retd.)
Centre of Advanced Study in Geology
University of Delhi, Delhi

Transformation: Dr. Kakoli Gogoi

Course Coordinators: Dr. Kakoli Gogoi and Prof. Meenal Mishra

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BGYCT-135: PETROLOGY

BLOCK 1: IGNEOUS PETROLOGY - I

Petrology is a branch of geology that deals with the study of rocks. Rocks are naturally occurring chemical compounds, formed by geological processes. Since immemorial period, rocks play significant role in human lives. Rocks caves provided shelter for an early man. Moreover, striking of stones/rocks by early man led to discovery of fire. Rocks provide metallic as well as non-metallic ores including limestone, rock phosphate, gypsum, sand and clays which are useful in cement, fertilizers, chemical, glass and ceramic industries. Sand is an important component of the building material. Fossil fuels such as coal and petroleum are derived from the rocks. Rocks find several applications in our daily life of the modern world. Rocks are classified into (a) igneous, (b) sedimentary and (c) metamorphic. Igneous rocks are formed by primary processes, such as cooling and crystallisation/consolidation of the magma. Whereas, metamorphic rocks are formed by the metamorphism of pre-existing rocks (igneous, sedimentary or metamorphic). Sedimentary rocks are formed by weathering and disintegration of igneous, metamorphic or even sedimentary rocks. Rock cycle shows an intimate relation between other cyclic processes of Earth. Texture and structures provide useful information to understand geological processes. These processes are operating since inception of the Earth and are still continued.

This is the first block of the course which deals with igneous petrology. The block consists of three units.

Unit 1 Petrology deals with introduction to petrology. Here you would be introduced to fundamental concept of petrology. You will learn to classify major rock types and explain the concept of rock cycle. The uses of rocks to human beings have also been discussed along with the brief introduction to extraterrestrial rocks.

Unit 2 Texture and Structure of Igneous Rocks deals with textures, structures and forms of igneous rocks. In this unit you would learn about different types of textures based on factors such as crystallinity, fabric, granularity etc. and structures of igneous rocks due to mobility of magma or cooling of magma. The unit also give insight on forms of igneous rocks namely concordant or discordant bodies.

Unit 3 Classification of Igneous Rocks deals with classification of these rocks. We will discuss about the mineralogical classification of igneous rocks based on composition and proportion of minerals and colour index. Apart from this CIPW, tabular and IUGS classifications have also been discussed. We will also learn about chemical classification of igneous rocks based on silica percentage, silica saturation, alumina saturation, alkali lime index and total alkali silica.

Expected Learning Outcomes

After studying this block, you should be able to:

- define rocks, classify them and distinguish principal rock types;
- explain concept of rock cycle;
- discuss importance of rocks in our daily life;
- acquire an outline idea about the extraterrestrial rocks;
- discuss textures present in igneous rocks;

- recognise different structures and forms of igneous rocks; and
- classify igneous rocks on the basis of their mineralogical and chemical composition.

We hope that after studying this block you will be able to acquire knowledge of the basic concepts of rocks with special emphasis to igneous 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

Discipline of Geology

School of Sciences

IGNOU, Maidan Garhi

New Delhi – 110068 (India)

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

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

UNIT 1

INTRODUCTION TO PETROLOGY

Structure

1.1 INTRODUCTION

Rocks have always been a matter of fascination for human beings. Stones were among the first tools and weapons used by humans. The rock caves provided shelter to the prehistoric man. He could ignite fire by rubbing pieces of rocks. Rocks have been and are being explored by human beings for extraction of minerals and metals. Later, metals became the basis of wealth and the foundation of empires. After having learnt megascopic and microscopic properties of minerals in the course BGYCT-133, let us study about rocks. Rocks are the most common and abundant materials found on the Earth. On closer examination we observe that rock consists of smaller crystals or grains. Rock is defined as a naturally occurring solid aggregate of minerals. Its character and appearance depend on the nature and volume of the constituents mineral(s). They may occur in various colours and textures. They act as vehicles in all Earth processes such as volcanic eruptions, mountain building, weathering, erosion, and even earthquakes. The rocks provide a historical record of geologic events giving insight into interactions among components (crust and mantle) and spheres (lithosphere, atmosphere, hydrosphere and biosphere) of the Earth System. Now in this unit, you will be introduced to the basic concepts of petrology, i.e. study of rocks. Petrology (derived from the Greek word petra meaning 'rock', and logos meaning 'discourse or explanation'), is the branch of geology dealing with the origin, occurrence, structure and history of rocks.

Let us realise, what the term rock means to geologists? What are the rock constituents? How to distinguish one rock type from other? We will also discuss about rock cycle and the uses of rock to the human and society.

Expected Learning Outcomes

After reading this unit you should be able to:

- ❖ define rocks and discuss the importance of their study;
- ❖ classify and distinguish principal rock types;
- ❖ explain the concept of rock cycle;
- ❖ appreciate the uses of rocks to human beings; and
- ❖ discuss briefly about the extraterrestrial rocks.

1.2 WHAT ARE ROCKS?

We live on the rocks, even though we don't always see them. Strange! Unbelievable, isn't it.

These rocks are sometimes exposed on Earth's surface and we can see them, whereas, often they are concealed by the debris, soil, water and ice. Try to recall that in unit 9, Introduction to Structural Geology of the course BGYCT-131, you must have read that when a portion of the rock below appears at the surface it is termed as **outcrop.** The rocks which are not exposed on the surface are referred to **incrop.** Rock occurs at the Earth's surface either as broken chunks (pebbles, cobbles or boulders) that have moved down a slope or by being transported in ice, water or wind or as bedrock on the surface of the Earth. Geologists refer to an exposure of bedrock as an outcrop. An outcrop may appear as a rounded knob in the field, as cliff or ridge (Fig. 1.1a), along road-cuts (Fig. 1.1b) or on face of a stream cut (Fig. 1.1c).

Fig. 1.1: Field photographs showing appearance of rocks: a) as ridge; b) along road cutting; and c) along a river valley.

Now, let us discuss fundamental aspects related to rock and try to answer queries like:

What are the rocks?

How do they look like?

Where do they occur?

How do they form?

There are many definitions of rock. The most acceptable scientific definition is that: a **rock** is a coherent, naturally occurring solid, consisting of an aggregate of minerals. There may be exceptions like basalt, it may comprise glass and fine-grained minerals about which you will read further in this unit.

Now let us analyse the different aspects of this definition.

Coherent: This means that the mineral(s) are present together in a rock. A pile of unattached mineral grains, e.g. loose sands does not constitute a rock.

Naturally occurring: Bricks do not qualify as they are not naturally occurring material.

Aggregate of minerals or a mass of glass: You have read that the rocks crystallising from magma consist of aggregate of mineral grains grown together. Volcanic rock products often consist of glass which may be homogenous mass or an accumulation of tiny glass shards.

You must have learnt to appreciate that a single mineral crystal is considered as a “mineral specimen” and not a rock, even if it is meters long. There are some rocks that contain minerals of only one kind of mineral. They are called **monomineralic rock** for example dunite, anorthosite and limestone. For example, dunite is made up of mineral olivine; calcic plagioclase constitutes anorthosite rock and limestone is composed of mineral calcite. If a rock is made of more than one mineral, it is called a **polymineralic rock**. Granite is a good example of polymineralic rock because it consists of many light and dark coloured minerals like quartz, orthoclase, plagioclase, muscovite and biotite. Let us carefully examine a granite sample (Fig. 1.2) with hand lens; we will observe that some portions of the rock are translucent comprising the mineral quartz. Pink mineral with tabular habit and pearly luster is orthoclase (K feldspar-potash feldspar). Off white coloured mineral with tabular habit and striations, shows properties of plagioclase feldspar. Brown mineral grains occurring as thin sheets, showing pearly luster are mica grains; shinning mineral is muscovite and dark brown mineral is biotite. Dark minerals that occur as stubby crystals are probably hornblende, the most common mineral of the amphibole family. Other minerals occur in granite, but they are not as common as these four.

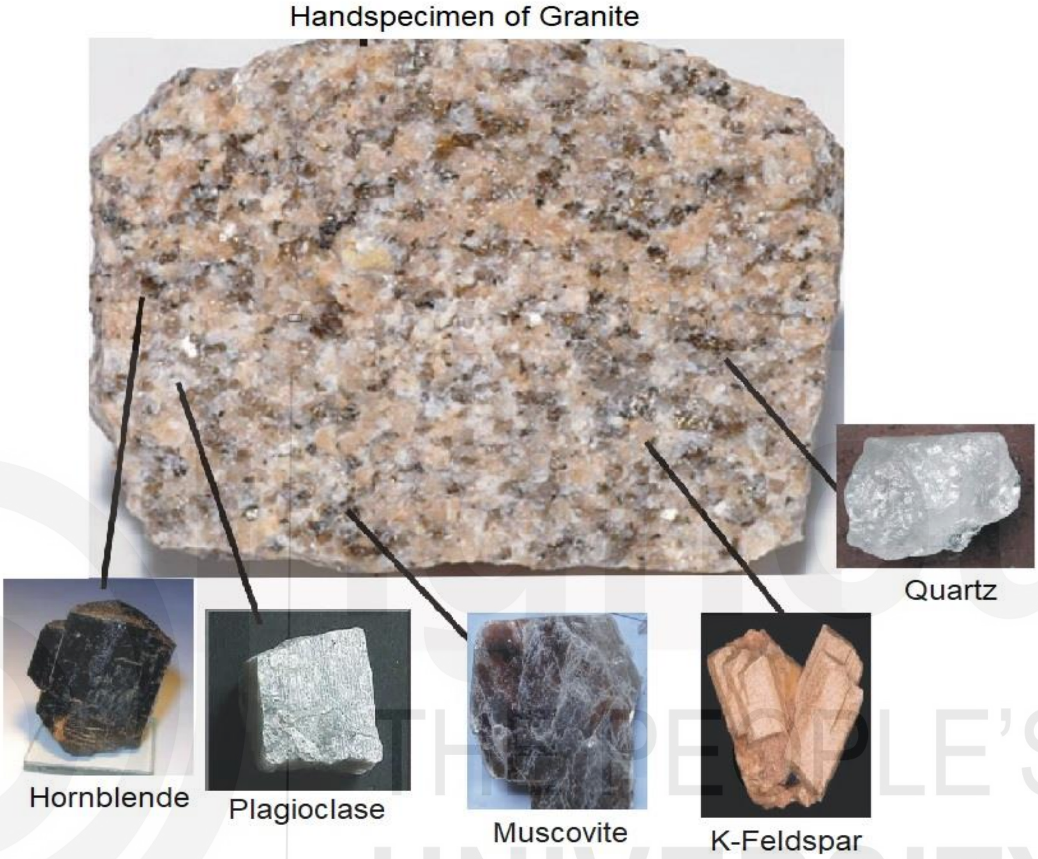

Fig. 1.2: Constituent minerals in a granitic rock.

A characteristic of rock is that each of the component mineral retains its properties in the mixture. Obsidian and pumice are considered as volcanic rocks even though they are made of glassy material. A few rocks are composed of non-mineral matter. Coal is considered as rock as it often occurs in layered structure although it consists of organic material.

What determines the physical appearance of a rock?

Rocks vary in colour, in the crystal or grain sizes and also the kinds of elements that compose them. Let us examine a road cut to visualise it. You may find a rough white and pink speckled rock composed of interlocking crystals, large enough to be seen with the naked eye. This may be igneous rock known as granite. Nearby you might see greyish rock containing many large glittering crystals of mica and some grains of quartz and feldspar which may possibly be micaceous sedimentary rock-like micaceous sandstone. Elsewhere you might see a rock, wherein, dark and light minerals are aligned forming bands or layers. This may be metamorphic rock like schist. The identity of a rock is determined partly by its mineralogy and partly by its texture. Here the term mineralogy refers to the constituent minerals of the rock. Texture describes the sizes, shapes and mutual relationship of constituent minerals. If in a rock most of the crystals or grains are a few millimetres in dimension that is they are large enough to be seen with the unaided eyes, the rock is categorised as coarse- grained. If they are not large enough to be seen, the rock is categorised as fine- grained.

According to the estimation made by Clarke and Washington, the lithosphere consists of 95% igneous rocks, 5% sedimentary rocks, including shale, sandstone and limestone (the metamorphic rocks being the altered equivalent of one or other of these rocks).

Now you must be curious to know about the origin of rock?

The discovery of the origin of rock was a century long struggle. Neptunists, led by Abraham Gottlob Werner (1749–1817) believed that all rocks were derived by the processes of chemical precipitation from ocean. Vulcanists (or plutonist) championed by James Hutton (1726–1797) were of the belief that most rocks initially formed were of igneous origin. Hutton used careful, observation to refute Neptunists' claims by demonstrating the presence of igneous rocks and showing evidence of Earth's internal heat. James Hutton, a Scottish gentleman farmer and doctor, with many others fostered the idea of the genetic scheme of classification of rocks. Modern geologists revere Hutton as the "Father of Geology".

Rocks are classified into three major groups based on their origin;

- igneous rocks
- sedimentary rocks
- metamorphic rocks

Igneous rocks: Rocks solidified from molten or partly molten magma are called igneous rocks. They are also referred **primary rocks**.

Sedimentary rocks: These rocks have resulted from the consolidation of loose sediments derived by mechanical and chemical weathering. These rocks are also termed as **secondary rocks** because they are derived from pre-existing rocks. Sedimentary rocks can also form from the chemical precipitation from solution or from an organic rock, consisting of secretions or remains of plants and animals at a normal temperature and pressure.

Metamorphic rocks: A rock derived from pre-existing igneous, sedimentary or metamorphic rocks when undergo mineralogical, chemical and/or structural changes are called metamorphic rocks.

You will read more about these rocks and their interrelationship further in this unit when we discuss the rock cycle.

1.3 WHY DO WE STUDY ROCKS?

You have studied that the rocks are aggregate of different minerals. In other words, minerals are the building blocks of the rocks. **Petrology** is the branch of geology that deals with the study of all the aspects of rocks. A **petrologist** studies rocks, identifies minerals present and makes observations.

Why do the petrologists study rocks? Let us look for an answer to this question.

Petrologists study rocks as they provide clues about Earth's origin and historical past because different rocks form under specific physico-chemical conditions. Petrologists can also interpret how the Earth processes of the past might influence the future. The processes that shaped and continue to shape, the Earth could be understood by studying rocks, and minerals. The rocks form the landscape and provide us with valuable mineral resources. Petrologists locate resources that contain important metals, mineral deposits and plan the mining activities. They also play an important role in exploration of oil and natural gas.

By now you must be questioning how the petrologists study rocks!

A petrologist studies the rocks by examining rock in an outcrop. They carefully record observations of the outcrop in the field and then examine a broken fist sized rock piece more closely with hand lens. Thereafter, its thin section is prepared and examined under the petrological or polarising microscope. Recall you have been introduced to the polarising microscope in Unit 8 of BGYCT-132. This microscope helps in carrying out petrographic studies of the rocks. The branch of geology dealing with the description and systematic classification of rocks by microscopic examination of thin sections is known as **petrography**.

Let us discuss significance of petrography in geological studies that

- helps to understand the environmental conditions of rock formation;
- throws light on the mineralogical composition and interrelationship between mineral grains;
- enables to determine the kinetics (energy of a body derived from its movement) of their formation.

The petrography helps in mineral identification and provides the basic information about the rocks. In the beginning of 1950s, sophisticated equipments became available that enabled the petrologists to examine rocks on even finer scale. Advanced research laboratories have instruments such as Electron Probe Micro Analyser (EPMA), X-ray diffractometers (XRD) and mass spectrometers. Geochemistry has proved to be indispensable tool for the petrologists. They make use of geochemical data such as major oxides, trace elements, rare earth elements and platinum group elements, stable and radiogenic isotopes. **Petrogenesis** deals particularly with the origin and evolutionary history of igneous rocks which depends on a thorough and systematic petrography and petrology.

Learners, you have learnt the fundamental concept of rocks. Before discussing about the classification of rocks, spend few minutes to perform an exercise to check your progress.

SAQ 1

a) Define rock.

b) Mention the three types of rocks.

c) Why do the petrologists study?

d) What is the significance of petrography?

Watch the following video to know more about uses of petrography.

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

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

1.4 CLASSIFICATION OF ROCKS

Classification schemes help us to organise and appreciate significant aspects or characteristics about the objects to be studied. They also help us recognise similarities and differences among them. In the beginning of eighteenth century, geologists struggled to develop a scientific way to classify rocks. By the end of the eighteenth century, after much struggle, it became clear that different rocks were formed under different conditions. Most geologists had accepted that the genetic scheme of classifying rocks as an approach that we continue to use even today. This approach became the foundation of the modern system of classification of rocks. Using these approaches geologists recognised three major groups of rocks (Table 1.1).

- Igneous rocks e.g. granite, basalt, dolerite
- Sedimentary rocks e.g. sandstone, shale, limestone
- Metamorphic rocks e.g. phyllite, quartzite, marble

Let us try to differentiate between the igneous, sedimentary and metamorphic rock.

Earlier you have learnt that igneous rocks form from cooling and consolidation of the hot molten magma. Therefore, they mostly consist of crystals of minerals which can be big or small and fit together like pieces of a jigsaw puzzle. However, there are exceptions, such as pitchstone, obsidian and volcanic glass where the cooling and consolidation is very fast. Igneous rocks do not contain fossils, but may contain gas bubbles. Igneous rocks exhibit interlocking relationship between the mineral grains (Fig. 1.3a).

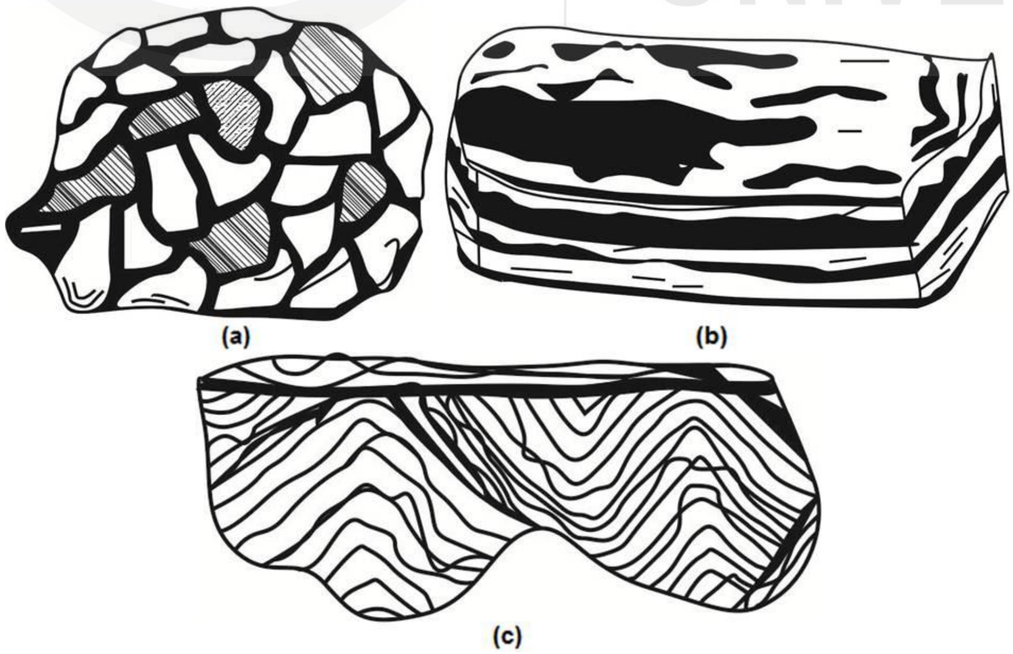

Fig. 1.3: Sketches showing different physical appearance of: a) Igneous rock; b) Sedimentary rock; and c) Metamorphic rock.

Sedimentary rocks are made up of mineral grains or sediments that have resulted from weathering and disintegration of the pre-existing rocks. The sediment grains can be big or small; and angular or rounded. The grains are often cemented to each other. Sedimentary rocks may be layered and may also contain fossils. The hand specimen of sedimentary rock can also show layering (Fig. 1.3b).

Metamorphic rocks are formed when pre-existing rocks (may be igneous, sedimentary or metamorphic) are subjected to heat and/or pressure. They show evidences of recrystallisation resulting in the formation of bigger crystals, banding of minerals or foliation (Fig. 1.3c).

Let us now summarise the general characteristics of igneous, sedimentary and metamorphic rocks in Table 1.1.

Table 1.1: Summary of three major groups of rocks.

Rock types	**Igneous rocks**	**Sedimentary rocks**	**Metamorphic rocks**
	 Granite	 Sandstone	 Phyllite
Mineral sources	Melting of rocks in the crust and upper part of the mantle	Weathering and erosion of rocks exposed at or near the surface or chemical precipitation	Rocks formed under high temperature and/or pressures in deep crust and upper mantle
Rock forming processes	Cooling, crystallisation and solidification of magma	Sediment deposition, burial, and lithification	Recrystallisation and re-orientation in solid state under the influence of temperature and pressure and formation of new minerals
Compositio n & texture	Composed of crystals and/ or glass. Mostly interlocking texture. May have layers in case of volcanic rocks	Mostly composed of sediments. Some may be crystalline, layered/stratified	Always crystalline, have aligned crystals, mostly foliations are developed. Classified using composition and texture
Classificatio n	Classified using texture, mineralogical and chemical composition	Classified using texture and mineralogical composition	Classified using texture and mineralogical composition
Examples	Granite, Basalt, Dolerite, Gabbro, Diorite	Sandstone, Shale, Siltstone, Limestone, Fossiliferous limestone	Quartzite, Slate, Phyllite, Schist, Marble

1.5 IGNEOUS ROCKS

About seven hundred types of igneous rocks are known today. Igneous petrology is the field of geology. Its objective is to study the textural and mineralogical characteristics of igneous rocks which are controlled by chemical and physical properties of magmas and their surroundings. The igneous rocks dominate crustal and upper mantle environments that provide understanding of melt generation and crystallisation mechanisms, diverse rock types and their link to tectonic settings. Study of igneous rocks is a key component of geology curriculum.

The word igneous is derived from the Latin word *ignis,* meaning 'fire' or 'to ignite'. Igneous rocks are formed due to cooling and crystallisation of hot molten material called magma, which rises up from the mantle inside the Earth. The magma can be derived from melting of pre-existing rocks in either crust or mantle. The cooling of magma can take place either in deeper conditions or on the surface of the Earth. The melting of rocks is caused by three processes like increase in temperature, a decrease in pressure, or a change in composition. Depending upon the cooling and crystallisation of magma that has taken place below or above the surface of the Earth, igneous rocks may be grouped as intrusive or extrusive.

Intrusive igneous rocks: They are also known as **plutonic igneous rocks**. These rocks crystallise when **magma** cools in the deeper conditions or magma chamber or intrudes the **country rocks** or **host rocks**. When the cooling of magma takes place below the surface of the Earth it is very slow. It has resulted in the formation of large crystals, giving rise to coarse grained rocks recognised by their interlocking crystals, visible in hand specimen, for example granite, granodiorite, gabbro, and diorite.

Extrusive igneous rocks: They are known as **volcanic igneous rocks**. Hot or partly molten rock material known as **lava** moves over the Earth's surface, where, its cooling occurs very rapidly in the contact with air and water. If the overlying rock has fractures, then the pressures may be released and a sizeable volume of molten rock will extrude on the surface. The lava cools and crystallises rapidly, it is fine grained or glassy. They may have air cavities, indicating that the volatile material or gas escaped from the molten material on release of pressure. In case of basalt, the open spaces or cavities called as vesicles that signifies top of the lava flows. The term glassy is used for those igneous rocks which do not possess discrete crystalline unit or structure. Extrusive igneous rocks, such as basalt, rhyolite, trachyte, and pitchstone are easily recognised by their fine grained or glassy texture.

Three types of igneous rocks based on their mode of occurrence have been recognized:

Plutonic rocks: The term plutonic is derived from word *Pluto* 'the Roman God' of the underworld. These rocks undergo cooling and consolidation beneath (Fig. 1.4a) the surface of the Earth or within the magma chamber. Plutonic rocks occur as intrusive bodies for example Mount Abu, Ladakh batholith.

Volcanic rocks: These rocks undergo cooling and consolidation at the surface of the Earth in contact with air or water such as basalt, rhyolite. They occur as extrusive bodies like lava flow for example Deccan basalts (Fig. 1.4b), Malani rhyolite in Jodhpur.

Hypabyssal rocks: These rocks undergo cooling and consolidation at the shallow level/ near the surface of the Earth such as dolerite (Fig. 1.4c). They are medium grained and occur often as dykes or sills.

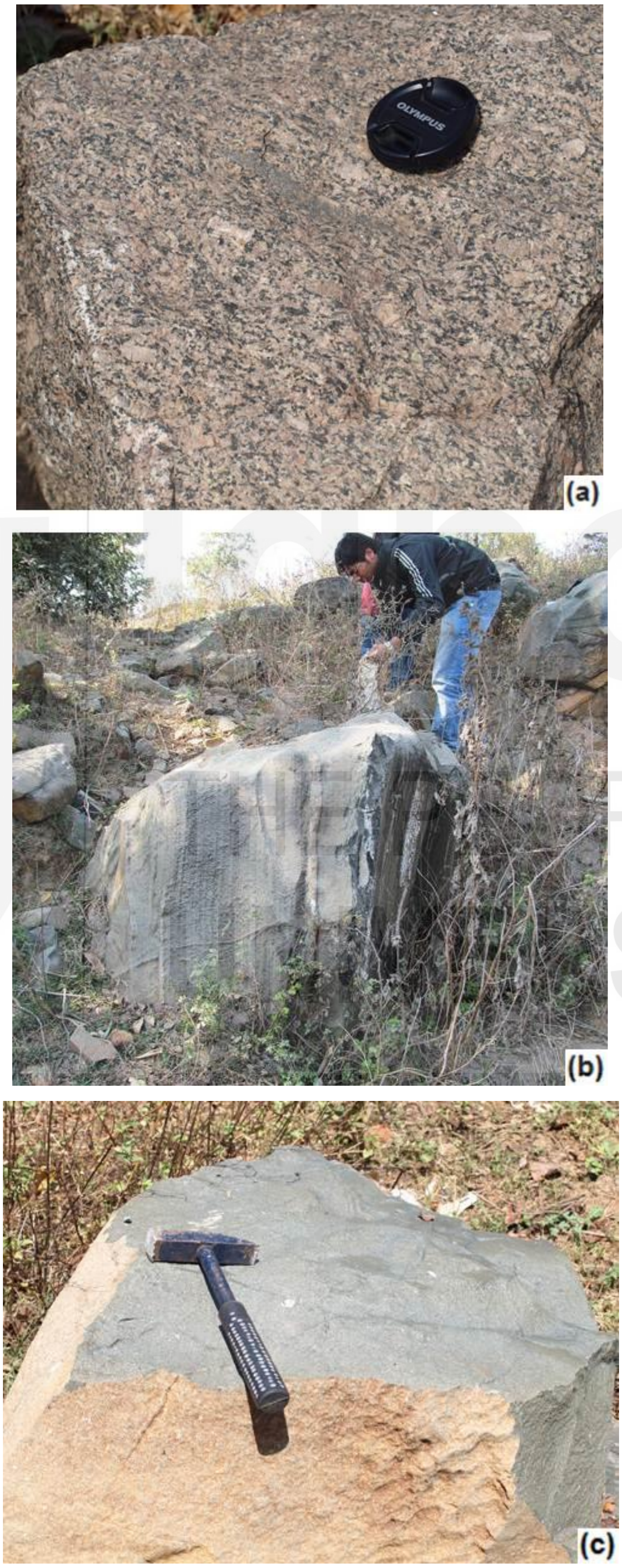

Fig. 1.4: a) Plutonic igneous rock, observe the coarse-grained granite; b) Volcanic igneous rock, basalt; and c) Hypabyssal igneous rock, photograph shows medium grained dolerite.

You have studied in units 6 and unit 7 of the course BGYCT-133 that most of the minerals in the igneous rocks are silicates, partly because silicon is so abundant in Earth's crust and partly because many silicate minerals melt at the high temperatures and pressures in deeper parts of the crust and in the mantle. The most common silicate minerals found in igneous rocks include quartz, feldspar, mica, pyroxene, amphibole and olivine.

1.6 SEDIMENTARY ROCKS

The layers of sedimentary rocks can be compared to the pages of book that record stories of earlier events and environments of our geological past. **Sedimentologists** are a specific group of geologists who study sedimentary rocks. We have learnt that sedimentary rocks are formed due to the decomposition and disintegration of the pre-existing rocks which can be igneous, metamorphic or even earlier formed sedimentary rocks. These rocks are produced by the process of weathering (physical, chemical and biological) by geological agents such as wind, river, glaciers, oceans and groundwater. Therefore, they are categorised as secondary rocks. The sedimentary rock is the rock that forms at or near the surface of the Earth by processes:

- by cementing together of loose clasts (fragments or detrital grains) that had been produced by physical or chemical weathering of pre-existing rock;
- by growth of shell masses or cementing together of shells and shell fragments;
- by accumulation and subsequent alteration of organic matter from living organisms; or
- by precipitation of minerals from water solutions.

Sediments are the precursors of sedimentary rocks that are found at Earth's surface as layers of loose particles, such as sand, silt, and the shells of organisms. These particles originate in the processes of weathering and erosion. The loose grains of sediments transform into sedimentary rock by following five steps-

i) **Weathering** refers to the entire chemical, physical and biological processes that break up and decay rocks into fragments and dissolved substances of various sizes.

ii) **Erosion** refers to the combination of processes that separates rock or regolith such as abrasion, plucking caused by moving air, water or ice.

iii) **Transportation** can occur by gravity, wind, water or ice. They can carry sediments. The ability of a medium to carry sediment depends on its viscosity and velocity.

iv) **Deposition** is the process by which sediments (a) settles out of transporting medium due to decrease in velocity or (b) precipitate from a solution due to saturation or change in temperature/pressure, the medium is no longer able to carry sediments.

v) **Lithification and diagenesis** are the transformation of the loose sediment into solid rock. Diagenesis is the process that occurs after deposition, but, prior to lithification. In these processes the sediments accumulate in layers and are compressed under their own weight and/or what buries them and form a hardened mass.

The sedimentary rocks may be classified into two groups based on their origin:

a) **Clastic sedimentary rocks**: They are also known as terrigenous rocks. They comprise **siliciclastic** sediments which are made up of physically deposited particles such as grains of quartz and feldspar derived from weathered pre-existing rock. The term ‘clastic’ is derived from the Greek word *klastos*, meaning ‘broken’. These sediments are laid down by geological agents like water, wind and ice. Common minerals in siliciclastics rocks are silicates because silicate minerals predominate in the rocks that weather to form sedimentary particles (Fig. 1.5a). The most abundant silicate minerals in siliciclastic sedimentary rocks are quartz, feldspar and clay minerals. Clay minerals are formed by weathering and alteration of pre-existing silicate minerals, such as feldspar, micas, pyroxene and amphiboles.

b) **Non clastic sedimentary rocks**: They comprise the biological and chemical group of sediments that are formed by the process of precipitation with or without organic materials. For example, halite is chemical sediment that precipitates directly from evaporating seawater. Calcite is precipitated by marine organisms to form shells or skeletons which form biological sediments when the organisms die. The most abundant minerals of chemical and biological sediments are carbonates such as calcite, the main constituent of limestone (Fig. 1.5b). Dolomite rock comprises calcium magnesium carbonate formed by precipitation from seawater.

Different kinds of sedimentary rocks are identified on the basis of their mineral composition. According to some estimates, 70% to 85% of all the sedimentary rocks on the Earth are clastic, whereas, 15% to 25% are carbonate biochemical or chemical rocks.

The sedimentary rocks were once sediments; they are the records of the conditions at Earth’s surface when and where the sediments were deposited. Using the evidences provided by a sedimentary rock’s texture, physical structure and mineral content geologists can work backward to infer the source rock for the sediments (also known as provenance, from which they were derived) and the depositional environment.

(a)

Fig. 1.5: a) Clastic sedimentary rock, coarse and medium grained sandstone; and b) Non clastic sedimentary rock, limestone.

1.7 METAMORPHIC ROCKS

We have discussed igneous and sedimentary rocks now let us learn about metamorphic rocks.

The term metamorphic derive its name from the Greek words *meta* meaning 'change' and *morphe* meaning 'form'. Charles Lyell in 1833, first proposed the word metamorphism in his book 'Principles of Geology'.

A **metamorphic rock** forms when a pre-existing rock or **protolith** undergoes a **solid-state change** (without melting) in response to elevated temperatures and pressure in presence of a chemically active fluid. This may take thousands or millions of years. **Metamorphism** is essentially an isochemical process, i.e. the bulk chemical composition of a rock body is more or less unchanged from the protolith, or original rock. This process is characterised by the growth of new minerals from pre-existing minerals through recrystallisation and deformation of existing minerals involving change in shape and orientation of mineral grains.

Let us discuss the causes of metamorphism.

- **Heat**: Increased heat allows chemical bonds to break easier.
- **Pressure**: Enhanced pressure causes minerals with 'open' lattices to collapse, forming more dense crystals.
- **Differential Stress**: When forces are not equal in all directions, minerals may deform and change shape.
- **Hydrothermal Fluids**: Apart from water, hydrothermal fluids are solutions that chemically react with minerals.

To understand metamorphism, you can consider an analogy of a caterpillar and a butterfly. Caterpillars undergo metamorphosis because of hormonal changes in their bodies to form butterfly. Similarly, the rocks undergo metamorphism when they are subjected to heat, pressure, compression and shear in presence of hot chemically active fluid.

So, we have learnt that the metamorphic rocks are formed when the pre-existing rock (which can be igneous, sedimentary or metamorphic rock) is subjected to high temperature and pressure deep within the Earth causing changes in the mineralogy, texture or chemical composition while maintaining its solid form. The temperatures of metamorphism are below the melting point of the rocks (about 700°C), but, high enough (above 200°C) for the rocks to be changed by recrystallisation and chemical reactions. Metamorphism can produce a group of minerals which together make up a metamorphic minerals assemblage. The texture in metamorphic rocks is defined by the new or re-arrangement of mineral grains. Commonly, the texture results in metamorphic foliation defined by the parallel alignment of platy minerals (such as mica) and/or the presence of alternating light coloured and dark coloured bands. For example, the metamorphism of granite (a rock with randomly oriented crystals) can produce a metamorphosed rock like schist showing parallel alignment of platy minerals or gneiss with alternating light coloured and dark coloured bands (Fig. 1.6). We have discussed that the formation of metamorphic minerals and textures takes thousands to millions of years.

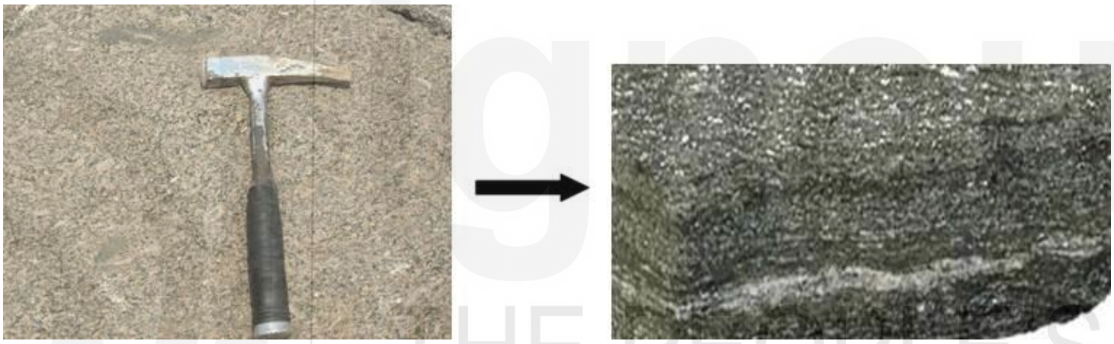

Fig. 1.6: Granite transformed to schist during the process of metamorphism.

Let us list the most common processes occurring during the process of metamorphism.

- **Recrystallisation** changes the shapes and sizes of grains without changing the identity of the mineral, e.g. limestone may recrystallise to marble.
- **Phase change** occurs when a mineral retains the same composition, but, with a different crystal structure, e.g. kyanite (chemical composition is Al_2O_5 and crystal system is triclinic) may change to sillimanite (chemical composition is Al_2O_5 and crystal system is orthorhombic).
- **Metamorphic reaction** or **neocrystallisation** (derived from the Greek word *neos,* for 'new') results in the growth of new mineral crystals that are different from those of the protolith. This is very slow process and happens through diffusion of atoms in solid state.
- **Pressure solution** takes place when the mineral grains dissolve where their surfaces are in contact. It occurs when the rock is squeezed in one direction more than the others, at low temperature, and usually in the presence of water.
- **Plastic deformation** happens when a rock is squeezed or sheared at elevated temperatures and pressures and at high temperature. This takes place without changing the composition of the minerals. The minerals behave like soft plastic and change shape without breaking.

Common minerals found in the metamorphic rocks are silicate minerals like quartz, feldspar, micas, pyroxenes and amphiboles. They are the most abundant minerals in metamorphic rocks because most of the parent rocks (protolith) are rich in silicate minerals. Several other minerals include kyanite, andalusite and some varieties of garnet. Limestone composed of calcite mineral ($CaCO_3$) is metamorphosed to marble (Fig. 1.7a). Similarly, sandstone dominantly comprises of quartz mineral which is metamorphosed quartzite (Fig. 1.7b).

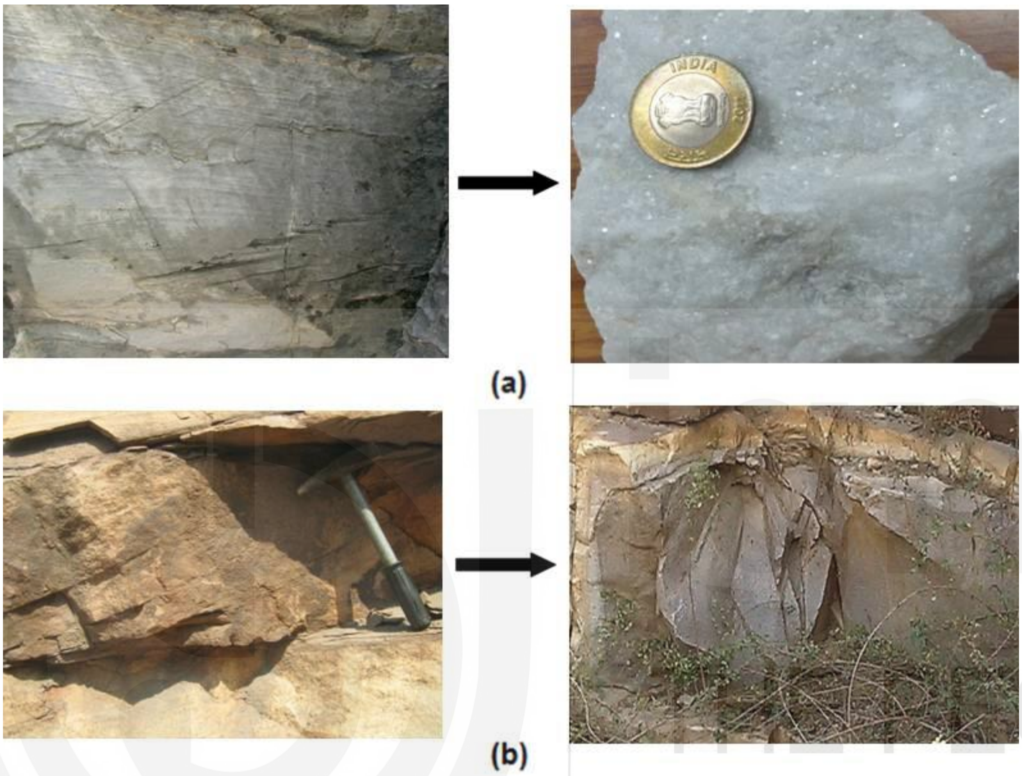

Fig. 1.7: a) Limestone is metamorphosed to marble; and b) Sandstone is metamorphosed to quartzite.

Learners, you have learnt the classification of rocks into igneous, sedimentary and metamorphic rocks. Before discussing about the rock cycle spend few minutes to perform an exercise to check your progress.

SAQ 2

a) Distinguish between intrusive and extrusive igneous rocks.

b) List three types of igneous rocks based on the mode of occurrence.

c) Mention the steps in the formation of sedimentary rocks.

d) What are the common processes involved in the formation of metamorphic rock?

1.8 ROCK CYCLE

Do you know that rocks tell us a story?

'As stable as a rock' is a familiar expression which implies that a rock is permanent and remains unchanged over the long time period. But this is no longer true. The Earth has witnessed the change and transformation of the rock's innumerable times in the time span of 4.57 Ga in its history. The process is in continuum. We just need to understand the language of rocks in order to decipher the narration of the story.

Let us read the simplified story of the rocks on the Earth before learning about the concept of **rock cycle**. Earth was originated from a ball of molten material during the birth of the solar system. The molten material cooled, and solidified at the surface, forming a shell of solid igneous rock. While the Earth's crust was being formed, volcanic activity, spewed gases and steam to create the first atmosphere and oceans. Therefore, the first climate came into existence. The climatic conditions generated on the surface of the planet worn down the igneous rock into sediments. As the mountains wore down the eroded sediments were transported and accumulated into the low-lying areas or depressions. The piles of sediment stacked up to hundreds or thousands of feet. The intense weight of the sediments began to coat the sediment grains as mineral cement. The combination of compaction and cementation caused the sediments to bind together into solid sedimentary rock in a process called **lithification**. The sedimentary rock, formed at the bottom was driven deeper into the Earth under increasing pressure and temperature. The minerals in the rock recrystallised, rearranged and formed distorted structures forming new minerals giving rise to metamorphic rock. Even though, a new rock has formed, the process of heating and pressurisation did not stop. Eventually, the minerals reached their melting points and the rocks turned into liquid magma. The return of the melted rock completes the cycle and the rocks go on to become igneous again, then sedimentary and metamorphic rocks.

Hope you enjoyed reading this story the basic concept about the rock cycle.

Now let us go through Fig. 1.8 and discuss rock cycle.

You have read that magma is molten fluid or material inside the Earth. It is the source of all the igneous rocks. Since the Earth was largely molten during its origin, magma may be considered as the beginning of the rock cycle. **The relationship between igneous, metamorphic and sedimentary rock constitutes a rock cycle.** Geologists consider rock cycle to have been operating through ages; it is intimately involved with other cyclic processes of the Earth. This is one of the basic concepts of geology and emerging out of as the **principle of uniformitarianism** (the present is the key to the past) given by Hutton in 1785. Rock cycle is particularly closely related to the plate tectonic processes. Basically, the rock cycle is a continuous process. It starts with the cooling and consolidation of mantle derived magmas which may erupt on the surface or confine below to deeper level. The erosion of rocks exposed on the surface of the Earth produced clastic materials which are transported to low lying depositional basins. The deeply buried sediments in due course of time undergoes deformation and metamorphism. The tectonic cycle leads to deformation, reconstitution, uplift and accompanying erosion of fresh rocks so that the cycle continues. Thus, plate tectonics is the driving force for rock cycle.

The rock cycle operation may be viewed as a function of energy changes or redistribution of energy within the Earth systems. The rock cycle illustrates the role of various geologic processes which act to transform one type into another.

The rock cycle allows us to visualise interrelationship amongst various components of the Earth system. This knowledge is linked to the other processes that act upon and within the planet. The Earth is constantly recycling and transforming its rocky crust. The rock cycle explains how geological processes can change a rock from one type to another through geological time. Movements of tectonic plates are the main forces driving the rock cycle. You have studied about plate tectonics in unit 16 of BGYCT-131 course.

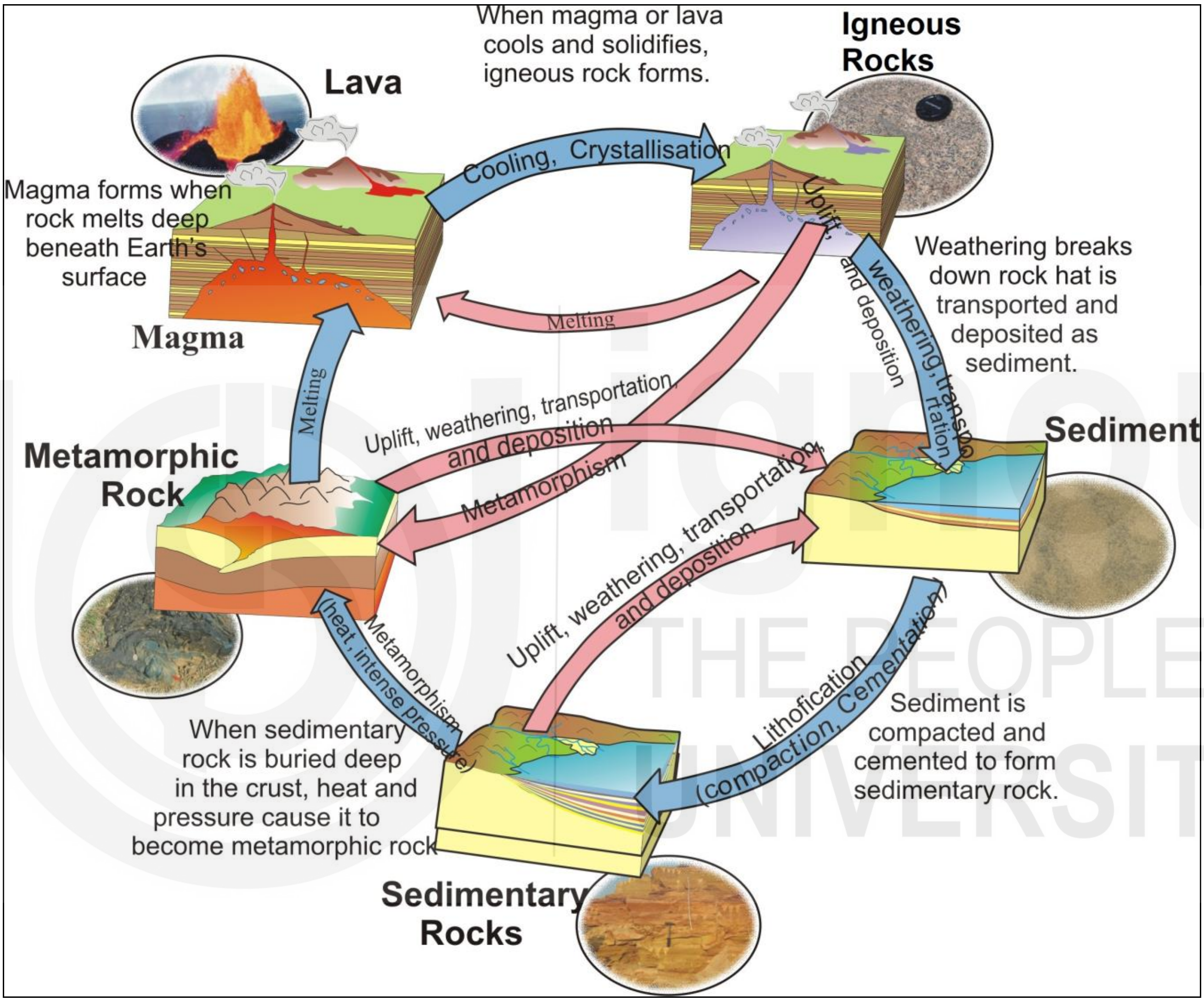

Fig. 1.8: Rocks are constantly forming, transforming and reforming. The rock cycle helps to understand origin of three rock groups.

1.9 USES OF ROCKS

You must be pondering that what is the use of studying rocks to the human and our society? Have you ever thought of it?

Rocks are naturally occurring chemical compounds that have been formed by geological processes. They provide chemicals that are essential for the life on the Earth. Geologists aim to understand properties of the rocks and infer their origin. Such inferences and deductions enhance understanding of many important aspects of our planet like its origin, economically important resources. For example, the knowledge that oil and natural gas occurs in certain kinds of sedimentary rocks that are rich in organic matter allows us to explore for oil reserves more intelligently. Understanding of the formation and properties of rocks guides us in solving environmental problems, e.g. landslide. Geologists are responsible to locate and assist in the extraction of mineral deposits such as gold, metallic ores, coal, petroleum, building materials and economically useful clays. They explore common, but vital materials such as stone aggregates for making concrete and road building, limestone for the cement, fertilizer and chemical industries, and sand for building or glass manufacture. The underground storage of radioactive and other wastes depends on analysis of the rock to be used as a repository. Human and our society depend on mineral resources. They are essential for the development of our cities such as infrastructure, power generation, transportation and communication. They enrich us in art, and we wear them as personal adornments.

Let us discuss about the uses of rock to man and society.

- **Ceramics, pottery, glass utensils**: You must have used ceramics and pottery. Ceramics are made up of mixtures of clay and earthen elements. Glasses are made from silica sand, limestone, etc. The utensils are made from metals – usually aluminum or steel or copper. We extract these metals from ores. Ore is a mineral deposit from which valuable metals can be recovered profitably.
- **Gemstones**: They have been prized for thousands of years for their colour, clarity, rarity, shape and durability. They are found in rocks and form in different geological situations.
- **Food industry**: Minerals like sodium chloride (halite) and calcium carbonate (calcite) and other mineral products used in preparation of food, bread, soups and cereal, are powdered with these ingredients. Sand is used to filter water, e.g. diatomite (silica mineral formed from fossilised algae). Diatomite and bentonite clay both are used to purify drinks, such as beer, fruit juices and wine.
- **Fertiliser industry**: Phosphate rock, potash and lime are used in agricultural fertilisers and some other mineral products to improve soil quality. A sedimentary rock known as glauconitic sandstone is directly crushed and used as fertilizer in agricultural fields.
- **Packaging industry**: Food, cold and energy drinks may be packaged in cans made from aluminium or steel, or in glass made from silica sand which we get from rocks. Plastic packaging is made from chemicals obtained from hydrocarbons.
- **Building materials**: Have you ever thought from where do we get tonnes of building material used in construction of roads and buildings? Rocks like sandstones, quartzite, slate, etc. are used as building stones. These are locally available material. Apart from these a wide range of materials such as iron used in the framework of building, clay in bricks and roofing tiles, slate for roofing tiles, limestone, clay, gypsum in cement, plaster of Paris, silica sand in window glass, sand and gravel and crushed rock as aggregates are used in the construction of buildings. The paints and pigments are derived from rock and mineral sources. Granite is popularly used in buildings, bridges, paving, and monuments and as polished granite slabs and tiles. For example, Red Fort in

Delhi and Agra are made up of red sandstone while Taj Mahal in Agra is of marble.

- **Power generation**: Energy used at home, industries, services and transportation is derived from fuel minerals such as coal and petroleum. Coal is used for domestic and industrial purposes such as thermal power houses for generation of electricity. The geologists play a crucial role in exploration of hydrocarbon reserves. We get many by-products from petroleum industry such as plastic and many organic products. The nuclear power reactors use naturally occurring radioactive materials such as uranium, thorium and potassium associated with rocks.
- **Transportation**: Every journey you make depends on minerals (rocks are aggregate of minerals), whether by car, train, plane, boat or foot. Aggregates (crushed rock, sand and gravel) are used for roads and footpaths, while railway tracks made from steel are laid on aggregate (known as ballast). Airports, railway stations and shipping ports all use large amounts of construction material to build their infrastructure.
- **Information and computer technology**: Many of us have access to a computer and mobile phone, and many services depend on computers and other forms of telecommunication. These technologies require a wide spectrum of minerals and metals, including copper, gold, platinum, tantalum, tin, zinc and nickel. Quartz crystals have unusual properties that are useful for high-tech applications. For example, superconductors, lasers, molecular sieves and high-temperature ceramics have been developed from natural crystals, which are derived from rocks.

Watch the following videos to learn more about uses of rocks.

- **Geology Around Us-Part I**

  Link: http://egyankosh.ac.in//handle/123456789/63948
- **Geology Around Us-Part II**

  Link: https://youtu.be/BtmJ8lOfxek

  http://egyankosh.ac.in//handle/123456789/65950

1.10 INTRODUCTION TO EXTRATERRESTRIAL ROCKS

We have discussed about the rocks found on our planet. Now, let us have an idea about extraterrestrial rocks which generally referred to rock material found on the Earth, but they were solidified prior to arriving on the Earth.

The extraterrestrial rocks include a vast range of material. They include:

a) Meteorites

b) Micrometeorites

c) Lunar samples brought to the Earth by Apollo missions

a) **Meteorites** are the fragments of larger bodies called parent bodies which could have been small planets or large asteroids or comets that were once part of solar system. They can be classified generally into three types:

1. **Stony meteorites** are the most common type of meteorites. They resemble the rocks found on and within the Earth. Stony meteorites are composed mainly of the minerals like olivine and pyroxene having a composition that is roughly equivalent to the Earth's mantle. They are of two types- chondrites and achondrites.

   - **Chondrites** are the most common type of stony meteorite. They are made of olivine, pyroxene, and iron - nickel alloys that are magnetic in nature. They are composed of small round spheres called **chondrules.** They were possibly formed by rapid melting followed by rapid cooling early in the history of the solar system. The chondrites have mostly radiometric age dates of about 4.6 Ga.

   - **Achondrites** are composed of the same minerals as chondrites, but they lack chondrules and resemble igneous rocks found on the Earth. The chondrules are absent because they have been heated, melted, and recrystallised.

2. **Iron meteorites** are composed of alloys of iron and nickel. They have a much higher density than normal crustal rocks. They are magnetic. When cut and polished, iron meteorites show a distinct texture called a **Widmanstätten pattern** which results from slow cooling of a very hot solid material. Iron meteorites give us an idea of the composition of Earth's core.

3. **Stony Iron meteorite** consists of a mixture of stony silicate material and iron. They exhibit silicates embedded in a matrix of iron-nickel alloy. They also occur as a breccia, wherein the fragments of stony and iron material have been cemented together either by heat or chemical reactions.

b) **Micrometeorites** are essentially un-melted micrometeoroid that has survived entry through Earth's atmosphere. It ranges in size from 50 µm to 2 mm. They differ from meteorites in having a smaller size, more abundant, and are different in composition. They include cosmic dust and smaller interplanetary dust particles. Sometimes the meteoroids and micrometeoroids entering the Earth's atmosphere are visible as meteors or shooting stars.

c) **Lunar samples brought to Earth by Apollo Missions:** Six Apollo missions between 1969 and 1972 brought back 382 kilograms of lunar rocks, core samples, pebbles, sand and dust from the lunar surface. Study of rock and soil samples from the Moon has yielded and will continue to provide useful information about the early history of the Moon, the Earth and the inner solar system.

1.11 SUMMARY

Let us summarise about what we have learnt in this unit:

- Rock is a coherent, naturally occurring solid, consisting of an aggregate of minerals.

- Geologists study rocks as they (i) contain clues about Earth's historical aspect, (ii) provide us with valuable resources, (iii) help to locate and produce oil, natural gas, and ground water and building stones like granite, and (iv) discover the mineral deposits.
- Rocks based on their mode of origin have been classified into three groups- igneous, sedimentary and metamorphic.
- Igneous rock is a rock that solidified from the hot molten or partly molten material called magma. Igneous rocks may be intrusive and extrusive depending upon their placement below or above the surface. Based on their mode of occurrence, they are grouped into: plutonic, volcanic and hypabyssal.
- Sedimentary rock is a rock resulting from the consolidation of loose sediment or chemical precipitation from solution or an organic rock consisting of secretions or remains of plants and animals. Sedimentary rock may be classified as (a) mechanically formed clastic rocks, and (b) chemically formed nonclastic rocks.
- Metamorphic rock is a rock derived from recrystallisation of pre-existing rocks by mineralogical, chemical or structural changes in response to temperature, pressure and chemically active fluids at the depth of the Earth's crust.
- Rock cycle is a continuous process closely related to the plate tectonics. Rock cycle starts with cooling and consolidation of magma derived from the mantle, which are subsequently exposed to atmospheric agencies to form sedimentary rocks under normal temperature and pressure or metamorphic rocks under increased temperature and/or pressure.
- The rocks are of manifold utility in every sphere of human life. Therefore, they are used in industries like ceramics, pottery, glasses and utensils, gemstones, food, fertilizer, packaging, building materials, power generation, transportation and information and computer technology.
- The extraterrestrial rocks include a vast range of material like meteorites, micrometeorites and lunar rocks brought to the Earth by Apollo missions.

1.12 ACTIVITY

1. Try to explore rocks around you and collect different types of rock and identify them. Write their physical characters in a notebook.
2. Make a list of uses of rocks you see in your daily life.

1.13 TERMINAL QUESTIONS

1. Discuss the classification of rocks. Give suitable examples.
2. What is rock cycle? Mention its significance.
3. Discuss about uses of rocks to human beings.
4. What are the extraterrestrial rocks? Add a note on kinds of terrestrial rocks.

Audio/Video Material-Based Questions:

- Why do you study textures in igneous rock?
- List few minerals and rocks used in the manufacture of glass and mirror.
- Name the rocks used as building stones.
- Mention about the rocks and minerals used in manufacture of computer.
- Write about the fossil fuels used in power generation.

1.14 REFERENCES

- Ehlers Ernest G. and Blatt, Harvey (1999) Petrology, Igneous, Sedimentary, Metamorphic. CBS Publishers & Dist, New Delhi, ISBN: 9788123910321.

1.15 FURTHER/ SUGGESTED READINGS

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- Singh, Parbin: Engineering and General Geology. S.K. Kataria and Sons. ISBN: 8188458511, 9788188458516, 600p.
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1.16 ANSWERS

Self Assessment Questions

1. a) Rock is a coherent, naturally occurring solid, consisting of an aggregate of minerals.

   b) Rocks are classified into three groups, based on their origin- igneous, sedimentary and metamorphic rocks.

   c) Petrologists study rocks as they provide clues about the Earth's origin and geological past, unravel how the Earth processes of the past might influence the future, provide us with valuable resources like metals, mineral deposits, and explore non-renewable energy resources like coal, oil and natural gas.

   d) Petrography is significant in geological studies because it helps to understand the environmental conditions of rock formation. It throws light on the mineralogical composition and interrelationship between mineral grains. It enables to discern the kinetics (energy of a body derived from its movement) of their formation.

2. a) Intrusive igneous rocks are formed from magma at deeper level and are known as intrusive or plutonic rocks. Intrusive igneous rocks crystallise when magma cools in the magma chamber or intrudes the country rocks below the Earth's surface. They form when the magma erupts at the Earth's surface as lava and undergoes rapid cooling in the contact of air and water.

b) Plutonic, volcanic and hypabyssal.

c) The loose grains of sediment transform into sedimentary rock by following five steps-weathering, erosion, transportation, deposition, lithification and diagenesis.

d) Recrystallisation, phase change, plastic deformation, pressure solution, metamorphic reaction or neocrystallisation.

Terminal Questions

1. Please refer section 1.4 and Table 1.1
2. Please refer section 1.8 and Fig. 1.8.
3. Please refer section 1.9.
4. Please refer section 1.10.

UNIT 2

TEXTURES AND STRUCTURES OF IGNEOUS ROCKS

Structure

2.1 INTRODUCTION

You have been introduced to the igneous rocks in the previous unit. You have also learnt that the slow cooling of magma takes place in the deeper parts of the Earth and large size crystals are formed. On the contrary, magma undergoing rapid cooling in shallower depth or on the surface of the Earth yielded fine grained crystals. The rapid cooling of lava/melt molten rock on the surface of the Earth produces fine grained minerals or glass. The igneous rocks vary in grain size from very coarse, medium to fine grained or even glassy in hand specimen and under the microscope. Thus, igneous rocks display variety of textures. Thus, the term texture refers to physical appearance of a rock. In this unit we will discuss textures and structures of igneous rocks. Further we will also discuss the forms of the igneous rocks in which they occur in the field.

Expected Learning Outcomes

After reading this unit you should be able to:

❖ define texture;

❖ discuss textural elements such as crystallinity, granularity; and

❖ recognise the forms and structures of igneous rocks in the field.

2.2 TEXTURES OF IGNEOUS ROCKS

We have studied that the igneous rock crystallises from the hot molten magma or melt that gives rise to diverse type of textures. In this unit we will discuss about textures found in igneous rocks.

Texture is defined on the basis of glass vs. mineral grains proportions, their sizes, shapes and mutual arrangements. Perhaps you may have questions asking about importance of textural and structural studies!

These textures and structures provide an idea about the geological processes during its crystallisation. They also provide us valuable information about physical chemistry and cooling history of the igneous rocks. Let us consider an example - if you observe granite and basalt and compare their physical properties, you will find distinct differences as mentioned below:

- **Colour**- granite is light coloured or leucocratic whereas basalt is dark coloured or melanocratic in appearance.
- **Grain size**- granite is coarse grained, whereas, basalt is fine grained or sometimes glassy.
- **Mutual relationship**- in case of granite the crystal is large enough to be seen with unaided eyes but it is not possible in case of a basalt.

However, many more unravelled differences can be discerned when granite and basalt are studied under the petrological microscope. We hope that the concept of granite and basalt that display different textures is clear to you now.

Thus, the textures help us to identify different rock types. **The term texture is applied to megascopic (as observed in hand specimens with unaided**

eyes) as well as microscopic features (as observed in thin section under the microscope).

We have already discussed that the texture of an igneous rock~~s~~ represents intimate relationship between the mineral grains and the glass.

Let us discuss following textural elements with reference to igneous rocks.

- Crystallinity/ degree of crystallisation
- Granularity/ grain size
- Shape of the mineral grains
- Mutual relationship amongst crystals and glass as well

We have learnt that the igneous rock comprises of crystallised as well as non-crystallised components. Study of shape of crystals and mutual relationship between mineral grains and glassy matter is described as fabric. Thus, **fabric** is defined as the arrangement, orientation and mutual relationship of mineral grains or crystals and/or glass. Fabric is a non-compositional property of rock, comprises of textures and structures both.

Watch the following video to more about fabric of igneous rocks.

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

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

Let us discuss the above-mentioned textural elements in detail.

2.2.1 Crystallinity

Crystallinity or degree of crystallisation refers to degree or amount of crystals formed during the process of solidification of magma. The igneous rocks may be composed of the crystals, partly crystals and partly glassy matter or totally glassy matter. **Degree of crystallisation** is measured by the ratio between the crystallised matter and the glass in an igneous rock. It is the modal percentage of mineral grains relative to glass and varies between 0 – 100 %.

Let us learn few more terms related to crystallinity.

Crystallites are embryo of crystals, organised to full crystalline status. They have more varied shapes. Longulites are cylindrical rods with rounded ends. Globulites are minute spherical drops or pellets, often quite opaque and consist of iron oxide. When globulites are aligned like string of beads, the resulting form is called margarites. Scopulites are rods or needle with divergent plumes. Trichites are filamentous or hair-like.

Microlites are somewhat larger bodies and can be recognised as minute crystals. They are usually rod or needle shaped and exhibit crystal outlines appropriate to their mineralogical nature.

Glass: Highly viscous liquid, disordered atomic structure, formed by rapid cooling of silicate melts during crystallisation. This term is specifically used for a rock or portion of a rock which is devoid of crystalline structure. It is formed when a highly viscous magma is rapidly supercooled, wherein the atomic groups and the molecules present in them are not properly and regularly arranged in a definite order to form crystalline substance.

On the basis of crystallinity or degree of crystallisation, textures of igneous rocks are grouped as:

1. **Holocrystalline**: The prefix 'holo' implies entirely or wholly composed of well-defined crystal faces of constituent minerals in the rock, e.g. orthoclase in granite, augite in gabbro. Holocrystalline texture is seen in plutonic rocks (Fig. 2.1a).
2. **Hemicrystalline/ Microcrystalline**: When the rock comprises partly of crystalline and partly of glassy material, e.g. dolerite, basalt, the rock is known to exhibit hemicrystalline texture. This is mainly observed in the rocks which are crystallised near the surface or at an intermediate depth from the surface (Fig. 2.1b). The other synonym terms in use are merocrystalline or hypocrystalline.
3. **Holohyaline**: The rocks exhibiting this texture are entirely made up of glassy matter or non-crystalline matter (like crystallites and microlites). This results when the rate of cooling is very rapid. This texture is mostly seen in volcanic rocks, e.g. obsidian, pitchstone, nephelinite (Fig. 2.1c).

Fig. 2.1: Rocks: show a) holocrystalline granite specimen; b) hemicrystalline Dolerite; and c) holohyaline volcanic outcrops.

Crystallinity is largely controlled and governed by following factors:

- **Rate of cooling**- Faster the cooling finer will be the crystals. Volcanic glass is formed by rapid cooling of the lava. Slower rate of cooling favours crystal growth of the bigger crystals.
- **Depth of cooling and volume of magma**- Higher the depth, slower will be the cooling rate as heat deccipiation is slow. Similarly, volume of the magma have significant bearing on crystal growth. Larger the volume slower will be the rate of cooling, hence larger crystals will be formed.
- **Composition and viscosity of magma**- Highly viscous lavas such as rhyolite or siliceous magma favours formation of non-crystalline and/or glassy rocks. Contrarily, less viscous basaltic or mafic lavas/magmas give rise to crystalline rocks e.g. phyric and aphyric basalts. Magma with high viscosity have high volatile content as compared to less viscous magmas.

Watch the following videos to learn more about glass.

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

  Link: https://www.youtube.com/watch?v=9NU3SL7HWF4
- **Igneous Textures, Processes and Pathways: Volcaniclastics**

  Link:

2.2.2 Granularity

We have already discussed about crystallinity, now let us introduce you to few important technical terms related to granularity. Grain size or granularity in igneous rocks shows wide variation. It varies from a meter size (e.g. pegmatite) to few centimeters to even > 0.01 mm size of a microlite or sometimes even glassy as found in volcanic rocks. Generally, **phaneritic** and **aphanitic** terms are used to describe coarse- and fine-grained rocks, respectively. Coarse-grained crystals can be seen with unaided eyes and mineral grains in rocks are identified easily. Whereas, study of fine-grained minerals in rocks requires petrological microscope for their identification. Synonym terms for aphanitic texture are hyaline or glassy texture (Fig. 2.2). The alternative terms used for phaneritic and aphanitic rocks are phyric and aphyric respectively.

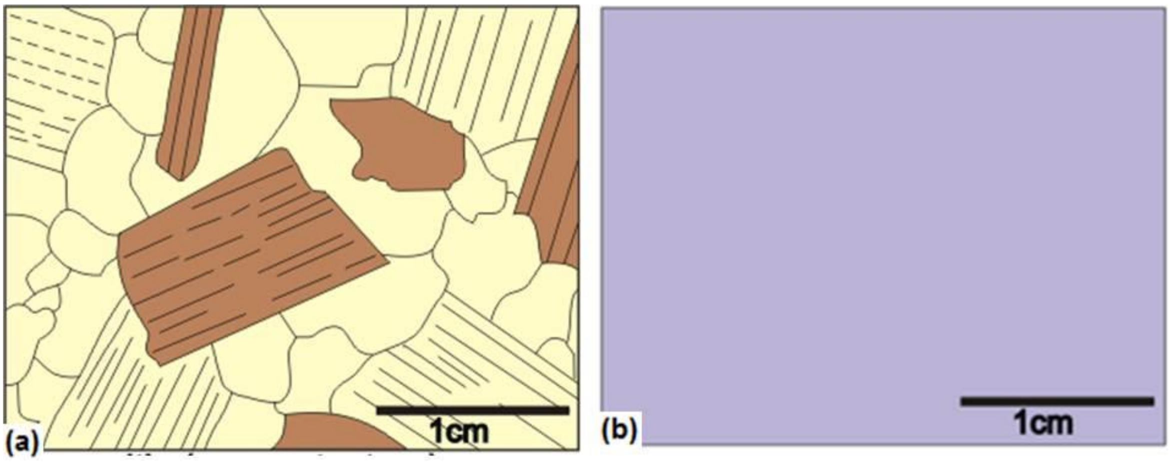


Fig. 2.2: a) Phaneritic; and b) Aphaneritic texture.

1) **Phaneritic rocks**: In these rocks minerals grains are large enough to be visible with unaided eyes. Such types of textures are commonly associated with the magmatic intrusions and they reflect crystallisation at low degree of undercooling. Phaneritic texture also indicates low rate of nucleation, formed under plutonic conditions, and emplaced on the surface due to upliftment. Phaneritic texture is classified into following sub-types. They are referred to as:
   - fine-grain (< 1mm)
   - medium-grain (1-5 mm)
   - Coarse-grain (3 mm-5cm)
   - very coarse-grain (>3 cm)

Rapid cooling of lava flow (being in contact of air or water) results in a fine-grained or glassy rock (< 1mm). The cooling in hypabyssal rocks such as dykes and sills is relatively slow as it takes place under shallower depth that result in medium-grained rock (1-5mm). Large igneous intrusions at much deeper levels undergo very slow cooling that result in the formation of coarse and very coarse-grained igneous rocks (e.g. pegmatite).

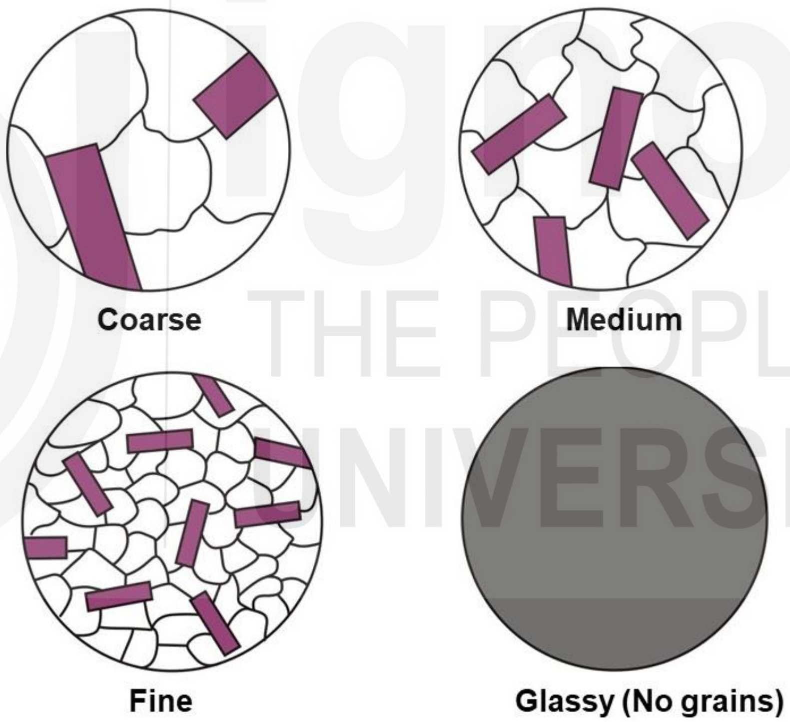


Fig. 2.3: Coarse, medium, fine and glassy texture (megascopic view).

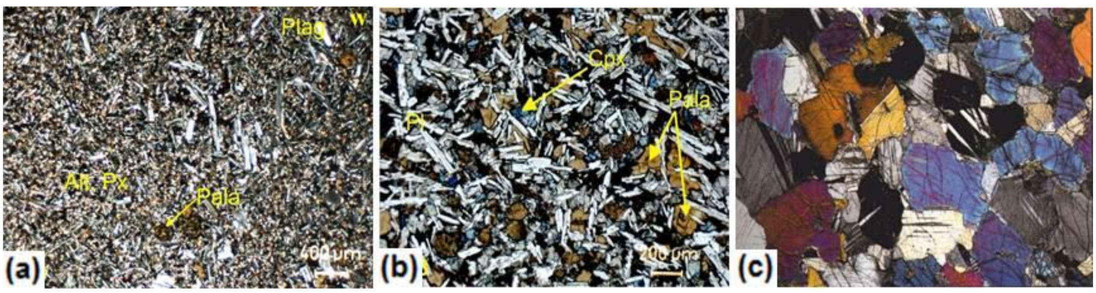


Fig. 2.4: Photomicrographs showing: a) fine-grained texture; b) medium-grained texture; and c) coarse-grained texture; Abbreviations used: Plag-plagioclase, Cpx-clinopyroxene, Alt. px-altered pyroxene, Pala-palagonite. (Photo credit: Prof. J. P. Shrivastava)

2) **Aphanitic rocks**: They are fine-grained and have too small crystals to be identified with the unaided eyes or even with the help of a hand lens. They are further classified into two sub-types such as:

- **Microcrystalline**: In this the grains are visible only under the microscope (Fig. 2.5a).
- **Cryptocrystalline**: In this case only felty mass is seen and mineral grains are not visible under the microscope (Fig. 2.5b).

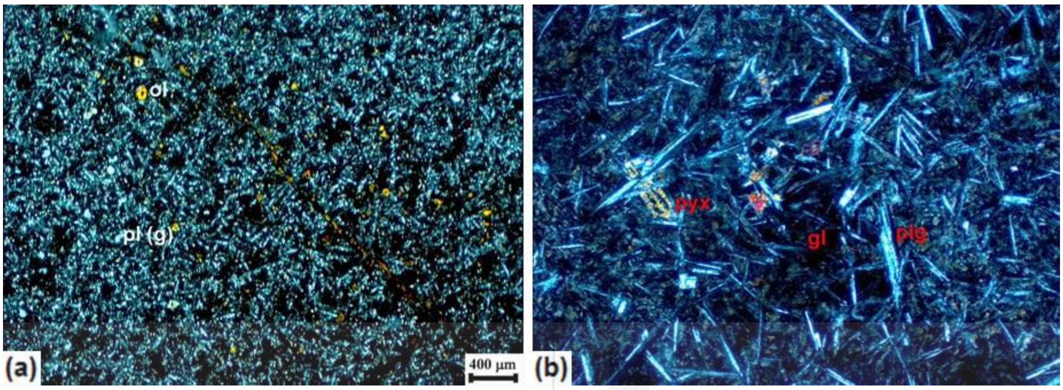


Fig. 2.5: Photomicrographs showing aphanitic texture: a) microcrystalline; and b) the interspaces between the plagioclase laths are occupied by cryptocrystalline material; Abbreviation used: ol-olivine, pl-plagioclase, g/gl-glass, pyr-pyroxene. (Photo credit: Prof. J. P. Shrivastava)

Watch the following videos to learn more about phaneritic and aphanitic textures.

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

  Link: https://www.youtube.com/watch?v=tw7vVvp6R_U

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

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

Let us learn about the factors controlling grain size or granularity in igneous rocks, viz. rate of cooling, viscosity, volatile content, and complexity of the magma composition.

- **Rate of cooling**: If crystallisation is delayed due to slow cooling only a few centers of crystallisation are initiated. Slow diffusion of ions favours large crystal development.
- **Viscosity**: If the magma is viscous, it opposes ionic diffusion thereby, hindering crystallisation. Viscosity is directly related to water vapour and gaseous (e.g. CO_2, H_2S, Cl, F) phases along with the silica and to some extent alumina contents as SiO_4 and AlO_4 units readily forms linkages or polymers to produce dense networks. Thus, fine-grained or glassy rocks like rhyolite (obsidian) resulted from siliceous viscous magma.
- **Volatile content**: Presence of volatiles, particularly H_2O, in magma reduces the viscosity, but, promotes larger crystal growth. Pegmatites crystallised from hydrous magmas are invariably very coarser than granites. Aplites are fine-grained as they form from dry magmas. In the volatiles besides H_2O

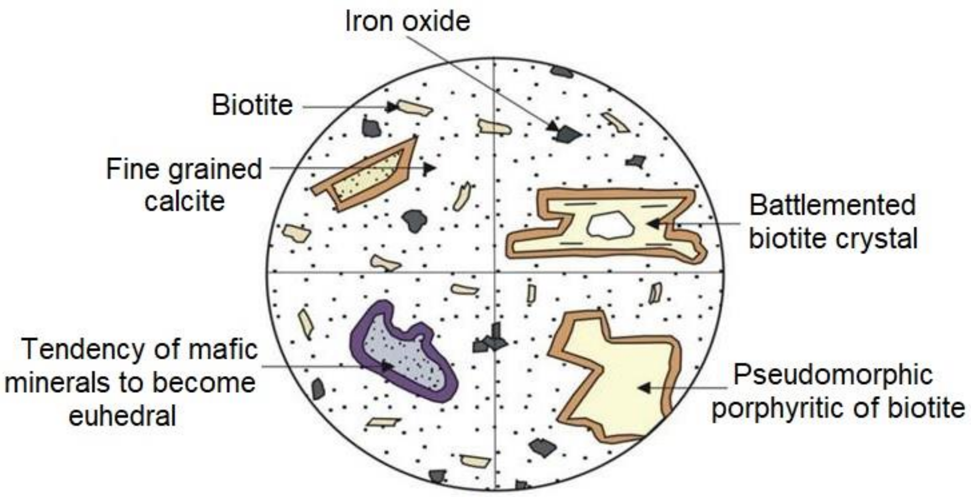
CO_2 is also present. CO_2, other important volatile constituents in magma has an opposite effect; rather it has drying effect on magma. Common metal cations, e.g. Fe, Mg, Ca, Na, K, etc. and dissolved water in magmas hinder linkage formation or Si-O polymerisation and decrease viscosity. Water rich magma is therefore more fluid.

- **Molecular concentration and chemical activity**: Minerals like zircon, apatite, sphene, rutile, ilmenite form small sized grains because the concentrations (molality) of their constituents is not high in the magma.
- **Complexity of magma composition**: Complexity of magma increases with the number of chemical components.

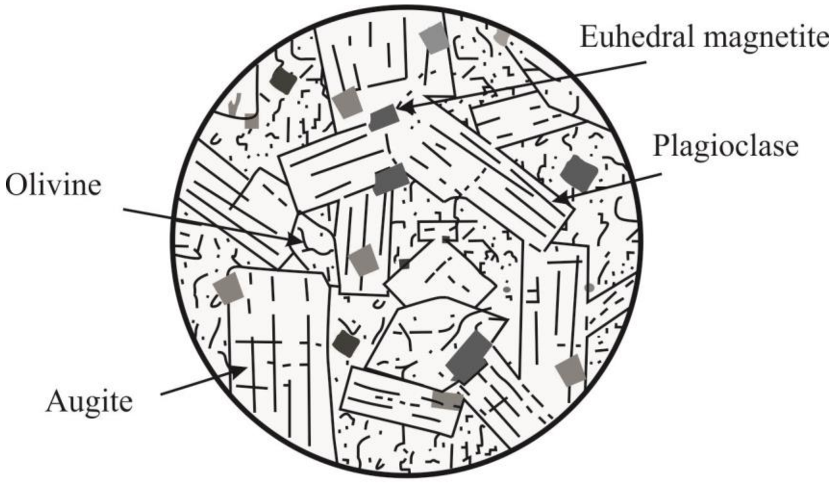
2.2.3 Shape of the Crystals

Let us discuss the three important terms euhedral, subhedral and anhedral and their resulting textures that are universally used to describe relative proportion of the grain shape.

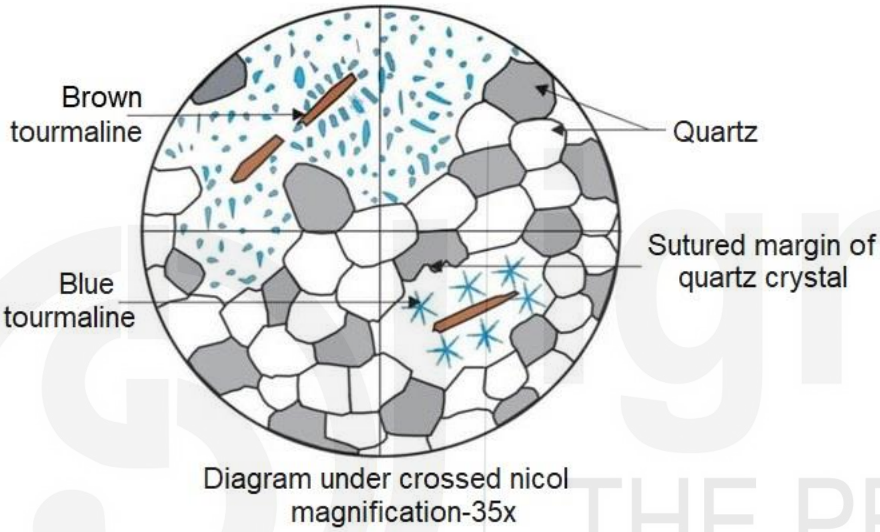
1. **Euhedral** term is used for the mineral grains which possess fully developed grain/crystal outlines. All the faces are perfectly or near perfectly developed. **Idiomorphic** and **automorphic** are equivalent terms, used for euhedral grains. **Panidiomorphic granular texture** (pan-all; idio-one's own; morph-shape) comprises majority of grains with euhedral shape (e.g. pegmatite).
2. **Subhedral** refers to crystal forms with less or partly developed crystal faces or grain boundaries. **Hypidiomorphic granular texture** (hypo-less or below) consists of dominantly of mineral grains with partly developed or subhedral shape, e.g. gabbro, granite. Thus, hypidiomorphic granular texture is the commonest of the granular texture, also called granitic because this is mostly found in granite rock.
3. **Anhedral** term is used for mineral grains lacking crystal outlines. When majority of the grains are anhedral resulting, texture is known as **allotriomorphic granular texture** (*allotrio*-alien), also called as **xenomorphic granular texture**, e.g. aplite. This texture is also called aplitic because this is best developed in aplites (hypabyssal equivalent of granite).



(a)



(b)



(c)

Fig. 2.6: Shapes of crystals and resulting textures: a) Panidiomorphic granular texture; b) Hypidiomorphic granular texture; and c) Allotriomorphic granular texture. (Sketch credit for (a) and (b): Prof. J. P. Shrivastava)

We know that the crystals tend to develop crystal grains in length, breath and height, thus, exhibits three-dimensional geometry during the process of crystallisation. On the basis of mineral grain dimensions, the mineral grains in the igneous rocks can be grouped as:

1. **Equidimensional**: The mineral grains are equally developed in all the dimensions, e.g. garnet, olivine, leucite.

2. **Prismatic**: The mineral grains show more distinct growth in one direction (along C axis) than the other two directions/axes, e.g. augite, hornblende. If the width and breadth is insignificant as compared to the length, then it is called **acicular** or needle shaped, e.g. sanidine.

3. **Tabular**: The mineral grains have greater development in length as compared to width, e.g. plagioclase, orthoclase.

4. **Platy or sheet**: The mineral grains are developed in length and breadth in relation to height e.g. mica.

5. **Irregular**: The mineral grains are irregularly developed in all the dimensions, e.g. quartz in granite.

Watch the following video to know more about homogenous textures.

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

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

The following factors control shape of the grains in igneous rock:

- **Crystal habit**: It is controlled by internal structure of an individual mineral.
- **Conditions of their growth**: Plagioclase may be euhedral, elongated, lath shaped as present in dolerite and basalt, subhedral somewhat tabular in gabbro and diorite, plagioclase is often subhedral to anhedral in granite and aplite. This is due to differing conditions of crystallisation may have given rise to different shapes and sizes of the same mineral.
- **Order of crystallisation**: Shape of crystals is often guided by its position in the order of crystallisation. Earlier formed crystals are more developed than later formed crystals.
- **Slow cooling and favourable diffusion process**: This allows formation of euhedral crystals.

Learners, you have learnt about the crystallinity and granularity in igneous rocks. Before discussing about the mutual relationship between minerals and non-crystalline material, spend few minutes to perform an exercise to check your progress.

SAQ 1

a) Define texture.

b) Define crystallite, microlite and glass.

c) List the textural elements.

d) List three types of granular textures based on the shape of the crystals, citing examples of igneous rocks.

e) List the mineral grains based on their three-dimensional geometry. Give examples.

2.2.4 Mutual Relationship between Crystal and Non-Crystalline Material

We have read that apart from describing the shape, fabric also includes mutual relationships of crystals and non-crystalline matrix/glass. It is has been discussed under two sub-groups:

- Equigranular texture
- Inequigranular texture

1) **Equigranular textures**: When the majority of the grains are of equal size, it is said to have equigranular texture, e.g. granite and gabbro. It can be grouped into three sub-types:

   - **Microgranitic**- It occurs in fine grained rocks, where shape of the grains is mostly anhedral or subhedral.
   - **Orthophyric**- If in a fine-grained rocks grains are mostly euhedral.

- **Felsitic**- If grains are very fine or microcrystalline or cryptocrystalline.

2) **Inequigranular textures**: In an igneous rock if the grain size difference becomes so pronounced that one set of grains is distinctively larger and associated with another set which is much finer in size, then it is termed as inequigranular. They are of following types:

- Porhyritic texture
- Poikilitic texture
- Intersertal/intergranular texture

Usually, there is a marked difference in the grain size of the rock. But, if the variation of larger to smaller is systematic and gradual, then it is known as **seriate texture**.

Let us discuss types of inequigranular textures. They are-

a) **<u>Porphyritic texture</u>**: In this, the larger grains are surrounded by the groundmass consisting of smaller grains (microcrystals) or glassy part. The larger grains are termed as **phenocryst**. Please note that this texture is visible both megascopically (Fig. 2.7a) and microscopically (Fig. 2.7b and 2.9a). Porphyritic texture resulted due to change in physicochemical conditions, molecular concentration and insolubility.

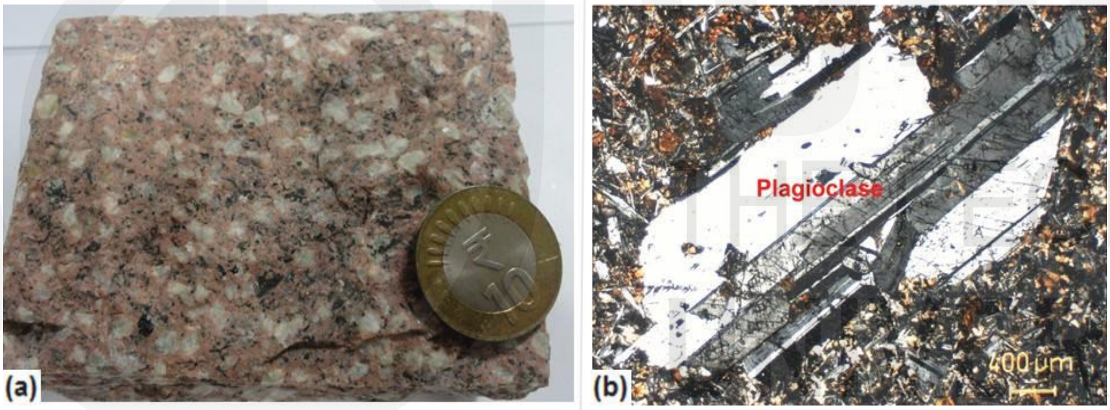


Fig. 2.7: Porphyritic texture: a) Handspecimen showing phenocrysts (white) in mottled pinkish groundmass; and b) Photomicrograph showing plagioclase phenocryst in groundmass consisting of fine-grained plagioclase, augite, glass and iron oxide. (Photo credit: Prof. J. P. Shrivastava)

The term **microphenocryst** is subjectively used to distinguish finer phenocrysts from coarser ones for which the term **megaphenocryst** is used.

Porphyritic texture is of three types:

- **Vitrophyric**: phenocryts are enclosed by glassy groundmass (Fig. 2.8a)
- **Felsophyric**: phenocryts are enclosed by cryptocrystalline groundmass
- **Glomeroporphyritic**: phenocryts are the early formed crystals of minerals such as olivine, pyroxenes and plagioclase (Fig. 2.8b and 2.9b) clubbed together and form distinct clusters of crystals or crystal aggregates

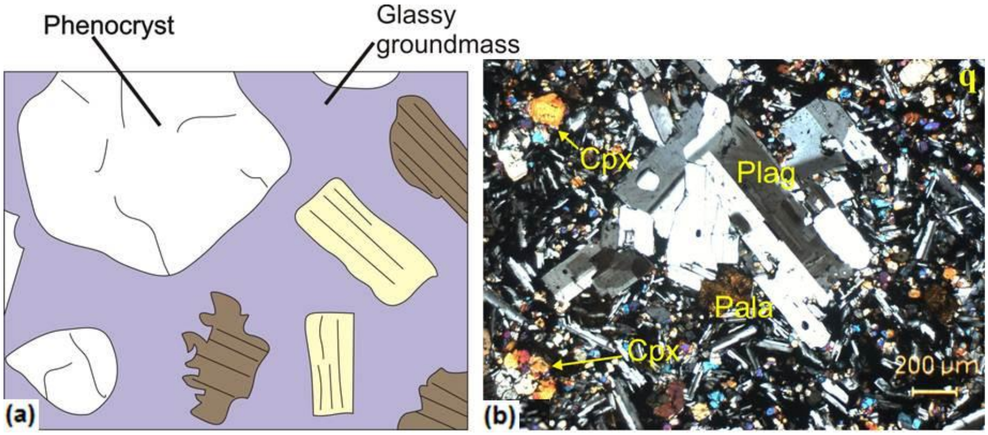
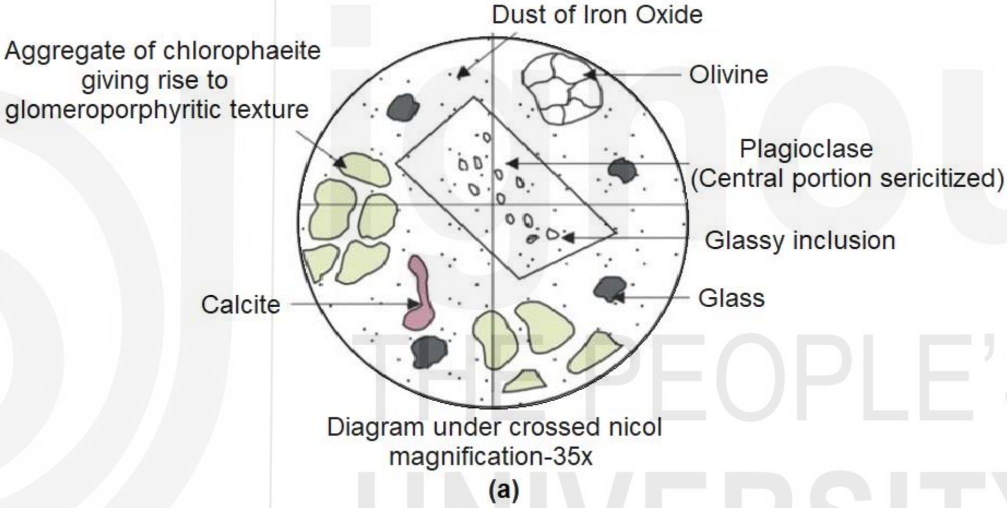


Fig. 2.8: Types of Porphyritic texture: a) Sketch of vitrophyric texture showing phenocrysts in glassy groundmass; and b) Photomicrograph of glomeroporphyritic texture showing cluster of plagioclase crystal as phenocryst in groundmass consisting of fine-grained plagioclase, augite, palagonite and iron oxide. (Photo credit: Prof. J. P. Shrivastava)



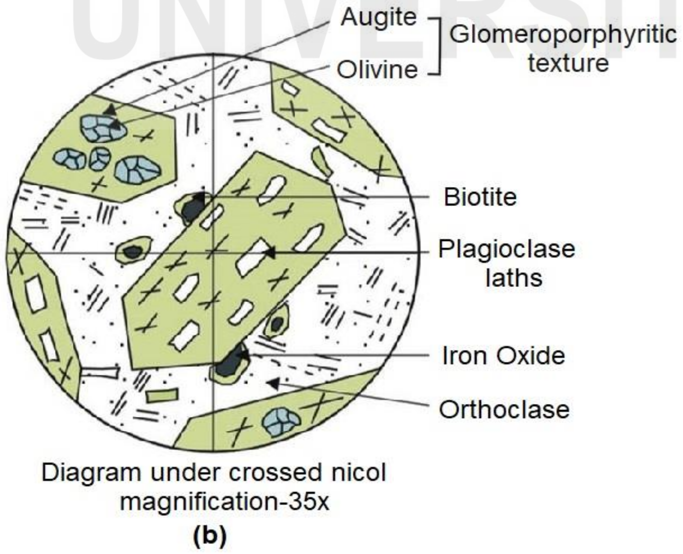


Fig. 2.9: Sketches showing: a) Porphyritic texture in basalt, euhedral grains of plagioclase occur as phenocrysts, and b) Glomeroporphyritic texture showing cluster of olivine grains as phenocryst in the groundmass of augite in alkali gabbro. (Sketch credit: Prof. J. P. Shrivastava)

b) **Poikilitic texture**: In this texture the larger grain encloses smaller mineral grains. The larger or host or house crystal is known as **oikocryst** and the enclosed crystals are known as **chadocrysts**. Poikilitic texture can be of three types:

1. **Ophitic texture**: This is the most common texture found in fine to medium grained mafic rocks like dolerite and basalts. The microscopic view exhibits that augite encloses smaller laths of plagioclase feldspar (Fig. 2.10a and b).
2. **Subophitic texture**: When the crystals of augite grains are smaller and partially enclose the plagioclase laths then the texture is known as subophitic. Ophitic and subophitic textures resulted due to nearly simultaneous crystallisation of plagioclase and pyroxene minerals that differ in their crystallisation properties (Fig. 2.10b).
3. **Hyalophitic texture**: It is similar to ophitic texture, but the difference is that the diversely oriented plagioclase grains are completely surrounded by the glass.

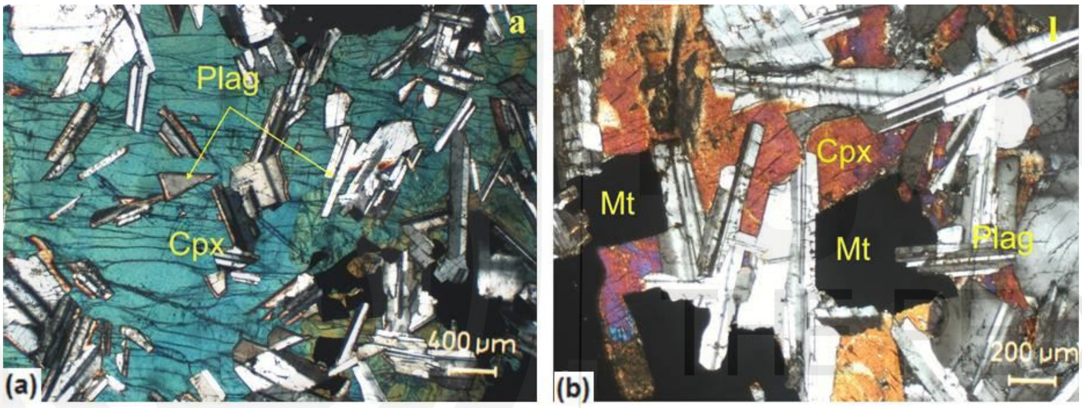


Fig. 2.10: Photomicrographs showing: a) ophitic, a big plate of Cpx, i.e. augite encloses laths of plagioclase, and b) subophitic texture. (Photo credit: Prof. J. P. Shrivastava)

c) **Intersertal/ Intergranular texture**

The mafic rocks like basalt, often shows a variety of textures depending on the mutual relationship between the grains and the groundmass, which comprise mainly plagioclase, pyroxene and glass. The volcanic glass may be replaced by secondary alteration products like palagonite. When the corners of randomly oriented plagioclase laths touch each other to form a network and the polygonal interstitial spaces are filled by granular anhedral pyroxene, the texture is known as **intergranular texture** (Fig. 2.11). When the interlath polygonal spaces are filled-up by glass or its devitrified product, the texture is known as **intersertal texture**.

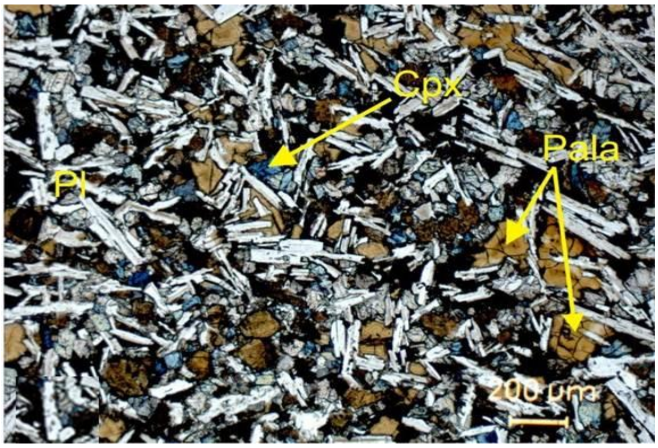


Fig. 2.11: Photomicrograph showing intergranular and intersertal texture, notice the polygonal spaces between the plagioclase (Pl) laths are filled by secondary altered product of glass (Pala-palagonite) and somewhere by augite (Cpx). (Photo credit: Prof. J. P. Shrivastava)

2.2.5 Intergrowth Textures

Intergrowth texture results from intergrowth which means the state of interlocking of grains of two different minerals. Intergrowth texture results due to simultaneous crystallisation of two mineral components of the magma at a particular temperature or due to eutectic crystallisation of the two mineral components of magma at a particular temperature. Let us discuss.

1) **Graphic texture**: Graphic texture is commonly found in granites and results from the intergrowth between quartz and orthoclase. The quartz blebs are aligned parallel to a well-defined crystallographic orientation giving rise to the effect of cuneiform writing on a background of K-feldspar (host). It resembles ancient German alphabets. Quartz is disposed in the form of prismatic wedge-shaped areas intersecting at an angle of about 60^o. When this texture is observed in hand specimens (Fig. 2.12), it is called **graphic texture** and when it is in a microscopic level called as **micrographic** (term used for texture observed under microscope) and the rock is called **granophyre**. Sometimes such type of an intergrowth is ultra-small and can be seen under the scanning electron microscope under high resolution.

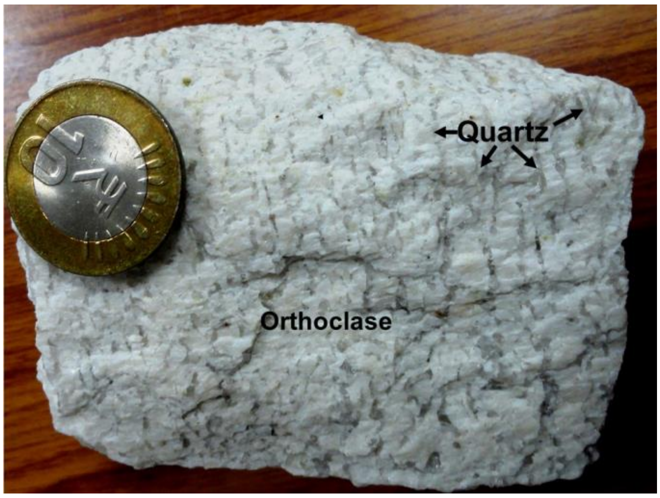


Fig. 2.12: Hand specimen of a granite showing graphic texture. Notice the elongated belbs of grey quartz in the host of white orthoclase.

2) **Myrmekitic texture:** Myrmekitic texture results from the intergrowth of quartz and plagioclase (usually oligoclase). The intergrowth of quartz is in the form of worm-like rods within the plagioclase. It is also referred ~~as~~ to **symplectite**. It is found in some granite and metamorphic rocks.

3) **Corona texture**: It refers to those resulting from reactions in magmas and exhibit concentric arrangement of characteristic minerals. The zone of reaction products surrounding a mineral is called a **reaction rim** or **kelyphitic borders**. For example, olivine is enclosed with the rim of pyroxene. There may be a number of successive rings around the central mineral.

Watch the following video to know more about inhomogeneous textures.

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

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

2.2.6 Exsolution Textures

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.

- **Perthitic texture**: Exsolution of alkali feldspar and albite produces perthites which comprises thin strings, films and patches of albite oriented within K-feldspar host, e.g. orthoclase/ microcline (Fig. 2.13). **Microperthitic texture** is the texture which is resolvable under the microscope. It is commonly developed in coarse plutonic rocks like granite, gabbro.
- **Antiperthite texture**: It is the reverse of the perthitic texture. In this case the belbs and patches of orthoclase or microcline occur within plagioclase and gives rise to antiperthic intergrowth (Fig. 2.13).

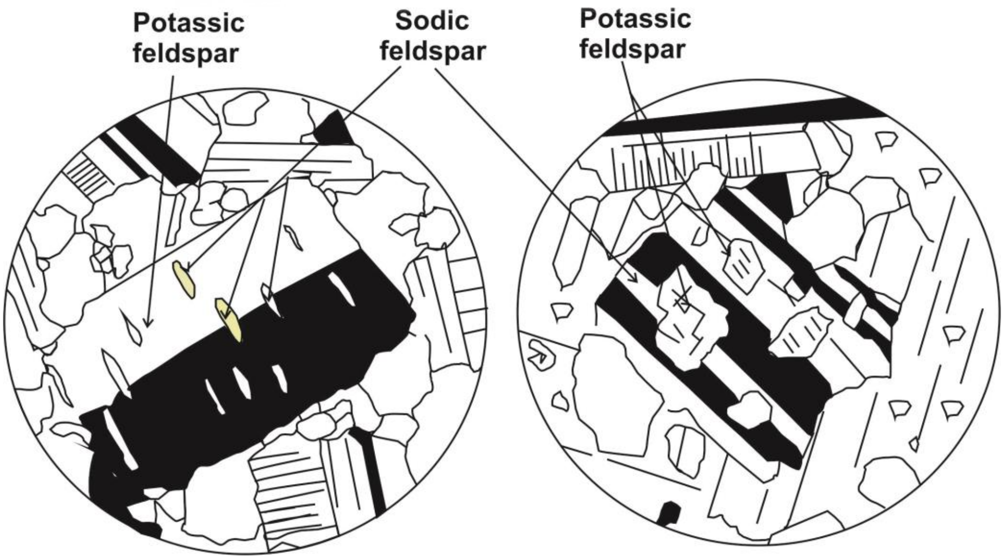


Fig. 2.13: Perthite and antiperthite textures.

Watch the following video to know more about exsolution intergrowth and textures.

- **Exsolution Intergrowth**

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

2.2.7 Miscellaneous Textures

1) **Directive/ Flow texture**: The term directive indicates directional arrangements of mineral grains, indicating flows or bands. When the magma during the process of its crystallisation undergoes flow movement, the crystallising minerals tend to arrange themselves in a regular directive bands which results in a flow texture. The direction of the flow may be interrupted by early formed crystals, but the flow bands will produce stream line without distorting the bigger crystals, such texture is known as **flow texture** (Fig. 2.14).

Fig. 2.14: Flow structure in rhyolite, notice the plagioclase crystals arranged parallel to flow of magma, marked by red arrow.

2) **Trachytic texture**: This texture is particularly observed in some volcanic rocks such a trachyte. In basaltic rock, the calcic plagioclase, glassy and cryptocrystalline material show parallel or sub-parallel alignment and preferred orientation due to flowage of magma in molten state which is referred as to **trachytic texture**.

3) **Eutaxitic texture**: This term is used for the parallel alignment of pumice fragments in welded ignimbrites which are pyroclastic rocks. Ignimbrite is formed by the widespread deposition and consolidation of ash flows. The wavy laminations swirl around volcanic lithic fragments, indicating flow pattern in the dark bands. The stretched lithic, pumice and crystal fragments are aligned and welded together with a devitrified, cryptocrystalline and microcrystalline groundmass (Fig. 2.15).

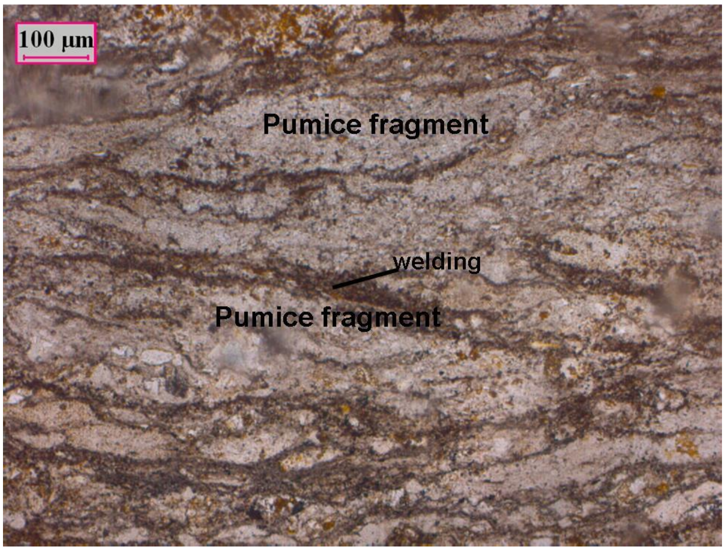


Fig. 2.15: Photomicrograph of medium grained pyroclastic rock showing eutaxitic texture, notice the welding of stretched pumice fragments.

4) **Devitrification**: Let us introduce you to the term devitrification.

We have discussed the term 'glass' earlier in this unit. Let us recall it.

If a highly viscous magma is rapidly supercooled then the atomic groups and the molecules present in them are not able to get properly and regularly arranged in a definite order to form crystalline substance. Such supercooled viscous melt or semi-solid material gives rise to disordered as **glass**. This condition of non crystalline state is unstable or metastable. The glasses tend to change themselves in a long course of time into an irregular arrangement of atoms and molecules thus they form cryptocrystalline mass. This process of **devitrification** is promoted if the glassy material is placed under increased pressure and temperature with chemically active fluids. Devitrification in natural glasses usually produces a mass of minute crystals of cryptocrystalline character forming **felsitic texture** and such rocks are known as **felsites**. **Perlitic cracks** in crystals are evidences of their original glassy condition. Perlitic cracks refers to curved or spherical cracks found in glassy or devitrified igneous rocks, formed by contraction during rapid cooling of the magma (Fig. 2.16a).

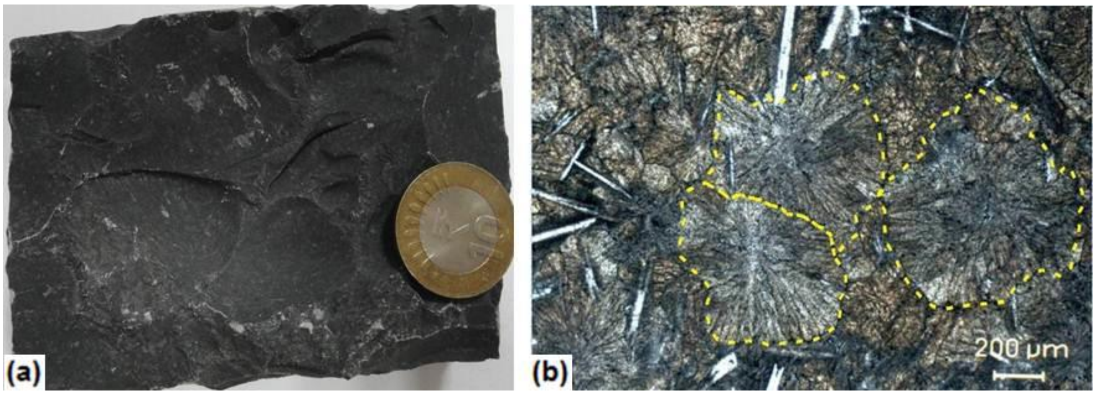


Fig. 2.16: a) Perlitic cracks in pitchstone, notice curved or spherical cracks; and b) Spherulitic texture. (Photo credit: Prof. J. P. Shrivastava)

5) **Spherulitic texture**: More rapid cooling and crystallisation of viscous magma yields spherulitic texture. Spherulitic aggregates are radiating arrays of fibrous or needle-like crystals. This texture is common in glassy felsic volcanic rocks (Fig. 2.16b).

6) **Spinifex texture**: This texture is characteristic of komatiitic rock (an ultramafic rock of volcanic origin). Spinifex texture is defined as randomly oriented, extremely fine-grained, slender hollow crystals or acicular olivine phenocryst formed by rapid cooling or quenching of ultramafic lavas.

Learners, you have learnt about the the mutual relationship between minerals and non-crystalline material, intergrowth texture, exsolution textures and miscellaneous textures. Before discussing about the structures in igneous rocks, spend few minutes to perform an exercise to check your progress.

SAQ 2

a) Distinguish between equigranular and inequigranular textures.

b) What is seriate texture?

c) Define graphic texture. How it forms?

d) What is exsolution intergrowth? Cite and example.

2.3 STRUCTURES OF IGNEOUS ROCKS

We have discussed in detail about textures, let us learn about few common igneous structures.

The term structure is very much different from texture. Structure is used for larger features of a rock, observed in the field on large outcrops like flow banding, layering, vesicles, etc. If you observe a basaltic outcrop you would describe its structure as vesicular or amygdaloidal. Even today, the petrologists use the terms texture and structure interchangeably.

2.3.1 Vesicular and Amygdaloidal Structures

The lavas are heavily charged with gases and other volatiles. When the lava is erupted on the surface, the volatile constituents escape from the fluid with the decrease of pressure, thus forming cavities, bubbles or vesicles of variable dimensions and shapes, such as spherical, elliptical, cylindrical or irregular in shape. The individual openings are known as **vesicles** and the structure as a whole is known as **vesicular structure** (Fig. 2.17a and b). But, if the vesicles are filled-up by some low temperature secondary minerals such as quartz (Fig. 2.17a), calcite (Fig. 2.17b), zeolite, chalcedony it is termed as **amygdale**. Volcanic rocks containing amygdales are said to have **amygdaloidal structure**. They are called so because their shapes sometimes suggest resemblance to almonds.

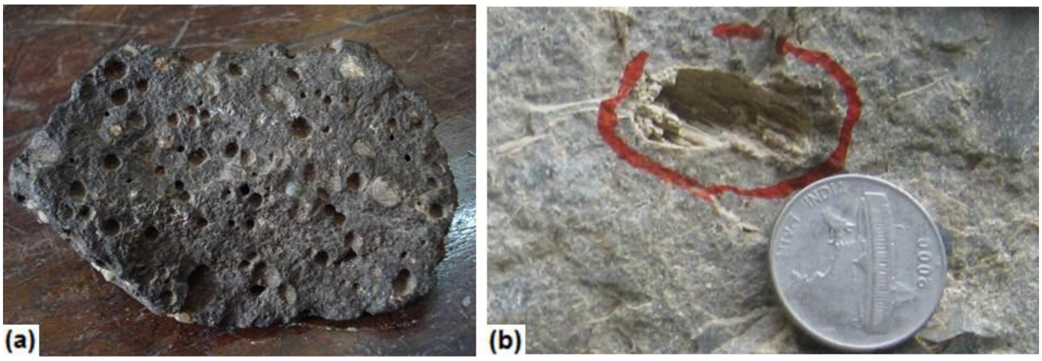


Fig. 2.17: Volcanic rock showing vesicular and amygdaloidal texture: a) Notice vesicles and vesicles filled-up with quartz; and b) Vesicular cavity is filled-up with calcite crystal, encircled with red.

2.3.2 Scoriaceous and Pumiceous Structures

Lava which is heavily charged with volatiles and gaseous constituents, on consolidation and cooling gives rise to ‘scoria’ and the resulting structure is called **scoriaceous structure**. Scoria is a clinkery looking extrusive, highly vesicular basalt. If the vesicles are so abundant that they make up over 50% of the rock and the rock has a density greater than 1, then the rock is said to be scoriaceous. **Pumice** is a volcanic rock containing numerous irregular shaped cavities or vesicles that remain after trapped volatiles escape from the cooling lava. Such structures are characteristic of highly siliceous lavas because they are highly charged with volatiles. If vesicles are so abundant that they make up over 50% of the rock and the rock has a density less than 1 (i.e. it would float in water), then the rock is known as pumiceous. Vugs are angular cavities in a rock formed by collection of volatile fluid between existing crystals the resulting structure is known as **vuggy structure**.

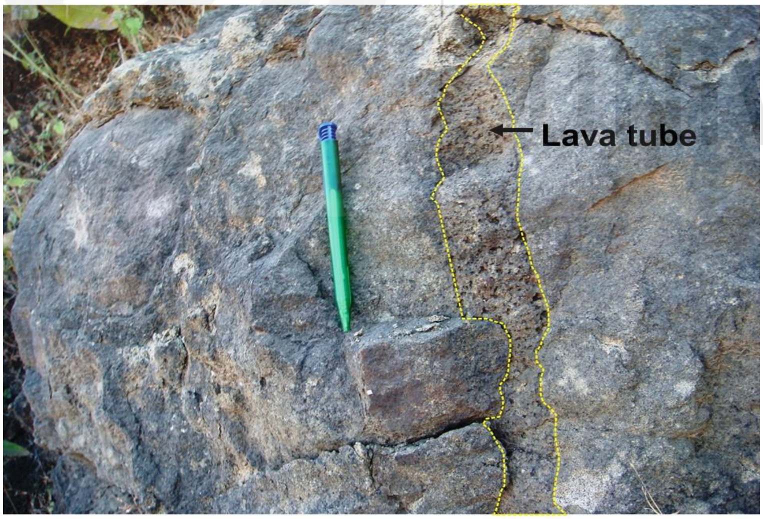


Fig. 2.18: Lava tube. (Photo credit: Prof. J.P. Shrivastava)

2.3.3 Lava Tunnel

On cooling and consolidation of lava, the enclosed fluid lava drains out through some channel ways known as **lava tunnel**. The hardened basaltic flows commonly contain cave-like tunnels called **lava tubes** that are supposed be conduits carrying lava (Fig. 2.18). These conduits develop in the interior of a flow where temperatures remain high long after the molten material on the surface hardens. Lava tubes are important features because they serve as insulated pathways that facilitate advancement of lava to great distances from its source.

2.3.4 Blocky and Ropy Lava

They are two different appearances represented by lava flows. The surface is covered with the mass of rough jagged, angular blocks of all dimensions with dangerously sharp edges and spiny projections. This is known as **blocky lava** or '**aa**' structure. On the other hand, very mobile lavas solidify with comparatively smoother surface often highly glazed which exhibit wrinkled, ropy or corded forms that often resemble with the twisted braids of ropes. The structure is known as **ropy lava** is also called '**pahoehoe**' (Fig. 2.19). Blocky and ropy lava flows as described above are known by their Hawaiian names, i.e. aa and pahoehoe flows. Pahoehoe means "on which one can walk." Both the lavas can erupt from the same vent. However, pahoehoe lavas form at higher temperatures and contain more fluid than aa lava flows. Apart from this pahoehoe lava flow can change into an aa lava flow, although the reverse does not occur.

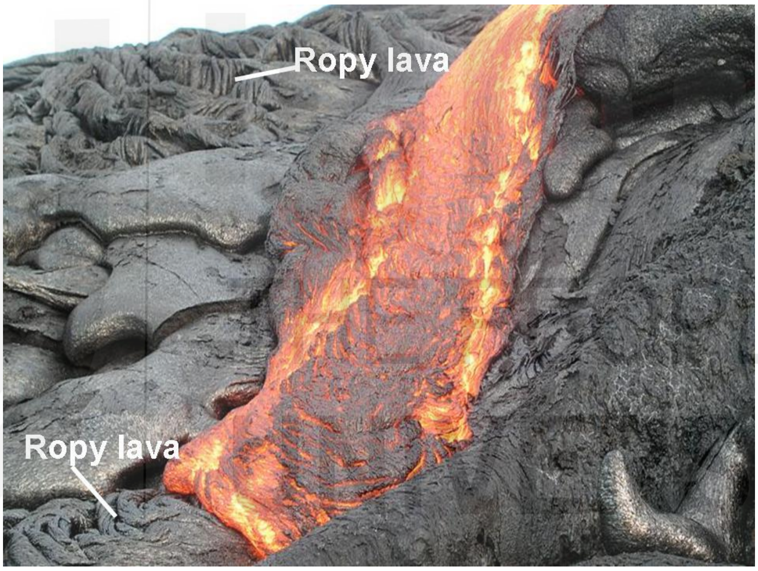


Fig. 2.19: Ropy lava. (Source : www.usgs.gov)

2.3.5 Platy and Sheet Structure

The development of different set of parallel partings or joints giving rise to plates of rock mass, often intersected by closely spaced, irregular joint planes or surfaces is known as **platy structure**. The development of one set of well-defined horizontal joints or surfaces is known as **sheet structure**.

2.3.6 Pillow Lava

This is a peculiar ellipsoidal pillow-shaped structure (Fig. 2.20), which occurs mostly in basic/mafic lavas. Such types of lavas appear as pile of small masses like pillows or cushions. They are produced by extrusion of lava under water logged sea water or sediment, rain-soaked air or beneath the ice-sheets. Pillows generally have a vesicular crust or glassy skin. Chilled margins develop at the peripheral portion of pillow due to sudden cooling.

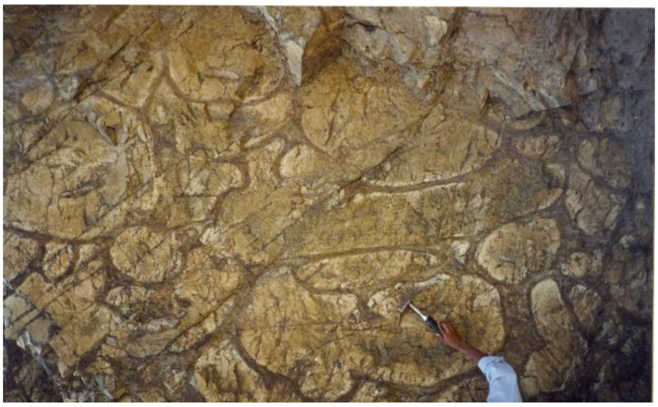


Fig. 2.20: Elliptical shaped pillow lava, showing chilled margins from Chitradurga district, Karnataka.

2.3.7 Columnar/Prismatic Structure

When the uniform cooling and contraction in a homogeneous magma takes place, the parting planes tend to take on a regular columnar or prismatic form (Fig. 2.21a and b) which is characterised by four, five or six sides. Columnar structure is formed due to the development of centres of nucleation-contractions at equally-spaced intervals on the cooling surfaces.

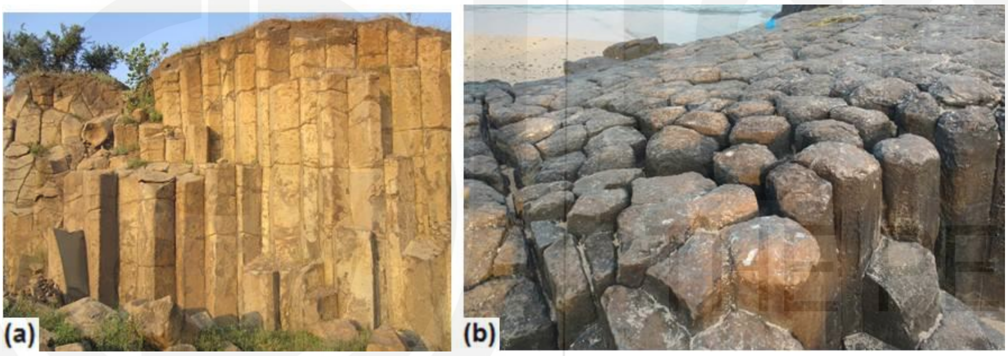


Fig. 2.21: Columnar jointing in: a) basalt (Photo credit: Dr. Omkar Verma)**; and b) Rhyolite.** (Source: www.gsi.gov.in)

2.3.8 Lava Flow Structure

The eruption of lava on the surface faces difficulty in movement due to viscosity. This results in the formation of dissimilar elongated lenticular patches arranged parallel to the flow of the lava. This is known as directional or flow structure.

Fig. 2.22: Flow structures in rhyolite. (Photo credit: Dr. Amit Kumar)

2.3.9 Rift and Grain

These structures developed due to three sets of mutually perpendicular, equally spaced joints, producing cubical blocks known as mural jointing. This rift and grain structure is taken into advantage by quarrymen to dress down big blocks of granite into smaller ones.

2.3.10 Perlitic Structure

This refers to produce spherical balls having a pearl-grey luster. The concentric shelly cracks formed by rapid cooling of viscous lava or magma.

2.3.11 Rapakivi Structure

Rapakivi is a term derived from the Finnish language which means 'rotten or crumbled stone'. This term is used for rounded crystals of potassic feldspar mantled by white rims of sodic feldspar. They consist of orthoclase crystals as large as 4 cm in diameter in fine grained mantled plagioclase. Mostly this structure is found in granitic rocks.

Watch the following video to know more about rapakivi structure.

- **Rapakivi Texture**

  Link: https://youtu.be/voXGUT4HSxY

Fig. 2.23: Rapakivi structure where large orthoclase ovoids mantled by plagioclase. (Photo credit: Ganga Prasad Bhartiya)

2.3.12 Xenoliths

Xenolith is an accidental foreign rock fragment trapped in another rock of igneous origin (Fig. 2.24). Xenolith itself may be igneous, sedimentary or metamorphic in origin. The term xenolith literally means 'foreign rock' but, some xenoliths are not entirely foreign to their hosts. They may be genetically related and known as **cognate** because both of them may have crystallised from the same magma. The unrelated xenoliths are always older than their host rocks because they existed before the magma around them was solidified.

Xenocrysts differ from the xenoliths. Xenolith is the term used for rock fragment, whereas, xenocryst refers to individual mineral fragment. The **xenocryst** term is used for the crystals that was accidentally incorporated in the magma and preserved in partly resorbed state. They can have foreign source or can be derived from the same country rock. Cognate are the xenocrysts genetically related to the enclosing rock.

Watch the following video to know more about structures of igneous rocks.

- **Physical Features of Volcanic Terrain**

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

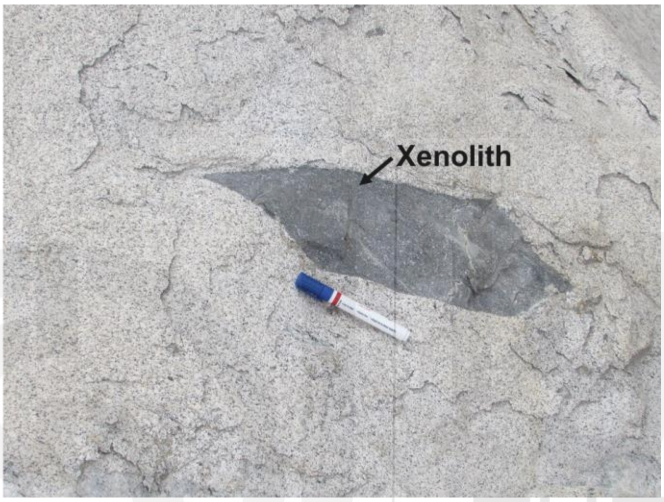


Fig. 2.24: Basaltic xenolith in granite. (Photo credit: Ihsan Ullah Lone)

2.4 FORMS OF IGNEOUS ROCKS

You better understand that the igneous rocks are formed due to cooling and consolidation of hot molten rock material. We have already learnt these terms earlier in this unit, let us recall.

The molten rock material occurring below the Earth's surface is called **magma**, but, when it comes out on the surface of the Earth, it is called **lava**. The deep-seated magma in the magma chamber ascends due to buoyancy or any tectonic activity and intrudes into the country rock (host rock) or it may come out at the surface and solidify. When the magma reaches to the Earth's surface, it forms '**extrusive**' igneous rock. When magma rises through the crust, it forcefully displaces pre-existing crustal rocks referred to as **host** or **country rock**. Igneous body is called as '**intrusive**' when magma solidifies beneath the surface of the Earth. We understand about intrusive igneous activity from the study of old, and now solidified, magma bodies exposed by the erosion. The intrusive or extrusive igneous rock bodies can occur in a variety of forms.

Concordant body: When the igneous body runs parallel to the bedding or foliation plane of the country rock.

Discordant body: When the igneous body cuts across the bedding or foliation plane and penetrates through the country rock.

Let us now discuss about forms of the igneous rocks.

2.4.1 Sill

Sill is a concordant igneous body, lying parallel to the planar structure such as bedding and foliation plane of the country rock (Fig. 2.25a and b). These sheet-like masses of igneous rock penetrated into the country rock and spread out parallel to the bedding or foliation planes.

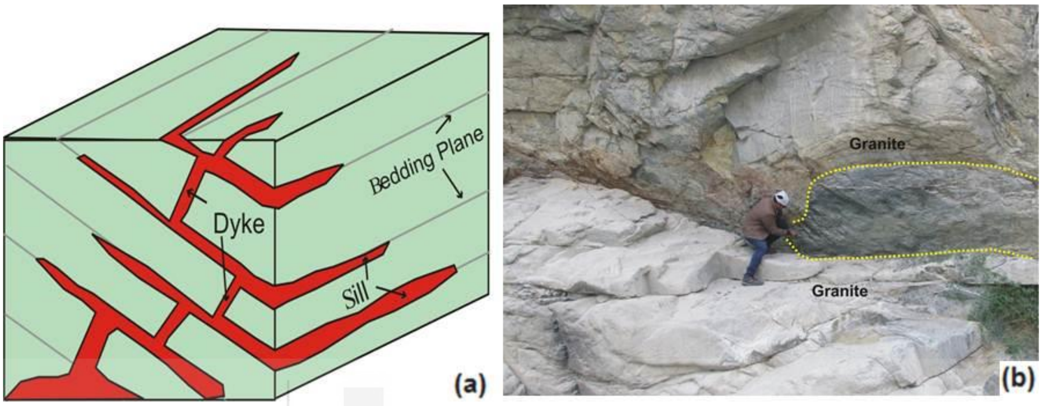


Fig. 2.25: a) Sill is concordant and dyke is discordant body; and b) Field photograph of sill. (Photo credit: Ihsan Ullah Lone)

2.4.2 Dyke

Dike is a discordant igneous body of more or less tabular shape and exhibits a cross cutting relationship with the country rock (Fig. 2.25a and 2.26a and b). The word *dike* is of Scottish origin meaning 'a wall of stone'. These are wall like masses of igneous rocks cutting across country rock which may be of igneous, sedimentary or metamorphic rock. Dykes formed by solidification of magma penetrate through fissures or fractures in the rocks.

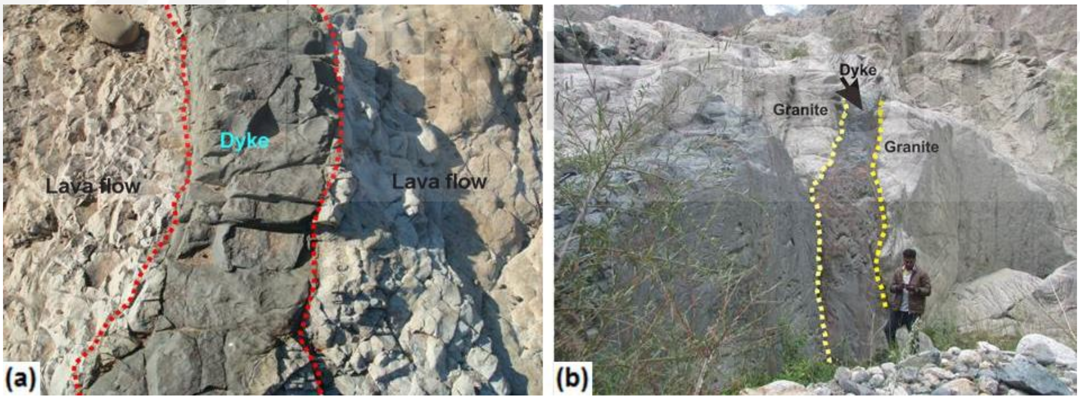


Fig. 2.26: Field photographs of dyke: a) dyke intruding Deccan lava flow (Photo credit: Prof. J.P. Shrivastava)**; and b) dyke intruding granite, Ladakh Batholith.** (Photo credit: Ihsan Ullah Lone)

Dykes are generally a few feet in thickness and commonly occur in groups which may exhibit some pattern. Based on their pattern, they are categorised as follows:

- **Radiating dykes**: When different dykes seem to radiate from a common centre (Fig. 2.27a).
- **Arcuate dykes**: When several dykes form arc like structure (Fig. 2.27b).

- **Ring dykes**: When arcuate dykes occur in a form of more or less a complete circle or ring (Fig. 2.27c).
- **Cone sheets**: Cone sheets refer to sheets of an igneous body which occurs in the form of inverted, co-axial cones, with thin layers of country rocks lying in between them. Both the cone sheets and ring dykes have near circular outcrop on surface, but the ring dykes are nearly vertical. The cone sheets converge toward the apex of the cone (Fig. 2.27d).

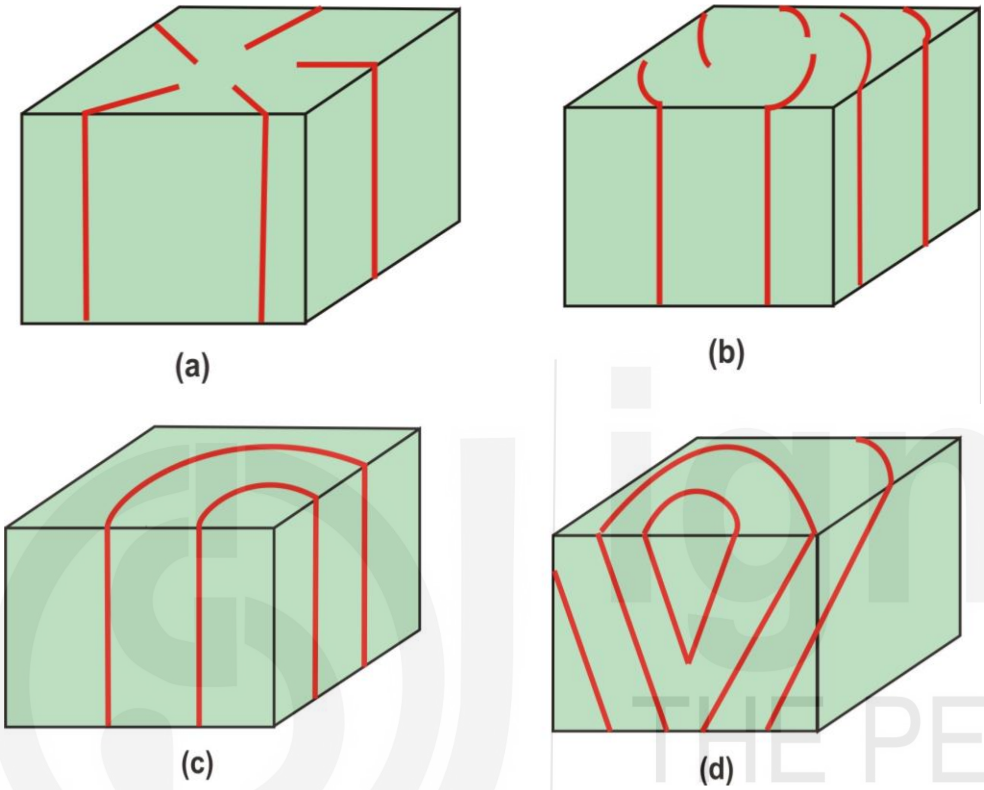


Fig. 2.27: Different types of dykes: a) Radiating; b) Arcuate; c) Ring; and d) Cone sheet.

2.4.3 Laccolith

Laccoliths are more or less concordant intrusive dome-like masses of igneous rock arching upward and has a more or less flat floor (Fig. 2.28). They are lens-shaped sub-structures formed by igneous rocks pushing up the overlying rocks and get exposed only after long continued erosion. In a typical laccolith, the diameter is only few times greater than the thickness.

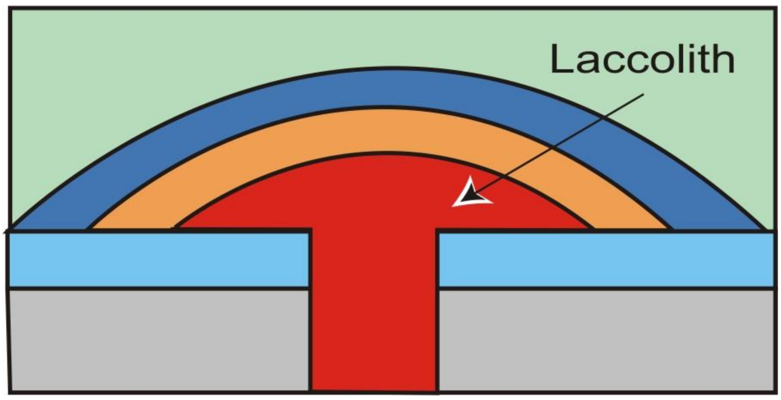


Fig. 2.28: Laccolith is concordant dome-like mass.

2.4.4 Bysmalith

Bysmalith is a special type of laccolith which is a roughly vertical cylindrical igneous intrusion bounded by steep faults. It results into a cylindrical plug like mass. Bysmalith is a body where the roof uplifts along a circular or arcuate fault.

2.4.5 Lopolith

The word lopolith is derived from the Greek word *lopas* means basins. Lopoliths are more or less saucer or basin shaped sunken concordant igneous bodies which are concave upwards (Fig. 2.29) in the form of basins.

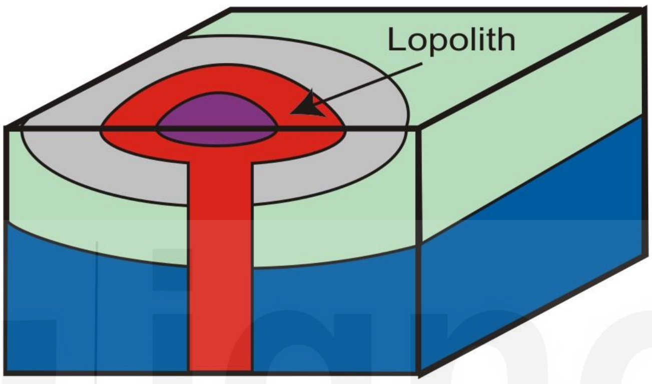


Fig. 2.29: Saucer shaped lopolith.

2.4.6 Phacolith

Phacoliths are concavo-convex concordant igneous rocks which occur along the crest and trough of folds of the country rocks (Fig. 2.30).

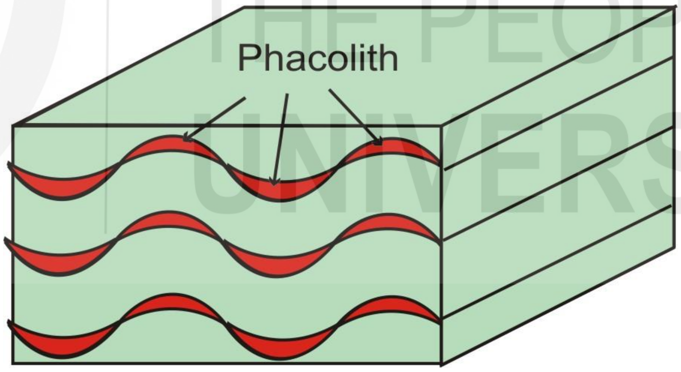


Fig. 2.30: Phacolith are lens shaped igneous rocks which occur in folded strata.

2.4.7 Chonolith

Chonolith is an igneous intrusion whose form is so irregular that it can not be classified as a laccolith, dike, sill or any other recognised body.

2.4.8 Volcanic Neck

It is a pipe-like elevated discordant igneous monolith mass (body) in which lava consolidated (Fig. 2.31). Volcanic landforms on land comprising of cinder cones which are easily eroded as they are composed of unconsolidated volcanic materials. Thus, the volcanoes on land are continually being eroded and lowered by weathering. Even after most of the cones have been eroded away and the rock occupying a volcanic pipe being composed more often of a resistant material that may remain standing above the surrounding terrain. The best-known volcanic pipes are the diamond-bearing structures of the South Africa. The rocks filling these pipes must have been originated at a depth of at least 150 kilometers, where pressure is high enough to generate diamonds and other high-pressure minerals.

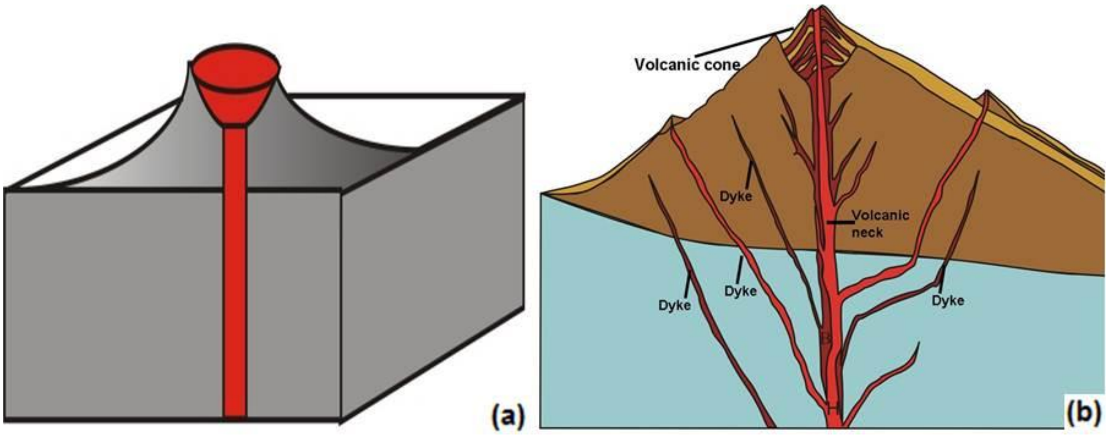


Fig. 2.31: Volcanic neck.

2.4.9 Batholith

Batholith is the largest intrusive of all igneous bodies (*bathos* means depth, *lithos* means stone). They occur as huge linear structures extending several hundreds of kilometers and up to 100 kilometers wide (Fig. 2.32a). Batholiths are plutonic igneous rock masses which occupy the core of the mountain, e.g. Ladakh batholith (Fig. 2.32b), Mt Abu batholith. Batholiths are always made up of granitic (felsic) and intermediate rock types and are often referred to as **granite batholiths**. They are formed at some depth below the Earth's surface and exposed only after the removal of overlying cover of the rock masses. They do not have determinable floor, but, have steep walls.

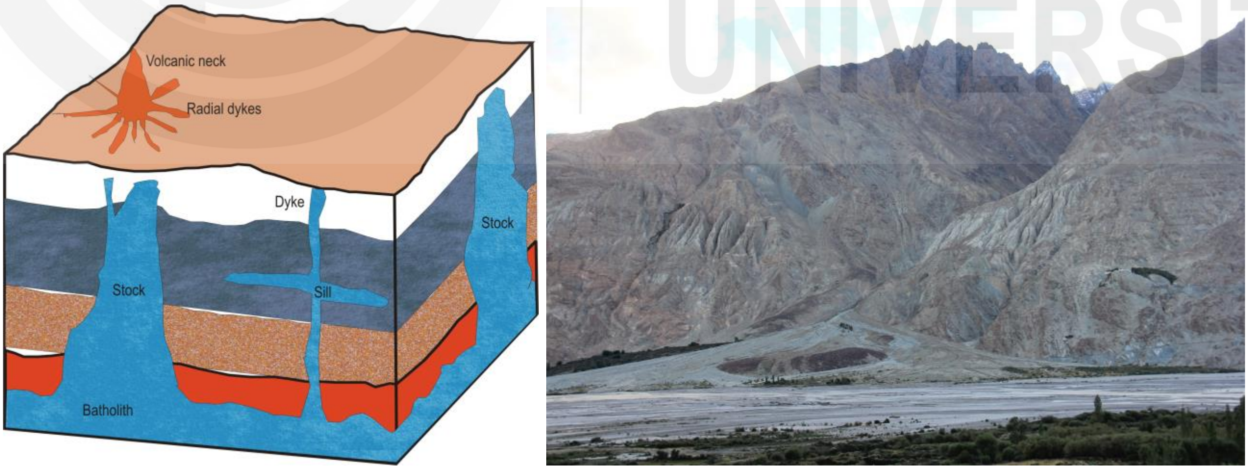


Fig. 2.32: a) Block diagram of some intrusive bodies; and b) Field photograph of Ladakh Batholith.

2.4.10 Stock

It is an intrusive mass of plutonic igneous rocks, but, smaller in size than the batholith and usually possessing more or less circular or elliptical cross section (Fig. 2.32a).

2.4.11 Boss

Boss is a mass of plutonic igneous rocks (or stocks) which has circular outline upon the surface.

2.5 SUMMARY

In this unit, we have learnt about the texture, structure and forms of the igneous rocks. Let us summarise about what we have learnt in this unit:

- Textures in igneous rocks include crystallinity/ degree of crystallisation, granularity/ grain size and fabric. Fabric includes mineral orientation, the shape of the mineral grains and mutual relationship of the crystals and glassy matter.
- On the basis of crystallinity igneous have been grouped as: holocrystalline texture, hemicrystalline/ microcrystalline texture, holohyaline texture.
- The coarse-grained igneous rocks are called as phaneritic rocks and fine-grained rocks are known as aphanitic rocks. Aphanitic texture can be grouped as microcrystalline and cryptocrystalline.
- Factors controlling grain size or granularity in igneous rocks are the rate of cooling, viscosity, volatile content, and complexity of the magma composition.
- Shape of the crystals can be euhedral, anhedral and subhedral. The resulting texture can be grouped as panidiomorphic granular texture, allotriomorphic granular texture and hypidiomorphic granular texture.
- Texture can be equigranular or inequigranular. Inequigranular textures can be further grouped as porphyritic, ophitic, intergranular or intersertal.
- Glass tends to change themselves in a long course of time into irregular arrangement of atoms and molecules, thus, they form cryptocrystalline masses. The process of devitrification is promoted if the glassy material is placed under increased pressure and temperature with chemically active fluids.
- Structures found in the igneous rocks can be vesicular and amygdaloidal, cellular or scoriaceous, lava tunnels, blocky and ropy lavas, pillow lavas, columnar/prismatic structures, lava flow structures, rapakivi structure, etc.
- Concordant body refers to the igneous body, running parallel to the bedding or foliation plane of the country rock. Discordant body refers to the igneous body cutting across the bedding or foliation plane and penetrating through the country rock.
- Forms of the igneous rocks can be sill, dyke, laccolith, bysmalith, lopolith, phacolith, chonolith, volcanic neck, batholith, stocks and bosses.

2.6 ACTIVITY

- Try to explore rocks around you and collect different types of igneous rocks and identify them. Write their textural characteristics in a notebook.

2.7 TERMINAL QUESTIONS

1. What is granularity? Discuss in detail with neat and labeled diagrams wherever necessary.
2. Describe the types of inequigranular textures found in igneous rocks.
3. Explain the structures found in igneous rocks.
4. Discuss forms of the igneous rocks with the help of neat and labeled diagrams.

Audio/Video Material-Based Questions:

- Differentiate (a) fabric and texture, and (b) primary and secondary textures.
- List the components of texture.
- List the processes of formation and growth of crystals.
- What is glass? Mention the textures formed devitrification of glass.
- What is perlitic texture?
- What is palagonite?
- Explain how felty texture is seen under the polarising microscope?
- Draw diagram of banded rhyolite as seen under polarising microscope.
- Distinguish between: a) Intergranular and intersertal texture
  b) Aphanitic and Phaneritic texture
  c) Porphyritic and poikilitic texture
  d) Perthite and antiperthite
  e) Dyke and lava flow
- List the types of crystal habits present in igneous rocks.
- What are ‘battlemented’ crystals?

2.8 REFERENCES

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

2.9 FURTHER/SUGGESTED READINGS

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2.10 ANSWERS

Self Assessment Questions

1 a) Texture is defined as the overall physical appearance of a rock based on the size, shape, and arrangement of its mineral grains and it also describes the mutual relationship between the adjoining grains of mineral materials.

b) Crystallites are embryo of crystals organised to full crystalline status. They have more varied shapes. Microlites are somewhat larger bodies can be recognised as minute crystals. They exhibit crystal outline appropriate to their mineralogical nature. Glass is term specifically used for rocks or portions of rocks which are devoid of crystalline structure. It is formed when a highly viscous magma is rapidly super-cooled, wherein the atomic groups and the molecules present in them are not properly and regularly arranged in a definite order to form crystalline substance.

c) Crystallinity / degree of crystallisation; Granularity/ grain size; Shape of the mineral grains; Mutual relationship of the crystals and glassy matter.

d) Panidiomorphic granular texture; hypidiomorphic granular texture; allotriomorphic granular texture.

e) Equidimensional (garnet, olivine, leucite); prismatic (natrolite); tabular (plagioclase, orthoclase); platy or sheet (mica); irregular (quartz in granite).

2 a) If in an igneous rock the difference of the grain size becomes highly pronounced, i.e. one set of the grains is distinctly larger associated with another set which is distinctly fine then it is termed as inequigranular. When the majority of the grains are of equal size, it is said to have equigranular texture, e.g. granite and gabbro.

b) If the variation of larger to smaller grain size is systematic and gradual, then it is known as seriate texture.

c) Graphic texture results due to the intergrowth between quartz and orthoclase.

d) 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 intergrowths are produced.

Terminal Questions

1. Your answer should include the points discussed under Section 2.2.2.
2. Your answer should include detailed description about porphyritic, poikilitic, intergranular and intersertal textures.
3. Your answer should include the points discussed under Section 2.3.
4. Your answer should include the points discussed under Section 2.4.

UNIT 3

CLASSIFICATION OF IGNEOUS ROCKS

Structure

3.1 INTRODUCTION

The igneous rocks show great variations both in chemical and mineralogical compositions as well as in textural characteristics. We have learnt about textures, structures and forms of igneous rocks in Unit 2 of this course. Let us discuss about classification and nomenclature of igneous rocks. Time to time attempts has been made by petrologists to classify igneous rocks. The classification of igneous rocks has been the subject of debate amongst the petrologists. Over the past decade, most geologists have accepted the IUGS (International Union of the Geological Sciences) classification as the standard. Since this classification is being widely adopted which we will discuss later in this unit.

Now we will discuss and introduce to you much simpler classification that will allow to easily identify the more common igneous rocks.

Classifications in the Earth sciences are designed to reduce complexity. Most classifications are what we use are genetic. For example, aphanitic rocks are or volcanic origin while phaneritic rocks are plutonic.

Igneous rocks have been classified on the basis of their texture, mode of occurrence, mineralogy, and chemical composition. We have already learnt about the classification of igneous rocks based on texture and mode of occurrence in Unit 2. Remember that the classification of igneous rocks is based on their mode of occurrence, i.e., plutonic, hypabyssal and volcanic rocks and texture as phaneritic, aphanitic and fragmental. Let us discuss about the classification of igneous rocks based on their mineralogy and chemical composition in this unit.

Expected Learning Outcomes

After reading this unit you should be able to:

- ❖ explain the classification of igneous rocks in the field;
- ❖ classify igneous rocks based on their mineralogical composition; and
- ❖ discuss the classification of igneous rocks based on their chemical composition.

3.2 Field Classification

Now let's look at a much simpler classification. We call this as **field classification** because it requires little detailed knowledge of rocks and can be easily applied to any igneous rock, we might pick up during the field trip. Field classification utilises the characters like texture, mineralogy and colour. Though identification of igneous rocks on the basis of colour is unreliable however in the classification of certain fine grained (aphanitic) igneous rocks which contain no visible mineral grains, colour is the only other available property. Learners are thus cautioned to use colour only as a last resort.

In order to use this classification during the fieldwork, you must first determine the rock's texture. According to field classification there are five basic textures; phaneritic (coarse), aphanitic (fine), vesicular, glassy and fragmental. Now examine the rock sample collected by you and determine its textural group in the following manner. Refer to Table. 3.1. If it is glassy, vesicular or fragmental you cannot determine mineralogy and hence the name is simply obsidian for a glass, tuff for a fragmental or pumice/scoria for a vesicular rock. In case of phaneritic and few aphanitic rocks you can determine the mineralogy. Identify one or two key minerals, not all of the minerals in the rock. For instance, granites and rhyolites will have quartz and potassium feldspar (K-feldspar). Amphibole is only abundant in diorite or andesite. If the rock is coarse-grained (phaneritic) then it must be one of the rocks in the row labelled as coarse grained, i.e. granite, diorite, gabbro or peridotite.

Table 3.1: Field classification.

Grain size	Felsic (light colour)	Intermediate	Mafic (dark colour)	Ultramafic
Coarse	Granite	Diorite	Gabbro	Peridotite
Fine	Rhyolite	Andesite	Basalt	
Vesicular	Pumice		Scoria	
Glassy	Obsidian			
	Minerals Present			
	Quartz K-feldspar Sodic plagioclase	Sodic & calcic plagioclase	Calcic plagioclase Pyroxene	Pyroxene Olivine

3.3 CLASSIFICATION BASED ON MINERALOGICAL COMPOSITION

You have read that minerals are the building blocks of rocks in the BGYCT-133 course. The classification of the rocks based on minerals forms the fundamental basis of mineralogical classification. Let us discuss following classification schemes based on mineralogy of igneous rocks. They can be

- Based on composition and proportion of minerals
- Based on colour index
- CIPW classification
- Tabular classification
- IUGS classification

3.3.1 Composition and Proportion of Minerals

The minerals occurring in igneous rocks can be classified as primary and secondary minerals.

a) **Primary minerals:** They are formed at the time of formation of the rocks or in other words formed during the cooling and crystallisation of magma. Primary minerals may be further subdivided into:

1. **Essential minerals** are those minerals whose presence are necessary and considered to be essential for naming or nomenclature of the particular rock. For example, quartz, orthoclase and plagioclase should be present for naming a rock as granite; minerals augite and labradorite are necessary for a rock to be named as basalt. Quartz and orthoclase minerals in granite; augite and labradorite in basalt are considered as essential minerals.

2. **Accessory minerals** are also formed at the time of primary crystallisation of magma but their presence is not necessary and not used in naming the particular rock, e.g. magnetite, apatite, zircon. They are present in small quantity. Some minerals are present in very small quantity but they can

be used in naming the rock such as hornblende or biotite granite. Hornblende or biotite can be prefixed with granite and named as biotite granite or hornblende granite, depending on the mineral present.

b) **<u>Secondary minerals</u>**: They are formed by alteration of primary minerals which may be primary or secondary such as clay minerals, biotite, chlorite, xeolite. Primary alteration refers to the alteration of primary minerals by water vapours at the time or subsequent to the cooling and crystallisation of magma, whereas, secondary alteration is due to secondary processes such as weathering and alteration. In this process, primary minerals alter into secondary minerals. For example, pyroxenes changes into chlorite, plagioclase changes into clay minerals on weathering. This is one of the oldest criteria used for classification of igneous rocks, but it is still in use. Igneous rocks can also be classified on the basis of minerals present. Since colour of the rock depends upon the minerals present in it, in addition to the grain size to some extent. Depending on the commonly occurring minerals the igneous rocks, it has been broadly classified into:

- **felsic rock**, e.g. granite, rhyolite.
- **mafic rock**, e.g. basalt, gabbro.

The word felsic (feldspar and silica) is used for minerals that are lighter in colour. Silica and feldspar have low melting point, low specific gravity and are lately crystallised. Mafic or ferromagnesium rocks comprise minerals dark in colour, e.g. olivine, pyroxene, amphibole and biotite. Mafic minerals have high specific gravity, higher melting point and are early crystallised. As discussed above, the colour of the rock is also governed by grain size. Granite is a coarse-grained rock consisting of light-coloured minerals, but, when the rock of the same composition cools rapidly and forms glassy rock, it is known as obsidian which is dark in colour and if bears pitch-like or luster of an asphalt, called as pitchstone.

Let us read some examples of felsic-light coloured and mafic-dark coloured minerals:

Felsic minerals: Quartz, feldspar, feldspathoid, muscovite, etc.

Mafic minerals: Pyroxene, amphibole, olivine, biotite, iron oxide, etc.

<u>3.3.2 Colour Index</u>

This classification is based on the percentage volume of ferro-magnesium or dark coloured minerals present in the rock. The groups are:

- **Leucocratic**: ‘Leuco’ means light ‘cratic’ means coloured. When the rock is dominantly composed of light-coloured minerals and poor (<0.33%) in dark coloured minerals it is known as leucocratic.
- **Mesocratic**: ‘Meso’ means medium, when the dark coloured minerals vary between 33-67%. It represents intermediate colour, i.e. neither dark nor light in appearance.
- **Melanocratic**: ‘Melano’ means dark, when the dark coloured minerals are more than 67% in the rock.

3.3.3 CIPW Classification

This classification scheme is quite old and is based on the normative calculation from the bulk chemistry of the rocks. This is quasi-chemical method of classifying rocks. Thus, it is also known as **norm classification.** A norm is a means of converting the chemical composition of an igneous rock to an ideal mineral composition. This method of classification was devised by four Americans (Cross, J.P. Iddings, V. Pirsson and H.S. Washington) in 1931. This system of rock classification is abbreviated as 'CIPW' classification and is widely accepted by the petrologists. The basic principle of classification is to understand relationship between major element chemistry and possible mineralogical composition of the investigated rock. Norms are series of arbitrarily selected minerals that are formed from chemical composition of rocks. The series of standard rules governing formulation of major minerals which generally follow the Bowen's reaction series are used for norm calculation. This is a theoretical exercise and the norms calculated may or may not tally with the mode (actual individual minerals percentage by, calculated by determining volume of the minerals and converting them into their weight by multiplying density and recalculating by 100%). The norm is divided in to sialic and a femic group, important minerals of each group is mentioned in Table 3.2.

Table 3.2: List of sialic (rich in silica and aluminum) and femic (rich in iron and magnesium) minerals.

Sialic Minerals		Femic Minerals	
Minerals	**Composition**	**Minerals**	**Composition**
Quartz	SiO2	Wollastonite	CaO.SiO2
Corundum	Al2O3	Enstatite	MgO.SiO2
Orthoclase	K2O.Al2O3.6SiO2	Ferrisilite	FeO.SiO2
Albite	Na2O.Al2O3.6SiO2	Diopside	CaO(Mg.Fe)SiO2
Anorthite	CaO.Al2O3.2SiO2	Hypersthene	(MgFe)OSiO2
Leucite	K2O.Al2O3.4SiO2	Forsterite	2MgO.SiO2
Nepheline	Na2O.Al2O3.2SiO2	Fayalite	2FeO.SiO2
Kalsilite	K2O.Al2O3.2SiO2	Acmite	Na2O.Fe2O3.4SiO2
		Magnetite	FeO.Fe2O3
		Limonite	FeO.TiO2
		Apatite	3(CaO.P2O5)CaF2

This classification system is in use from several years and has been revised. Earlier the process of calculation was done manually and time taking and tedious. Now the calculation of norm is carried using computer codes.

Let us discuss advantages and limitations.

CIPW classification uses several chemical constituents normally present in the rock. Fine grained and glassy rocks can also be classified using this classification. CIPW norms of slightly altered igneous and metamorphic rock can give hint to their original nature. The disadvantage is that the chemical composition is essential for calculating norms. The calculated norms may not match with the actual mineralogy, i.e. mode, as norm is a hypothetical mineralogy.

3.3.4 Tabular Classification

This classification takes into consideration both the silica content and relative proportion of feldspars, i.e. alkali feldspar and plagioclase. Let us look at Table 3.3, which portrays tabular classification. This classification scheme takes into consideration (i) the mode of occurrence, (ii) SiO2 percentage and free quartz, (iii) proportion of K-Feldspar, lime (calcic) and sodic (Na) plagioclase. Apart from these, on the basis of silica saturation 3 categories have been made:

- oversaturated
- saturated and
- undersaturated

Further, oversaturated is divided into two groups, i.e. Group I and II; saturated in one group, i.e. Group III; undersaturated in three groups, i.e. Group IV, V and VI.

Table 3.3: Tabular Classification (source : Tyrell, 1973).

	OVERSATURATED			SATURATED			UNDERSATURATED		
	I Quartz	II Quartz + Feldspars		III Feldspars			IV Feldspars + Feldspathoid	V Feldspathoid	VI Mafic minerals predominant
		Predominant Orthoclase	Predominant Plagioclase	Predominant Alkali Feldspar	Predominant Soda-Lime Plagioclase	Predominant Lime-Soda Plagioclase			
PLUTONIC Felsic / Mafic	Igneous quartz veins	Granite X	Granodiorite (tonalite) X	Syenite X X	Diorite X X	Anorthosite Gabbro X	Nepheline syenite Theralite & Teschenite X	X Ijolite X	Peridotite Picrite
HYPABYSSAL		←			Aplites		→		
		←			Porphyries			→	
			←		Lamprophyres				→
		Granophyre Felsite				Dolerite	Tinguaite		
		←	Pitch stone			→ Tachylite			
VOLCANIC		Rhyolite	Dacite	Trachyte	Andesite	Basalt	Phonolite	Leucitophyre	Olivine-rich Basalts
		←	Pitch stone		→			Nepheline basalt	
		← Obsidian	→			Tachylite		Leucite basalt	Limburgite
Av. Silica %	90	72	66	59	57	48	54.5	43	41

Let us discuss, for example oversaturated igneous rocks which contain quartz and feldspar (Table 3.3). They are sub-divided into two predominant types:

1. quartz
2. quartz and feldspar.

Similarly, you can observe for saturated igneous rocks. They comprise three predominant sub-groups-

1. alkali feldspar,
2. soda lime plagioclase, and
3. lime soda plagioclase.

The unsaturated igneous rocks are divided into three predominant sub-groups-

1. feldspars and feldspathoids
2. feldspathoids
3. mafic minerals

Tabular classification also takes into consideration, the mode of occurrence. The plutonic division in the first column of the tabular classification has been divided into felsic and mafic.

3.3.5 IUGS Classification

Let us discuss IUGS classification.

This classification has brought uniformity and rationality in the field of classification of igneous rock. IUGS stands for International Union of Geological Sciences. IUGS established a sub-commission for classifying plutonic rocks. This classification was recommended by IUGS in 1973 which was further elaborated by Le Bas and Streckeisen in 1991. The rocks are classified and named on the basis of their actual mineral contents measured in volume percent, i.e., on the basis of their quantitative modal composition. The modal composition is usually determined from a number of thin sections of the same rock by point counting on a grid pattern. IUGS classification is strictly a quantitative mineralogical classification (Fig. 3.1). To classify a rock correctly on the basis of modal proportions of minerals, the percentages of five minerals must be determined, such as:

- Q- Quartz and polymorphs of SiO_2.
- A- Alkali feldspars includes albite
- P- Plagioclase feldspars more calcic
- F- Feldspathoids (foids)
- M- All other phases (mafics)

The mineralogy of a rock reflects its chemical composition, for example:

- rocks which contain free quartz are rich in silica could be granite,
- rocks with plagioclase dominant feldspar are high in calcium may be gabbro or diorite, etc.
- rocks dominated by mafic minerals contain considerable magnesium and iron may be peridotite or dunite, etc.

The IUGS classification distinguishes the common rocks first on the basis of the grain size i.e. plutonic (coarse-grained) and volcanic (fine-grained). The rocks with mafic minerals less than 90% are classified according to their light-coloured constituents, i.e., quartz, plagioclase, alkali feldspar (orthoclase, microcline, albite) and feldspathoid minerals.

The quantitative mineralogical composition is plotted in QAPF double triangle joined at A-P base for classification purpose the composition is recalculated on the percentage basis and projected on QAPF plane so that Q+A+P=100 or F+A+P=100.

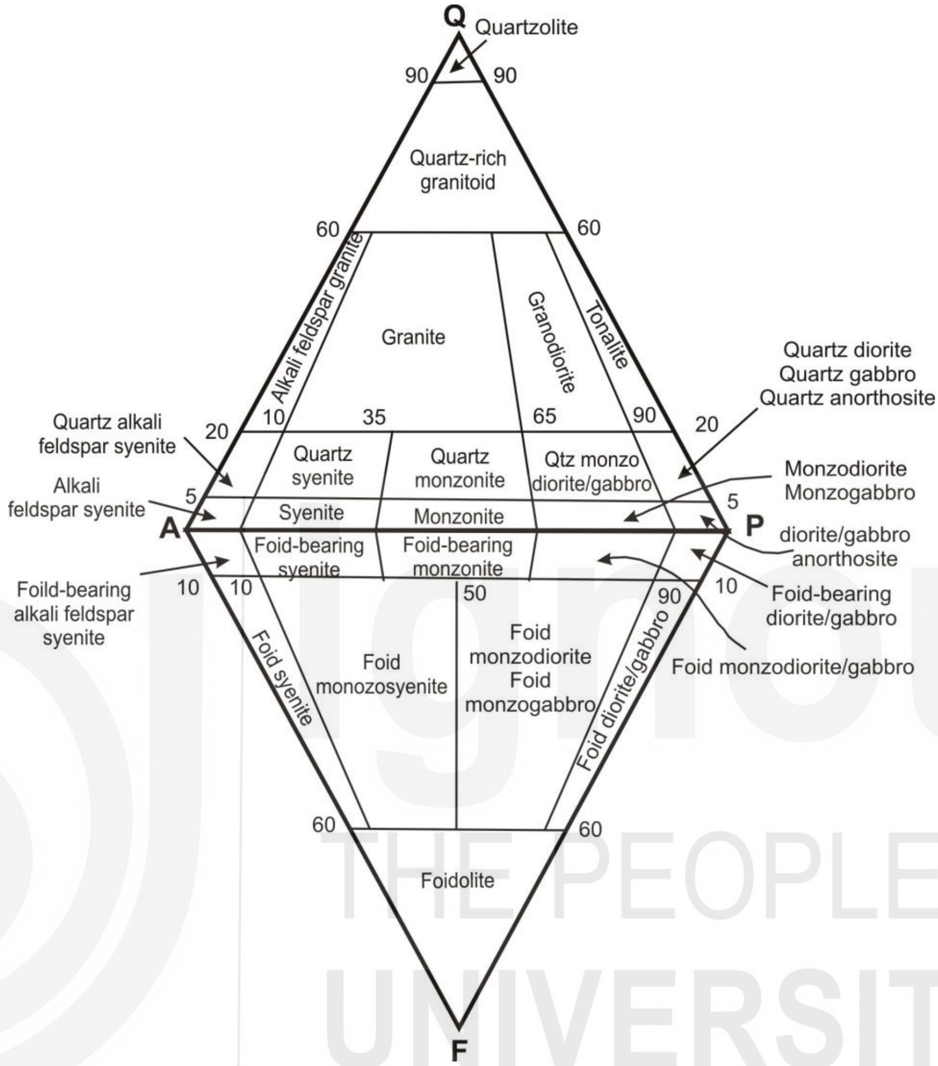

Fig. 3.1: IUGS classification of plutonic (phaneritic) rock.

The rocks with 90-100% are ultramafic rocks and are classified on relative proportion of mafic minerals.

A small number of plutonic igneous rocks are low in silica and contain feldspathoids (foids) rather than quartz. Second classification triangle is used for these rocks i.e., FAP. A rock cannot appear on both triangles because quartz and feldspathoids are chemically incompatible when mixed they will react to form feldspar of intermediate silica content.

Let us learn how to calculate?

The triangle permits classification of plutonic rocks that contain a little as 10% QAP; the rest of the rock consists of mafic minerals. The technique used is to determine percentages of the Q, A, P, minerals along with the mafic constituents. Now assume that a rock has 50% mafic minerals, 15% Q, 20% A, and 15% P. We have learnt that the mafic minerals are not included in classification triangle. The Q, A, P, are so recalculated as to equal 100 thus giving Q-30%, A-40%, P-30% (Fig. 3.2).

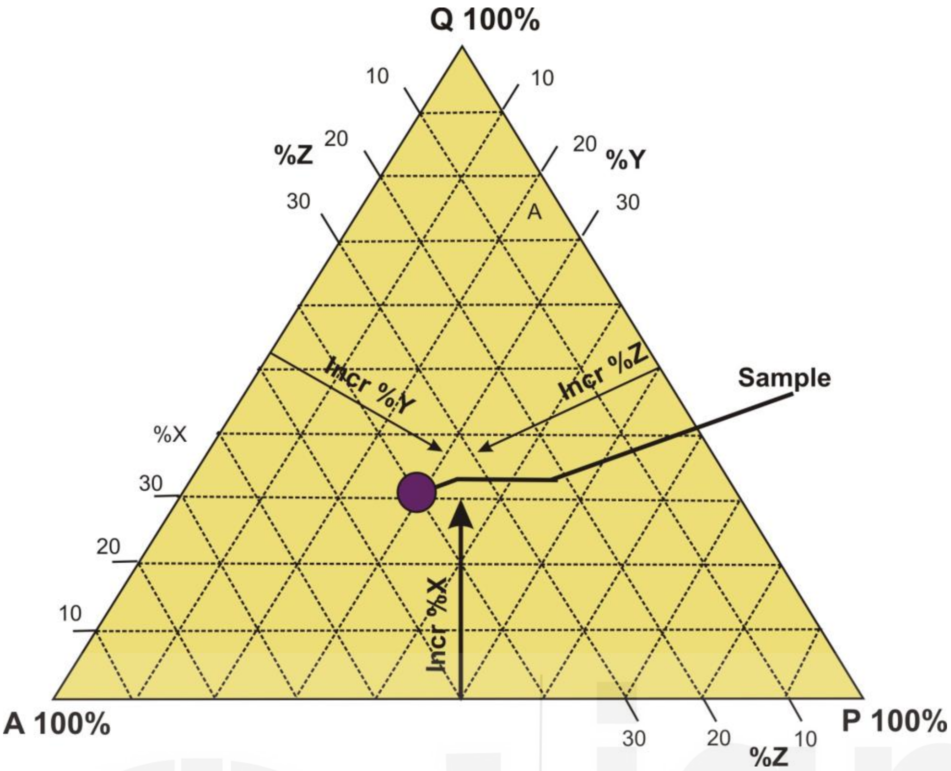

Fig. 3.2: Plotting the sample in IUGS diagram; lines parallel to base represents percentage of quartz (Q), that parallel to right side alkali feldspar (A) and the one parallel to left, plagioclase feldspar (P). The modal percentage of these minerals is recalculated to 100 and plotted. Purple point depicts A-40%, Q-30%, P-30%

The drawbacks of IUGS classification is that there is no place for texture of the rock except for making distinction in phaneritic and aphanitic rocks. Rocks like serpentinite, kimberlite do not fit into IUGS classification.

Learners, you have learnt about the classification of igneous rocks based on mineralogical composition. Before discussing about the classification based on chemical composition spend few minutes to perform an exercise to check your progress.

SAQ 1

a) What are the primary minerals? Give examples.

b) What are the felsic and mafic rocks?

c) Give an example of dark coloured rock, consisting of silica and orthoclase.

d) Why CIPW is known as quasi-chemical method of classifying rocks?

3.4 CLASSIFICATION BASED ON CHEMICAL COMPOSITION

We have studied in course BGYCT-133 that the minerals have fixed chemical composition and the rocks are the aggregate of minerals. But here we are concerned with the chemical composition or the chemistry of rocks. Since minerals are made up of chemical elements, therefore using chemical composition is most ideal way of classifying rocks. Chemical classification requires partial or complete analyses. A number of chemical classifications of igneous rocks have been devised. Few are listed below:

- Silica percentage
- Silica paturation
- Alumina saturation
- Alkali lime index
- Total Alkali Silica (TAS)

3.4.1 Silica Percentage

Shand and Holmes (1935) devised a method of classification on the basis of the silica content present in the rock. The igneous rocks vary between wide limits in their chemical composition. Thus, rock such as granite may contain about 70 to 80% of silica and very little quantity of iron, magnesium and lime while at the other end, there are rocks like peridotite dunite, etc. which may contain about 35 to 40% of silica and larger quantities of iron, magnesium and lime. Thus, igneous may be classified as:

1. **Acid igneous rocks**: These rocks have more than 66% SiO2 content. They are also called felsic or silicic rocks, e.g. granite, rhyolite.
2. **Intermediate igneous rocks**: These rocks having 52 to 66% of SiO2, e.g. syenite or diorite, trachyte, andesite.
3. **Basic igneous rocks**: The SiO2 content in these rocks vary between 45 to 52%. They are also called mafic rocks, e.g. gabbro and basalt.
4. **Ultrabasic igneous rocks**: In these rocks SiO2 contents is less than 45%. They are also called ultramafic rocks. They have high Mg content, e.g. dunite, peridotite, pyroxenite.

This is the classification of igneous rocks based on percentage of silica. The grouping of rocks on the basis of their silica contents is a chemical parameter. Let us summarize, the classification scheme based on silica percentage as given in Table 3.4.

Table 3.4: Igneous rock classification based on silica percentage.

SiO2 (in wt%)	Rock types	Examples
75-66	Acidic/ felsic	granite, rhyolite
52-66	Intermediate	granodiorite, andesite
45-52	Mafic/basic	diorite, gabbro, basalt
<44	Ultrabasic/ultramafic	peridotite, dunite

3.4.2 Silica Saturation

Shand in 1913 and Holmes in 1917 classified igneous rocks on the basis of **free silica** into three groups:

1. **Silica oversaturated rocks** contain more than 66% SiO2, i.e. free quartz mineral is found. Such rocks are also known as acidic or felsic rocks.

2. **Silica saturated rocks** are typically those which have sufficient silica to form stable silicate mineral but seldom free quartz occur. They contain more than 52 - 66% SiO2.

3. **Silica undersaturated rocks** contain insufficient silica and silica deficient minerals like olivine, nepheline, leucite and are devoid of quartz mineral. Rocks contain 45 - 52% SiO2.

3.4.3 Alumina Saturation

You have read that silica is the most abundant oxide constituent in igneous rocks. Next to silica, alumina is the most abundant oxide present in the rocks. Shand in 1943 devised classification based on alumina saturation.

$$A/CNK = \frac{Al_2O_3}{CaO + Na_2O + K_2O} \text{ [mol\%]}$$

$$A/NK = \frac{Al_2O_3}{Na_2O + K_2O} \text{ [mol\%]}$$

On the basis of alumina, the rocks have been divided into three subtypes:

1. **Peraluminous**: This group contains excess of alumina than required for formation of feldspars, which can be chemically expressed as: Al2O3>(CaO+Na2O+K2O)

   A/CNK>1

   Minerals like muscovite, corundum, kyanite should be present.

2. **Metaaluminous**: Molecular percentage of this category is expressed in the form:

   Al2O3<(CaO+Na2O+K2O) and Al2O3>(Na2O+K2O)

   A/CNK<1 and A/NK<1

   This group does not contain alumina rich minerals and also lack alkali pyroxene and amphibole. This group is quite common in igneous rocks.

3. **Peralkaline**: This group is alumina poor and oversaturated with alkalis. On a molecular basis will be expressed as: Al2O3<(Na2O+K2O)

   A/NK<1

3.4.4 Alkali Lime Index

In 1931 a petrologist by name Peacock examined suites of rocks throughout the world. He used this classification for a related series of igneous rocks using SiO2, Na2O, K2O and CaO data. He plotted CaO vs SiO2 and (Na2O+K2O) vs SiO2. Commonly CaO decreases and Na2O + K2O increases with respect to SiO2. Peacock noted that the two curves intersect at different values of SiO2 for different suites. He used the value of SiO2, where the two curves intersect known as the **Peacock Index** or **Alkali Lime Index**, to divide the rock suites into following:

Name of Suite	Peacock Index
Alkalic	<51
Alkali-Calcic	51-56
Calcic-Alkalic	56-61
Calcic	>61

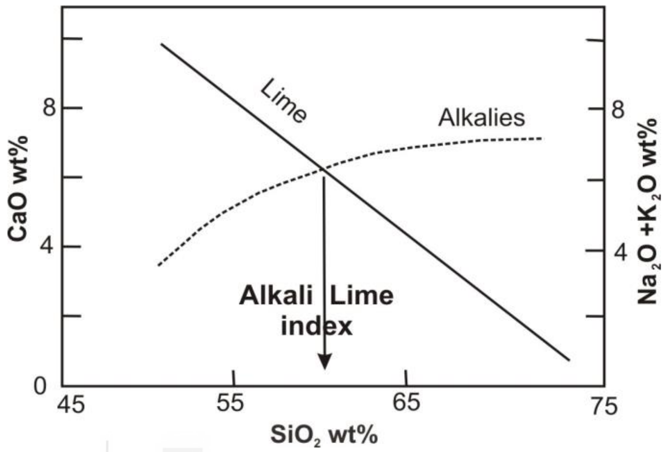

Fig. 3.3: Silica versus lime and alkali plot.

Learners, you have learnt about the schemes using chemical composition for classifying igneous rocks. Before discussing about the TAS classification spend few minutes to perform an exercise to check your progress.

3.4.5 Total Alkali Silica (TAS)

The most popular chemical classification scheme is total alkali silica contents based (TAS) diagram was given by Le Bas and others in 1986 (Fig. 3.4). The TAS (Total Alkalis vs Silica) classification scheme uses major chemistry to classify igneous rocks. It is a simple X-Y graph with the X-axis showing silica (SiO2) wt% and the Y-axis showing alkalis (Na2O+K2O) wt%. A boundary line separates alkaline rocks from subalkaline rocks (Fig. 3.4). This is the most acceptable chemical classification based on major oxides. The TAS plot help in classifying the rocks ranging from rhyolite to picrobasalt, phonolite.

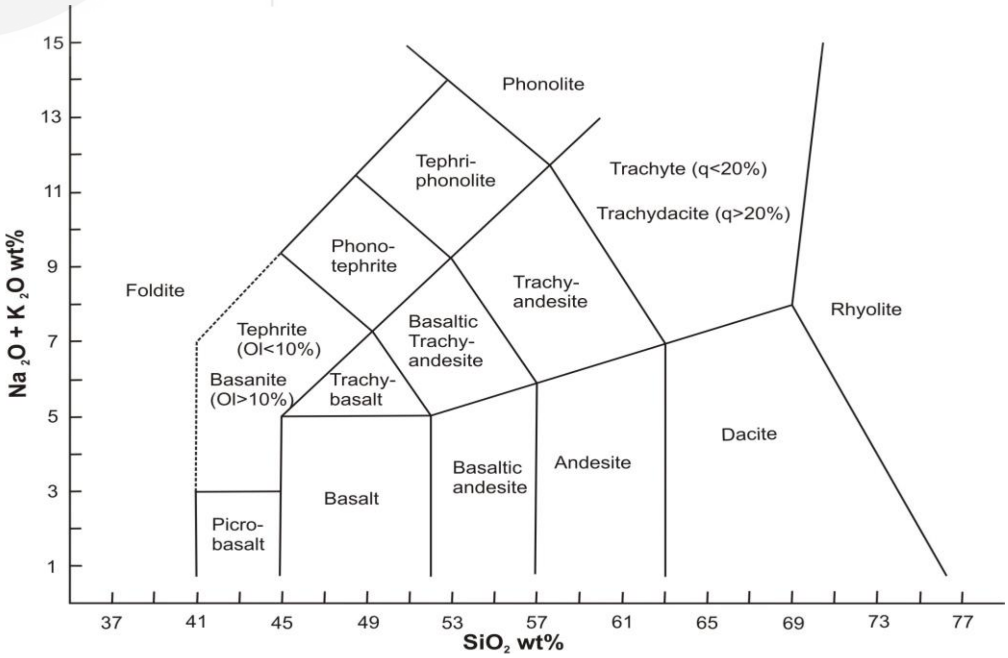

Fig. 3.4: Total Alkali silica (TAS) diagram.

SAQ 2

a) List the classification of igneous rocks based on silica percentage.

b) List the igneous rocks based on silica saturation.

c) List the igneous rocks based on alumina saturation.

d) What is alkali lime index?

3.5 SUMMARY

In this unit we have learnt an art of classification of igneous rocks. Let us summarise about what we have learnt in this unit:

- Igneous rocks can be classified on the basis of mineralogical composition and chemical composition.
- Mineralogical classification is based on the composition and proportion of minerals present in the rock. This classification is based on colour index, modal percentage as in IUGS classification or quasi-chemical classification, like CIPW.
- Tabular classification combines principles of mineralogical and chemical classification. It considers the silica content, and relative proportion of feldspars, i.e. alkali feldspar and plagioclase and mode of occurrence.
- Chemical classification is based on percentage of silica, saturation of silica and aluminium in rocks and alkali lime.
- Total Alkali Silica (TAS) diagram uses (Na_2O + K_2O) and SiO_2. percentage.

3.6 ACTIVITY

1. Explore rocks around you and collect different igneous rocks and try to classify them on the basis of their colour index.

3.7 TERMINAL QUESTIONS

1. Discuss the mineralogical classification based on colour index of rocks.
2. Explain the concept of CIPW classification.
3. Discuss the basis of tabular classification.
4. What is the basis of IUGS classification?
5. Discuss the TAS classification.

3.8 REFERENCES

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

3.9 FURTHER/SUGGESTED READINGS

- Mukherjee, P.K. (2000) A Text Book of Geology. The World Press, Kolkata, ISBN:81-87567-09-0, 638p.

- Singh, Parbin (2013) Engineering and General Geology. S.K. Kataria and Sons. ISBN: 8188458511, 9788188458516, 600p.
- Tyrell, G. W. (1973) The principles of Petrology. John Wiley & Sons. ISBN 0470894806, 9780470894804, 349p.
- Shrivastava, J. P. (2009) Igneous Rocks National Science Digital Library, CSIR, New Delhi) http://hdl.handle.net/123456789/1034**,** CSIR, New Delhi

3.10 ANSWERS

Self Assessment Questions

1 a) Essential minerals are those whose presence is necessary in the bulk mineral composition and are considered to be essential for naming or nomenclature of the particular rock. Give example of granite and basalt.

b) Felsic rocks comprise light color minerals like silica and feldspar. These minerals have low melting point, low specific gravity and are late crystallised. Mafic or ferromagnesium rocks comprise of minerals dark in colour, e.g. olivine, pyroxene, amphibole and biotite. Mafic minerals have high specific gravity, higher melting point and are early crystallized.

c) Obsidian is a glassy rock with dark in colour and same composition as granite.

d) This classification is based on the calculation of norm from the bulk chemistry of rocks.

2 a) Please refer Table 3.3.

b) Silica oversaturated rocks contain more than 66% SiO2; silica saturated rocks contain more than 52-66% SiO2; silica undersaturated rocks contain 45-52% SiO2.

c) Peraluminous, peralkaline, metaaluminous.

d) The value of SiO2 of where the two curves [CaO and alkali (K2O+ Na2O)] intersect known as the Alkali Lime Index or Peacock Index.

Terminal Questions

1. Please refer to the subsection 3.2.2.
2. Please refer to the subsection 3.2.3.
3. Please refer to the subsection 3.2.4 and Table 3.3.
4. Please refer to the subsection 3.2.5.
5. Please refer to the subsection 3.2.5.

GLOSSARY

Aa	:	It is Hawaiian word used for Blocky lava for "ouch, this hurts" when you walk on it barefoot.
Aphanitic	:	It consists of a mosaic of crystals too small to be seen without magnification. They can be either cryptocrystalline or microcrystalline.
Aphyric	:	Nonporphyritic, aphanitic texture.
Archaean	:	Eon defined as the time between 4 billion years ago to 2.5 billion years ago. Most of the oldest rocks on Earth, including large portions of the continents, formed at this time.
Asthenosphere	:	A ductile physical layer of the Earth, below the lithosphere. Movement within the asthenosphere is the main driver of plate motion.
Batholith	:	A large intrusion of igneous rock, usually granite, formed deep beneath the surface of Earth so the rock cooled very slowly.
Bowen's Reaction Series	:	A series of mineral formation temperatures that can explain the minerals that forms in specific igneous rocks.
Columnar jointing	:	Type of joints in which rock divides into columns. This type of jointing results due to contraction in basaltic rocks.
Columnar structure	:	A common geological structure found in basaltic and other types of lava. In this rock has been divided into prisms and columns. Commonly it has six sides but sometimes 8 sides can also develop.
Continental crust	:	The layers of igneous, sedimentary, and metamorphic rocks that form the continents. Continental crust is much thicker than oceanic crust. Continental crust is defined as having higher concentrations of very light elements like K, Na, and Ca, and is the lowest density rocky layer of Earth. Its average composition is similar to granite.
Crystallisation	:	The process by which crystalline phases are separated from liquid, viscous or dispersed state.
Cumulate	:	Accumulation of crystals produced by crystal-melt fractionation.

Cumulophyric : A type of porphyritic texture in which several phenocrysts are aggregated together, the matrix is usually glassy or aphanitic.

Deccan Traps : Large flood basalt province in India that occurred around the same time as the K-T Extinction, 66 million years ago.

Extrusive : Igneous rocks formed by eruptions on the Earth's surface.

Fayalite : A mineral belonging to olivine group having the composition of Fe_2SiO_4. It is found both in crystalline and massive form.

Flood basalt : Rare very low viscosity basaltic eruption that covers vast areas.

Glassy : Term used for glass like texture developed in volcanic rocks.

Groundmass : General term for the fine-grained. In igneous rocks, this is the part of the rock that is not phenocrysts. In sedimentary rocks, it typically refers to the fine-grained components, namely mud. In metamorphic rocks, it is usually referring to material between porphyroblasts or a low-grade rock with only microscopic mineralisation.

Holocrystalline : Igneous rocks which are entirely composed of complete crystals.

Intrusive rocks : Igneous rocks which crystallise below the surface of the Earth, e.g. dyke, sill, stock and batholih.

Lava : Molten rock erupted on the surface of Earth from a volcano.

Magma : Molten rock with dissolved volcanic gases, beneath the Earth's surface.

Magma chamber : A reservoir of magma below a volcano.

Melanocratic : A term used for those rocks which contain more than 66% dark coloured minerals.

Mineralisation : The process of inclusion of ore minerals in pre-existing rock bodies.

Obsidian : Dark-colored volcanic glass, with extremely small microscopic crystals or no crystals. Typically form from felsic volcanism.

Oligoclase : A kind of feldspar with composition between albite and

		anorthite but its chemical composition is closer to albite.
Olivine	:	It is an orthosilicate with chemical composition (Mg Fe)$_2$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.
Ophitic texture	:	Rock texture where lath shaped crystals of plagioclase are completely or partially surrounded by augite crystal. This texture is found in ultrabasic or volcanic rocks.
Pahoehoe	:	Hawaiian word for a "ropy" surface formed due to cooling of lava.
Perlitic	:	Texture made of concentric cracks in silicic glass.
Phenocryst	:	They are the bigger crystals present in porphyritic rocks as compared to crystals of other minerals.
Pillow lava	:	Lava that has been erupted beneath the sea, forming characteristic "pillow" shapes as it comes into contact with cold water.
Plagioclase	:	They are the common rock-forming minerals of albite-anorthite isomorphous series.
Pyroclastic	:	Rocks or rock textures that are formed from explosive volcanism.
Pyroclastic flow	:	A collapsed part of the eruption column that travels down at very hot temperatures at very fast speeds.
Pyroxene	:	A group of important rock-forming minerals dominantly composed of iron, magnesium and calcium sometimes sodium, potassium. Important rock forming minerals of this group are enstatite, bronzite, hypersthene, diopside, diallage, augite, aegirine.
Texture (Igneous rocks)	:	Physical appearance of rock as it appears from size, shape and fabric of constituent particles.
Vesicles	:	Bubbles formed by volcanic gases in lava, which become "frozen in" as the lava cools.
Viscous	:	Viscous refers to magmas that are thick and move very slowly.

Vitric : Glassy.

Vitrophyre : Texture in which large crystals (phenocrysts) are surrounded by glassy matrix.

Volcanic ash : Volcanic tephra that is less than 2 mm in diameter.

Xenolith : Rock fragment/block which are originated from older rocks and included in igneous rocks. They do not have genetic relationship with host rock. Example: sandstone in granitic rock.