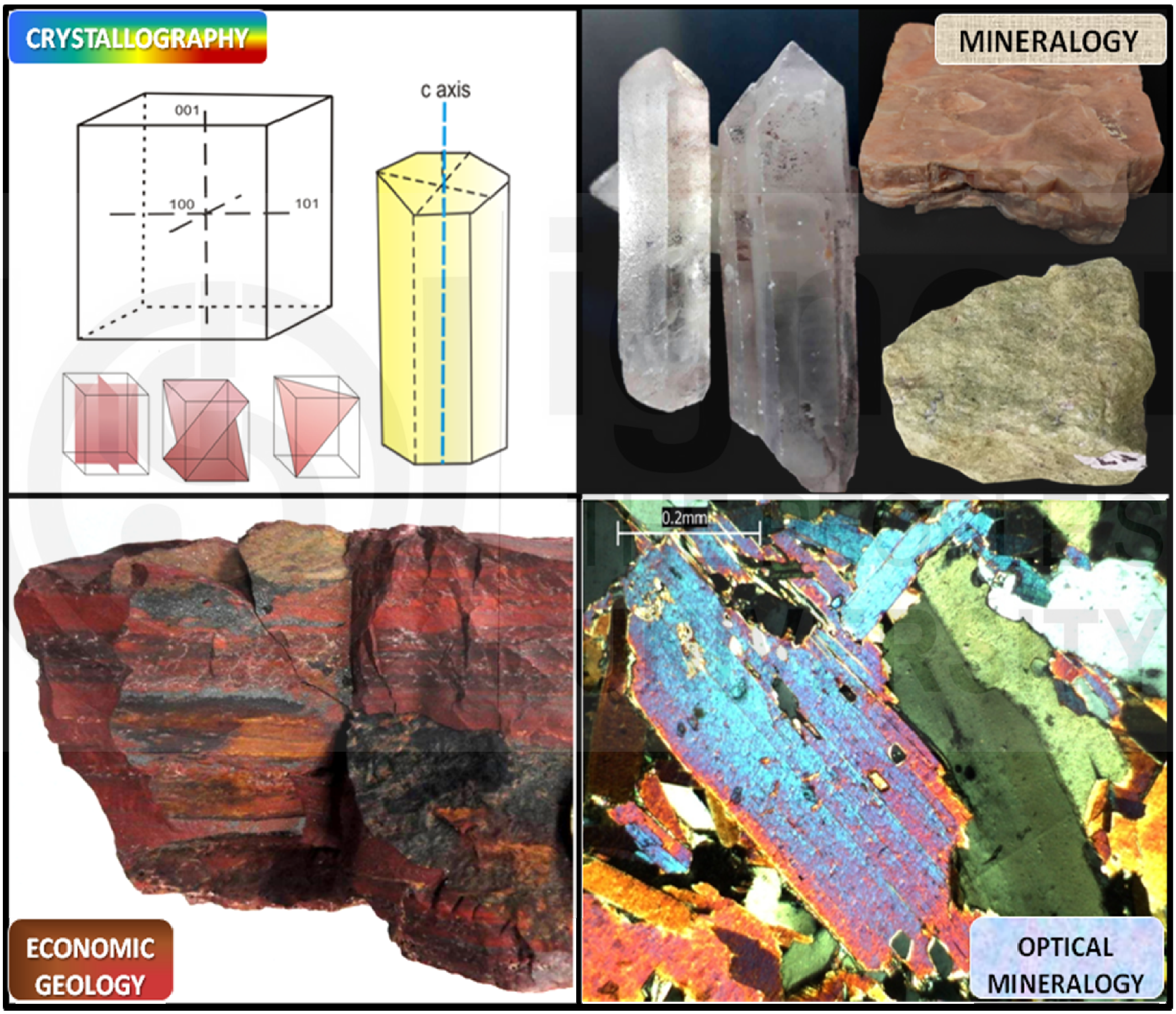
Indira Gandhi National Open University
School of Sciences

BGYCT – 133
CRYSTALLOGRAPHY, MINERALOGY AND ECONOMIC GEOLOGY



Optical Mineralogy and Economic Geology

Vol. 2

Indira Gandhi National Open University
School of Sciences

BGYCT - 133
CRYSTALLOGRAPHY, MINERALOGY AND ECONOMIC GEOLOGY

Volume

2

OPTICAL MINERALOGY AND ECONOMIC GEOLOGY

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
Centre of Advanced Study in Geology
University of Delhi, Delhi

Prof. M. A. Malik
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
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Department of Earth Sciences
Manipur University
Imphal, Manipur

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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

Dr. S.D. Shukla (Retd.)
(Units 8 & 9)
Department of Geology
SGRR(PG) College, Dehradun

Dr. Nishi Rani
(Units 11 to 14)
Centre of Advanced Study
in Geology
University of Delhi, Delhi

Prof. Meenal Mishra
(Units 10 to 12)
School of Sciences
IGNOU, New Delhi

Dr. Kakoli Gogoi
(Unit 15)
School of Sciences
IGNOU, New Delhi

Content and Language Editors

Prof. Pankaj Srivastava (Units 8 to10)
Department of Geology
Jammu University, Jammu

Prof. J. P. Shrivastava (Units 11 to 15)
Centre of Advanced Study in Geology
University of Delhi, Delhi

Transformation: Prof. Meenal Mishra

Course Coordinators: Prof. Meenal Mishra and Prof. Benidhar Deshmukh

Audio Visual Materials

Dr. Amitosh Dubey
Producer, EMPC, IGNOU

Prof. Meenal Mishra and Prof. Benidhar Deshmukh
Content Coordinators

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-133: CRYSTALLOGRAPHY, MINERALOGY AND ECONOMIC GEOLOGY

List of audio / video materials related to this course

1. **Geology at IGNOU -1**

   Link: http://egyankosh.ac.in/youtubevideo.jsp?src=YRFrgUyDWXw&title =Geology%20at%20IGNOU%20-1

2. **Geology Around Us - 1**

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

3. **Minerals and Their Uses**

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

4. **Microscopic Study of Basaltic Rocks**

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

5. **Introduction to Ore Deposits**

   Link: http://egyankosh.ac.in//handle/123456789/53454

6. **Classifications of Ore Deposits**

   Link: http://egyankosh.ac.in//handle/123456789/53455

7. **Early Magmatic Deposits**

   Link: http://egyankosh.ac.in//handle/123456789/53456

8. **Late Magmatic Deposits**

   Link: http://egyankosh.ac.in//handle/123456789/53457

9. **Contact Metasomatic and Contact Metamorphic Deposits**

   Link: http://egyankosh.ac.in//handle/123456789/53458

10. **Hydrothermal Mineralisation**

    Link: http://egyankosh.ac.in//handle/123456789/53461

11. **Textures Related to zoning in Igneous rocks**

    Link: https://www.youtube.com/watch?v=Wrbw0MQzSQU

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

VOLUME 2: OPTICAL MINERALOGY AND ECONOMIC GEOLOGY

The course **BGYCT-133 Crystallography, Mineralogy and Economic Geology** consists of four blocks, which have been packaged in two volumes. The **Volume 1** consists of two blocks namely, crystallography and mineralogy. The **Volume 2** consists of two blocks namely, Optical Mineralogy and Economic Geology.

The first block of this volume, **Block 3: Optical Mineralogy** will introduce you to the parts and functions of polarising microscope, optical properties of minerals under plane polarised light and between cross nicol and optical properties of common rock-forming minerals.

After studying about optical properties of common rock-forming minerals in Block-3, you shall learn about economic geology and metallic and non-metallic minerals in the next block. Minerals are the building blocks of rocks, and their study is important for geologists to locate potential mineral deposits. **Block 4: Economic Geology** introduces you to the basic concepts of economic geology. In this block, you will learn about the basic concepts of ores and ore deposits, processes of ore formation, metallic minerals, non-metallic minerals deposits and coal and petroleum.

Expected Learning Outcomes

After studying this volume, you should be able to:

- examine properties of light used in mineral identification;
- elaborate the parts and functions of polarising microscope;
- recognise optical properties used for mineral identification and explain optical properties of common rock-forming minerals under ordinary light, polarised light and between cross nicol;
- discuss basic concepts of ore and ore deposits and processes of their formation;
- describe different types of minerals of economic significance used in different industries viz.. building and construction; refractory, fertiliser, chemical, paints and pigments, abrasive, ceramic and glass manufacturing industries, and
- discuss origin, mode of occurrence, formation of coal and petroleum and their Indian occurrences.

After studying this volume, you will be equipped with the basic knowledge of optical mineralogy and economic geology. In the next core course, you would learn about different types of rocks, their textures and structures, process of their formation and their megascopic and microscopic characteristics.

We wish you all success in this endeavour!

Indira Gandhi National Open University
School of Sciences

BGYCT - 133
CRYSTALLOGRAPHY, MINERALOGY AND ECONOMIC GEOLOGY

Block

3

OPTICAL MINERALOGY

Course Design Committee

Block Preparation Team

Course Contributors

Dr. S. D. Shukla (Retd.) (Units 8 & 9)
Department of Geology
SGRR (PG) College, Dehradun

Prof. Meenal Mishra (Unit 10)
School of Sciences
IGNOU, New Delhi

Content and Language Editor

Prof. Pankaj Srivastava
Department of Geology
Jammu University, Jammu

Transformation: Prof. Meenal Mishra

Course Coordinators: Prof. Meenal Mishra and Prof. Benidhar Deshmukh

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BGYCT-133: CRYSTALLOGRAPHY, MINERALOGY AND ECONOMIC GEOLOGY

BLOCK 3: OPTICAL MINERALOGY

Optical mineralogy deals with the microscopic study of minerals. It is the study of the interaction of light with the minerals under the polarising microscope or petrological microscope. Optical mineralogy is the study of the interaction of light with minerals which is commonly limited to visible light. The optical properties of the minerals are studied in transmitted light under the polarising microscope. Microscopic examination of a mineral or/and rock specimens is the principal technique used for mineralogical identification of geological materials (minerals and rocks) by the mineralogists and petrologists. This helps us in identification and understanding their genesis. Polarising microscope is used to determine the nature of rock(s) and its constituent minerals. The polarised light passes through mineral and rock thin sections and optical properties are observed leading to the identification of these mineral.

This block comprises three units, wherein we will be introduced to the parts and functioning of polarising microscope, optical properties of minerals under plane polarised light and between cross nicol and optical properties of common rock-forming minerals.
Unit 8 Polarising Microscope is an introduction to the fundamental concepts of light, parts and functioning of polarising/petrological microscope. In **Unit 9 Optical Properties of Minerals** you will be introduced to basic concepts of microscopic study of minerals and the optical properties under ordinary light, plane polarised light and between the cross nicols. In **Unit 10 Optical properties of Rock-Forming Minerals** you will learn to identify common rock-forming minerals under plane polarised light and between cross nicols.

Expected Learning Outcomes

After studying this block, you should be able to:

- describe the properties of light used in polarising microscope for mineral identification;
- list different parts of a polarising microscope;
- discuss the functioning of polarising microscope;
- list and discuss the optical properties of minerals used for their identification under ordinary light and under polarised light;
- list and identify the optical properties of minerals used for their identification between cross nicol;
- recognise the optical properties of common rock-forming minerals under polarised light;
- explain the optical properties of various rock-forming minerals between cross nicol; and
- identify the diagnostic optical properties of different rock-forming minerals

We hope that after studying this block you will be able to get understand of the parts and functioning of polarising microscope, know the optical properties used for identification of minerals under the polarising microscope and identify the rock-forming minerals under the polarising microscope.

Wishing you success in this endeavour!

UNIT 8

POLARISING MICROSCOPE

Structure

8.1 INTRODUCTION

We have discussed about the physical properties of the minerals used in the identification of minerals in Unit 4 Minerals of this course. We had also discussed the physical properties of the common rock-forming minerals in Unit 6 Rock-Forming Minerals-I and Unit 7 Rock-Forming Minerals-II. The techniques used in the identification of minerals have evolved with time due to invention of sophisticated instruments. The studies of optical properties of minerals are carried using basic properties of light and response of the minerals to polarising light under a special kind of microscope known as **petrological microscope** or **polarising microscope.** This microscope is different than commonly used microscopes. **Optical mineralogy** is the study of the interaction of light with minerals which is commonly limited to visible light. Optical mineralogy is used to identify the mineralogical composition of geological materials (rocks/minerals) to know and understand their origin and evolution. In this unit, you will be introduced to the working of polarising microscope. A petrologist uses microscopes to determine the nature of rocks and minerals. Microscopic examination of a mineral and rock sample mounted on a thin section (glass slide) is the principle technique used for mineralogical identification.

Expected Learning Outcomes

After reading this unit, you should be able to:

- recognise the importance of microscopic study;
- describe the properties of light used for microscopic study;
- list different parts of a polarising microscope; and
- discuss the functioning of polarising microscope.

8.2 PREPARATION OF THIN SECTION

You have read that rock is an aggregate of minerals. It becomes difficult to identify the constituent minerals especially when the rock is fine or medium grained in hand specimen. You have read in earlier section that petrological microscope is also referred as polarising microscope because polarised light is used in the identification of the minerals. Optical properties are studied in **transmitted light**. In polarising microscope, as the name suggests the specially transformed rays known as polarised light are passed through rock / minerals thin sections and optical properties are observed leading to mineral identification. In **polarised light** the vibrations take place only in one plane. This is distinct from ordinary light in which the vibrations take place in all directions perpendicular to the direction of propagation of the ray. Thin sections of the minerals or rocks are prepared by grinding the thin chip of the mineral or rock specimen to study optical properties of a mineral/rock. Both sides of the specimen are grinded. Then the sample is grinded to ~0.03 mm thickness and mounted on a glass slide with transparent cement (Canada balsam), with or without cover slip. At this thickness most of the **non-opaque** minerals permit the light to pass through them. Canada balsam is a resin, viscous, sticky, colourless or yellowish liquid that turns to a transparent yellowish mass when the essential oils in which it is dissolved, are allowed to evaporate. The thin sections of minerals are placed over the stage of polarising microscope and studied. The optical properties vary in different minerals. We will be discussing optical properties of various rock forming minerals in the next Unit 9, which are helpful in identification of minerals. The minerals which do not permit the light to pass through thin sections are said to **opaque minerals**. Especially treated sections of opaque minerals are studied in **reflected light** with the help of reflecting microscope popularly known as **ore microscope**. This study is called **ore microscopy**.

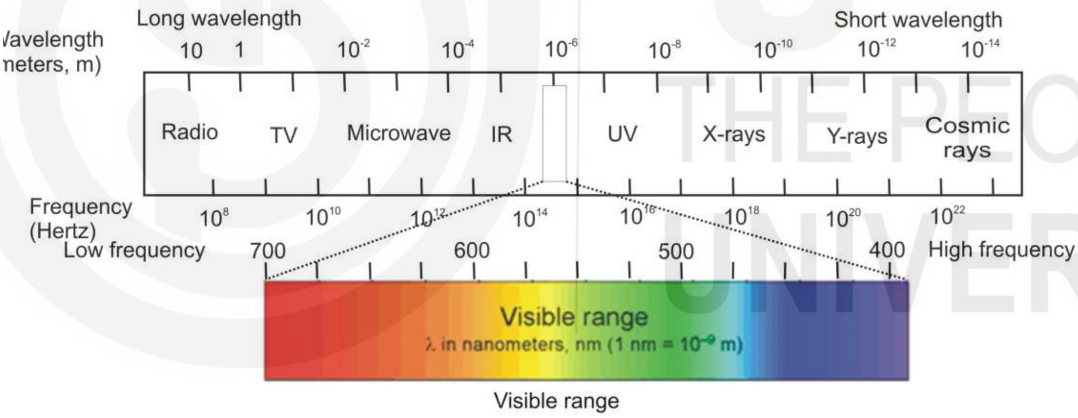
Let us read about the properties of light before discussing about the parts and functioning of polarising microscope.

8.3 PROPERTIES OF LIGHT

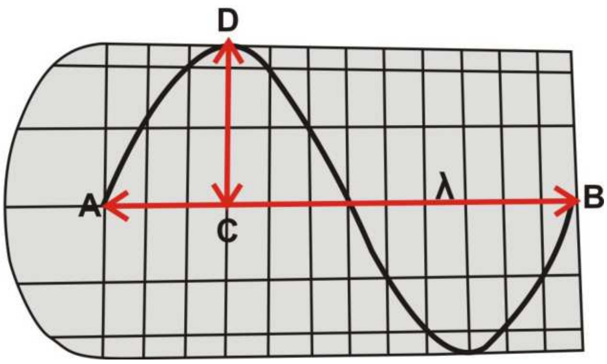
We have discussed that the microscopic studies of thin sections or small grains of minerals are dependent on light therefore it is important to introduce you to some behavioural characters of light. Let us briefly go through the basic principles of optics before studying about the parts and functioning of the polarising microscope.

8.3.1 The Nature of Light

You might have read that light is an electromagnetic vibration due to periodic variation in the energy given off by moving electrons. Light has properties of waves. Visible light is the portion of the electromagnetic spectrum that possesses the properties of both wave and a particle. The wave theory and corpuscular theory are two theories that explain all the properties of light. The light can be considered as simply the transfer of energy by vibrating particles along a path from the source to the observer for transmitted and reflected light microscopy. **White light** consists of many rays ranging in wavelength through the visible range from 400 nm to 700 nm of electromagnetic spectrum (Fig. 8.1a). The wave motion is like those waves that move out from a central point when a pebble is thrown into still water, where water merely rise and fall, and the wave front moves forward. These are propagated by motion of water particles which is **transverse** to the direction in which wave travels. The **wavelength** (λ) of such wave motion is the distance between successive crests and troughs. **Amplitude** is the maximum displacement of particle from its original position. Oscillatory motion of particles in a light wave is called as periodic motion because it repeats itself at regular intervals. It is distance C-D in Fig. 8.1b. The distance between any particle and the next, which is in like position or like **phase**, as A and B is the wavelength and the time required is the **vibration period** (Fig. 8.1b). A wavelength is the shortest distance between two points in exactly similar positions on a wave that move in the same direction.



(a)



(b)

Fig. 8.1: a) Visible range of electromagnetic spectrum (Source: www.guweb2.gonzaga.edu); **and b) Harmonic curve of light waves** (Source: Dana and Ford 1962)**. C-D is the Amplitude and A-B is the wavelength 'λ'.**

8.3.2 Polarised Light

You have read that the wave motion takes place with vibrations in all the directions at right angles to the direction of propagation. In ordinary light (Fig. 8.2a) the wave motion is confined to the vibrations in a single plane at right angles to the propagation of ray, the light is said to be plane polarised (Fig.8.2b) or simply polarised.

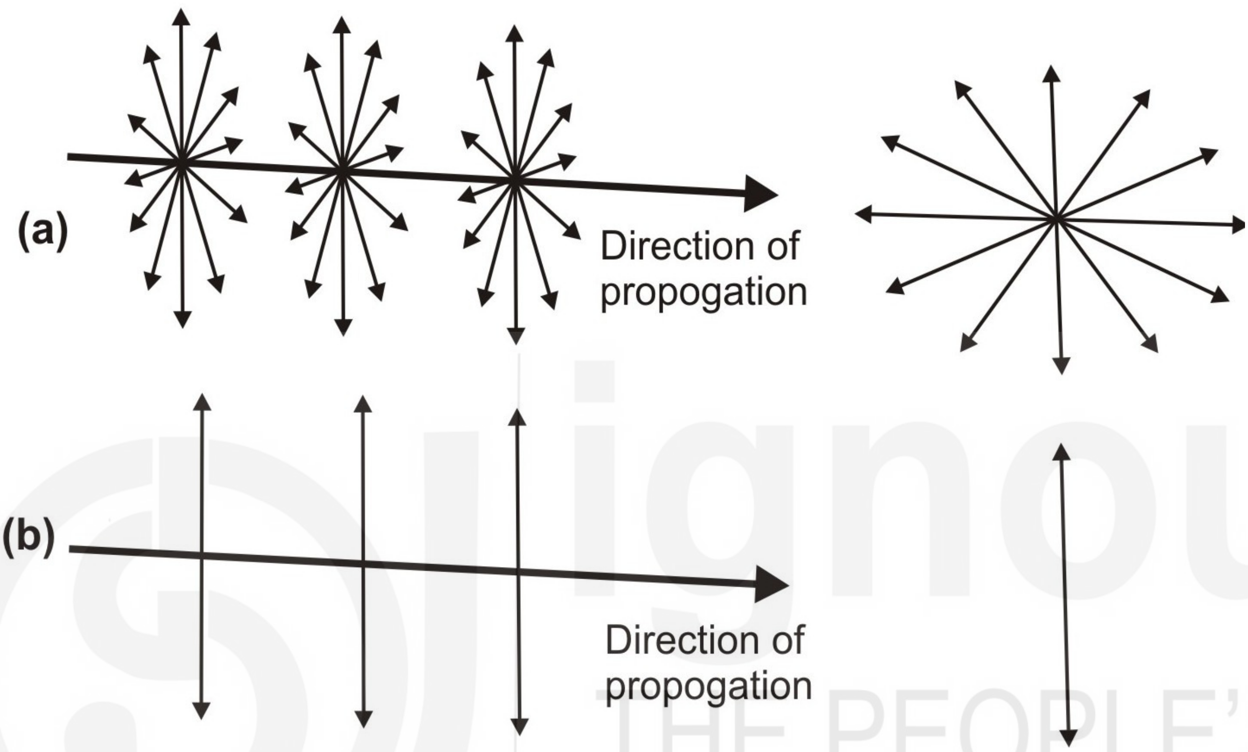
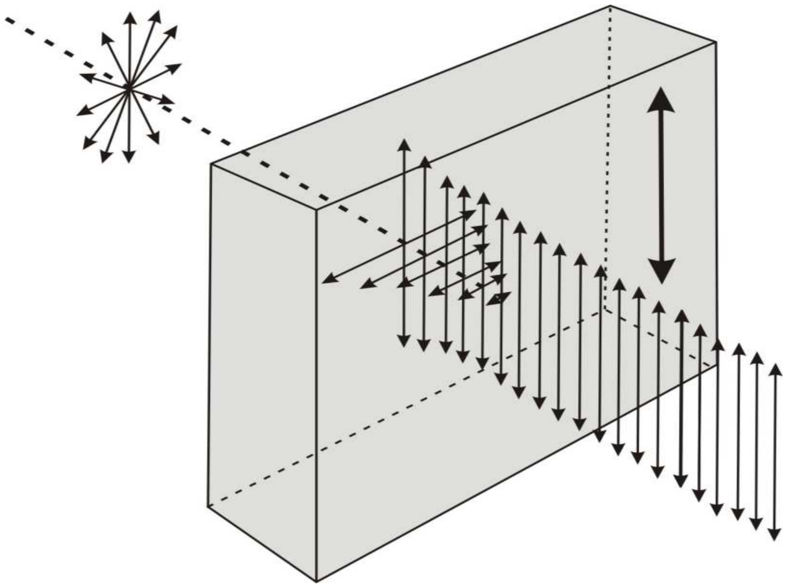


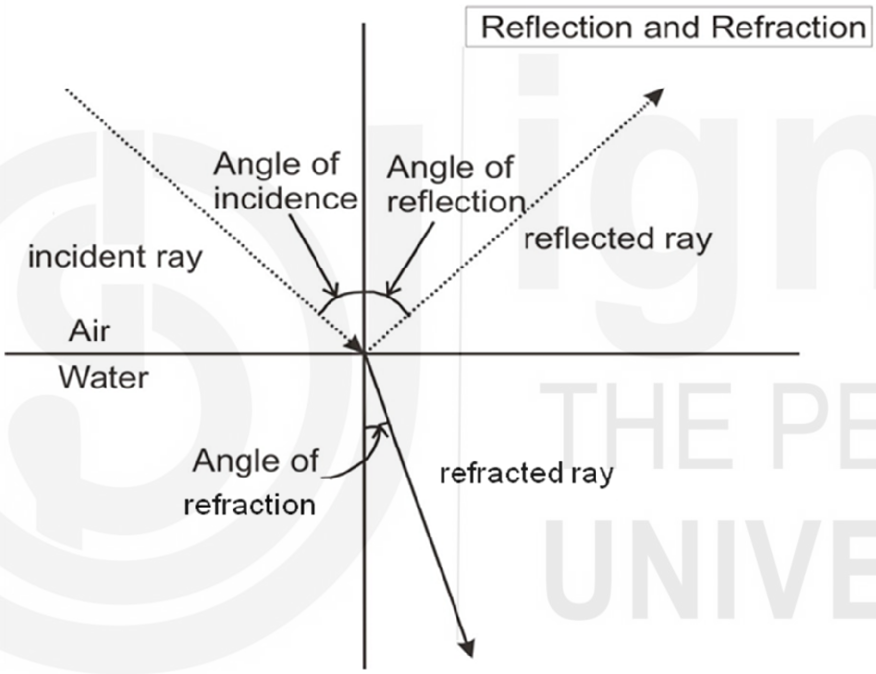
Fig. 8.2: Polarisation of light: a) Ordinary light vibrating in all direction perpendicular to the ray of light; and b) Polarised light vibrating only in one direction perpendicular to the ray.

There are the three principal phenomena of generating polarising light:

- **Absorption**: In the anisotropic crystals, the polarised rays of light are divided and may be differentially absorbed. If one ray suffers nearly complete absorption and the emerging light will be plane polarised (Fig. 8.3a).
- **Reflection**: Light reflected from a smooth, non-metallic surface is partially polarised with the vibration directions parallel to the reflecting surface. The extent of polarisation depends on the angle of incidence and the index of refraction of the reflecting surface (Fig. 8.3b).
- **Double refraction**: We will discuss in detail about double refraction (Fig. 8.3c) in the next section.



(a)



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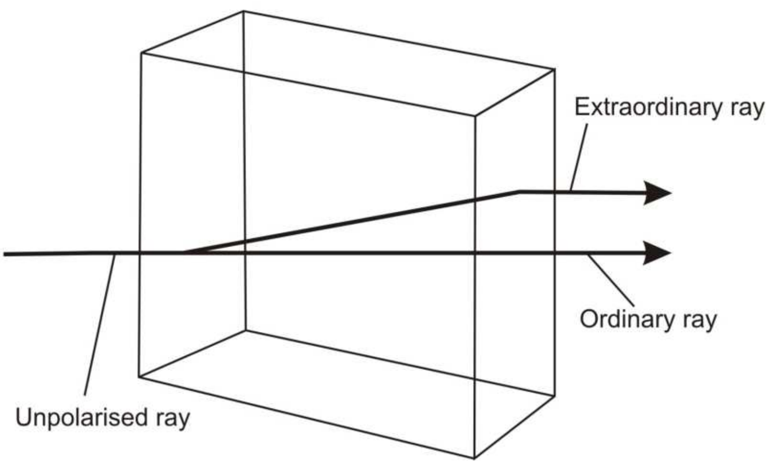


(c)

Fig. 8.3: Generation of polarised light by: a) Absorption; b) Reflection; and c) Double refraction.

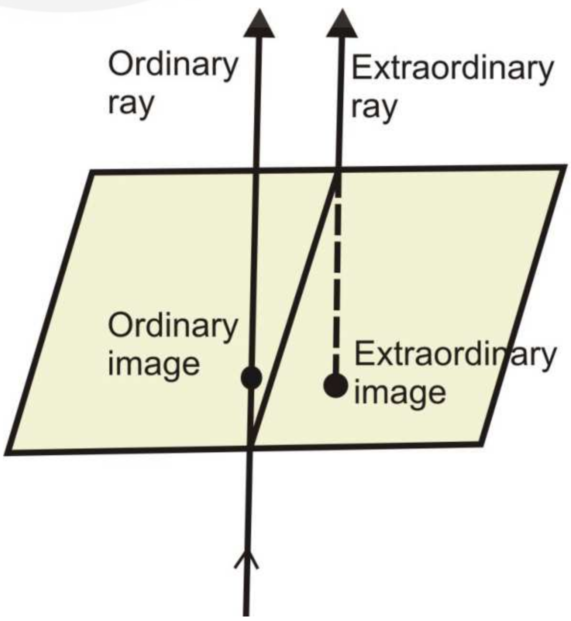
8.3.3 Double Refraction

Let us discuss about the phenomenon of double refraction.

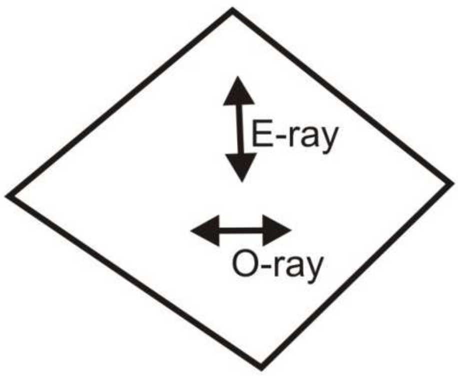
Double refraction is the phenomenon of splitting of the beam of ordinary light into two rays (ordinary and extraordinary rays see Fig. 8.4a) on passing through anisotropic medium. **Ordinary ray** (O-ray) consists of light vibrating parallel to long diagonal of the rhomb face, whereas **Extraordinary ray** (E-ray) of light vibrates parallel to short diagonal (as seen in Fig. 8.4b). Both the O-ray and E-ray travel with different velocities. O-ray does not bend or get refracted when it travels through the medium whereas E-ray is bent or refracted at an angle as it travels through the medium. They produce characteristic optical effects that can be recognised with proper instruments or, in some cases, they can be observed by naked eye. This phenomenon is very prominently visible with the help of colourless transparent variety of calcite called **iceland spar** (Fig. 8.4c). It is rhombohedron in shape with the composition of calcium carbonate. If the calcite rhomb/iceland spar is placed over a dot, two images of the dot are visible. If you rotate the rhomb over the dot you will notice that one of these images remains stationary and the other moves around the stationary dot. The image formed by the ordinary ray does not move and it is called **ordinary** or **real image**. The image of the dot which appears to move around the stationary dot is formed by extraordinary ray and is termed **extraordinary** or **virtual image**. The path of two rays is shown in figures 8.3a and b. It is seen that though the incident light is perpendicular to the lower surface of the rhomb, the extraordinary ray is refracted there, and is again refracted when it leaves the rhomb.

8.3.4 Nicol Prism

Nicol prism is used in the polarising/petrological microscope. The first efficient polariser called the Nicol Prism was named after the inventor William Nicol. You have read about double refraction in the previous section. Let us recall, what you have read?



(a)



(b)

(c)

Fig. 8.4: a) Path of Ordinary and Extraordinary rays; b) Directions of vibrations of Ordinary ray 'O' and Extraordinary ray 'E' (Source: Gribble, 1991)**; and c) Iceland spar.** (Source: www.gsi.gov.in).

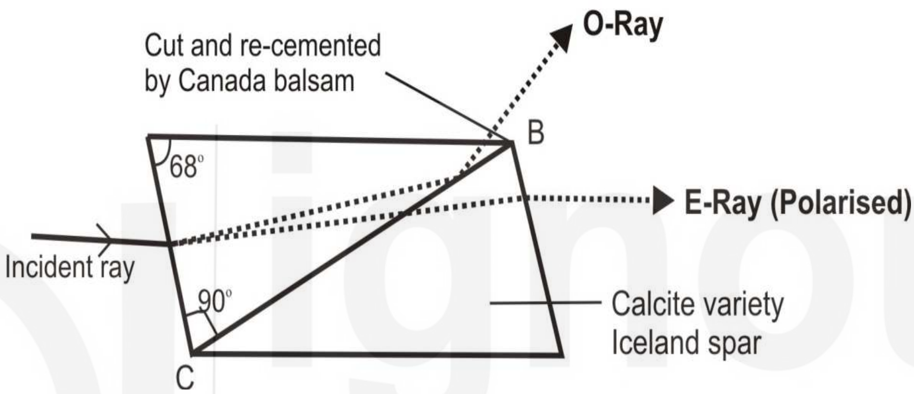
The phenomenon of double refraction involves the splitting of the beam of Ordinary light into two rays (i.e., O and E rays). The O-ray vibrates parallel to long diagonal of the rhomb face and E-ray of light vibrates parallel to short diagonal. The principle of Nicol prism is based on the elimination of one of these two rays. The crystalline material used in the construction of Nicol prism is iceland spar, which is optically clear variety of calcite (Fig. 8.5b). Calcite has such a strong double refraction that each ray produces a separate image when an object is viewed through a cleavage fragment. The long transparent rhombs of iceland spar are used. The ends of the crystal are ground till they make an angle of 68° to the long edge. Now the rhomb is cut into two parts through the plane which has three obtuse angles. After that the two halves are cemented at 90º angle and fixed back with the Canada balsam (refractive index: 1.54). The basic purpose of cutting and re-cementing is to put a thin film of the Canada balsam between the two halves of the rhomb. The sides of the nicol are surrounded by a black matt surface which will absorb any unwanted light. The inclination of this thin film of the Canada balsam is such that there is total reflection of O-ray. Thus, the grinding of the side to an angle of 68° with the long edge and the inclination of the Canada balsam thin film is crucial.

On entering the prism, light is resolved into two: O-ray and E-ray. The O-ray is totally reflected at the Canada balsam surface because of the greater refraction. The E-ray with refractive index close to that of the balsam proceeds essentially undeviated through the prism and emerges as plane polarised light (Fig. 8.5b). This phenomenon depends on the double refraction of the mineral calcite. Refractive Index (denoted as n) of a material can be expressed as ratio between velocity in air (V) and its velocity in denser material (v) that is:

$n = V/v$

The vibration direction of the polarised light is parallel to the short diagonal of the rhomb face at the end of the Nicol prism (Fig. 8.5b).

(a)



(b)

Fig. 8.5: a) Iceland spar crystal exhibiting double refraction (Source: www.itp.unihannover.de/fileadmin/arbeitsgruppen/zawischa/static_html/kalcal.html)**; and b) Construction of Nicol prism. CB = the plane through which rhomb is cut and recemented, IR = incident ray enters the rhomb, OR = Ordinary ray is totally reflected out from the film of the Canada balsam and ER = extraordinary ray comes out as plane polarised light.**

8.3.5 Isotropic and Anisotropic Minerals

Let us differentiate between isotropic and anisotropic minerals before proceeding further. All transparent substances, for optical considerations can be divided into two groups: isotropic and anisotropic.

1. Isotropic substance transmits light with equal velocity in all the directions as all the three axes are equal and interchangeable (Fig. 8.6a).
2. Anisotropic crystals transmit light with different velocities in different directions (Fig. 8.6b).

Isotropic substances: This group includes those materials whose refractive index is not dependent on the direction in which the light travels. The isotropic substances possess a single and constant refractive index for each wavelength. Highest degree of symmetry is present in the minerals crystallising in the isometric/cubic system as all the three axes are equal and interchangeable. Thus, minerals crystallising in cubic/isometric system are isotropic. Isotropic materials include noncrystalline substances such as glass, amorphous solids, liquids, and gases. Since air is a gas so it is isotropic.

Usually air has refractive index 1.0. If you mount a blank glass slide and view under plane polarised light, you will find that the field of view will be bright. When you rotate the stage, it will remain bright. When you cross the nicol by bringing the analyser in and view it again, the field of view will be completely dark. On 360° rotation of stage the darkness will persist. The glass is isotropic; therefore, it has no optical activity and double refraction. The minerals of cubic system and basal sections of uniaxial minerals behave like glass. Thus, in case of isotropic minerals as soon as nicols are crossed, the field of view appears totally dark and remains so when the stage is rotated.

Anisotropic substances: All the crystals except those of isometric system fall in this group. Minerals of tetragonal, orthorhombic, monoclinic, trigonal and hexagonal and triclinic systems are anisotropic. Anisotropic minerals because of their double refraction properties behave differently under crossed nicols. They transmit light in different directions with different velocities. The velocity of light in anisotropic substances varies with crystallographic direction. The light passing through anisotropic crystal splits into two polarised rays, i.e., O-ray and E-ray. These two rays vibrate in mutually perpendicular planes. Thus, a crystal has two indices of refraction, one associated with each polarised ray for a given orientation. Anisotropic substances can be further divided into uniaxial and biaxial minerals. The uniaxial minerals possess two refractive indices and biaxial minerals are characterised by three refractive indices. On rotation of the stage through 360°, you can make two important observations such as polarisation of colours and extinction. You will notice that on rotation of stage four times a mineral becomes extinct and between two extinction positions it shows range of polarisation colours.

Imagine, if all the minerals were isotropic optical mineralogy would have been a very dull branch of geology.

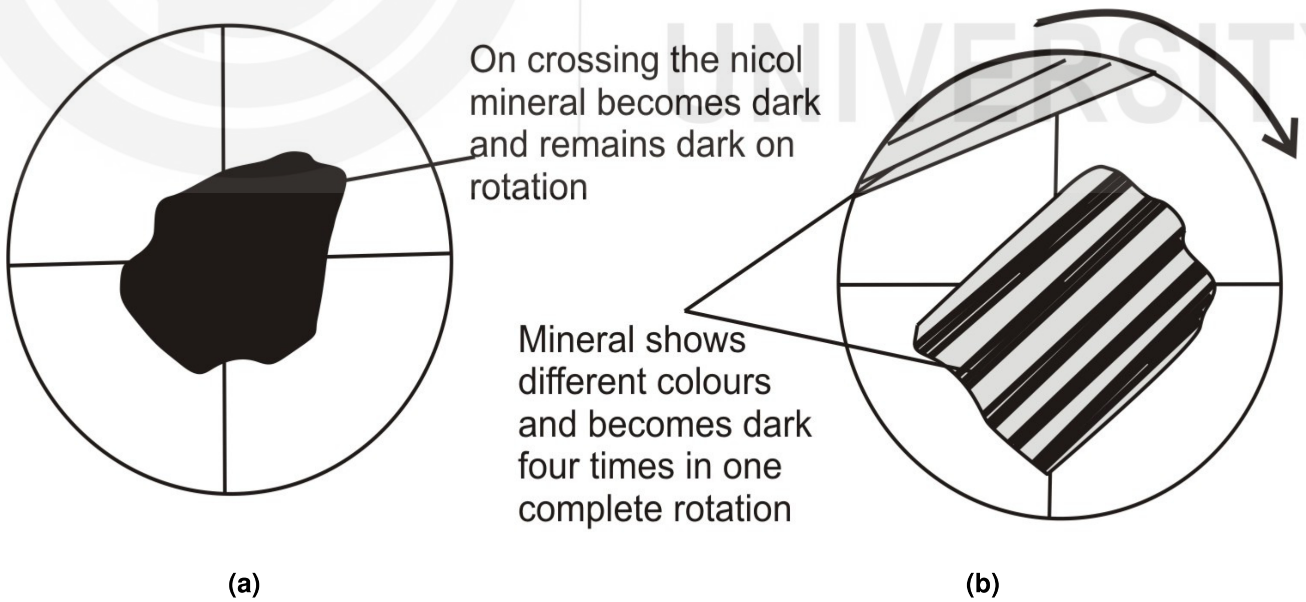


Fig. 8.6: a) Isotropic mineral under cross nicol remains dark on rotation; and b) Anisotropic mineral under cross nicol displays different colours and becomes dark four times in one complete rotation.

In the previous sections we have learnt about the properties of light. Before going to the next section spend 5 minutes to check your progress.

SAQ 1

a) What is polarised light?

b) What is double refraction?

c) Which variety of calcite is used in Nicol prism?

d) What is the function of Nicol prism?

e) What are isotropic substances?

8.4 POLARISING MICROSCOPE

You have read that the optical properties of minerals are studied with the help of polarising or petrological microscope in the transmitted light. The polarising microscope differs from a compound microscope (used in life science laboratory) in its basic principle of working. However, both of them have similar basic function that is to yield an enlarged image of an object placed on the stage. The basic components of compound microscope are:

- a base to provide stability to the instrument;
- a rotating stage with clips to hold the specimen under study and main optical system in the tube with objective and an eye piece; and
- coarse and fine adjustments screws are present to adjust the objectives, illuminating device or some artificial source of light.

You can convert a compound microscope to a polarising or petrological microscope by introducing two special devices **analyser** and **polariser**. The analyser is placed above the stage whereas polariser is placed below the stage. The stage holds the mineral specimen in the form of a thin transparent slice or thin section fixed to a glass plate.

Now let us get acquainted with the parts and functioning of polarising microscope (Fig. 8.7, Fig. 8.8a and b).

You have read above that a polarising microscope is different from other microscopes. The polarising microscope is equipped with one analyser and polariser. They are oriented at right angles to each other so that their polarisation directions are perpendicular to one another. Functionally the lower one is called as the polariser and the upper as analyser as it aids analysis.

Polarising microscopes can be monocular with one eye peice/ocular (Fig. 8.7), binocular microscope with two eye peices/ocular (Fig. 8.8a) and trinocular (with three eye peices/ocular; Fig. 8.8b). Binocular microscopes are more comfortable to look through for longer periods of time than a monocular microscope. A trinocular microscope has two eyepieces just like the binocular microscope but it also has a third eyetube for connecting a microscope camera (Fig. 8.8b).

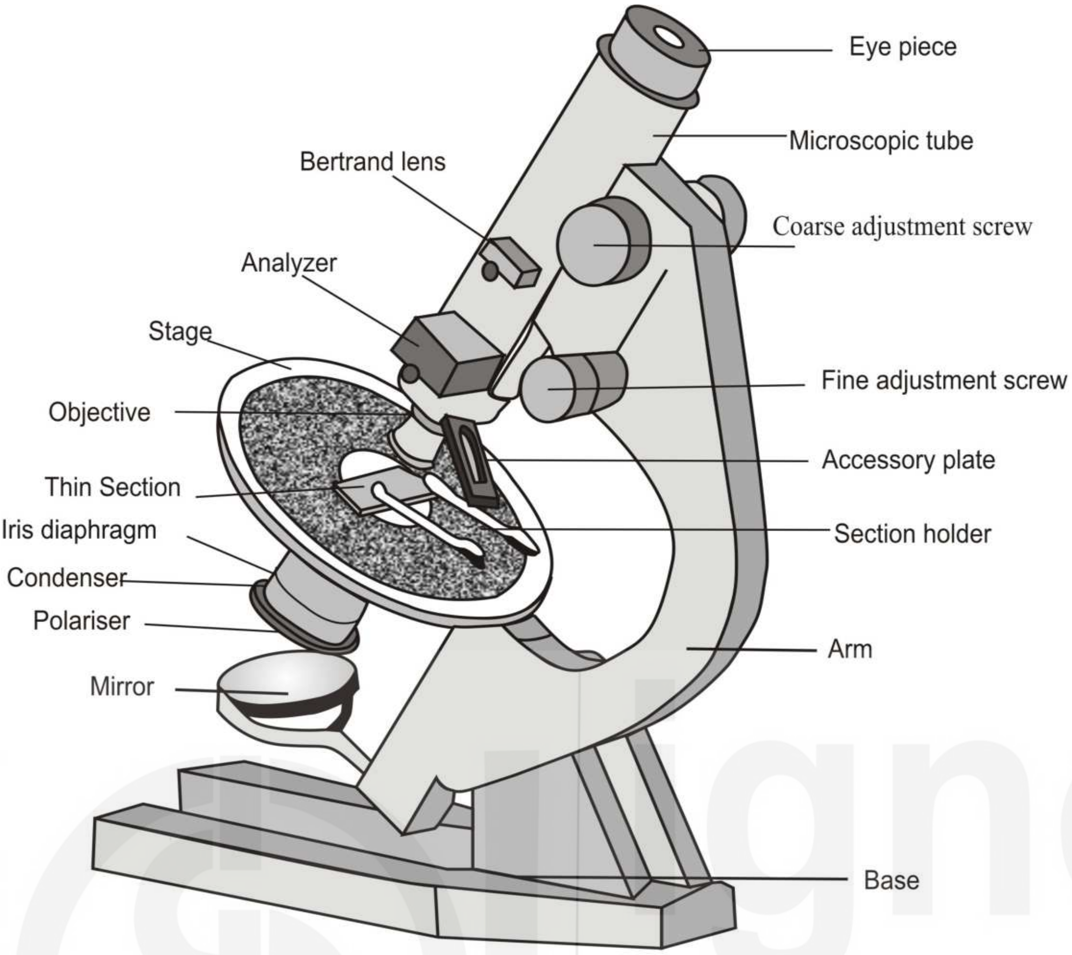
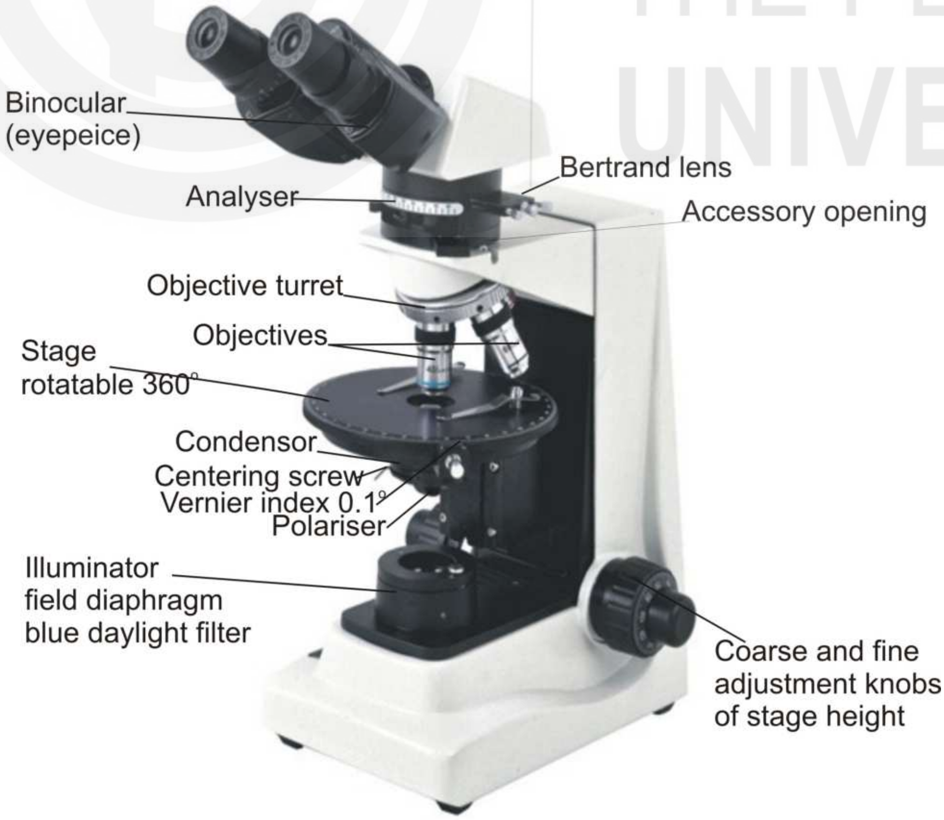


Fig. 8.7: Sketch of monocular (one eye piece) polarising microscope.



(a)

(b)

Fig. 8.8: Photographs of polarising microscope: a) Binocular microscope; and b) Trinocular microscopes, notice the camera attachment.

8.4.1 Parts of Polarising Microscope

Now let us illustrate and get acquainted with the parts and functioning of polarising microscope with the help of Fig. 8.7 and 8.8, which illustrates different parts of polarising microscope.

- **Light source**: The light source can be natural like sunlight; a concave mirror is present near the base of the polarising microscope which reflects the ordinary light upwards (Fig. 8.7). In case of an artificial light, it is an electric device. The lamp is present which is built into the microscope base (Fig. 8.8a and b). The bulb with tungsten filament or halogen bulb is used. It gives yellowish tint to the field view. Therefore, a blue filter is inserted above the light source to change the colour of light to that of daylight.
- **Polariser**: The light consisting of electromagnetic vibrations moves outward in every direction from a point source of white light, such as a microscope bulb or natural sunlight. The initially unpolarised ordinary light becomes polarised after passing through the polariser and vibrates in a single plane. The polariser is usually inserted in the path of light and is present below the graduated rotating stage. The light is polarised on passing through the polariser.
- **Condensing Lens**: It is also called as **condenser** or **convergent lens**. It is a small hemispherical lens attached to a swivel bar. Condenser can be inserted into the optical train when required. It serves to direct a cone of light on the thin section and give optimum resolution for the objectives used. The entire lens system below the microscope stage, including polariser, aperture diaphragm and condenser, can often be racked upwards or downward in order to optimise the quality of illumination. Condenser lens

is used when Bertrand lens is inserted. Both Bertrand lens and condensing lens are used in case of **conoscopic illumination** (Fig. 8.9b and 8.10b).

- **Substage diaphragm(s)**: One or two diaphragms may be located below the stage. They are used to reduce the area of light entering the thin section. They should be in focus at the same position as the thin section. The aperture diaphragm is closed to increase resolution, it can be seen when the Bertrand's lens is inserted.
- **Graduated Rotating Stage**: The graduated rotatable stage lies in between the two Nicols (polariser and analyser). Thin section of the mineral or rock is placed over this stage. The microscopic stage or disc is flat. It is capable of rotation and can be locked at any point. The vernier scale is attached to the stage. The rotation can be accurately measured with the help of vernier scale. It is employed for precise angular measurement. The mineral/rock thin section is attached to the centre of the stage by metal spring clips.
- **Objective lens**: It is placed at lower end of microscope tube / barrel. The function of objective lens is to produce an image which is sharp and clear. The objectives of three power for image magnification are used for mineralogical work: low, medium and high. These objectives are mounted on nose piece and can be successively rotated into position. The important properties of the objectives are magnification, numerical aperture and the degree of aberration correction. The quality of the intermediate image is determined by numerical aperture and the degree of aberration correction. The accessory plates can be inserted in the slot in the microscopic barrel just above the objective lens.
- **Microscope tube / barrel**: This sits above the microscopic stage. The microscope is focused either by moving the microscope stage up or down (newer models) or by moving the upper microscope tube up or down (older models) using focusing screws. Both coarse and fine adjusting knobs are present.
- **Accessory slot**: There is accessory slot below the analyser into which accessory plates, e.g. quartz wedge, or gypsum plate, can be inserted. The slot is oriented so that accessory plates are inserted at 45° to the cross wires.
- **Analyser**: It is the second polariser called analyser mounted within the microscope tube. It can be pushed in and out so that it can be in the light path (inserted position) or out of the light path (analyser out position). The analyser is similar to the polariser; it is also made of polarising film but oriented in a North-South direction, i.e. at right angles to the polariser. When the analyser is inserted into the optical train, it receives light vibrating in an East-West direction from the polariser and cannot transmit it; thus, the field of view is dark and the microscope is said to have crossed polars (CP or XP). With the analyser out, the polariser only is in position; plane polarised light is being used and the field of view appears bright.
- **Ocular/Eye piece**: It is placed at upper end of microscope tube. The eye piece merely enlarges the image including any imperfection resulting from poor quality objective. Ocular (or eyepiece) contains microscope cross wires which can be independently focused by rotating its uppermost lens.

Eyepieces of different magnification are available. Monocular heads are standard on student microscopes whereas Binocular heads are used in advanced microscopes.

- **Bertrand lens**: It is used for studying minerals in convergent light. It is inserted into the upper microscope tube. This lens is used to produce and examine interference figures which fills the field of view, provided that the convergent lens (condenser) is also inserted into the optical path train. If the microscope does not possess a Bertrand Lens the entire eye piece should be removed to examine the interference figures.

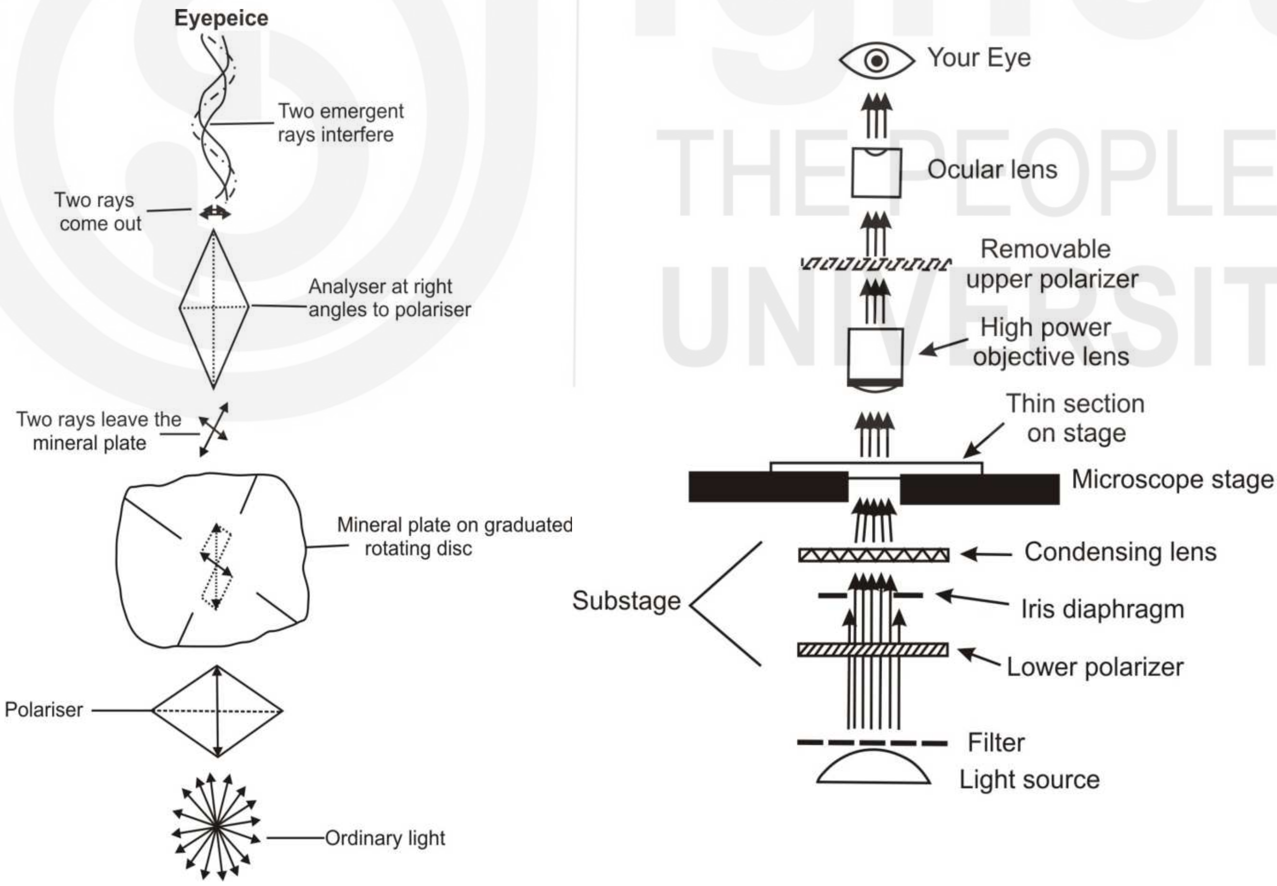
- **Optical Accessories**:

a) Quartz wedge is used for the determination of interference colour, optical sign and the nature of vibration-direction of the mineral.

b) Mica plate is also known as quarter-wave plate. It which gives a pale neutral gray interference colour, when it is put into the slot of the tube. It is used for determining the optical sign of a mineral.

c) Gypsum plate also known as sensitive-tint plate because it produces sensitive violet red interference colour of first order. It is used for determining the optical sign of a mineral.

d) Bereck compensator is an optical device made of calcite mineral.



(a) (b)

Fig. 8.9: Diagram showing optical path of polarising microscope: a) Orthoscopic illumination; and b) Conoscopic illumination.

8.4.2 Functioning of Polarising Microscope

We have discussed about the parts of a polarising microscope in the above section, now let us learn about the functioning of the polarising microscope.

The light source is placed below the stage of the microscope. The light is initially unpolarised. We have learnt in the previous section that the light entering the polariser is resolved into two vibration directions which are at right angles to one another. The light first passes through the lower polariser called the polariser. It becomes polarised such that it is vibrating from the users right to left. When the light leaves the polariser it starts vibrating parallel to the short diagonal of the Nicol prism. These directions are referred to as East (right) and West (left). They are parallel to the vibration direction of the mineral. This is called **Plane Polarised Light** or abbreviated as **PPL**. We have discussed earlier that the rays leaving the mineral plate are broken into two vibrations. One ray is parallel to long diagonal which is reflected out. Another one is parallel to short diagonal of the analyser and reaches to the eyepiece.
The light passing through a hole in the rotatable stage of the microscope enters the lower lens, called the objective lens (Fig. 8.9a and 8.10a).

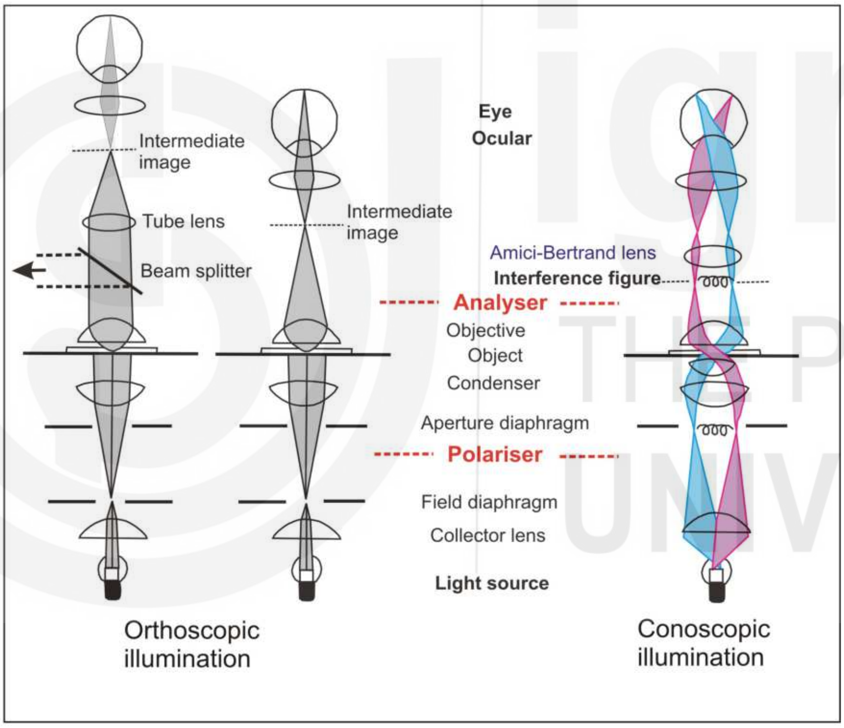
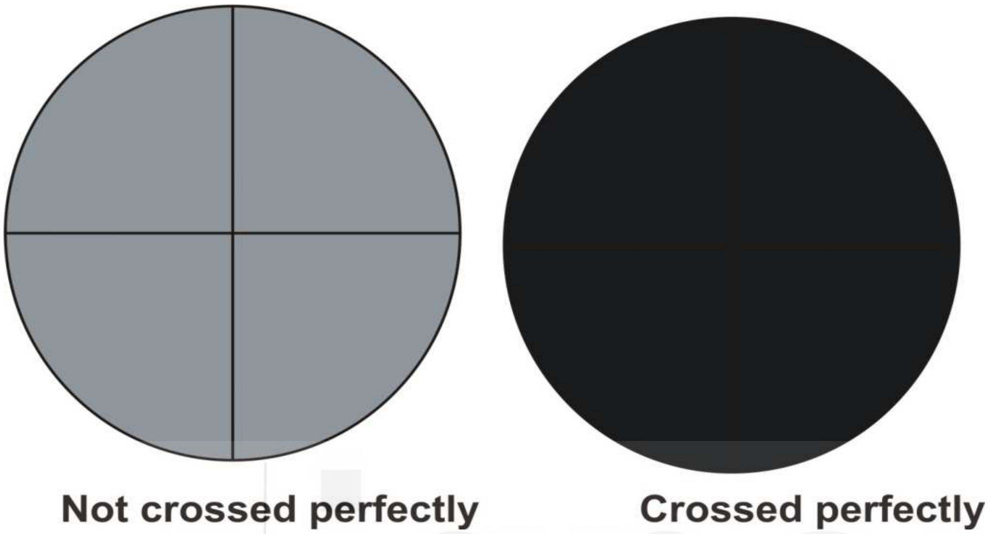


Fig. 8.10: Diagram showing: a) Orthoscopic; and b) Conoscopic illumination in polarising microscope.

If the analyser is out that means it is not in the light path, then the polarised light will be transmitted through the ocular lens. If the analyser is in, then the plane polarised light coming from the lower polariser will be blocked, hence no light will be transmitted though the ocular lens above. However, the analyser is similar to polariser but is oriented at right angle to polariser. It has a polarisation direction exactly perpendicular to that of the lower polariser. These directions are usually referred to as North-South. When the analyser is inserted, without a mineral specimen then the field of view becomes dark. The analyser receives light vibrating in an East-West direction from the polariser but because of orientation cannot transmit it, as it is absorbed. The above arrangement of analyser to polariser is referred as **Crossed Polars** and is abbreviated as **XP**.

The important requirement for microscopic studies is that the vibration directions of these two nicols should be properly crossed, i.e. should be exactly at 90°. If the nicols are properly crossed the field of view should be perfectly dark. If not, rotate the polariser gently with one hand till a maximum position of darkness is achieved (Fig. 8.11).



(a) (b)

Fig. 8.11: Sketch showing: a) incorrectly; and b) correctly crossed Nicol.

We will further discuss in unit 9 the optical properties in minerals studied both under plane polarised light (PPL) and between cross nicols (XP).

The polarising microscope may be assembled either for orthoscopic or conoscopic illumination (Fig. 8.9b and 8.10b). The **orthoscopic illumination** provides the eye with a realistic virtual image with a flat field showing object on the microscopic stage. It is carried using single polarising device or with cross polars. Orthoscopic illumination uses weakly converging light and allows the mineral sample to be examined with the upper polariser filter either in the cross polar condition or under plane polarised light. These observations in the **conoscopic illumination** or **convergent light** are carried using arrangement such as Bertrand lens and the condensing lens (Fig. 8.9b and 8.10b). Conoscopic illumination uses strongly converging light to produce optical phenomenon called interference figures which are observed at the upper focal plane of the objective lens. The interference figure allows determination of optical class, optic sign, dispersion characteristics, 2V angle and indicatrix orientation. Thus in orthoscopic illumination we make observations under plane polarised light or cross nicols whereas in case of conoscopic illumination Bertrand lens and condenser are inserted in the optical path.

We hope that now you are now familiar with the working of the polarising microscope. It is possible to study the minerals and rocks with the help of polarising microscope in details and identify them in orthoscopic and conoscopic illumination.

In the previous sections we have studied about the parts and functioning of polarising microscope. Before going to the next section spend 5 minutes to check how you are progressing.

SAQ 2

a) How is analyser different from polariser?

b) PPL is the abbreviation used for _______ _______ _____.

c) What is conoscopic illumination?

d) What is the function of substage diaphragm?

8.7 SUMMARY

In this unit, we have discussed about the parts, principle and functioning of Polarising microscope. Let us now summarise:

- The objective of optical mineralogy is microscopic study of the minerals with the help of polarising microscope. Thin sections of the minerals or rocks are prepared by grinding a chip of minerals and rocks till it thins down to a thickness of about 0.03 mm.
- Double refraction is shown by all anisotropic minerals, other than cubic system. This property is shown by colourless transparent variety of calcite called iceland spar.
- Nicol prism is constructed using iceland spar. This is an important device used in the polarising microscope. It functions on the principle/property of double refraction of calcite mineral.
- Ordinary and extraordinary rays travel with different velocities. In polarising microscope the ordinary light passes through polariser and mineral plate placed on the stage. Two rays leave the mineral plate. Analyser is at right angle to the lower polariser. Two rays come out and these two emergent rays interfere as they differ in phase.

8.8 ACTIVITY

Take a crystal of iceland spar and put it on a dot on a paper. Rotate the crystal and observe two images of the dot. It is because of double refraction as explained in Section 8.3.2.

8.9 TERMINAL QUESTIONS

1. Discuss the various parts of polarising microscope.
2. Describe the functioning of polarising microscope.
3. Discuss about the phenomenon of double refraction and the principle used in the construction of nicol prism.
4. What is difference between isotropic and anisotropic substances?

8.10 REFERENCES

- Dana, J.D. and Ford, W.E. (1962), A Text book of Mineralogy, Asia Publishing House, New Delhi.

- Gribble, C.D. (1991) Rutley's Elements of Mineralogy, 27th Edition. CBS Publishers and Distributors, Delhi.
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8.11 FURTHER /SUGGESTED READINGS

- Dana, J.D. and Ford, W.E. (1962) A Text book of Mineralogy, Asia Publishing House, New Delhi.
- Gribble, C.D. (1991) Rutley's Elements of Mineralogy, 27th Edition. CBS Publishers and Distributors, Delhi.
- Mahapatra, G.B. (2012, Reprinted) A Textbook of Geology, CBS Publishers, Delhi
- Singh, P. (2013) Engineering and General Geology, S.K. Kataria & Sons, Delhi.

8.12 ANSWERS

Self Assessment Questions

1 a) In plane polarised light, the vibrations take place in all directions.

b) Double refraction is the splitting of the beam of ordinary light into two beams which traverse the crystals at different speeds- Ordinary (O-ray) and extraordinary (E-ray) rays. Ordinary ray consists of light vibrating parallel to long diagonal of the rhomb face and the extraordinary ray of light vibrates parallel to short diagonal of the rhomb (calcite var. Iceland spar), which is generally used to produce polarised light.

c) Iceland spar.

d) Nicol is an important device and used in the polarising microscope. It functions on the phenomenon double refraction of mineral calcite.

e) Isotropic substance transmits light with equal velocity in all the directions as all the three axes are equal and interchangeable

2. a) In both of these nicol prisms are used. The difference is of position, one is at right angle to another. Nicol below the disc or microscopic stage is called polariser and that in the microscopic tube as analyser. While studying the optical properties under plane polarised light only polariser is used whereas for cross nicol position both analyser and polariser are used.

b) Plane polarised light.

c) In the conoscopic illumination in the assembly of microscope the Bertrand lens is not inserted.

d) Substage diaphragm is located below the stage. Its function is to reduce the area of light entering the thin section.

Terminal Questions

1. Please refer subsection 8.4.1.
2. Please refer subsection 8.4.2.
3. Please refer subsection 8.3.4.
4. Please refer subsection 8.3.5.

UNIT 9

OPTICAL PROPERTIES OF MINERALS

Structure

9.1 INTRODUCTION

We have learnt the identification of physical properties of minerals in hand specimen in Unit 4 Minerals. Now in this unit we will study the optical properties used in the identification of minerals under the polarising microscope. We have already discussed about the parts and functioning of polarising microscope in the previous unit. The optical properties of the minerals are immensely helpful in mineral identification. The microscopic or optical study of minerals and rocks in transmitted and polarised light to this day remains one of the classic and indispensable method for identification of mineralogy. Polarised light microscopy is a nondestructive way of identification of mineral phases wherein they can be studied within their textural framework. It allows an estimate of chemical compositions and provides clues to the history of formation of the mineral and rock, using specific textural characteristics such as structure, fabric, mineral assemblage textures.

Now let us discuss the optical properties of minerals that you would study under ordinary light, plane polarised light and between the cross nicols.

Expected Learning Outcomes

After reading this unit you should be able to:

- ❖ discuss the optical properties of minerals under ordinary light;
- ❖ explain the optical properties of minerals under polarised light; and
- ❖ identify the optical properties of minerals between cross nicols.

9.2 STUDY OF OPTICAL PROPERTIES OF MINERALS

We have discussed petrological microscope and its working in previous unit. The common practice is to use a lower power objective, i.e. 2.5 x or 5 x depending upon the microscope you are using. This gives a wider view and better illumination. Higher magnification objectives say 10 x or 40 x could be used later. The polarising microscope you use has the provision either to include or exclude the use of analyser. In that case you can study the optical properties of minerals in two positions, namely:

- Properties under plane polarised Light (analyser in and polariser out)
- Properties between crossed nicols (both analyser in and polariser in)

But if we assume you have the provision of including or excluding the use of polariser and analyser then you can carry three types of optical studies. In that case properties of the minerals in thin sections can be examined by you in the following three positions:

- Properties under ordinary light (polariser and analyser out)
- Properties under Plane polarised light (analyser in and polariser out)
- Properties between Crossed Nicol(both polariser and analyser in)

If the polariser is not removable from the optical system of the microscope, the properties under ordinary light are to be studied under plane polarised light only.

Let us list optical properties of minerals studied under ordinary light, plane polarised light and between cross nicol (Table 9.1).

9.3 OPTICAL PROPERTIES UNDER ORDINARY LIGHT

Now let us now describe the optical properties of minerals observed under ordinary light. We have discussed that while observing the optical properties under ordinary light polariser and analyser are excluded from the optical system of the microscope. Again you are reminded that if you do not have the facility or provision of excluding polariser from that optical assembly of the microscope, in that case the properties discussed under ordinary light are studied under Plane polarised light. Let us elaborate on the optical properties studied and observations made under the ordinary light.

Table 9.1: Optical properties of minerals under plane ordinary light, polarised light and between cross nicol.

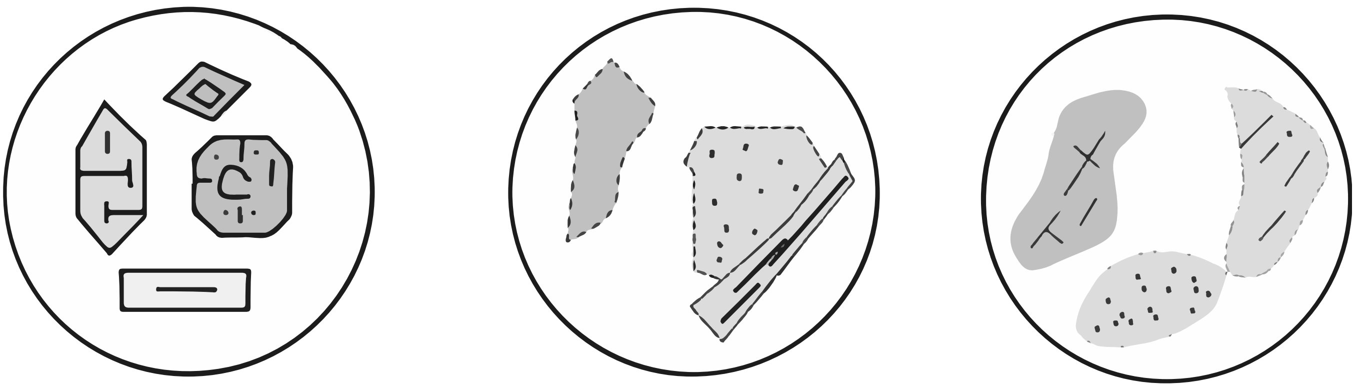
Ordinary Light (both polariser and analyser out)	Plane Polarised Light (PPL)-analyser out	Between Cross Nicol (XP)-analyser in
Form/Habit	Pleochroism	Isotropism/Anisotropism
Colour	Pleochroic haloes	Polarisation/Interference colours
Transparency	Twinkling	Extinction and extinction angle
Refractive Index (R.I.)		Twinning
Relief		Zoning
Cleavage		Alteration
Inclusion and Alteration		

9.3.1 Form

The form is related to crystalline nature of the mineral and it can be regular or irregular. We shall consider two aspects in this study:

A) **Shape**: We can observe the fundamental shapes of the minerals under the microscope. They may be following types:

- **Euhedral**: Complete outline or boundary of the mineral grain can be seen like hexagonal, rectangular, etc (Fig. 9.1a).
- **Subhedral**: Only the partial outline or boundary of the mineral grain is observed (Fig. 9.1b).
- **Anhedral**: The minerals grains are irregular in shape and the grain boundaries are not visible (Fig. 9.1c).



(a) (b) (c)

Fig. 9.1: Shapes of mineral grains: a) Euhedral; b) Subhedral; and c) Anhedral.

B) **Habit**: It reflects natural state of growth of the minerals. You have read the term 'habit' in Unit 4 Minerals of this course. It is very useful in recognition of those minerals that are characteristically well developed, such as garnet, zircon and sphene. Many minerals like hornblende usually exhibit a distinctive prismatic habit. Tabular habit is characteristic of feldspars. Mica is flaky in nature. Fig. 9.2 exhibits the habits of the above mentioned minerals as viewed under the microscope.

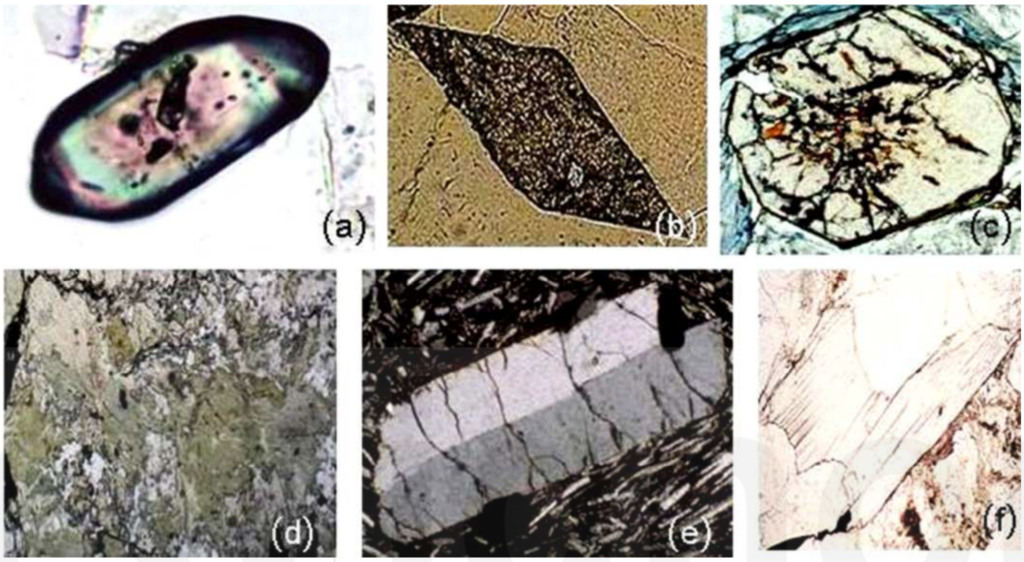
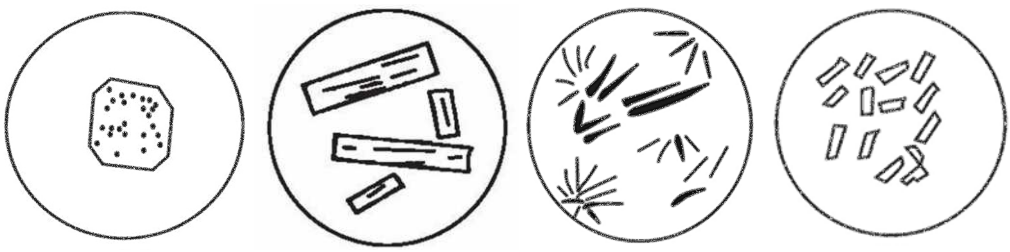


Fig. 9.2: Common minerals habits as viewed under the microscope: a) Zircon; b) Sphene; c) Garnet; d) Hornblende; e) Feldspar; and f) Muscovite.

Let us now list the commonly recognised habits:

- **Equant**: The length and width of a mineral are nearly equal (Fig. 9.3a).
- **Prismatic or columnar**: The length is more than the width of the mineral (Fig. 9.3b).
- **Acicular**: They exhibit needle shaped crystals which may be radiating or otherwise (Fig. 9.3c).
- **Lath shaped**: They are prismatic but are very small (Fig. 9.3d).



(a) (b) (c) (d)

Fig. 9.3: Common minerals habits: a) Equant; b) Prismatic; c) Acicular; and d) Lath shaped.

9.3.2 Colour

Colour is related to the wavelength of visible light. White light consists of all the wavelengths between these two extremes, i.e from violet (wavelength λ = 0.00039 mm or 390 nm) to red (λ = 760 nm). Minerals exhibit a wide range of colour (i.e. the natural or body colour of a mineral), ranging from colorless minerals to colored minerals (e.g. brown biotite and green hornblende). Minerals like quartz and calcite show different colours in hand specimen but in thin section at thickness of 0.30mm, they appear colourless. Minerals like biotite and hornblende display their typical diagnostic colours even at this thickness. Biotite will exhibit shades of yellow/brown while hornblende appears in shades of green and blue. However you cannot identify the minerals only with the help of colour in ordinary or plane polarised light. In order to confirm its identification other supporting optical properties are required. We will study about this in the following sections. Coloured minerals generally show different shades of colour depending on their orientation. You will find listed in Table 9.2 few commonly coloured minerals.

In the thin section mineral can appear as opaque or non-opaque.

- **Non-opaque minerals**: If a mineral is transparent or translucent first its colour is determined. Most of the minerals acquire **transparency** at 0.03 mm. The coloured minerals in thin section are much less diverse than those in hand specimen. Many minerals that appear pink, green, yellow, blue or even black may be completely colourless or nearly so in normal thin section. Some minerals that appear colourless are quartz, feldspar, etc. More strongly coloured minerals are hornblende, biotite, etc.
- **Opaque minerals**: Mostly metallic minerals are opaque like hematite (Fe_2O_3), magnetite (Fe_3O_4), pyrite (FeS_2). They have sharp boundaries and appear black or brownish black under PPL.

Table 9.2: Commonly coloured minerals. (Source: Alexander, 2009)

Colour in Thin Section	Minerals
Pale yellow/brown	Biotite
Pink	Hypersthene,few garnet, andalusite
Green	Hornblende, actinolite, chlorite, hypersthene, tourmaline, aegerine
Strong yellow	Staurolite
Pale brown	Augite, hornblende
Blue/Brown	Tourmaline

9.3.3 Relief

The thin sections of mineral/rocks are trapped between two thin layers of resin or cementing material to which the glass slide and the cover slip are attached. The surface relief of a mineral is basically constant except for carbonate minerals. This depends on the difference between the Refractive Index (RI) of the mineral and the RI of the enclosing resin. If the difference between the RI of the mineral and the resin is greater then the surface of mineral will appear rougher. The surfaces of the mineral in thin section are made up of tiny elevations and depressions, which reflect and refract the light. If the RI's of the mineral and resin are similar the surface appears smooth. Certain minerals stand out more sharply as compared to others when observed in the thin section. **Relief** is the distinctness with which a mineral stands out from the embedding medium when observed in plane polarised light under the microscope. Relief is the degree of visibility of the mounted mineral specimen. Most commonly Canada balsam, with refractive index of 1.54, is used as the mounting medium. If any mineral has a RI exactly similar to Canada Balsam, for example halite (RI-1.54); it is visible as it is totally lost or camouflaged by Canada balsam. Relief is dependent on the difference between the Refractive Index (RI) of the mineral and the medium on which it is mounted. It is linked to the refractive index of the mineral (speed at which light passes through) relative to the speed it passes through the mounting medium used to prepare the thin section. The term **negative relief** is used when the refractive index of the mineral is lower than the mounting medium. Conversely it is **positive relief** when the mineral has higher refractive index than the mounting medium. Greater the difference in refractive index between the mineral and mounting medium, higher is relief. Relief may be categorised as (Fig. 9.4):

- **Poor relief**: Minerals with similar R.I. to Canada balsam show indistinct borders which tend to merge with the mounting medium, e.g. quartz, feldspars (Fig. 9.4a);
- **Negative relief**: Mineral with lower R.I. to Canada balsam show poor outline, e.g. leucite, augite (Fig. 9.4a);
- **Positive, high** or **strong relief**: Mineral with higher R.I. than Canada balsam will have well marked borders and the cleavage cracks, e.g. garnet,zircon (Fig. 9.4a and b).

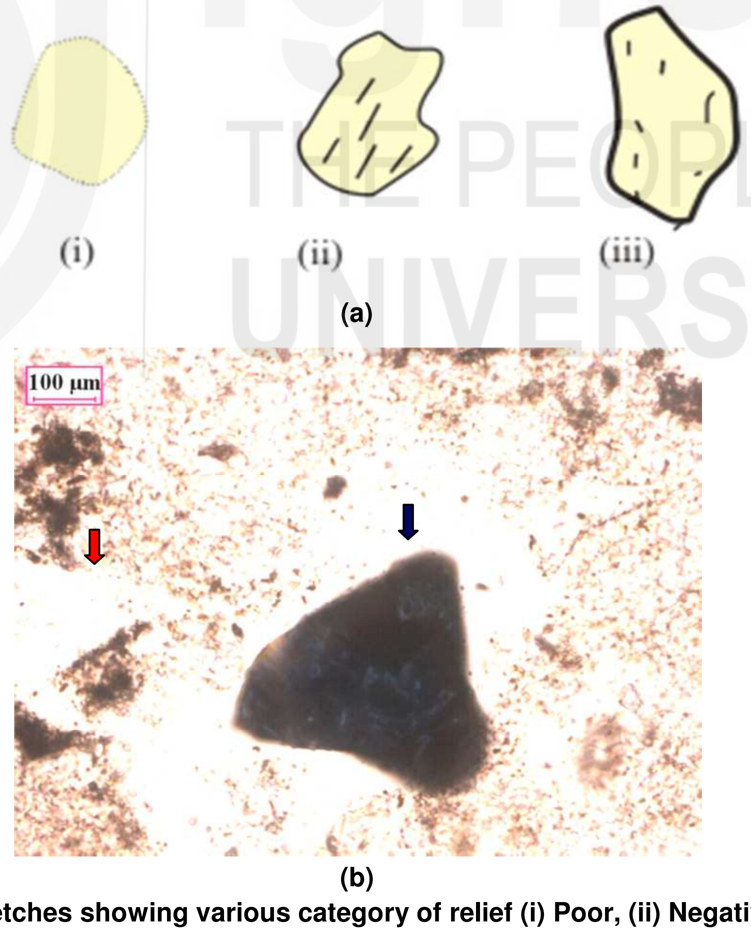


Fig. 9.4: a) Sketches showing various category of relief (i) Poor, (ii) Negative, and (iii) Positive; and b) Mineral quartz (red arrow) and zircon (black arrow) showing low and very high relief, respectively under plane polarised light. (Photo credit: Dr. Meenal Mishra)

9.3.3 Refractive Index

When rays of light travel from a source through a medium of higher RI into a medium of lower RI medium, they are partly reflected back into the higher RI medium. We have learnt that relief depends on the refractive index of the mineral and the medium in which it is embedded. Now we shall discuss the determination of refractive index (n) using petrological microscope. If the mineral has more refractive index than Canada balsam it will appear to be raised up. It will indicate that the mineral has positive relief and higher refractive index. On the other hand, if the mineral appears to be depressed it is said to have negative relief and lower refractive index than the embedded medium, i.e. Canada balsam. The descriptive scheme for the relief of minerals with reference to their refractive indices is given in Table 9.3. The relative refractive indices of two minerals or one mineral and the mounting medium can be observed by studying the Becke's effect. The Becke's Line method also known as Central illumination method is commonly employed for determination of refractive index of a mineral. This can be performed with the help of petrological microscope easily by using high power objective field of microscope should not too illuminated. You could do this by cutting down the unnecessary light by partially closing down the iris diaphragm located below the stage so that only the desired field of view is brightly seen.

Table 9.3: Descriptive scheme for relief of minerals with reference to their refractive indices.

Refractive Index (RI)	Description of relief
1.40 – 1.50	Very low
1.50 – 1.58	Low
1.58 – 1.67	Moderate
1.67 – 1.76	High
> 1.76	Very high

Becke's test: This technique allows you to judge the value of the refractive index of the mineral with respect to that of the oil. The mounting material may be Canada balsam (RI=1.54) or epoxy (RI=1.51). Care must be taken to make sure that the objective movements should be very small otherwise the image will become defocused completely and no useful purpose would then be served in such case. The principle involved is the total reflection of light incident at more than the critical angle when passing from a mineral of greater RI to that of lesser index in thin section. Please refer to Fig. 9.5 and follow the following steps to perform Becke's test.

- The edge of the mineral in contact with the mounted medium, is sharply focused after reducing the illuminated area (iris diaphragm has to be partially closed).
- A sharp line visible just inside the boundary of the mineral is known as **Becke's line**. It is a bright narrow band which appears at the mineral-liquid interface and moves towards the material with the higher RI.
- Focusing tube is raised by increasing the distance between mineral and the objective and movement of bright Becke's line is carefully observed.

- If Becke line moves towards the mineral body, the mineral has more refractive index which means that it has positive relief, i.e. **($n_{mineral}$>n_{liquid})** (Fig. 9.5a).
- Now focusing tube is lowered by decreasing the distance between mineral and the objective and movement of bright Becke's line is carefully observed.
- If it moves away from the margin towards outside, the mineral has less refractive index than the mounting medium (Fig. 9.5b). It will indicate that the mineral is negative in relief **($n_{mineral}$<n_{liquid})**.

In general as a rule when objective is raised Becke line moves towards higher refractive index.

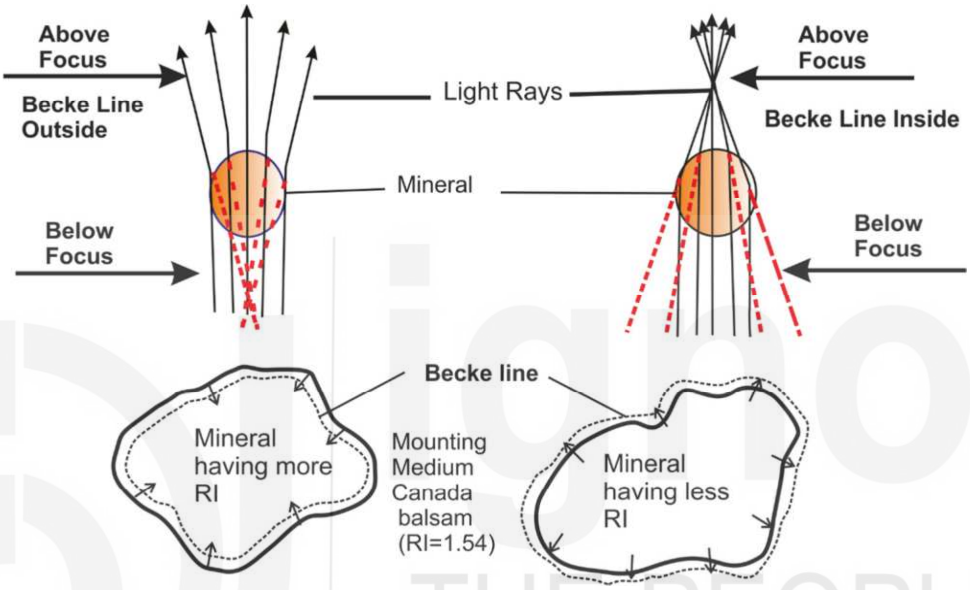


Fig. 9.5: Formation of Becke's line. Becke's test performed to determine a) Positive relief ($n_{mineral}$>n_{liquid}); and b) Negative relief ($n_{mineral}$<n_{liquid}).

9.3.4 Cleavage

You have read the definition of cleavage in Unit 4 of this course while discussing about the physical properties of minerals.

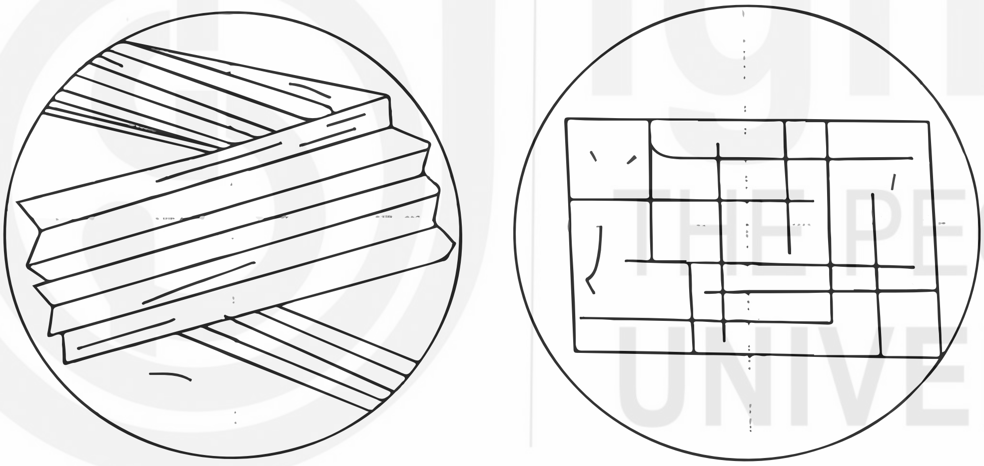
Let us recapitulate what we had learnt? **Cleavage** is an ability of the mineral to crack or break along well-defined crystallographic planes within the lattice structure. It is quite clear in hand specimens but it becomes even more revealing in thin sections. Cleavage appears as parallel straight lines. Under the microscope the cleavages appear as parallel lines in the mineral grain, which may be distinct faint or absent. Cleavage is not haphazard but has definite crystallographic orientation. If you look at the thin section of olivine you will find cracks. On examining thin section of mica or hornblende you will find perfect one set or two set cleavage. Now try to differentiate between the two. If there are more than one set of cleavages then the angle between the cleavages is measured to identify the minerals. The set of visible cleavage depends on the direction in which section is cut. Prismatic sections of hornblende, augite will show only one direction of cleavage, whereas in their basal section shows 2 sets are discernible. Minerals belonging to pyroxenes and amphibole groups have one directional cleavage in sections, cut parallel to 'C' axis while excellent two directional cleavages in basal sections. In pyroxenes the angle between two sets of cleavages is nearly 90^{o} while amphiboles it is 120^{o}.

Let us illustrate the method to find out the cleavage angle? Keep one set of cleavage parallel to the cross wire and reading ‘a’ is taken on the scale of the microscopic stage. Now rotate the stage till the second set of cleavage becomes parallel to the same cross wire. In this position reading ‘b’ is taken. The difference between these two readings is the **cleavage angle**.

Some of the important minerals and the cleavage sets exhibited by the minerals include:

- One set: Muscovite, biotite (Fig. 9.6a), etc.
- Two sets: Found in minerals like hornblende (at an angle of 56^o and 124^o) and orthoclase has cleavage angle of 90^0 (Fig. 9.6b), augite has 2 set of cleavage intersecting at 87^o and 93°, etc.
- Three sets: Calcite shows 3 set perfect rhombohedral cleavage.
- Absent: Cleavage is absent in minerals like quartz and olivine.

Minerals may have even four directional cleavages in an octahedral pattern, e.g. fluorite or six (sphalerite) sets of cleavages. However, the number of sets visible under the microscope depends on the orientation of the section. Minerals like olivine, nepheline, garnet and leucite are examples with imperfect or poor cleavage developments.



(a) (b)

Fig. 9.6: Cleavage as visible under microscope: a) One set of cleavage in muscovite or biotite; and b) Two sets of cleavages at 90^0 in orthoclase, plagioclase or microcline.

9.3.5 Inclusion and Alteration

You should mention in the optical properties about the inclusions, if seen. Olivine has numerous inclusions of opaque iron oxides. You will also find several tiny inclusions of quartz, mica and zircon.

Alteration of minerals in thin section usually gives turbid or cloudy areas within the mineral. The most common cause of alteration is by water or carbon dioxide coming into contact with a mineral. They chemically react with some of its elements, and produce a new mineral phase(s). For example, water reacts with the feldspars and produces clay minerals which give cloudy appearance to the colourless feldspar grain in PPL. The alteration may be so advanced that the mineral is completely replaced by a new mineral. Quartz appears clear as it does not readily undergo alteration. Olivine crystals show severe effects of alteration and a secondary mineral called serpentine originates (Fig. 9.7).

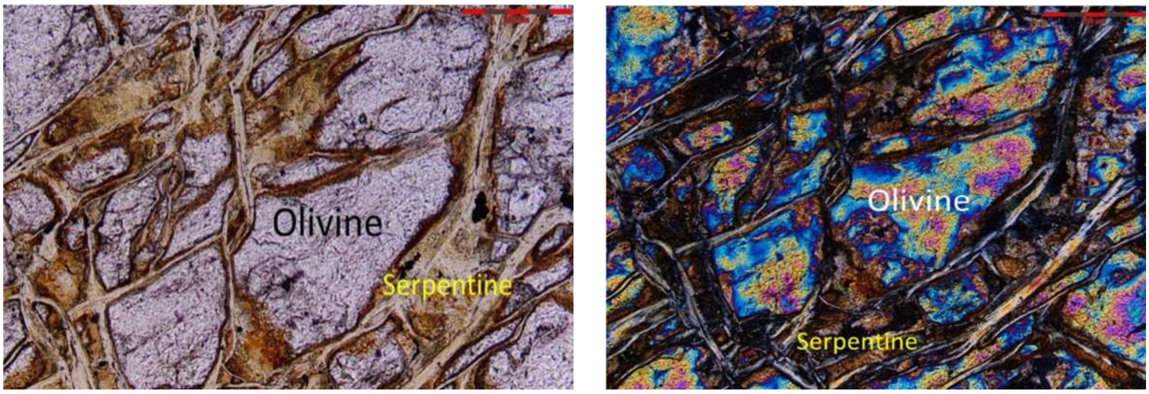
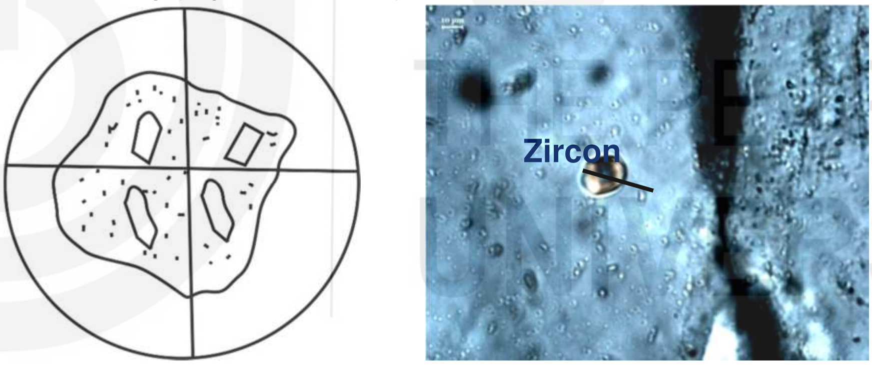


Fig. 9.7: Replacement seen in olivine mineral along the cracks by secondary mineral, serpentine (brown in colour and fibrous form) in PPL: left panel; and Crossed polars: right panel. (Photo credit: Dr. Amit Kumar)

Following three types of inclusions are commonly seen in the minerals (Fig. 9.8 to 9.10).

- **Regular**: These inclusions are of well defined crystals (Fig. 9.8a and b).
- **Irregular**: These are generally of fluid inclusions and are irregularly distributed (Fig. 9.9).
- **Acicular**: These inclusions are needle shaped which may be simple or radiating (Fig. 9.10a and b).



(a) (b)

Fig. 9.8: a) Sketch showing regular inclusion; and b) Microphotograph of zircon (zoned colourful mineral) as inclusion in quartz. Notice regular fluid inclusions distributed in quartz crystal. (Photo credit: Dr. Meenal Mishra)

Fig. 9.9: Irregular inclusions.

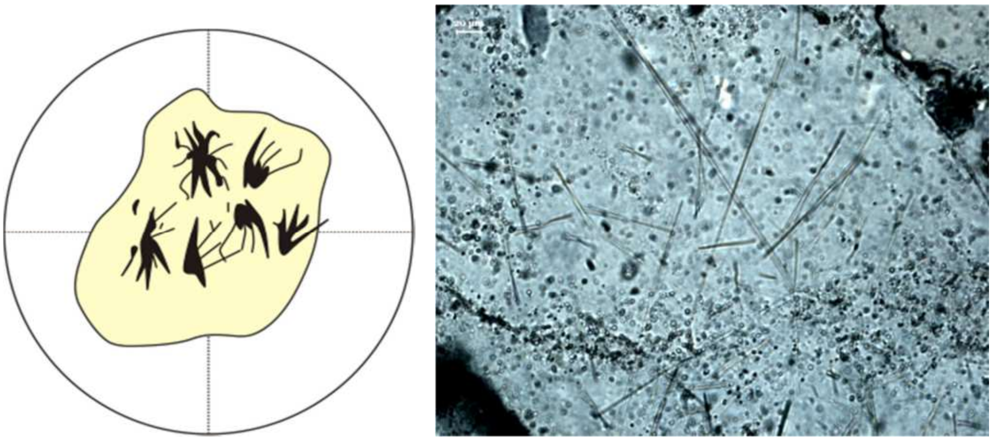


Fig. 9.10: Acicular inclusions: a) Sketch; and b) Photomicrograph of needle like inclusions and regular fluid inclusions in quartz. (Photo credit: Dr. Meenal Mishra)

9.4 OPTICAL PROPERTIES UNDER PLANE POLARISED LIGHT

It is important to note that the above optical properties can be studied in ordinary light as well as plane polarised light (in case the analyser is not removable) but for the properties described below can only be observed in polarised light only. **Thus theoritical properties under plane polarised lightform/habit, colour, transparency, relief, refractive index (R.I.), cleavage, inclusion and alteration, apart from pleochroism and pleochroic halos** about which we have already discussed in detail in the above section.

Thus optical properties studied under plane polarised light are listed below:

- Form/habit
- Colour and Transparency
- Relief
- Refractive Index (R.I.)
- Cleavage
- Inclusion and alteration
- Pleochrism and pleochroic haloes
- Twinkling

9.4.1 Pleochroism

Pleochroism is one of the most characteristic and significant property of anisotropic minerals. The word ‘Pleo’ means many and ‘chroism’ refers to colours. This means that this phenomenon has to do with more than one colour. You should remember that colourless mineral do not show pleochroism. In some minerals the change in quality and quantity of colour is observed on rotation of the microscopic stage. The change in colour (light to dark) results from the absorption of certain colours (wavelength) from the incident white light. You can define **pleochroism** as the variation in colour resulting from differential absorption of wavelength in different directions. It is exhibited by coloured minerals when the stage is rotated in the plane polarised light. The change can be both in intensity and shade. When the change is only in two shades the phenomenon is called **dichroism**. The minerals of the tetragonal, trigonal and hexagonal systems (uniaxial minerals) exhibit dichroism. The uniaxial minerals contain only two polarised light components in mutually perpendicular directions. The minerals belonging to orthorhombic, monoclinic and triclinic systems, i.e. biaxial category exhibit more than two changes in their absorption of colours. Pleochroism is exhibited by some of the coloured anisotropic minerals, e.g. biotite shows light yellowish brown to greenish and dark brown (Fig.9.11a) and hornblende exhibits light green to dark green (Fig.9.11b).

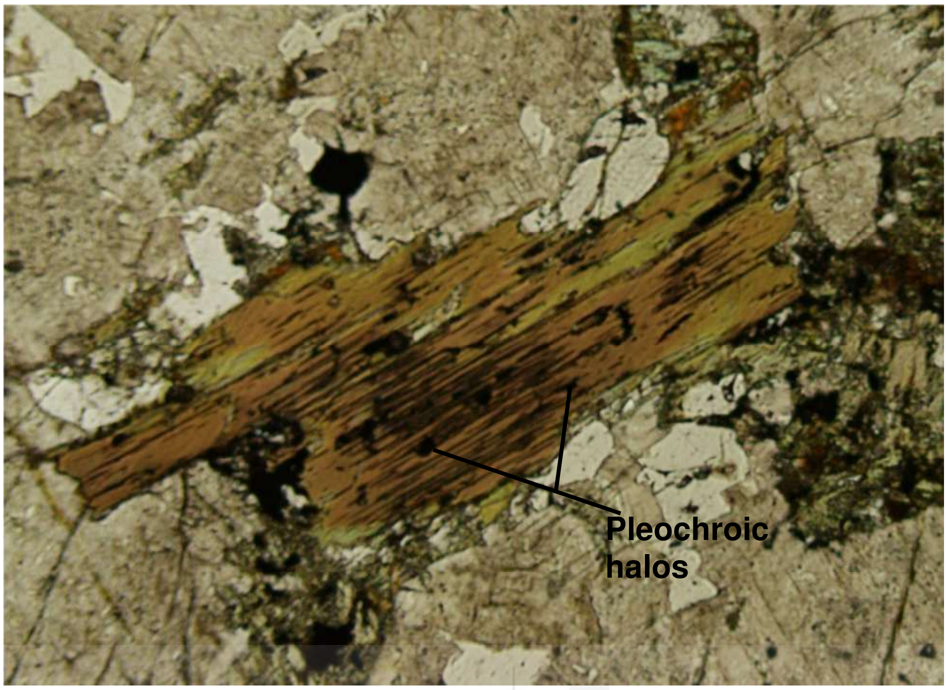
Biotite is the best example of pleochroic (dichroic) mineral. Its section cut perpendicular to cleavage change from straw yellow to dark brown. The extremes of colours are observable at an interval of 90^o. Dark brown colour is achieved when cleavage is parallel to E-W cross wires, i.e. vibration direction to the polariser. It is pale yellow when the cleavage coincides with N-S cross wires. This has two-fold variations with respect to the ordinary ray and extraordinary ray in **dichroic mineral** is known as **pleochroic scheme**.

Minerals belonging to orthorhombic, monoclinic and triclinic systems, i.e. biaxial category exhibit three main possible vibration directions (X, Y and Z). Hypersthene and hornblende present best example. Pleochroic scheme of hornblende is pale green, dark green and brown whereas for hypersthene it is pink, yellow and light green. You can observe these changes in a single mineral grain but in mineral thin section this difference in three shades is clearly noticed in a number of different crystals. You will note that not all the doubly refracting minerals are pleochroic or so distinct as biotite and hornblende. However you can study the minerals in two groups:

- **Pleochroic**: It can be divided into two groups:
  1. **Strongly pleochroic**: Biotite, hornblende, tourmaline, hornblende, aegerine augite, staurolite
  2. **Faintly pleochroic**: Few augite, andalusite
- **Non-Pleochroic**: Quartz, feldspars (orthoclase, microcline, plagioclase), feldspathoids, olivine, apatite.

You should remember that both uniaxial and biaxial minerals when cut perpendicular to their optic axis/ axes will not show any pleochoism as along the optic axis they will not be doubly refracting.

Pleochroic haloes are circular little areas,characteristically present in few minerals, that tend to be strongly pleochroic. Biotite, tourmaline, hornblende, chlorite, muscovite, cordierite and fluorite often contain pleochroic haloes. They result due to the presence of radioactive inclusions in these minerals. These inclusions are the product of radioactive disintegration resulting in alpha particles. Generally, these inclusions are zircon, apatite or sphene.



(a)

(b)

Fig. 9.11: Minerals showing strong pleochroism: a) Biotite exhibiting pleochroism-dark brown to green colour. Notice the pleochroic haloes in biotite; and b) Hornblende mineral shows pleochroism-light green to dark green colour. (Photo credit: Mageswarii Gayu)

9.4.2 Twinkling

We can observe twinkling in anisotropic minerals with widely varying refractive indices (in contrast to R.I. of Canada balsam) on rapidly rotating stage under plane polarised light, e.g. calcite and dolomite. The twinkling effect is caused by rapid change in relief of minerals. Let us discuss an example of calcite. The refractive index of ordinary ray in calcite mineral is 1.66 and for extraordinary ray is 1.49. Refractive index of Canada balsam is 1.54. Thus, in one case relief will be positive and in another case it will be negative. Calcite is doubly refracting; it possesses two vibration directions for transmitted light. When the stage is rapidly rotated the mineral shows, in one position, a rough surface, well defined borders and conspicuous cleavages while in other position, a smooth surface, faintly defined borders and in conspicuous cleavages are visible. In these two extreme situations the contrasting relief are exhibited when the two vibration directions of calcite in a section are parallel in turn with the vibration direction of the light emerging from the polariser. This means that each of the two-vibration direction has its own R.I. A rapid rotation of the stage produces a rapid change of the relief which is described as **twinkling**. This effect is similar to those of stars.

In the previous sections we have studied about the optical properties under ordinary and plane polarised light. Before going to the next section spend 5 minutes to check how you are progressing.

SAQ 1

a) List the optical properties studied under plane polarised light and cross polars.

b) List types of inclusions.

c) What is the purpose of Becke's test?

d) Define pleochroism.

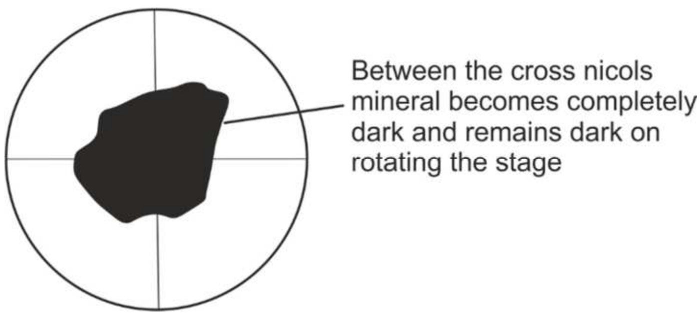
9.5 OPTICAL PROPERTIES BETWEEN CROSS NICOLS

We have read the optical properties of minerals in plane polarised light in the previous section. Now let us study the optical properties observed between cross nicols. In order to bring the microscope in this position (between cross polars) you have to insert polariser in the microscopic tube. Earlier also we have seen that in this position the short diagonal of lower nicol (polariser) is at right angle to the inserted upper nicol (analyser). Also, while making observations between cross nicols, if the mineral slide is not kept on the microscopic stage between the two nicols, the field will be completely dark. Let us go through the optical properties between cross nicols:

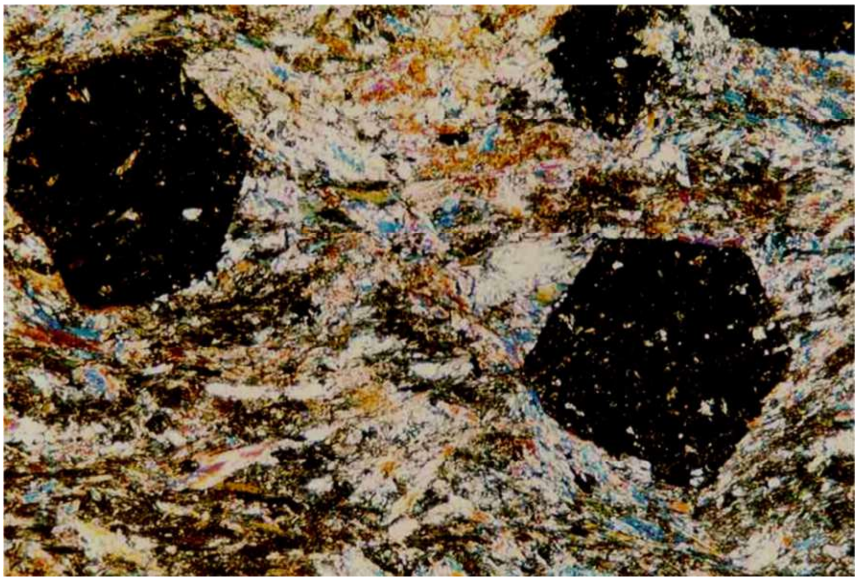
9.5.1 Isotropism/Anisotropism

Minerals may be either:

- **Isotropic**: Some minerals become dark when viewed under cross nicols and remain completely dark on the rotation of the stage. They are isotropic. The minerals crystallising in the cubic/isometric system and amorphous substances such as glass, Canada balsam show this property (Fig. 9.12a and b).



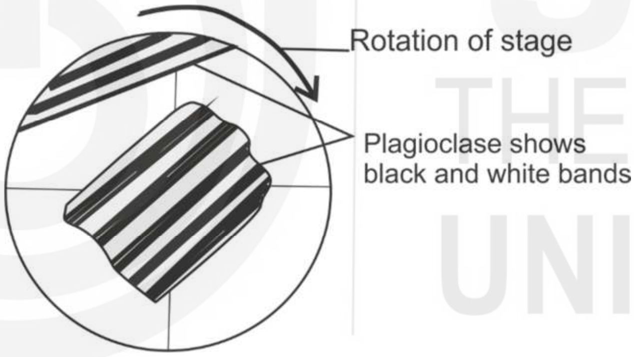
(a)



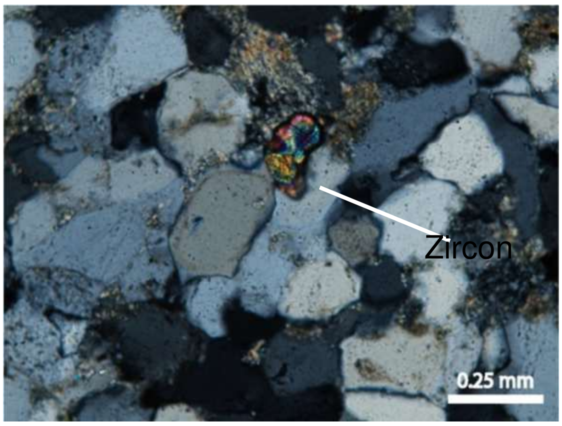
(b)

Fig.9.12: Isotropic mineral between cross nicols: a) Sketch; and b) Microphotograph of octahedral garnet (black) showing isotropism (MagnX20, Cross Nicol). (Photo credit: Dr. Meenal Mishra)

- **Anisotropic**: In the field of view, minerals become completely dark four times in one complete rotation. They include the minerals belonging to orthorhombic, monoclinic, triclinic, tetragonal, trigonal and hexagonal systems (Fig. 9.13).



(a)



(b)

Fig. 9.13: Anisotropism in different minerals: a) Plagioclase mineral shows different colours and becomes dark four times in one complete rotation; and b) Microphotograph showing quartz (shades of grey) and colourful zircon, between cross nicol. (Photo credit: Dr. Meenal Mishra)

9.5.2 Interference Colors

Optical mineralogy becomes colourful because of the interference colours. These colours fascinate the beginner. When the white light passes through an anisotropic mineral, all wavelengths are split into two polarised rays (O-ray and E-ray) which vibrate at 90^o to each other (about which we have discussed in earlier sections). The phase difference between the two rays will match the wavelength of same colour in the spectrum. Different colours have different wavelengths, so when the rays leave the crystal, some colours may be retarded, but most will not. Anisotropic minerals in the intermediate positions between the positions of extinction show various colours. These colours are the outcome of the interference of the two rays of lights having the same vibration plane (after their emergence from analyser) of which one is retarded with reference to the other. Interference colours reach their maximum intensity midway between two extinct positions, i.e. 45^o position.

Let us now examine and list the order of the colours along with the examples (Table 9.4).

Table 9.4: List of orders of interference colours.

Spectrum	Colours	Example
First Order	Grey, white, light yellow or sometimes light orange	Quartz, plagioclase, orthoclase, hypersthene, chlorite
Second Order	VIBGYOR- sharp, distinct rainbow colors, i.e. violet, indigo, blue, green, yellow, orange and red	Augite, hornblende,
Third Order	VIBGYOR- repeated but faint rainbow colors	Muscovite, biotite
Fourth and Higher Orders	Pale green and pink- very faint	Calcite zircon

Birefringence is a measure of the difference between the maximum and minimum refractive indices of particular mineral. In other words, it is the difference between refractive index of two rays, i.e. extraordinary ray and ordinary ray. Calcite shows highest birefringence. Thin section of quartz with standard thickness may vary from grey to white; olivine may show a wide range of colours from Newton`s scale of interference colours.

The colours depend upon the thickness, birefringence and crystallographic orientation of the section. Let us study the relationship between the degree of birefringence, the optical path difference, and the thickness of a specimen on thin section. Birefringence is the amount that the two rays are out of phase. They can be assigned a numerical value, or $n_1 - n_2$. Thus, birefringence is the difference between the principal refractive indices. The optical path difference is the difference in distance that each ray had to travel. It is also sometimes referred to as the retardation. The interference colors are the visible effect of this optical path difference. You can find out the numerical value for isotropic materials by multiplying the specimen thickness by the single refractive index of that mineral. However, in anisotropic materials, the numerical value for birefringence is substituted for the refractive index value, for example:

Optical path difference = $(n_1 - n_2) * t$(thickness of thin section)

This relationship is more clearly shown on the Michel-Lévy chart (Fig. 9.14). Interference colours can be first order, second order, and so on. Colour bands progress initially from shades of grey and white to yellow, orange, pink, red, purple, blue, green, back to yellow, and so on. This is similar to the colour order of a rainbow. If the interference colour and thickness of specimen is known, then the numerical value of birefringence can be determined with the help of blue arrows, as shown in Fig. 9.14.

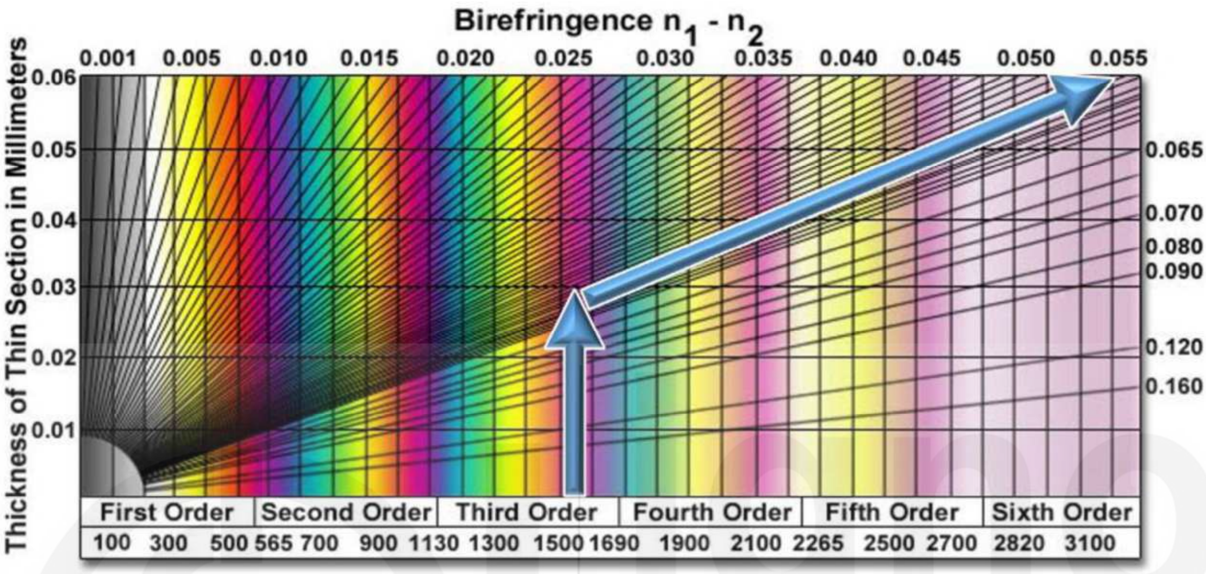


Fig. 9.14: Michel - Lévy birefringence chart.

9.5.3 Extinction

When the vibration direction of the ordinary and extraordinary rays of isotropic minerals are parallel to vibration directions of nicols in a petrological microscope, no light reaches the eye and the mineral is said to be in **extinction position**. This is because the light passing the polariser also passes through the mineral but is stopped by the analyser, as it has a vibration direction perpendicular to that of the polariser. This phenomenon occurs four times during the rotation of the stage of microscope, through an angle of 360° between crossed nicols. The isotropic mineral is always in the position of extinction between the cross nicols. In case of anisotropic mineral, the two adjacent position of extinction are separated from each other by 90°.

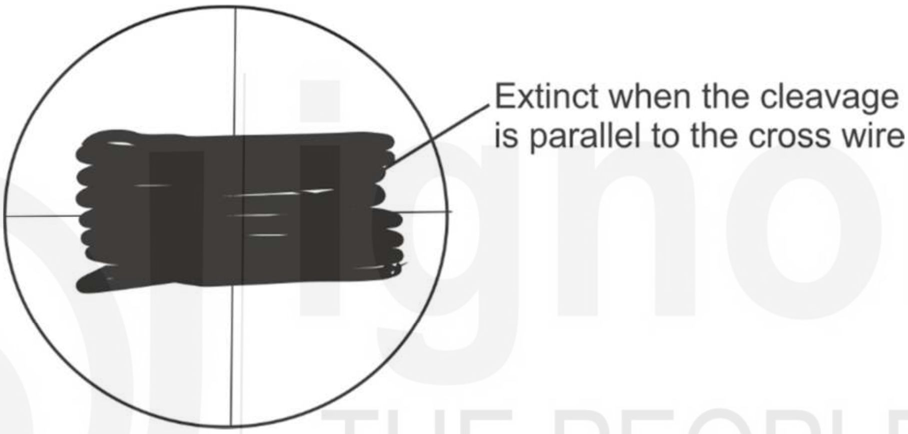
There is a definite relationship between extinction position and interference (polarisation) colours. The brightest interference colours are seen midway between two extinction position (45° from the extinction position). As we rotate the stage from its first extinction position, darkness will slowly start disappearing and polarisation colours will appear at their brightest at 45° from their extinction position. Now rotate the stage in reverse direction, polarisation colours disappear and it gradually becomes extinct.

Extinction angle is the angle between crystallographic direction and position of maximum extinction. This angle is measured with reference to cleavage crystal outline prominent crack, twin plane.

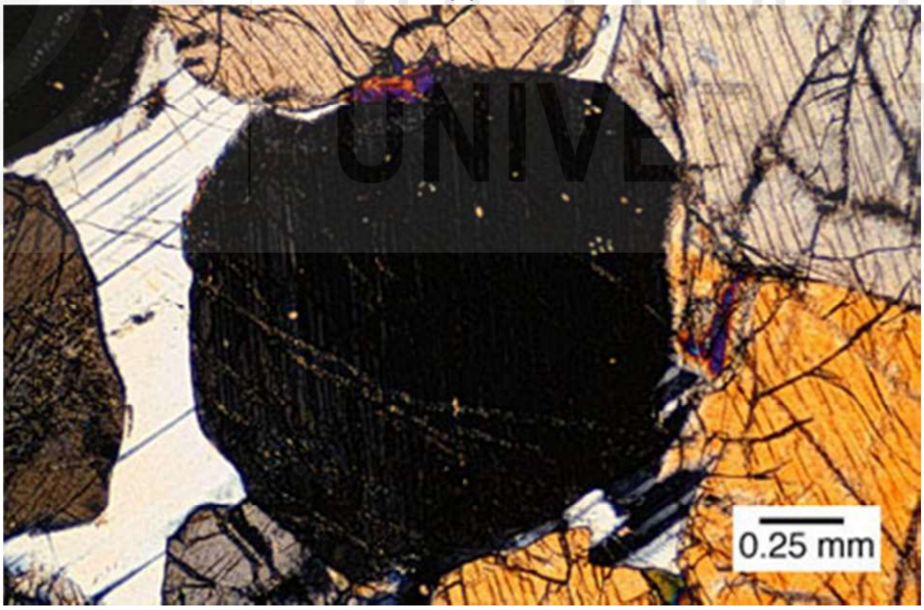
Types of Extinction: The extinction position is normally referred with respect to the outer edges of the crystal or its prominent cleavage direction. We have to keep the cleavage or crack parallel to a cross wire between cross nicol. On rotation of the stage the mineral becomes dark called as extinction position. On this basis there are four types of extinction recognised:

- **Straight or parallel extinction**: You will observe that the mineral becomes dark parallel to cross wire, without any further rotation of the stage, it is called as straight or parallel extinction (Fig. 9.15a and b).

- **Oblique or Inclined extinction:** You will find that when the mineral does not appear dark parallel to the cross wire but on rotation of the stage at a certain angle. This type of extinction is known as oblique extinction (Fig. 9.16a and b). In case of oblique extinction you can measure the extinction angle. Take the initial reading with cleavage parallel to cross wire. Then rotate the stage till the mineral grain becomes dark or extinct. The difference in angle will give you the extinction angle. Hornblende, augite shows oblique extinction.



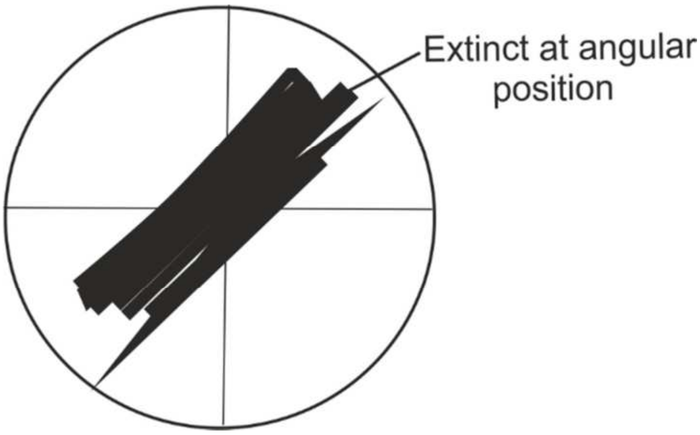
(a)



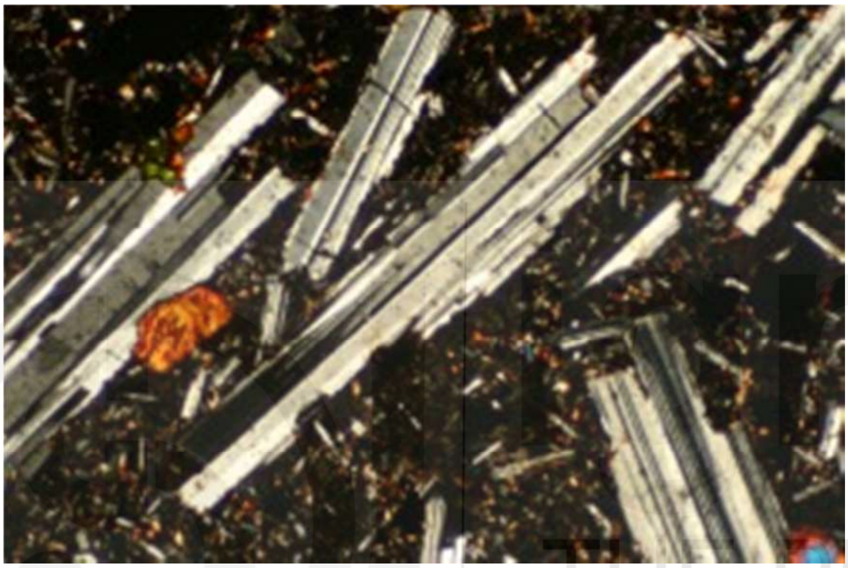
(b)

Fig. 9.15: a) Sketch showing straight extinction; and b) Parallel extinction seen in hypersthene mineral (black). Extinction is parallel to one set of cleavage. Note that hypersthene shows low First order interference colours and 2 sets cleavage at 90^{o}.

(Source: http://minerva.union.edu/hollochk/c_petrology/ig_minerals.htm)



(a)



(b)

Fig. 9.16: Oblique extinction: a) Sketch; and b) Note the oblique extinction in plagioclase. (Photo credit: Prof. J. P. Shrivastava)

- **Symmetrical extinction**: This type of extinction is shown by minerals with square outline or rhombic cross section. The mineral section becomes extinct parallel to diagonal of rhombic pattern, e.g. calcite (Fig. 9.17a).

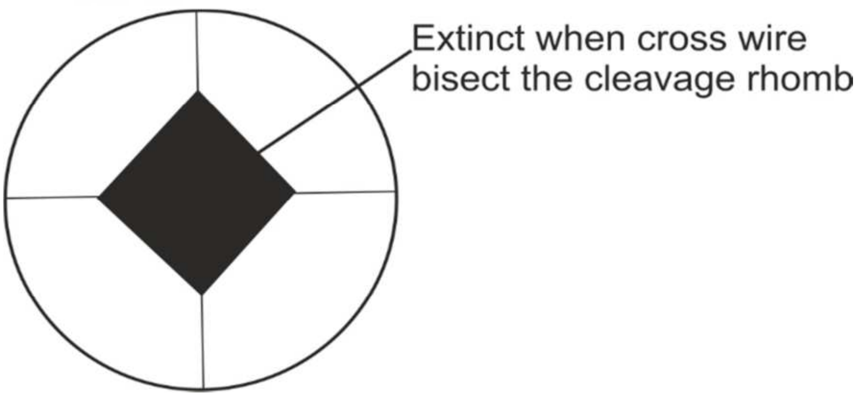


Fig. 9.17a: Symmetrical extinction.

- **Wavy or undulose extinction:** This type of extinction appears as a band or series of bands of darkness crossing a single crystal unit during rotation of the stage. This may be due to strain and deformation. Mineral never extinguishes completely, e.g. quartz (Fig. 9.17b).

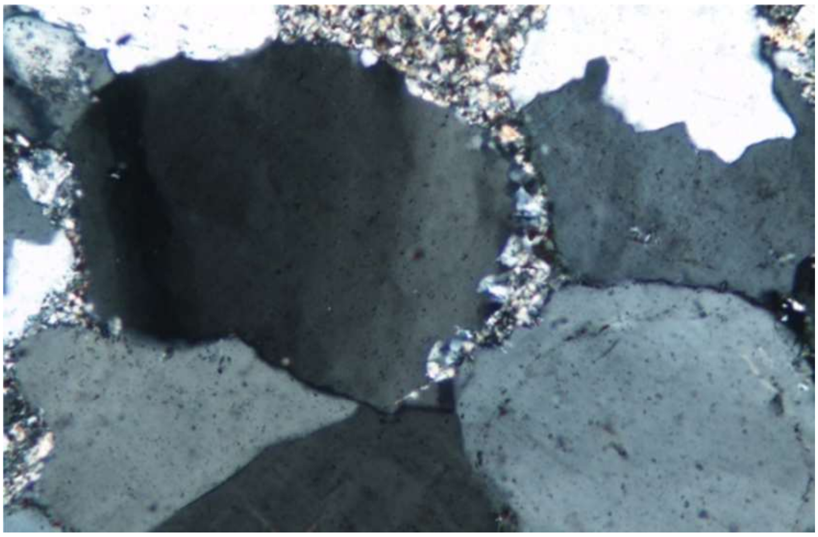


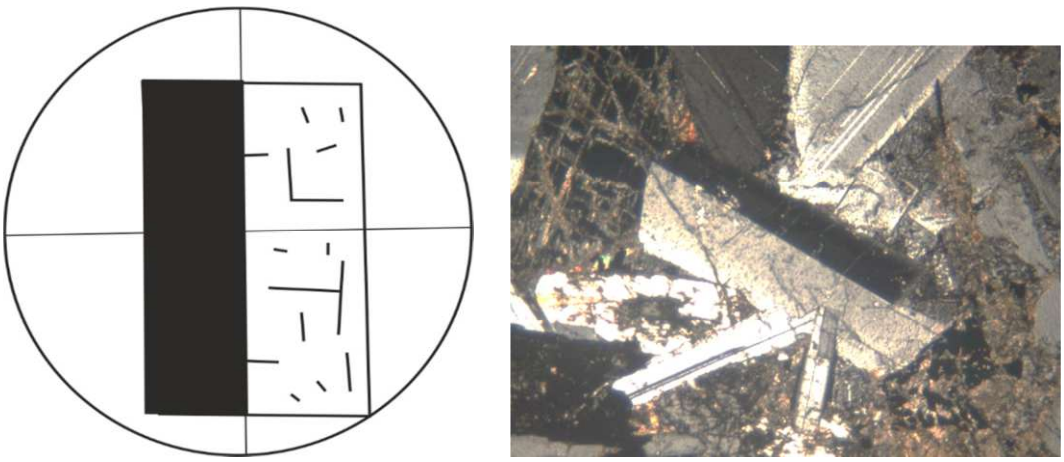
Fig. 9.17b: Wavy or undulose extinction seen in quartz. (Photo credit: Dr. Meenal Mishra)

9.5.4 Twinning

We have read in previous unit that the variation in habit of minerals is due to significant variations in the conditions during crystallisation including pressure, temperature, etc. Two or more crystals of the same or related mineral species may intergrow with each other. Such crystals are called twinned crystals. Twinning is very commonly seen in feldspars.

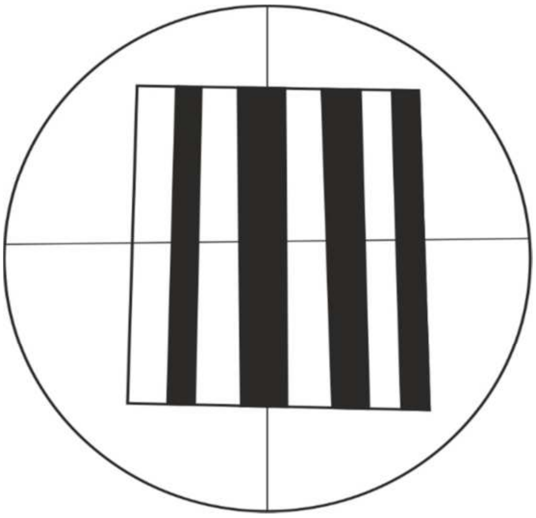
Following types of twinning are recognised.

- **Carlsbad twinning**: This type of twinning shows one set of dark and bright bands (Fig.9.18). They alternate their position on rotation of the stage, e.g. orthoclase (K feldspar).
- **Polysynthetic twinning**: It consists of many thin dark and alternating bright bands, e.g. plagioclase feldspars (Fig. 9.19). The bands alternate their position on rotation.

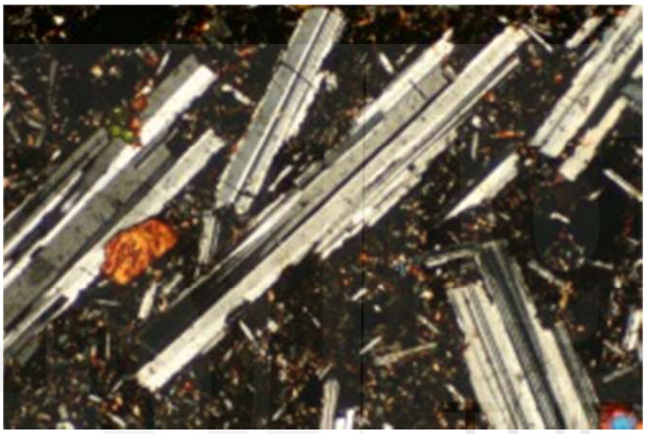


(a) **(b)**

Fig. 9.18: Carlsbad twinning: a) Sketch; and b) Photomicrograph of orthoclase showing Carlsbad twinning (simple banding).



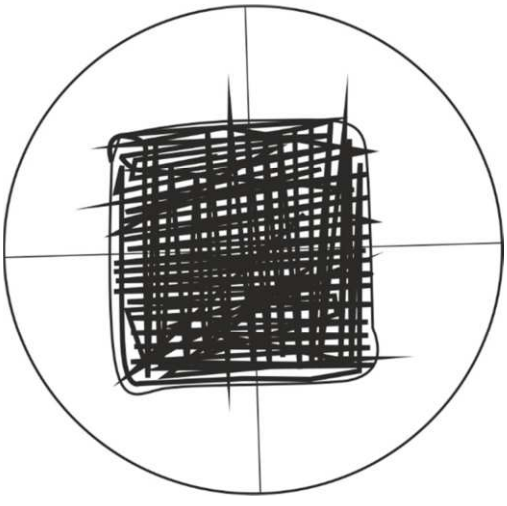
(a)



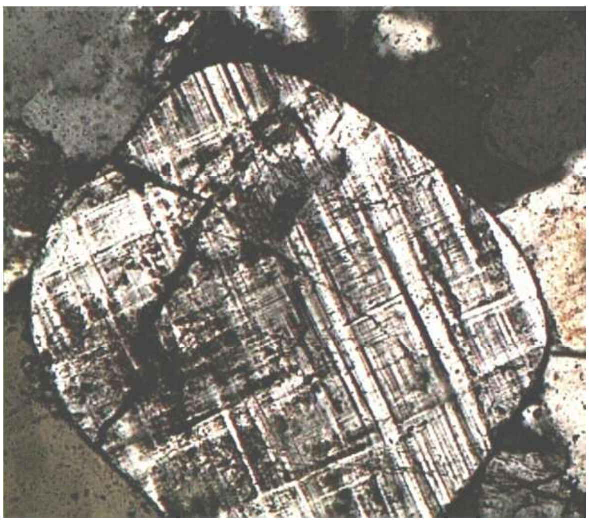
(b)

Fig. 9.19: Polysynthetic twinning: a) Sketch; and b) Photomicrograph of plagioclase showing polysynthetic twinning. (Photo credit: Prof. J. P. Shrivastava**)**

- **Cross hatch twinning**: In this polysynthetic twinning is closely present in two directions at right angles, e.g. microcline is a K-feldspar (Fig.9.20)



(a)



(b)

Fig. 9.20: Cross hatch twinning: a) Sketch; and b) Photomicrograph of microcline showing cross hatch twinning. (Photo credit: Dr. Meenal Mishra)

9.5.5 Zoning

Zoning is typical of minerals which form continuous solid solution series. It appears in form of concentric bands from centre outwards. Zoning reflects that mineral is compositionally not uniform throughout. Plagioclase is the best example of concentric zoning, in this we observe number of shells arranged concentrically around a central point (Fig. 9.21). Another type of zoning is hour glass zoning which you can observe in augite. Prismatic zoning is observed in tourmaline.

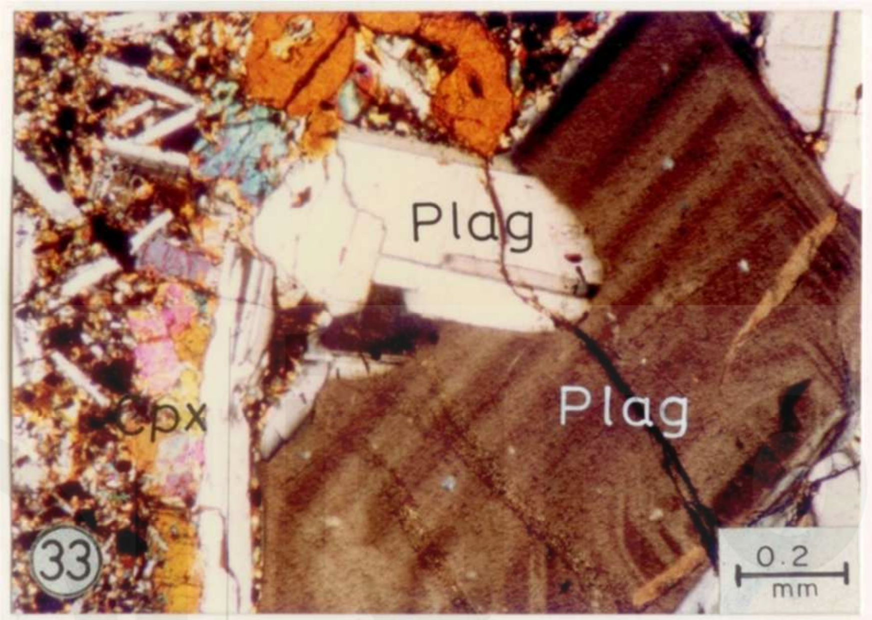


Fig. 9.21: Zoning seen in plagioclase feldspar between cross nicols. (Photo credit: Prof. J. P. Shrivastava)

- Watch the following video to know more about zoning and twinning.

  Microscopic Study of Basaltic Rocks

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

In the previous sections we have studied about the optical properties between cross nicols. Before going to the next section spend 5 minutes to check how you are progressing.

SAQ 2

a) What do you understand by angle of extinction and identify the types of extinction.

b) List the types of twinning exhibited by feldspars.

c) ________ mineral exhibits hourglass zoning.

d) Name the minerals exhibiting following optical properties.

Pleochroism, Twinkling, Rhombohedral cleavage, 2 sets cleavage at 90^o, Isotropism, Parallel extinction, Oblique extinction, Symmetrical extinction, Undulose extinction, Carlsbad twinning, Cross hatch twinning.

9.6 SUMMARY

In this unit we have learnt about basic concepts of optical mineralogy and the properties observed and studied under polarising microscope. Now let us summarise:

- Thin sections are examined in three positions: (1) ordinary light, (2) under plane polarised light, and (3) between cross nicols.
- Under plane polarised light (PPL) we study colour, pleochroism, form, cleavage, relief, twinkling, and alteration and inclusions.
- Between cross nicols or crossed polars (XP) the study of isotropism/anisotropism, interference colours, extinction, twinning and zoning are carried out.
- The minerals have their individual diagnostic characteristics which are collectively used for identification.
- Pleochroism is the variation in colour resulting from differential absorption of wavelength in different directions. The twinkling effect is caused by rapid change in relief of minerals.
- When the vibration direction of the ordinary and extraordinary rays of isotropic minerals are parallel to vibration directions of nicols in a polarising microscope, no light reaches the eye and the mineral is said to be in extinction position.
- Extinction can be straight or parallel, oblique or inclined, symmetrical, wavy or undulose.
- Twinning is very commonly seen in feldspars.
- Birefringence is a measure of the difference between the maximum and minimum refractive indices of particular mineral.

9.7 ACTIVITY

1. List the diagnostic properties of the minerals you have studied.

9.8 TERMINAL QUESTIONS

1. Describe the optical properties studied under plane polarised light, with the help of neat well labeled diagrams.
2. Describe the optical properties studied between cross nicols with the help of neat well labeled diagrams.
3. Write a short note on interference colours.

Audio/video material based questions

- Which mineral exhibits rhythmic zoning?
- What is hourglass structure?
- Why do you get twinning in minerals?

9.9 REFERENCES

- Alexander, P.O., (2009) A Handbook of Minerals, Crystals Rocks and Ores. New India Publishing Agency, New Delhi, 676p.
- http://minerva.union.edu/hollochk/c_petrology/ig_minerals.htm

  (website accessed between 25th and 30thJanuary 2019)

9.10 FURTHER/SUGGESTED READINGS

- Dana, J.D. and Ford. W.E. (1962) A Text book of Mineralogy, Asia Publishing House, New Delhi.
- Gribble, C.D. (2001) Rutley's Elements of Mineralogy. 27th Edition. CBS Publishers and Distributors, Delhi.
- Mahapatra. G.B, (2012 Reprinted) A Textbook of Geology, CBS Publishers, New Delhi.
- Singh, P. (2013) Engineering and General Geology, S.K. Kataria & Sons, Delhi.

9.11 ANSWERS

Self Assessment Questions

1 a) Please refer Table 9.1.

b) Pleochroism as the variation in colour resulting from differential absorption of wavelength in different directions. It is exhibited by coloured minerals when the stage is rotated in the plane polarised light.

c) Thin sections are mounted in the medium of Canada balsam which has refractive index (RI) 1.54. The difference in the RI of balsam and mineral determines the relief. Becke test indicates as to whether the mineral has more RI (positive) or less RI (negative) than the balsam.

d) Regular, irregular, accicular

2 a) Extinction angle is the angle between crystallographic direction and position of maximum extinction is called extinction angle. This angle is measured with reference to cleavage crystal outline or crack, twin plane. Four types of extinction are: (1) Straight extinction; (2) Oblique or Inclined; (3) Symmetrical extinction; (4) Wavy or undulose.

b) Carlsbad, polysynthetic and cross hatch

c) Augite

d) Pleochroism- hornblende, biotite, augite, hypersthene; twinkling- calcite, muscovite; rhombohedral cleavage –calcite; 2 sets cleavage at 90^o- orthoclase, plagioclase, microcline, hypersthene; isotropism-garnet; parallel extinction-biotite, muscovite, hypersthene; oblique extinction-hornblende, augite, orthoclase, plagioclase, microcline; symmetrical extinction- calcite; undulose extinction-quartz; carlsbad twinning- orthoclase, plagioclase; cross hatch twinning-microcline.

Terminal Questions

1. Please refer to section 9.3 and 9.4.
2. Please refer to section 9.5.
3. Please refer to subsection 9.5.2.

UNIT 10

OPTICAL PROPERTIES OF ROCK-FORMING MINERALS

Structure

10.1 INTRODUCTION

We have already discussed that the physical properties of minerals are important tools for their identification in hand specimens Unit 4 Minerals. Then in Unit 6 Megascopic study of Minerals we identified the common rock-forming minerals with the help of physical properties. Now in this unit we will learn to identify the common rock-forming minerals using optical properties. These studies are carried out using polarising microscope. The optical properties of the minerals are immensely helpful in their identification.

Expected Learning Outcomes

After reading this unit you should be able to:

- ❖ recognise the optical properties of rock-forming minerals under polarised light;
- ❖ explain the optical properties of rock-forming minerals between cross nicol, and
- ❖ identify the rock-forming minerals using their diagnostic optical properties.

10.2 WHAT ARE ROCK-FORMING MINERALS?

You have read about rock-forming minerals in Units 6 and 7 of this course.
Let us recall!
Rocks are naturally occurring, coherent solids consisting of aggregate of minerals. In other words minerals are the building blocks of rocks. Rock-forming minerals are the essential components of rocks commonly occurring in the Earth's crust. About 25 minerals are usually considered to play an important role in the composition of the crustal rocks. **Rock-forming minerals** are those minerals that make up the major components of a rock and they are used in the classification of rock types viz. igneous, sedimentary and metamorphic. Igneous rocks are formed from the cooling and crystallisation of magma. Sedimentary rocks are formed on decomposition and disintegration of the pre-existing rocks-igneous, metamorphic or even earlier formed sedimentary rocks. Metamorphic rocks are formed when a pre-existing rocks or protolith; undergoes a solid-state change in response to the modification of its environment, i.e. temperature and/or pressure. We will study in detail about rocks in BGYCT-135 course on Petrology.
About 92 percent of the minerals found on Earth’s crust are silicates (Fig. 10.1, Ronov, and Yaroshevsky, 1969). Silicates are regarded as building blocks of the common rock-forming minerals. Silicates are minerals that contain silicon and oxygen and usually one or more other elements. The silicate minerals are of great importance because 27% of the known minerals and 40% of the common minerals are silicates. With few exceptions all the igneous rocks make up approximately 95% of the upper 16 km of the Earth’s crust. Each group of rocks mentioned above characteristically has their own rock-forming minerals. Though many minerals are found in the igneous rocks, but those called rock-forming minerals are comparatively few. Common rock forming minerals in igneous rocks are quartz, feldspars (orthoclase, microcline, plagioclase), mica (muscovite, biotite), pyroxene (augite, hypersthene), amphibole (hornblende), olivine and garnet, nepheline. The rock- forming minerals of sedimentary rocks are quartz, orthoclase, plagioclase, muscovite, biotite, calcite, dolomite, anhydrite and clay minerals. The metamorphic rocks dominantly comprise rock forming silicate minerals like kyanite, andalusite, sillimanite, staurolite, chlorite, serpentine, garnet, wollastonite and glaucophane.

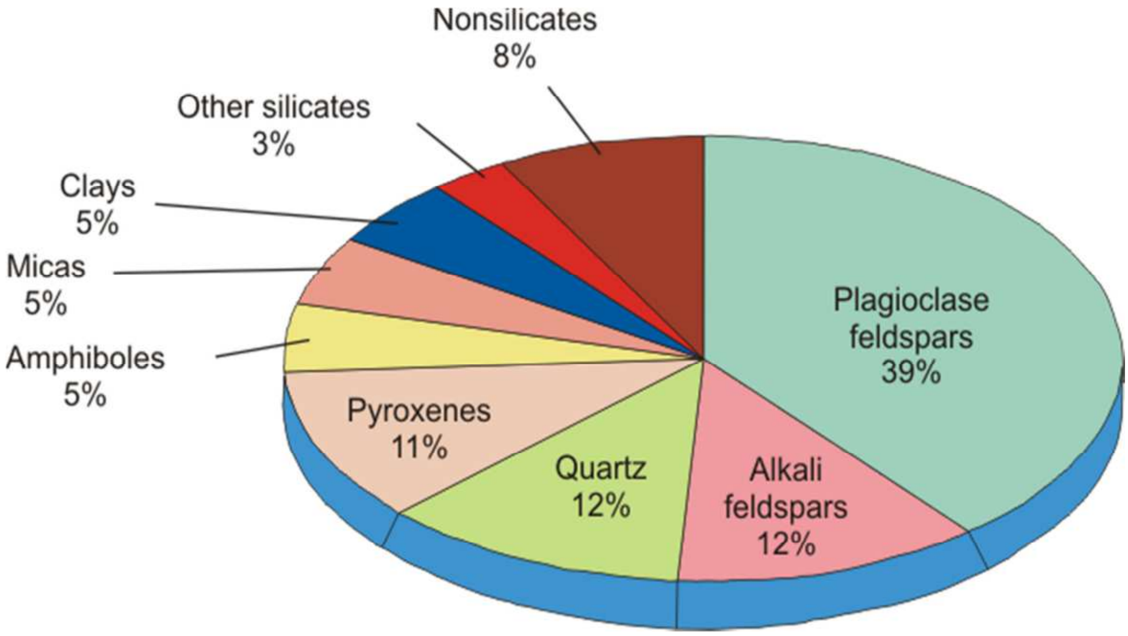


Fig. 10.1: Estimated volume percentages for common rock forming minerals in the Earth's crust, inclusive of continental and oceanic crust. Ninety two percent are silicates. (Source: Ronov, A.B and Yaroshevsky, A.A. 1969)

We have already discussed the physical properties of common rock-forming minerals in unit 6 of this course. Now let us discuss the optical properties of the common rock-forming minerals. We will discuss the silicate minerals like quartz, orthoclase, microcline, plagioclase, muscovite, biotite, augite, hypersthene, hornblende, olivine and garnet. Calcite is the common rock forming mineral from carbonate group that we shall be discussing.

Let us now examine the optical properties of some rock forming minerals summarised in Table 10.1a and 10.1b. Figures 10.2 to 10.14, show optical properties of minerals both in sketch and photomicrograph. In all the figures abbreviations used are as:

- **Under Plane Polarised Light - PPL**
- **Between Cross Polars or between Cross Nicol - XP**

10.3 OPTICAL PROPERTIES OF QUARTZ

Let us recall the physical properties of quartz that we learnt in Unit 6 of this course.

Quartz is the dominant mineral present on Earth's crust. It is a tectosilicate and occurs in wide range of colours such as white, grey, purple, yellow, brown, black, and pink, green, red in hand specimen. The diagnostic characters of quartz are conchoidal fracture, vitreous or glassy lustre, hardness 7 and absence of cleavage.

We will refer to Figure 10.2 while studying optical properties of quartz.

Under Plane Polarised Light

Colour- Usually colourless and clear in thin sections

Pleochroism- Non pleochroic

Form-Typically anhedral but may be euhedral prismatic

Cleavage-Absent

Relief- Low

Between Cross Polars

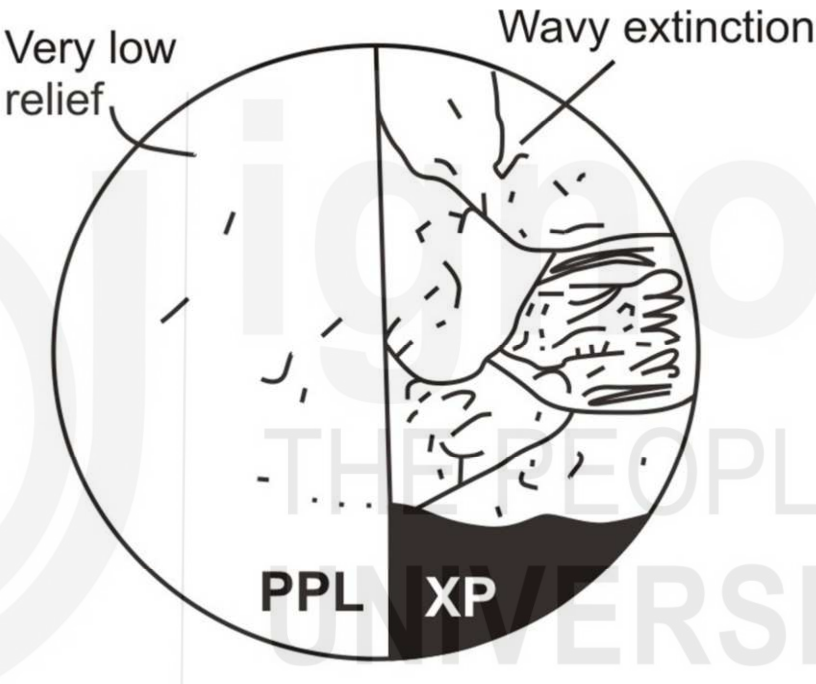
Isotropism/Anisotropism-Anisotropic

Interference colours- Maximum interference colours are first-order white and grey and yellow

Extinction- Undulose or wavy extinction common, often with a fan-like pattern

Twinning-Not seen in thin section

Diagnostic features-Colourless and clear, display First order white or weak yellow interference colours, lack of cleavage, lack of alteration and often shows undulatory extinction.



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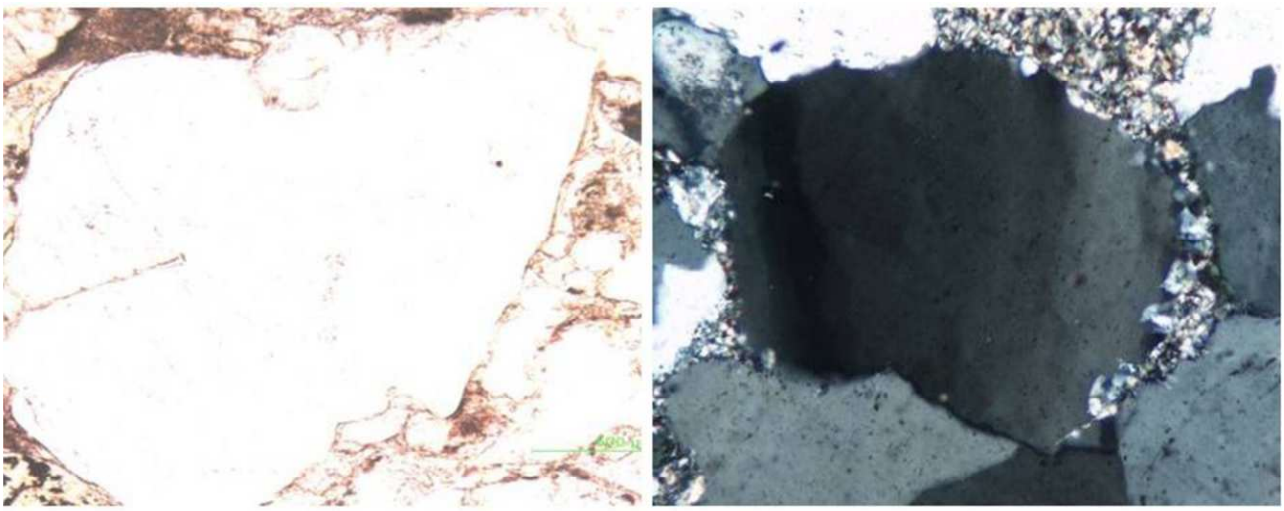
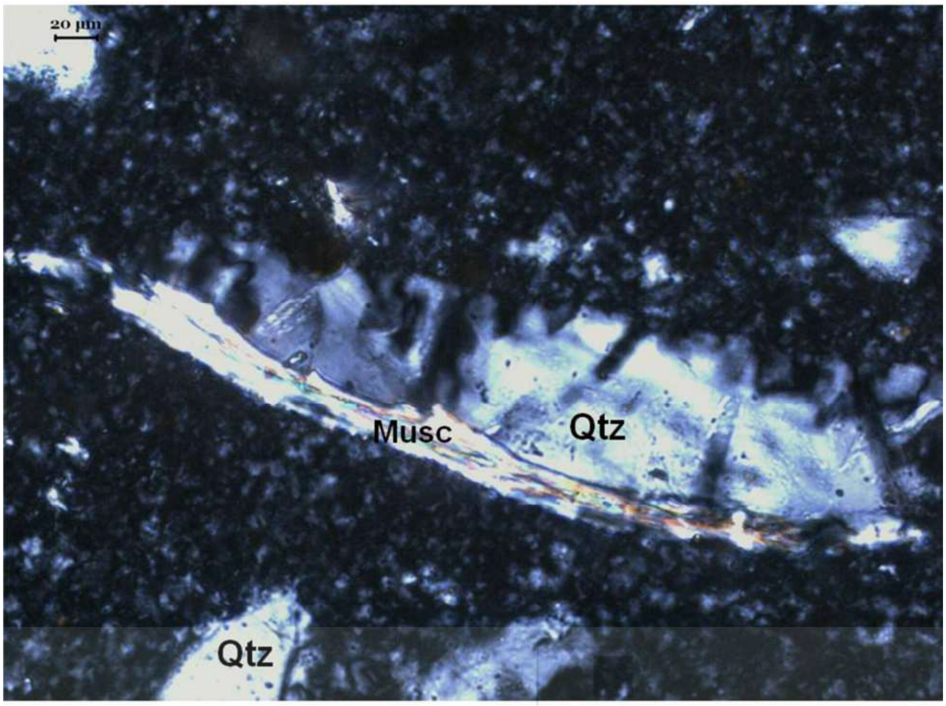


PPL XP

(b)



(c)

Fig 10.2: Quartz in thin section: a) Sketch of quartz with low relief in PPL and XP; and b) Photomicrograph of quartz under PPL and between XP; and c) Wavy extinction in quartz. Notice the elongated quartz (Qtz) grain along with flaky muscovite (Musc).

Please note that it is important for you to learn the diagnostic optical properties of quartz in order to identify it under the microscope.

10.4 OPTICAL PROPERTIES OF FELDSPAR GROUP MINERALS

Commonly the feldspar group minerals include orthoclase, microcline and plagioclase. Feldspars are group of rock-forming tectosilicate minerals that make up about 51% of the Earth's continental crust by weight (Ronov and Yaroshevsky,1969). We will discuss the optical properties of these three minerals.

10.4.1 Orthoclase

Let us recall the physical properties of orthoclase that we learnt in Unit 6 of this course.

Orthoclase is tectosilicate and potassium feldspar ($KAlSi_3O_8$) in composition. Orthoclase in hand specimen can be flesh red, colourless and light grey in hand specimen. The diagnostic features of orthoclase are tabular habit, flesh red colour, 6 hardness, two set cleavage at 90^o.

We will refer to Figure 10.3 while studying optical properties of orthoclase.

Under Plane Polarised Light

Colour- Usually colourless in thin sections but can be cloudy or turbid or pale brown in thin section because of alteration

Pleochroism- Non pleochroic

Form-Subhedral or anhedral crystals

Cleavage- Two set cleavage at 90^o; one set perfect cleavage and one set imperfect

Relief- Low

Between Cross Polars

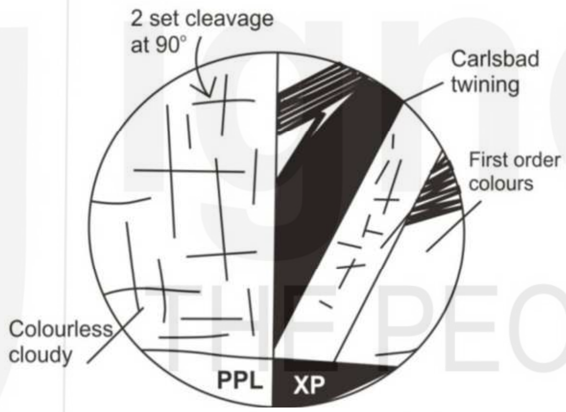
Isotropism/Anisotropism-Anisotropic

Interference colours- Maximum interference colours are first-order grey and white

Extinction- Oblique extinction, angle varies from 0^o to 12^o

Twinning- Carlsbad twinning present

Diagnostic features- Orthoclase is colourless and cloudy or turbid, display first-order interference colours and usually show one or two set distinct cleavage at 90^o; exhibits Carlsbad twinning



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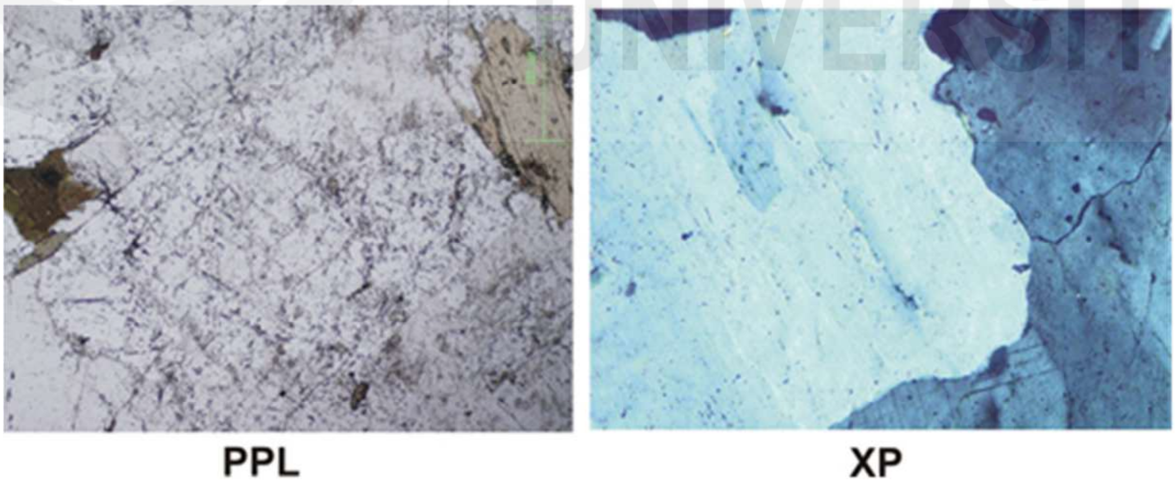


(b)

Fig.10.3: Orthoclase in thin section; a) Sketch of orthoclase with two set cleavage in PPL and XP; and b) Photomicrograph of orthoclase in PPL and Carlsbad twinning in XP. (Source: www.gsi.gov.in)

Please note that it is important for you to learn the diagnostic optical properties of orthoclase in order to identify it under the microscope.

10.4.2 Microcline

Let us recall the physical properties of microcline that we learnt in Unit 6 of this course.

Microcline is tectosilicate and potassium feldspar ($KAlSi_3O_8$) in composition. It can be white, grey, greyish yellow, yellowish, tan, salmon-pink, bluish green, green colour in hand specimen. The diagnostic features of microcline are tabular habit, green colour, 6-6.5 hardness, two set cleavage at 90°.

We will refer to Figure 10.4 while studying optical properties of microcline.

Under Plane Polarised Light

Colour- Usually colourless but can be cloudy in thin sections

Pleochroism- Non pleochroic

Form- Normally subhedral or anhedral plates or laths

Cleavage- Two set cleavage at 90°; one set perfect and one set poor

Relief- Low

Between Cross Polars

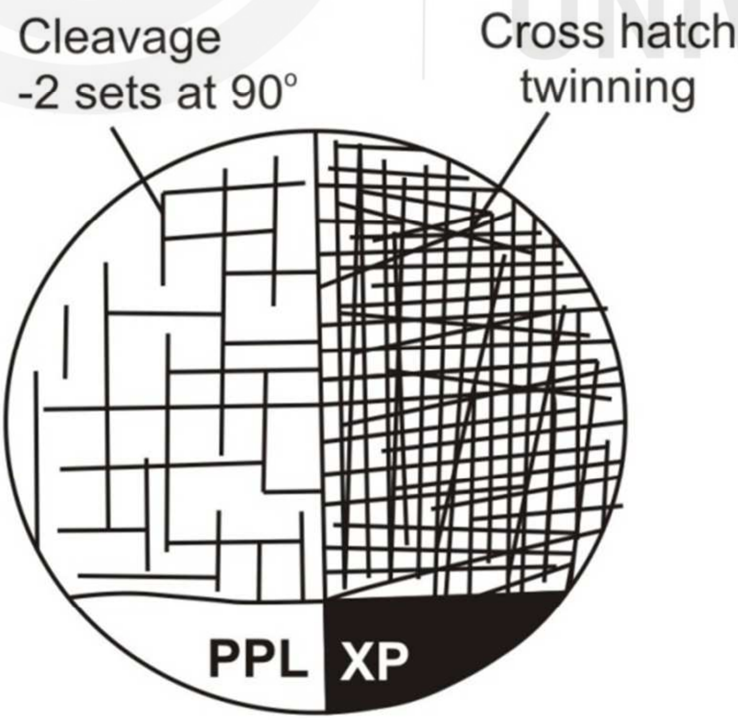
Isotropism/Anisotropism-Anisotropic

Interference colours- Maximum interference colours are first order light grey

Extinction- Oblique extinction, angle varies upto 15°

Twinning- Microcline has a distinctive cross hatch twinning pattern

Diagnostic features- Microcline is colourless, display first-order interference colours and usually shows one or two cleavages; exhibits typical cross hatch twinning.



(a)

(b)

Fig. 10.4: Microcline in thin section: a) Sketch of microcline with cleavage at 90^o in PPL and XP; and b) Photomicrograph of microcline in PPL and XP showing cross hatched twinning.
(Source: http://minerva.union.edu/hollochk/c_petrology/ig_minerals.htm).

Please note that it is important for you to learn the diagnostic optical properties of microcline in order to identify it under the microscope.

10.4.3 Plagioclase

Let us recall the physical properties of plagioclase that we learnt in Unit 6 of this course.

Plagioclase is sodic-calcic feldspar ($NaAlSi_3O_8$ to $CaAl_2Si_2O_8$) in composition. The diagnostic properties of plagioclase in hand specimen are its pale grey or white colour, two set of distinct cleavage at 90^o. The presence of striations on crystal faces is its special property.

We will refer to Figure 10.5 while studying optical properties of plagioclase.

Under Plane Polarised Light

Colour- Usually colourless but can be cloudy in thin sections

Pleochroism- Non pleochroic

Form- Normally subhedral or anhedral plates or laths

Cleavage- Two set cleavage at 90^o; one set perfect and one set poor

Relief- Low

Between Cross Polars

Isotropism/Anisotropism-Anisotropic

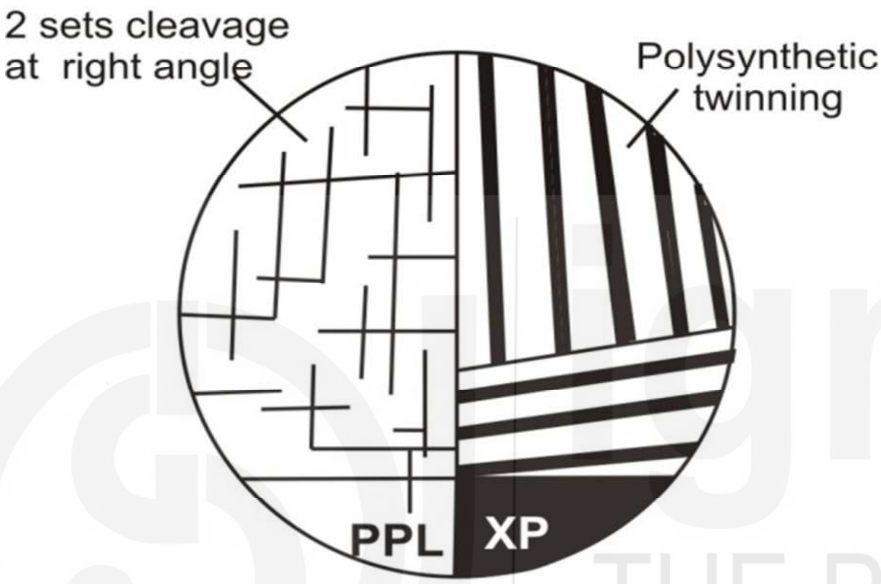
Interference colours- Maximum interference colours are of First order light yellow

Extinction- Oblique extinction, angle varies with composition

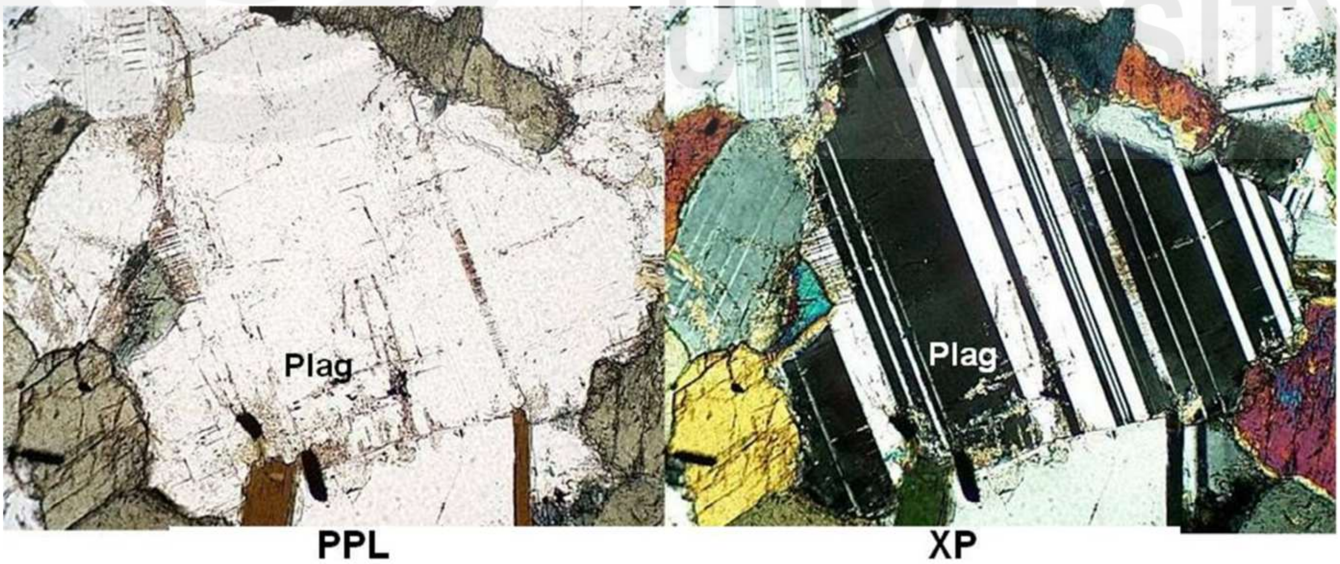
Twinning- Often polysynthetic twins give striped appearance present or sometimes Carlsbad twinning

Diagnostic features- Plagioclase is colourless, display First-order interference colours and usually shows one or two set cleavages. It exhibits oblique extinction and typical polysynthetic or sometimes Carlsbad twinning.

The feldspar shows concentric black-grey-white patterns when viewed between crossed polars called **zoning**. It is due to compositional heterogeneity in plagioclase (Fig. 10.6).



(a)



(b)

Fig.10.5: Plagioclase in thin section: a) Sketch of plagioclase with two set cleavage in PPL and XP; and b) Photomicrograph of plagioclase in PPL and notice polysynthetic twinning under XP. (Source: http://minerva.union.edu/hollochk/c_petrology/ig_minerals.htm)

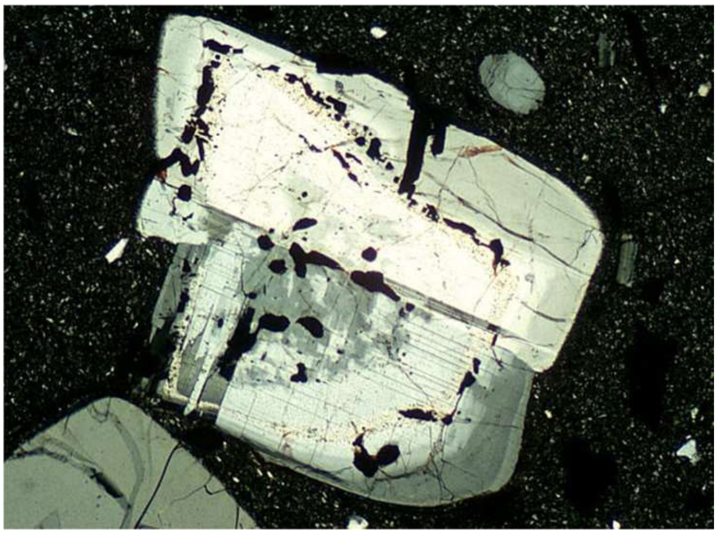


Fig. 10.6: Zoning seen in plagioclase feldspar between cross nicols. (Source: http://minerva.union.edu/hollochk/c_petrology/ig_minerals.htm)

Please note that it is important for you to learn the diagnostic optical properties of plagioclase in order to identify it under the microscope.

- Watch the following video to know more about zoning and twinning in plagioclase mineral.

  Microscopic Study of Basaltic Rocks

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

  Textures Related to zoning in Igneous rocks

  Link: https://www.youtube.com/watch?v=Wrbw0MQzSQU

10.5 OPTICAL PROPERTIES OF MICA GROUP MINERALS

We will discuss the optical properties of muscovite and biotite in mica group minerals. They are phyllosilicates and crystallise in monoclinic system.

10.5.1 Muscovite

Let us recall the physical properties of muscovite that we learnt in Unit 6 of this course.

Muscovite has chemical composition $KAl_2(Si_3AlO_{10})(OH)_2$. In hand specimen it is colourless or shinning white, silver with brownish tint, with sheet like form, 1 set perfect cleavage showing vitreous and pearly lustre. Muscovite exhibits special character called asterism.

We will refer to Figure 10.7 while studying optical properties of muscovite.

Under Plane Polarised Light

Colour- Usually colourless

Pleochroism- Usually non pleochroic,may be pale green pleochroic

Form-Tabular crystals, lamellar, flaky

Cleavage- One set perfect micaceous cleavage

Relief- Moderate

Between Cross Polars

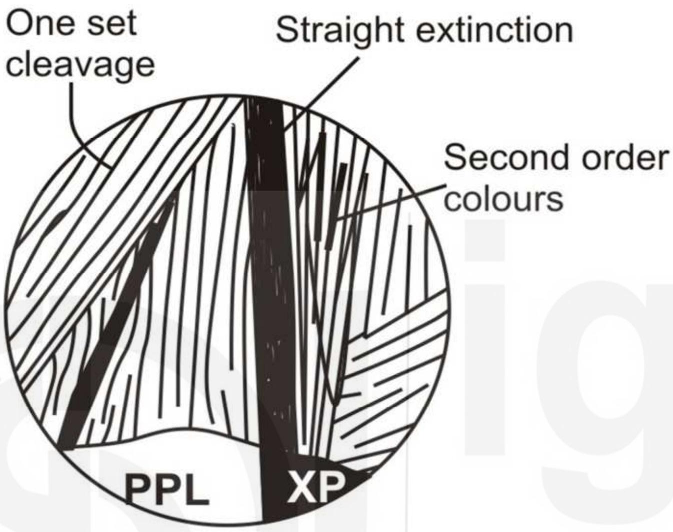
Isotropism/Anisotropism- Anisotropic

Interference colours- Upto second order yellow or red

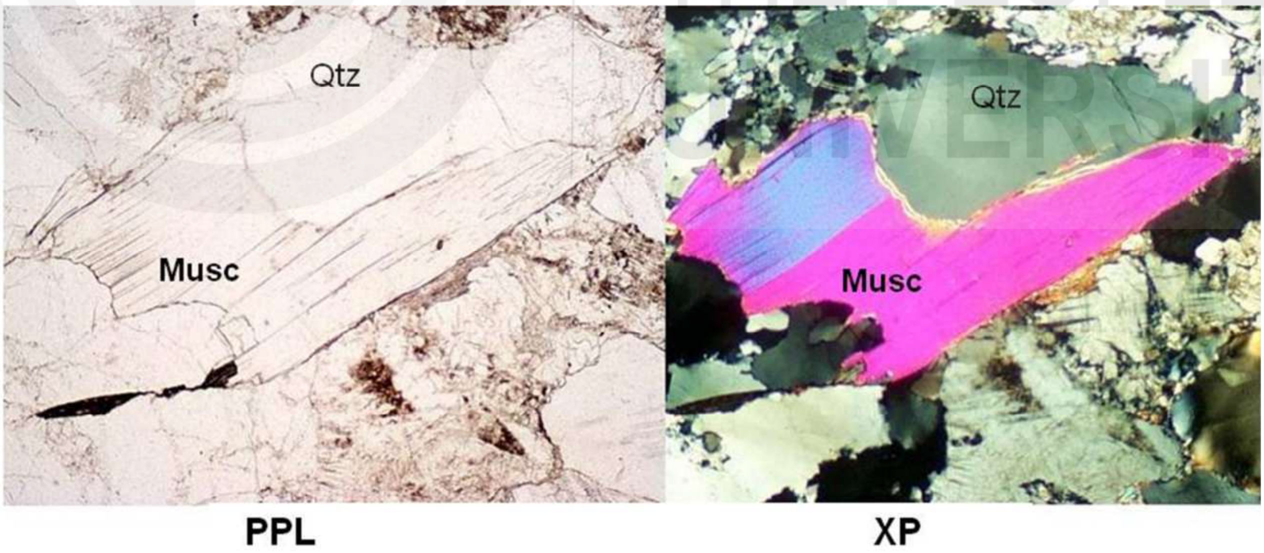
Extinction- Normally shows parallel extinction

Twinning- Twins may be present but hard to detect

Diagnostic features- Colourless to pale green under plane polarised light, flaky form, one set perfect cleavage, exhibiting Second order interference colours and parallel extinction



(a)



(b)

Fig.10.7: Muscovite in thin section: a) Sketch of muscovite with one set cleavage in PPL and XP showing straight or parallel extinction; and b) Muscovite (Musc) in PPL and XP. Notice quartz (Qtz) grain.
(Source:http://minerva.union.edu/hollochk/c_petrology/ig_minerals.htm)

Please note that it is important for you to learn the diagnostic optical properties of muscovite in order to identify it under the microscope.

10.5.2 Biotite

Biotite is a phyllosilicate with chemical composition $K(Mg,Fe)_{2-3}Al_{1-2}Si_{2-3}O_{10}(OH,F)_2$.

Let us recall the physical properties of biotite that we learnt in Unit 6 of this course.

In hand specimen biotite is black, dark green, dark brown in colour, one set perfect cleavage. Thin cleavage flakes are elastic and flexible and sheet like or lamellar form, lustre vitreous and pearly. Biotite exhibits special character called asterism.

We will refer to Figure 10.8 while studying optical properties of biotite.

Under Plane Polarised Light

Colour- Pale green, light brown, red brown or greenish brown.

Pleochroism- Exhibits strong pleochroism from light brown/green to dark brown/green (Fig. 10.8)

Form- May be in hexagonal plates or tabs or may occur more commonly as elongate flakes.

Cleavage- One set distinct (Fig. 10.8 and 10.9)

Relief- Moderate

Between Cross Polars

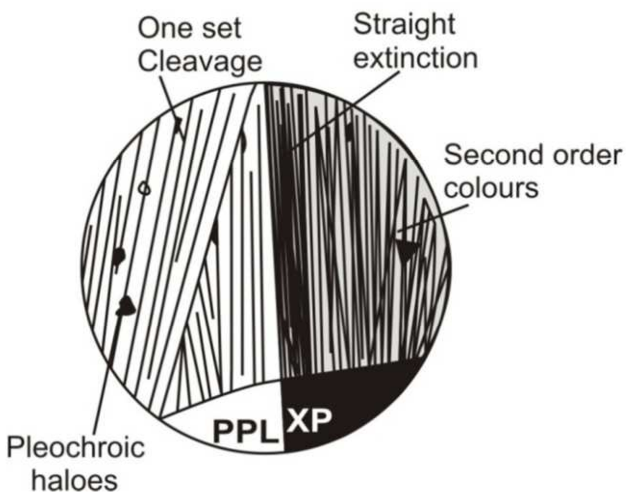
Isotropism/Anisotropism- Anisotropic

Interference colours- Strong interference colours range up to Second order red

Extinction- Parallel extinction

Twinning- Not easily observable

Diagnostic features- Brown to yellowish green, reddish brown or green, flaky form, strongly pleochroic, one set distinct cleavage and parallel extinction. Pleochroic haloes (Fig. 10.8 and 10.9) may be present



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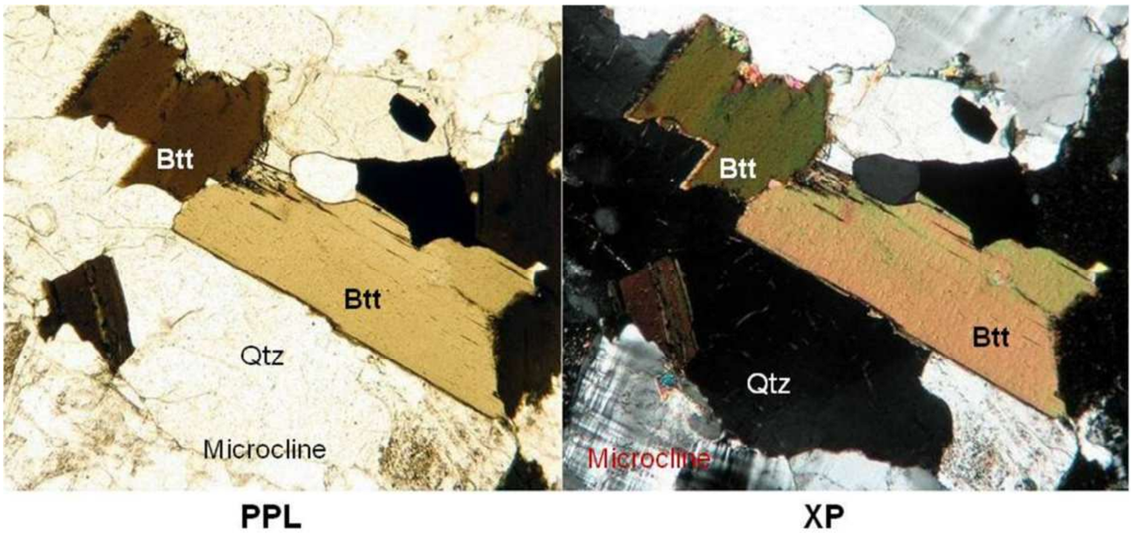


(b)

Fig.10.8: Biotite in thin section: a) Sketch of biotite with one set cleavage and pleochroic haloes in PPL and XP showing straight or parallel extinction; and b) Photomicrograph of biotite (Btt) in PPL and XP. Also notice microcline and quartz (Qtz).
(Source: http://minerva.union.edu/hollochk/c_petrology/ig_minerals.htm)

Let us recall we have learnt about pleochroic haloes in previous unit. They are circular little areas characteristically present in few minerals that tend to be strongly pleochroic (Fig. 10.9). These result due to the presence of radioactive inclusions (zircon, apatite or sphene) which are the product of radioactive disintegration.

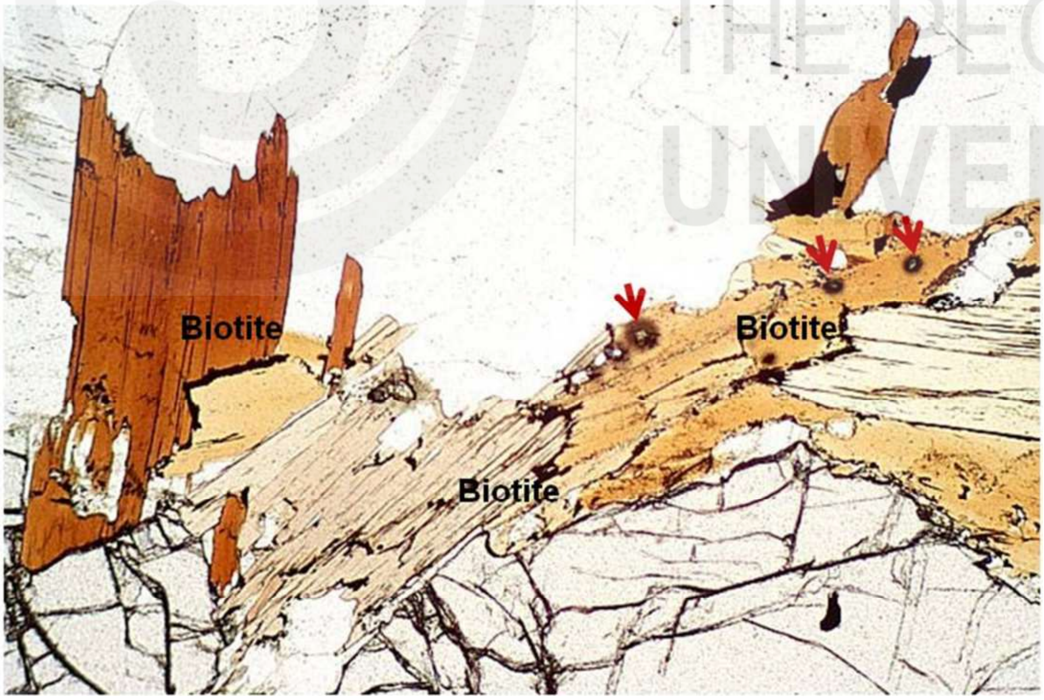


Fig. 10.9: Pleochroic haloes in biotite, notice small circular patches marked by red arrow. Notice one set cleavage and strong pleochroism displayed by biotite mineral.
(Source: http://minerva.union.edu/hollochk/c_petrology/ig_minerals.htm)

Please note that it is important for you to learn the diagnostic optical properties of biotite in order to identify it under the microscope.

In the previous sections we have discussed the optical properties of quartz, orthoclase, plagioclase, microcline, biotite and muscovite. Before going to the next section spend 5 minutes to check how you are progressing.

SAQ 1

a) What are rock-forming minerals?

b) Write the diagnostic characteristics of quartz mineral.

c) List the diagnostic twinning of orthoclase, microcline and plagioclase.

d) List the diagnostic optical properties of orthoclase, microcline and muscovite.

10.6 OPTICAL PROPERTIES OF PYROXENE GROUP MINERALS

The pyroxenes are a group of important rock-forming inosilicate minerals found in many igneous and metamorphic rocks. Pyroxenes that crystallise in the monoclinic system are known as clinopyroxenes and those crystallising in the orthorhombic system are known as orthopyroxenes.

We will read learn optical properties of augite in clinopyroxene and hypersthene in orthopyroxene.

10.6.1 Augite

The chemical composition of augite is $(Ca,Na)(Mg,Fe,Al)(Si,Al)_2O_6$.

Let us recall the physical properties of augite that we learnt in Unit 6 of this course.

Augite is green, greyish-green, greenish brown, dark brown, black in hand specimen; form is prismatic with stubby crystals having two set of cleavage at angles 87º and 93º.

We will refer to Figure 10.10 while studying optical properties of augite.

Under Plane Polarised Light

Colour- Pale green or purplish brown colour

Pleochroism- Slightly pleochroic

Form- Augite appears as short prismatic crystals with four or eight-sided cross sections

Cleavage- Two set good cleavages at 87^o and 93^o

Relief- High

Between Cross Polars

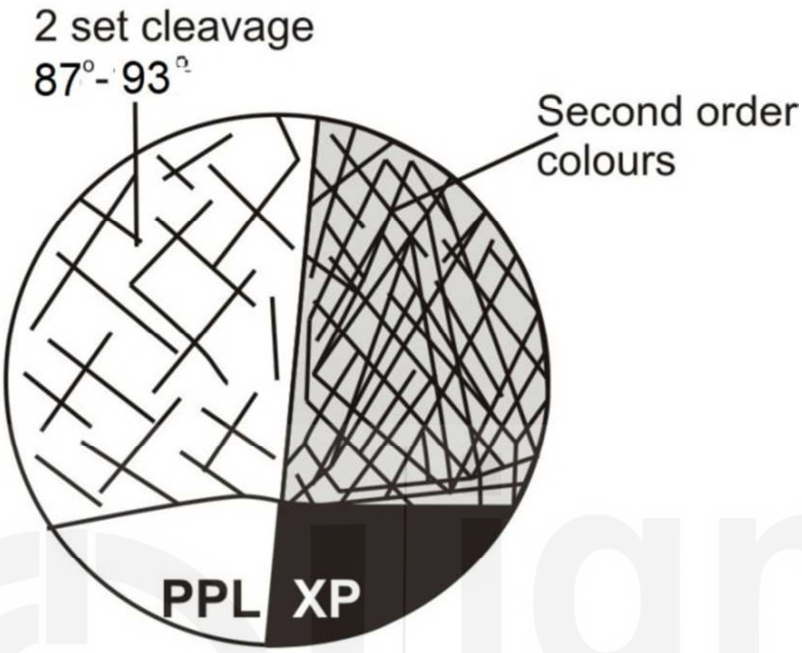
Isotropism/Anisotropism- Anisotropic

Interference colours- Maximum colours are middle Second order

Extinction- Oblique extinction, the maximum extinction angle varies from about 36^o to 45^o

Twinning- Simple or polysynthetic twins

Diagnostic features- Normally colourless, pale green or purplish brown, high relief, middle Second-order interference colours, two set distinct cleavages at 87^o and $93^o$and extinction angle at 36^o to 45^o.



(a)

PPL **XP**

(b)

Fig.10.10: Augite in thin section: a) Sketch of augite in PPL and XP showing cleavage; and b) Photomicrograph of augite in PPL and XP showing second order interference colours. Augite has two set cleavage. Also notice plagioclase grain (Plag).
(Source: http://minerva.union.edu/hollochk/c_petrology/ig_minerals.htm)

Please note that it is important for you to learn the diagnostic optical properties of augite in order to identify it under the microscope.

- Watch the following video to know more about augite mineral.

  Microscopic Study of Basaltic Rocks

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

10.6.2 Hypersthene

The chemical composition of hypersthene is $(Mg,Fe)Si_2O_6$.

Let us recall the physical properties of hypersthene that we learnt in Unit 6 of this course.

In hand specimen, hypersthene is grey, green, dark yellow, yellow-brown, and greenish-brown, brown, black in colour. Lustre is waxy, sub metallic and streak islight brown to greyish-white, form is prismatic with stubby crystals.It has two set of cleavage at angles 87º and 93º.

We will refer to Fig. 10.11 while studying optical properties of hypersthene.

Under Plane Polarised Light

Colour- Usually colourless or pale pink to green

Pleochroism- Strongly pleochroic

Form- Typically anhedral but may be euhedral, prismatic

Cleavage- Two set of cleavage at right angles

Relief- Moderately high to high

Between Cross Polars

Isotropism/Anisotropism- Anisotropic

Interference colours- Maximum interference colours are mid to upper First order, rarely upto second order blue

Extinction- Parallel extinction

Diagnostic features- High relief; light green pleochroic (light green-light pink); low birefringence; 90^{o} cleavage; parallel extinction.

Hypersthene shows schiller structure. This phenomenon is due to presence of regular and oriented inclusions of minute (sometimes microscopic), platy crystals in a regular manner along two or more intersecting planes.

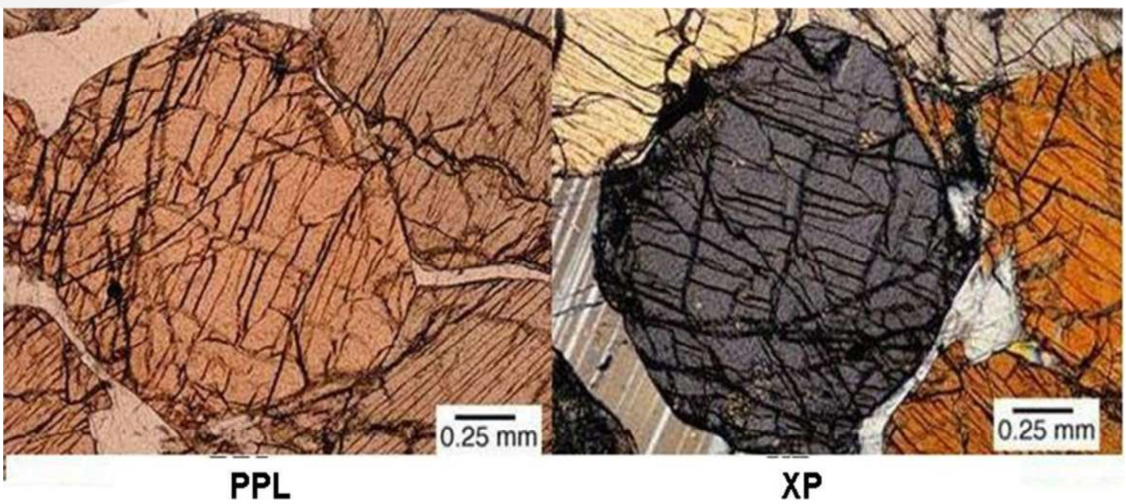


Fig. 10.11: Hyperthene showing 2 set cleavage and pleochroism under PPL. Parallel extinction seen between XP.
(Source: http://geolab.unc.edu/Petunia/IgMetAtlas/minerals/hypersthene.UX.html).

Please note that it is important for you to learn the diagnostic optical properties of hypersthene in order to identify it under the microscope.

10.7 OPTICAL PROPERTIES OF HORNBLENDE

Hornblende is inosilicate (double chain). The chemical composition of hornblende is Ca Na)$_{2-3}$(Mg Fe Al)$_5$ Si$_6$(Si Al)$_2$O$_{22}$(OH)$_2$.

Let us recall the physical properties of hornblende that we learnt in Unit 6 of this course.

Hornblende is black, dark green, dark brown, dark grey in colour. It occurs as prismatic or tabular crystals sometimes as columnar, radiating, acicular, fibrous and massive. It has two set perfect prismatic at cleavage angles of 56^o and 124^o.

We will refer to Fig.10.12 while studying optical properties of hornblende.

Under Plane Polarised Light

Colour- Various shades of green and brown shows pleochroism yellowish green to dark brown

Pleochroism- Strongly pleochroic

Form- Prismatic crystals with imperfect diamond-shaped cross sections

Cleavage- Two distinct cleavages at 56^o and 124^o

Relief- Moderate to high.

Between Cross Polars

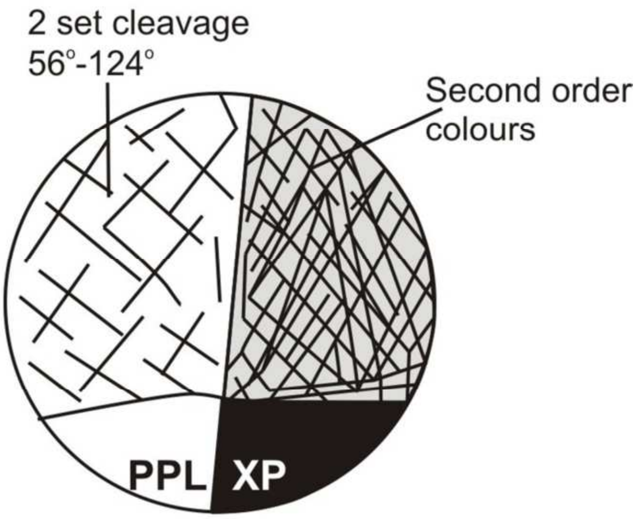
Isotropism/Anisotropism- Anisotropic

Interference colours- Maximum colours are about middle second order but may be masked by dark green or brown colour of the mineral.

Extinction- Oblique extinction, the maximum extinction angle varies from about 12^o to 30^o depending on composition.

Twinning- Commonly simple twins

Diagnostic features- Greencolour and strong pleochroism and characteristic prismatic form with 2 set cleavage (124^o to 56^o).



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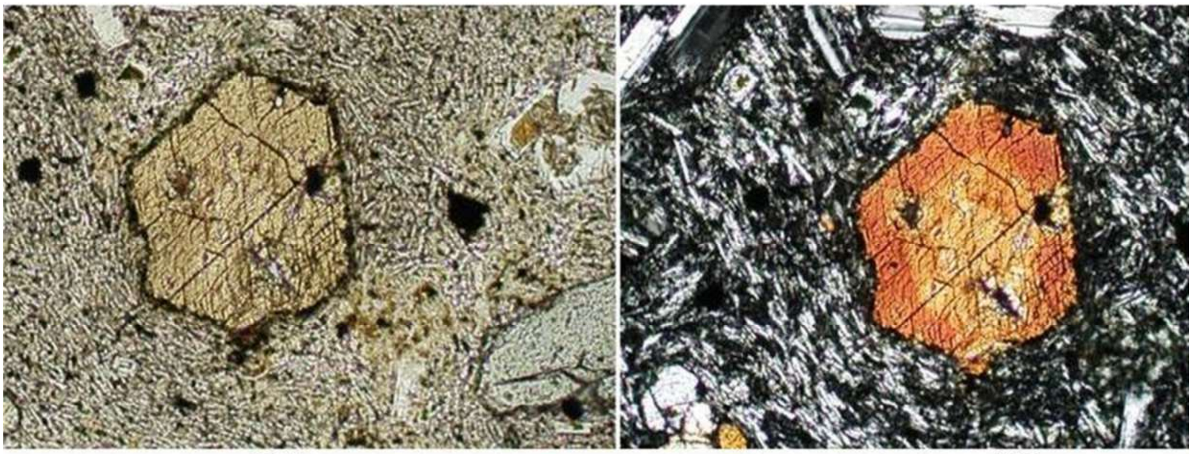


(b)

Fig.10.12: Hornblende in thin section: a) Sketch of hornblende in PPL and XP showing 2 sets of cleavage at 56° and 124°; and b) Photomicrograph of hornblende (with hexagonal shape) in PPL and XP. (Source: http://www.science.smith.edu/geosciences/petrology/petrography/hornblende/CrossPolars.html)

Please note that it is important for you to learn the diagnostic optical properties of hornblende in order to identify it under the microscope.

10.8 OPTICAL PROPERTIES OF OLIVINE AND GARNET

In this section we will discuss about olivine and garnet. They are nesosilicates.

10.8.1 Olivine

Olivine is having chemical composition of $(Mg\ Fe)_2SiO_4$.

Let us recall the physical properties of olivine that we learnt in Unit 6 of this course.

In hand specimen olivine is usually olive green, but can be yellow-green to bright green. It occurs as granular masses. Cleavage is absent.

Now we will refer to Figure 10.13 while studying optical properties of olivine.

Under Plane Polarised Light

Colour- Colourless, occasionally very light yellowish or greenish

Pleochroism- Non pleochroic

Form- Normally anhedral but grains have six-sided polygonal outline

Cleavage- Absent but internal fracturing of grains common

Relief- Moderately high relief

Between Cross Polars

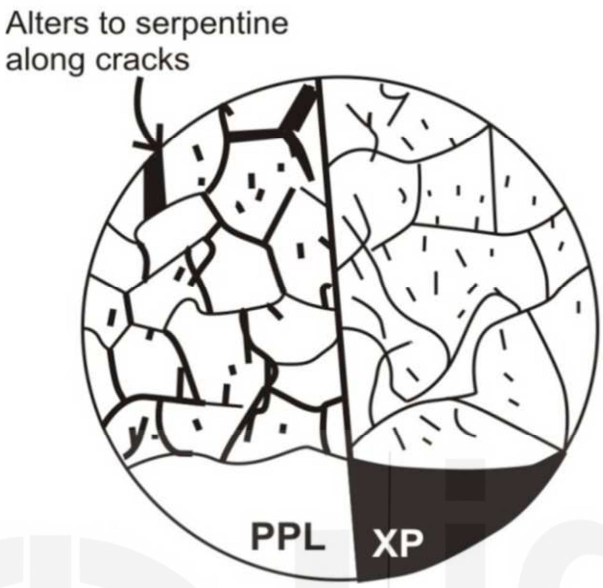
Isotropism/Anisotropism- Anisotropic

Interference colours- Bright second and Third-order interference colors

Extinction- Parallel to cleavage and crystal outlines

Twinning- Rare and poorly developed

Diagnostic features- Colourless, bright Second-order interference colours, high relief, irregular fracturing, lack of cleavage. It is commonly rimmed with brownish or greenish alteration products, often serpentine



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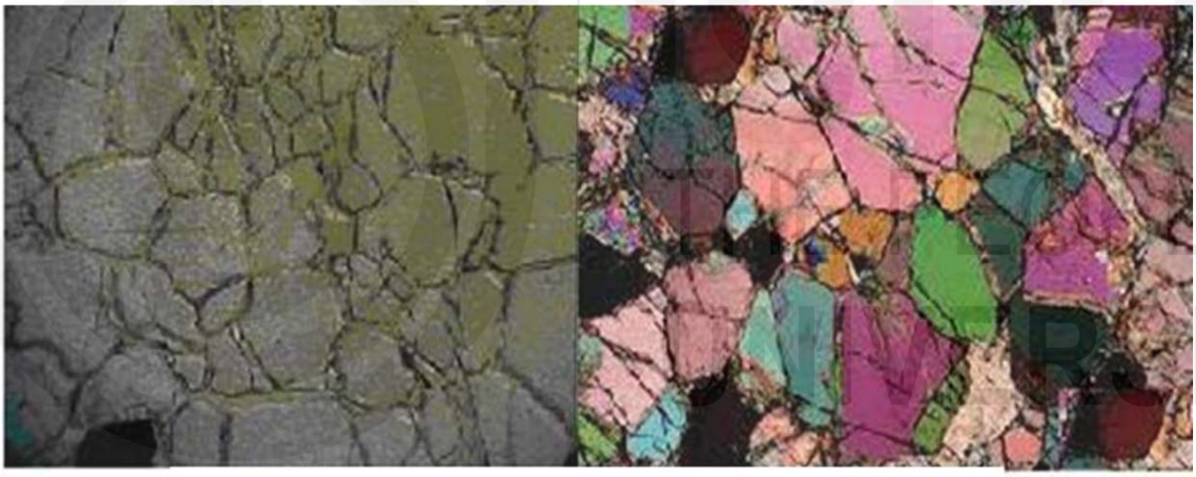


PPL **XP**

(b)

Fig.10.13: Olivine in thin section: a) Sketch of olivine in PPL and XP showing cracks filled with altered products; and b) Microphotograph of olivine in PPL and XP. (Source: http://minerva.union.edu/hollochk/c_petrology/ig_minerals.htm)

Please note that it is important for you to learn the diagnostic optical properties of olivine in order to identify it under the microscope.

10.6.2 Garnet

The chemical composition of garnet is $A_3B_2(SiO_4)_3$

where,

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

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

Let us recall the physical properties of garnet that we learnt in Unit 6 of this course.

Garnet is often red, reddish brown or black in colours. It typically occurs as perfect crystal rhomb dodecahedron crystal habit. It is also found as granular masses. Cleavage is absent. Hardness is 7-8.

We will refer to Figure 10.14 while studying optical properties of garnet.

Under Plane Polarised Light

Colour- Colourless or pink and light shades of red, brown, green or sometimes darker colours.

Pleochroism- Very slightly pleochroic

Form- Euhedral crystals are six or eight sided; irregular polygons or subhedral to anhedral crystals are also common

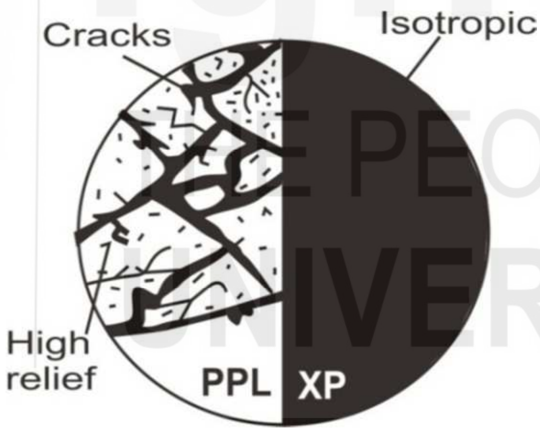
Cleavage- None, but irregular fractures are common

Relief- Very high

Between Cross Polars

Isotropism/Anisotropism- Garnet is isotropic

Diagnostic features- Very high relief, isotropic, colourless but often having a pale tinge, irregular fracture with inclusion present.



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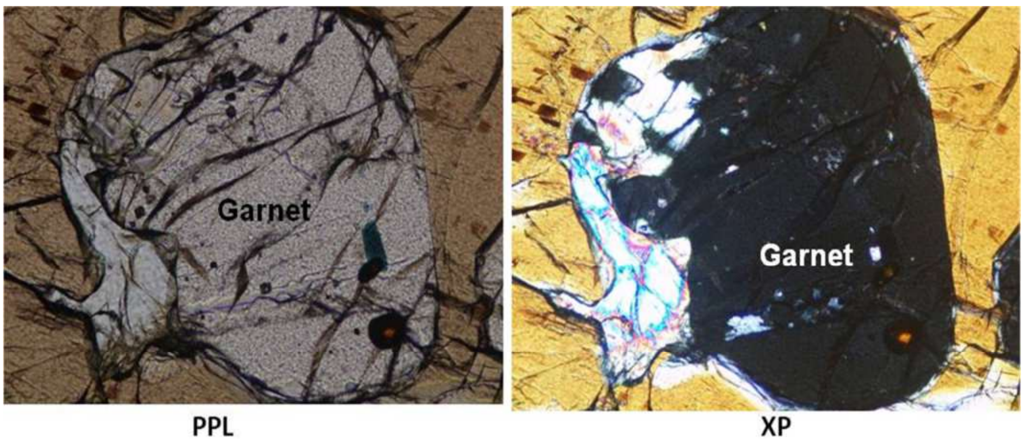


(b)

Fig.10.13: Garnet in thin section: a) Sketch of garnet showing cracks in PPL and isotropism XP altered products; and b) Photomicrograph of garnet in PPL and XP. Garnet shows isotropism. (Photo credit : Dr. Divya Prakash)

Please note that it is important for you to learn the diagnostic optical properties of garnet in order to identify it under the microscope.

10.8 OPTICAL PROPERTIES OF CALCITE

Let us recall the physical properties of calcite that we learnt in unit 6 of this course.

The colour of calcite in hand specimen is extremely variable but generally white or colourless or with light shades of yellow, orange, blue, pink, red, brown, green, black and grey. It possesses 3 set of perfect, rhombohedral cleavage. Hardness is 3.

We will refer to Figure 10.15 while studying optical properties of calcite.

Under Plane Polarised Light

Colour- Usually colourless and be cloudy in thin sections. Calcite tends to be grainy in appearance and shows pastel hues or twinkling effects

Pleochroism- Non pleochroic

Form- Typically fine to coarse grained subhedral to euhedral aggregates

Cleavage- 3 set perfect rhombohedral cleavage

Relief- High to Low, variable relief

Between Cross Polars

Isotropism/Anisotropism- Anisotropic

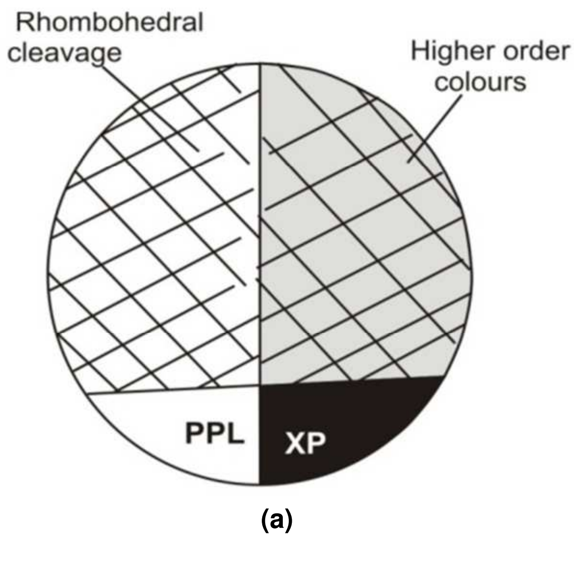
Interference colours- Interference colours are fourth or fifth order colour

Extinction- Symmetrical to cleavages

Twinning- Polysynthetic twinning

Twinkling: It is very prominent. When a thin section of an anisotropic mineral with widely differing refractive indices is rotated rapidly on the stage twinkling is the effect observed in plane polarised light. The 'twinkling' appearance is caused by the rapid changes in relief

Diagnostic features- Colourless, extreme birefringence, extremely high order interference colors and has a pearly appearance because of tiny patches of color; variable relief with stage rotation twinkling is observed. 3 set rhombohedral cleavage and polysythetic twinning seen.



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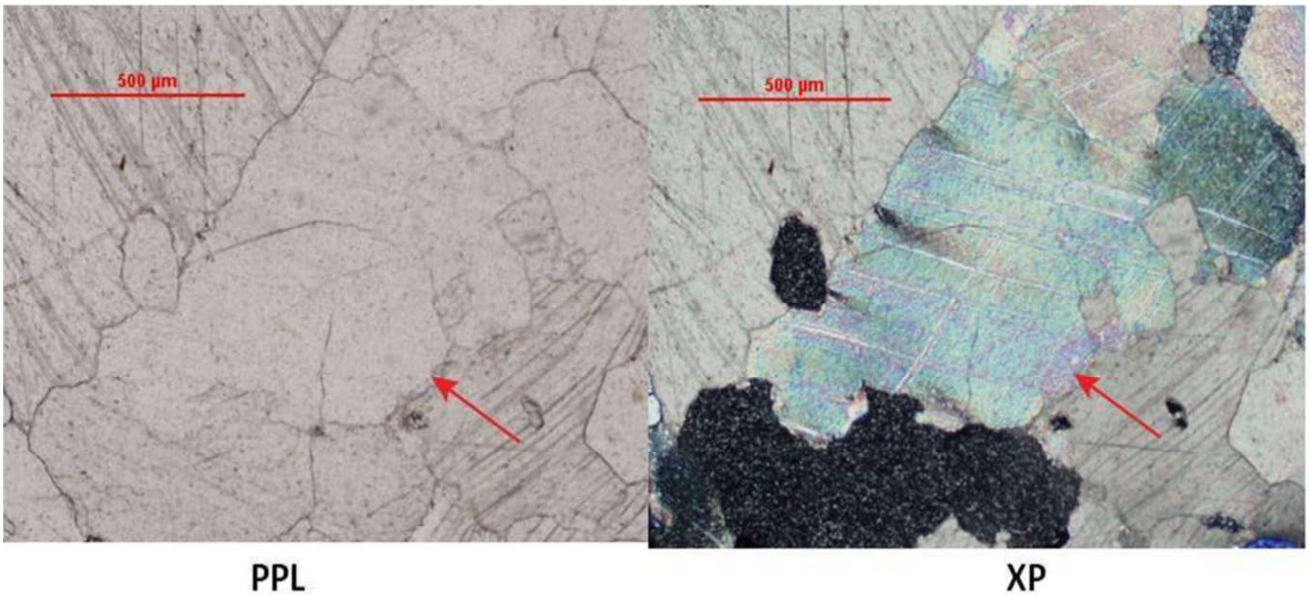

(b)

Fig.10.15: Calcite in thin section: a) Sketch of calcite with three set rhombohedral cleavage in PPL and XP; and b) Microphotograph of calcite. Notice twinkling and 3 set of cleavage in PPL and third order interference colours under XP. (Source: www.science.smith.edu/geosciences/petrology/petrography/calcite/calcite2.html)

Please note that it is important for you to learn the diagnostic optical properties of calcite in order to identify it under the microscope.

In the previous sections we have discussed the optical properties few more minerals. Before summarising what we have learnt in this unit spend 5 minutes to check how you are progressing.

SAQ 2

a) Mention one example of each orthopyroxene and clinopyroxene.

b) What is cleavage angle of augite and hornblende?

c) Mention extinction angle of augite and hypersthene.

d) What is schiller structure?

e) Which mineral exhibits isotropism between cross nicols?

f) How set of cleavage is shown by calcite?

10.9 SUMMARY

Let us summarise the important optical properties of minerals in Table. 10.1 and 10.2.

Table 10.1: Optical properties of minerals - 1.

A. OPTICAL PROPERTIES UNDER PLANE POLARISED LIGHT (PPL)						
Properties	**Quartz**	**Orthoclase**	**Microcline**	**Plagioclase**	**Muscovite**	**Biotite**
Colour	Colorless, clear	Colorless, cloudy	Colorless, cloudy	Colorless cloudy	Colorless	Brown to light yellow
Pleochroism	Absent	Absent	Absent	Absent	Slightly to pale green	Present, dark brown to light yellow
Cleavage	Absent	2 sets at 90^0	2 sets at 90^0	2 sets at 90^0	One set perfect	One set perfect
Form	Subhedral	Subhedral or anhedral	Subbhedral to anhedral	Subbhedral to anhedral	Tabular crystals, flakes or laths	Lath shaped
Relief	Very low	Low	Low	Low	Moderate	Moderate
B. OPTICAL PROPERTIES BETWEEN CROSS NICOLS (XP)						
Properties	**Quartz**	**Orthoclase**	**Microcline**	**Plagioclase**	**Muscovite**	**Biotite**
Isotropic / Anisotropic	Anisotropic	Anisotropic	Anisotropic	Anisotropic	Anisotropic	Anisotropic
Interference Colors	First order white and grey	First order white and grey	First order white and grey	First order white and grey	Up to Second order yellow or red	Second order red
Extinction	Undulose or wavy	Oblique varies from 0^o to 12^o	Oblique varies upto 15^o	Oblique, angle varies with composition	Parallel	Parallel
Twinning	Not detected	Carlsbad twinning	Cross hatch twinning	Polysynthetic twinning	Hard to detect	Poorly developed
Special properties	—	—	—	Zoning	—	Pleochroic haloes

Table 10.2: Optical properties of minerals - 2.

A. OPTICAL PROPERTIES UNDER PLANE POLARISED LIGHT (PPL)						
Properties	**Garnet**	**Olivine**	**Hornblende**	**Hypersthene**	**Augite**	**Calcite**
Colour	Pinkish to colorless	Mostly colorless	Shades of green and brown	Colourless or pale pink to green	Colorless	Colorless
Pleochroism	Absent	Absent	Present, yellowish green to dark green	Present	Present, pale green or purplish brown colour	Absent
Cleavage	Absent, cracks Present	Not seen, many cracks present	2 sets at 56^0& 124^0	2 sets at 90^0	2 sets at 87^0& 93^0	Rhombohedral 2 or 3 sets,
Form	Eubhedral to anhedral	Anhedral grains with polygonal outline	Prismatic	Mostly anhedral	Prismatic crystals	Euhedral to subhedral
Relief	Very high	Moderately high	Moderate to high	Moderate to high	High	Moderate
B. OPTICAL PROPERTIES BETWEEN CROSS NICOLS (XP)						
Properties	**Garnet**	**Olivine**	**Hornblende**	**Hypersthene**	**Augite**	**Calcite**
Isotropic / Anisotropic	Isotropic	Anisotropic	Anisotropic	Anisotropic	Anisotropic	Anisotropic
Interference Colors		Bright Second and third order	Mostly middle Second order	Upper First-order to Second order red	Mostly middle Second order	Up to Second order yellow or red
Extinction		Straight	Oblique, 12^0 to 30^0	Parallel	Oblique, 36^0 to 45^0	Parallel
Twinning		Poorly developed	Simple twins	_	Simple or polysynthetic	Hard to detect
Special properties	Cracks present	Cracks present	_	Schiller structure	_	Twinkling present

10.10 ACTIVITY

1. Find out the rock forming minerals in granite and basalt and write down their diagnostic optical properties.

10.11 TERMINAL QUESTIONS

1. Discuss the optical properties of feldspar group minerals.
2. Discuss the optical properties of mica group minerals.
3. Discuss the optical properties of pyroxene group minerals.

Audio/video material based questions

- Explain two types of zoning present in plagioclase.
- Name the types of twinning found in feldspar minerals, explain them.
- How do you identify augite in thin section?

10.12 REFERENCES

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10.13 FURTHER/SUGGESTED READINGS

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- Gribble, C.D. (2001) Rutley's Elements of Mineralogy, 27th Edition, CBS Publishers and Distributors, Delhi.
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- Singh, P. (2013) Engineering and General Geology, S.K. Kataria & Sons, Delhi.

10.14 ANSWERS

Self Assessment Questions

1 a) Rock- forming minerals are those minerals that make up the major components of a rock and they are used in the classification of rock types.

b) Colourless and clear, display First-order white or weak yellow interference colours, lack of cleavage, lack of alteration and often shows undulatory extinction. Rarely contains inclusions of other minerals.

c) Orthoclase-simple carlsbad twinning; microcline-cross hatch twinning; plagioclase-polysynthetic twinning.

d) Colourless to pale green under plane polarised light, form is flaky, Second-order interference colours; one set cleavage perfect; parallel extinction.

2 a) Augite and hypersthene.

b) Two good cleavages at 87^{o} and 93^{o}(in case of augite);124^{o} and 56^{o} (in case of hornblende) .

c) 36^{o} to 45^{o} (in case of augite) and parallel (in case of hypersthene).

d) Schiller structure is exhibited is due to presence of regular and oriented inclusions of minute size (sometimes microscopic), platy crystals in a regular manner along two or more intersecting planes.

e) Garnet.

f) 3 set Perfect rhombohedral cleavage.

Terminal Questions

1. Please refer Section 10.4.
2. Please refer Section 10.5.
3. Please refer Section 10.6.

GLOSSARY

Accessory minerals	:	These minerals are present in less quantities in a rock. Their presence and absence do not affect the definition and classification of a rock.
Accessory slot		Below the analyser, accessory slot is there into which accessory plates, e.g. quartz wedge, or gypsum plate, can be inserted. The slot is oriented so that accessory plates are inserted at 45o to the cross wires.
Alteration	:	This involves the process of physical or chemical change in the rocks or minerals after their formation.
Amorphous	:	This term is used for those rocks, minerals and materials which have no form and definite crystal structure.
Anisotropic		All the crystals except those of isometric system fall in this group. Minerals of tetragonal, orthorhombic, monoclinic, trigonal and hexagonal and triclinic systems are anisotropic.
Axial angle	:	It is the angle between two optical axis of a biaxial crystal.
Biaxial	:	Crystals crystallising in orthorhombic, monoclinic and triclinic system consisting of two optical axis.
Canada balsam		Canada balsam is a resin, viscous, sticky, colourless or yellowish liquid that turns to a transparent yellowish mass when the essential oils in which it is dissolved, are allowed to evaporate.
Conchoidal	:	This term is used to describe nature of the fracture
Euhedral	:	It is concerned with a form which is partially comprises of its own crystal faces in crystallography.
Double refraction		Double refraction is the phenomenon of splitting of the beam of ordinary light into on passing through anisotropic medium.
Extinction angle		When the anisotropic minerals are studied under the microscope in cross nicol, it is the angle between crystallographic structural direction and optical direction in which the mineral is in the condition of complete darkness.
Glassy	:	It is the term used for glassy texture developed in volcanic rocks.

Iceland spar		The phenomenon of double refraction is very prominently visible with the help of colourless transparent variety of calcite called iceland spar.
Isotropic	:	This group includes those materials whose refractive index is not dependent on the direction in which the light travels. The isotropic substances possess a single and constant refractive index for each wavelength.
Non-opaque		Non-opaque minerals permit the light to pass through them.
Opaque		Minerals which do not permit the light to pass through thin sections are said to opaque minerals.
Optical mineralogy		Optical mineralogy is the study of the interaction of light with minerals which is commonly limited to visible light.
Rock-forming minerals		Rock-forming minerals are those minerals that make up the major components of a rock and they are used in the classification of rock types viz. igneous, sedimentary and metamorphic.
Subhedral	:	It is concerned with a form which is partially comprises of its own crystal faces in crystallography.
Twinning	:	Formation of twinned crystals.
Twinning law	:	It is the law governing the relation between different parts of a plane. It is based on following factors: Axis of twinning or plane of twinning Internal of twinned plane Nature of twinned plane Few laws of twinning are: Albite law, Baveno law, Carlsbad law etc.
Uniaxial	:	Consisting only of one optical axis.