

General geology II (G102)

1st year students (2024–2025)



General geology (II)

Syllabus

Part I: Crystallography

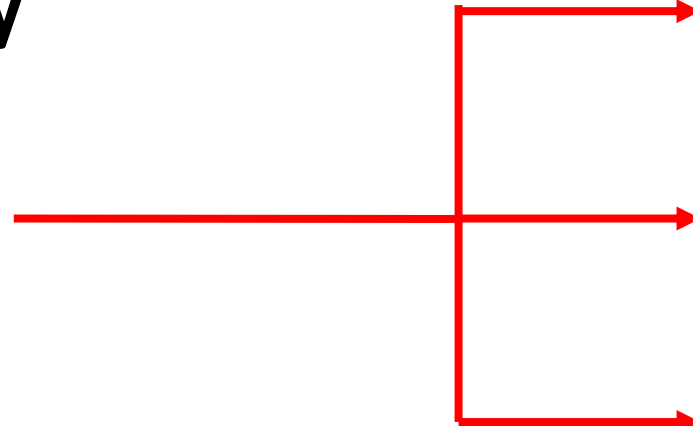
Part II: Mineralogy

Part III: Petrology

Igneous rocks

Sedimentary rocks

Metamorphic rocks



Part I: Crystallography

I.1. Define Crystallography and Crystal

I.2. Unit cell

I.3. Crystal lattice

I.4. Crystalline and amorphous substance

I.5. Crystal parts

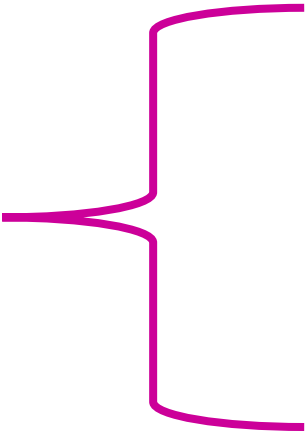
I.6. Elements of symmetry

I.7. Elements of crystallization

I.8. Crystal form

I.9. Crystal systems

**Crystal
Morphology**

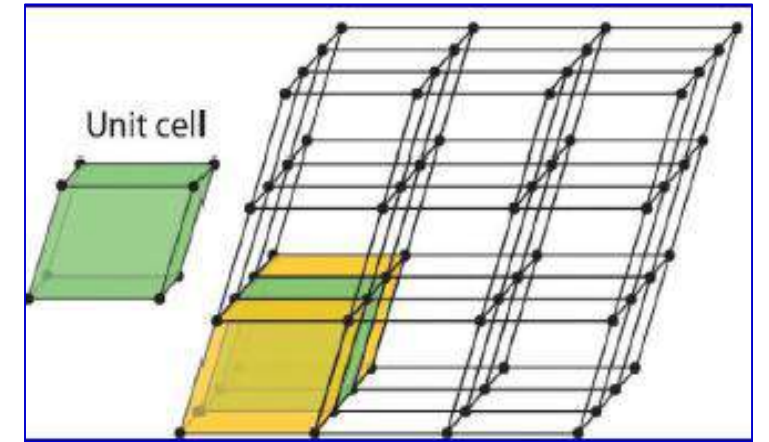
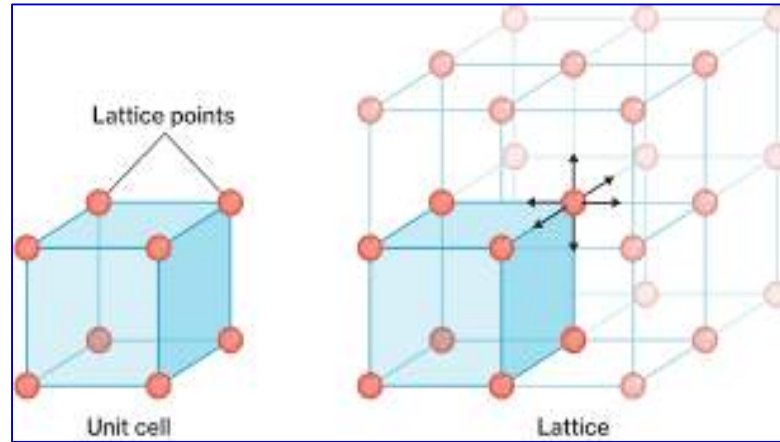


I.1. Define Crystallography and Crystal

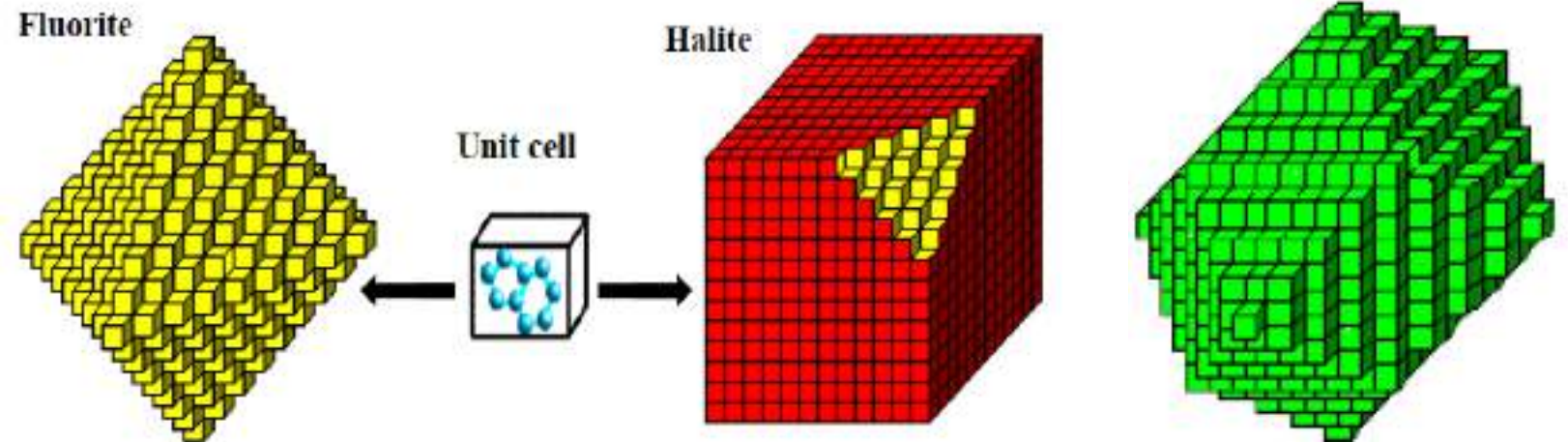
- **In General, *Crystallography*** is a branch of science concerned with the study of crystalline matter on the atomic scale either it was chemically or naturally formed.
- **In Geology, *Crystallography*** is the science deals with the study of mineral crystals in terms of morphology (external form) and internal structure
- ***A crystal*** is solid natural homogeneous material has an ordered internal structure [regular arrangement of its internal constituents (atoms, ions or molecules)].

I.2. Unit cell

Unit cell is the building block of crystal (The smallest group of similar or different elements arranged in a three dimensional geometrical shape

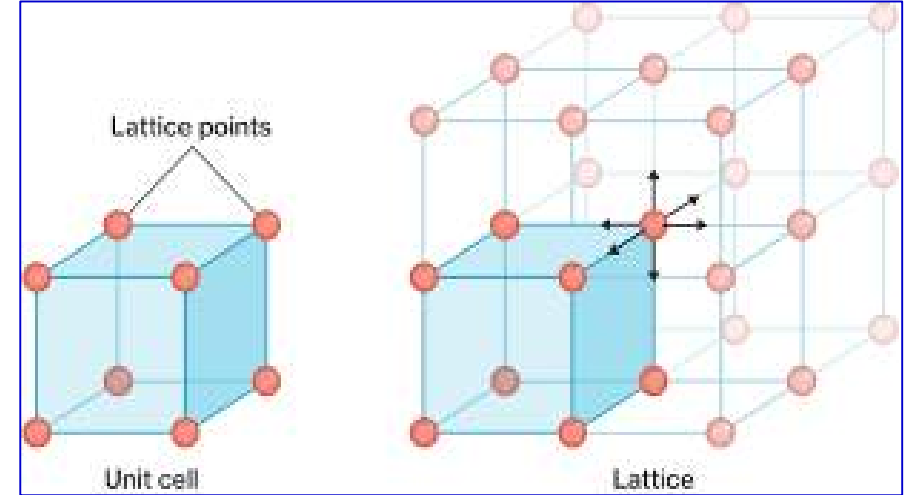


- The cubic crystal of NaCl (Halite) and fluorite is made up of very small cubelets by repetition



I.3. Crystal lattice

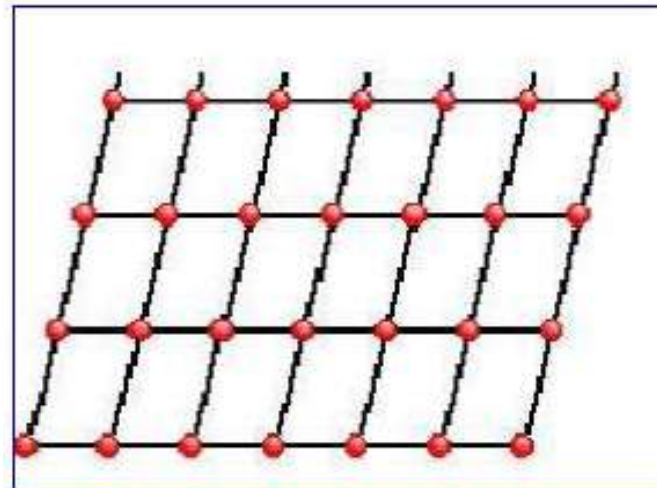
- **Crystal lattice:** the regular repetition of unit cells in in all three dimensions
- **Space lattice:** If each atom in unit cell is replaced by a point in space, then the resultant points in space are called space lattice
- Each point in a space lattice is called **a lattice point**



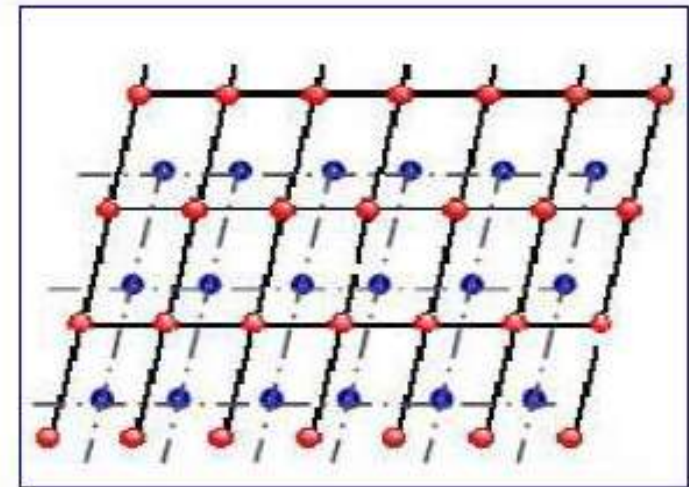
- **There are two types of crystal lattice:**

- a) **Bravais lattice:** If the surroundings of each lattice point is same.
- b) **Non-Bravais lattice:** If the surroundings of each lattice points are not the same

Bravais lattice



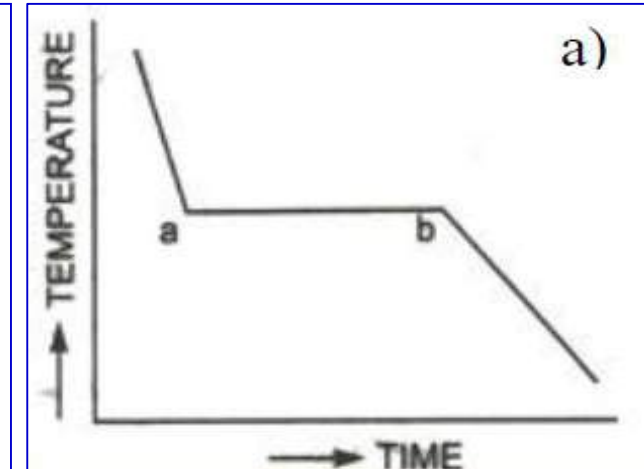
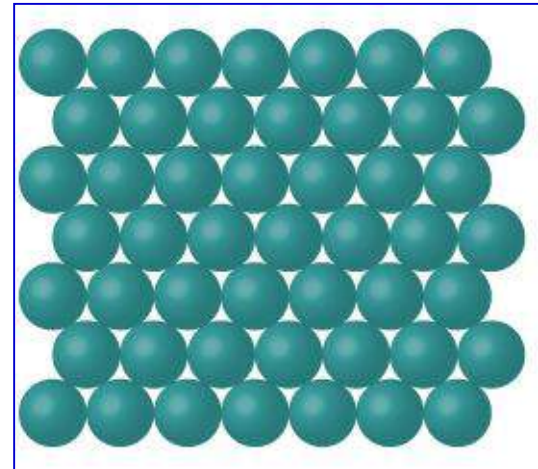
Non-Bravais lattice



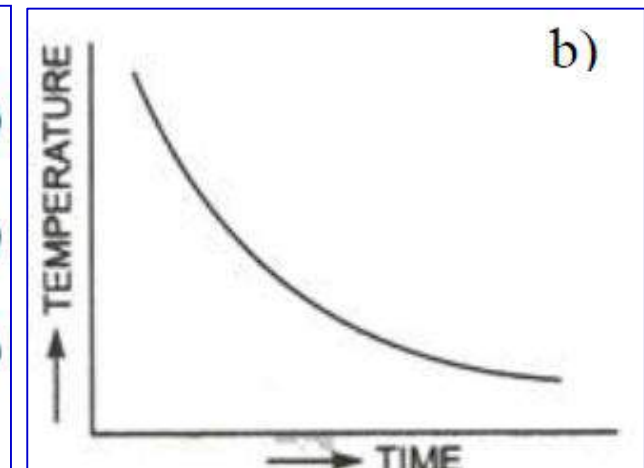
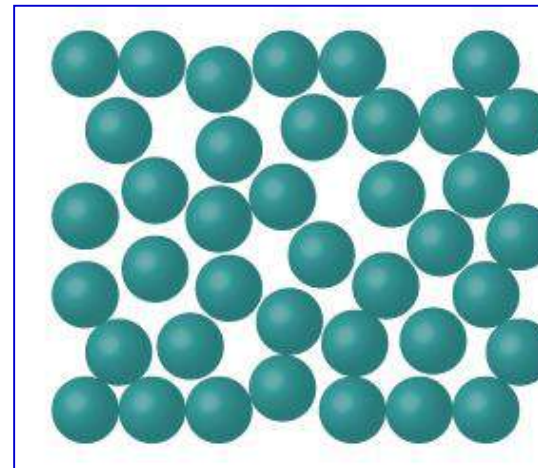
I.4. Crystalline and amorphous substance

Crystalline substance	Amorphous substance
Has ordered internal structure with or without crystal faces.	lacks ordered internal structure and crystal faces
Has sharp, well-defined melting points	does not have a definite melting point
Has periods of constant temperature during cooling and crystallization processes	formed by rapid cooling of melt (e.g., a piece of glass or opal)

Crystalline substance



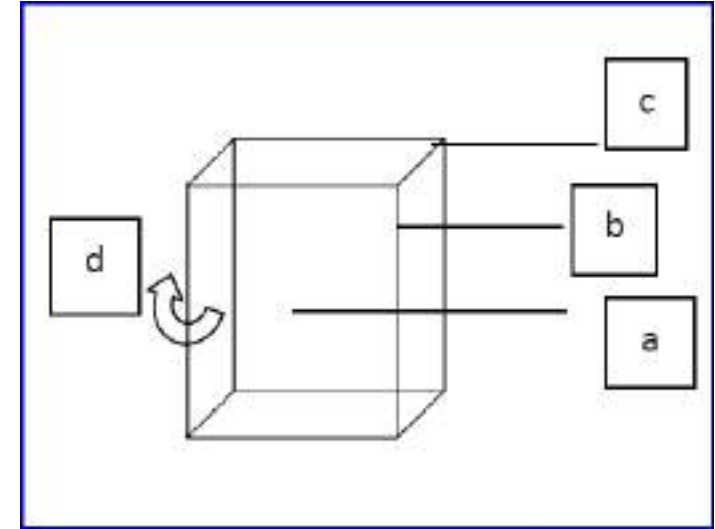
Amorphous substance



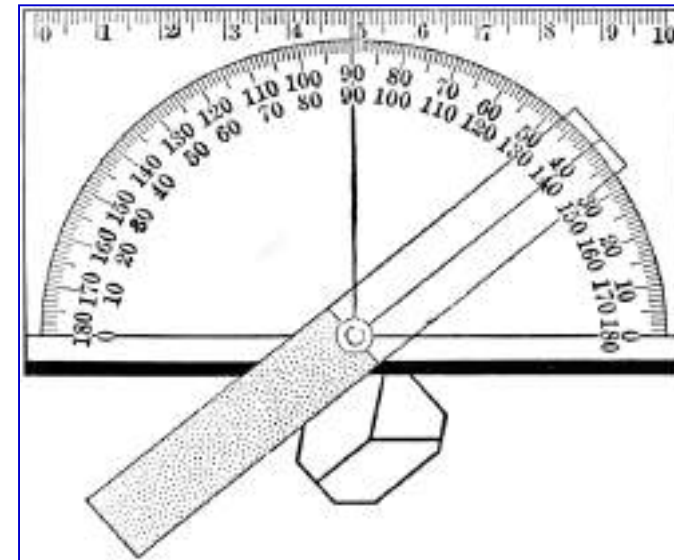
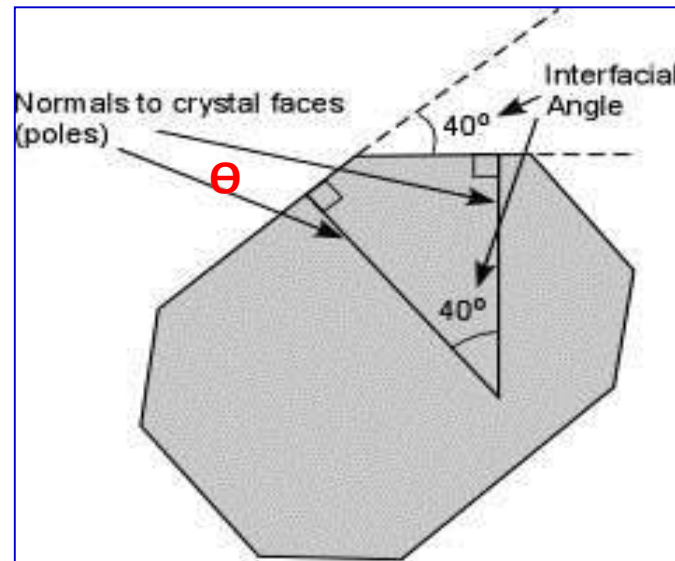
I.5. Crystal parts

Crystal consists of:

- a) Crystal faces:** The external smooth planer surfaces of the crystal.
- b) Crystal edge:** The line resulting from meeting of two neighboring faces
- c) Solid angle:** The point resulting from meeting of more than two adjacent faces
- d) Interfacial angle:** It is the angle between two neighboring faces



- ✓ The value of the angle can be estimated either by measuring the angle between lines that are perpendicular to the faces or by using contact goniometer
- ✓ The interfacial angle for a mineral is constant regardless to its size

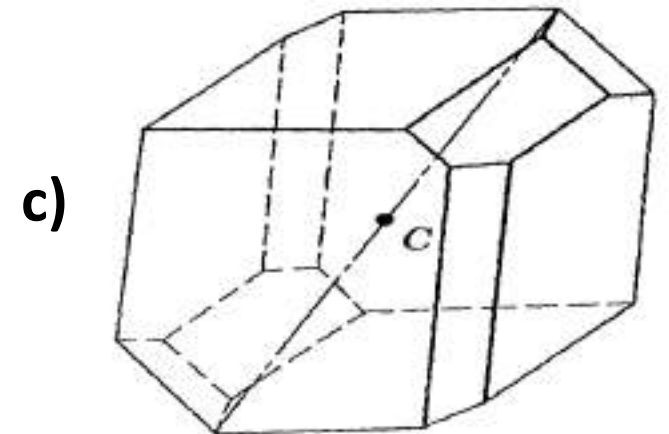
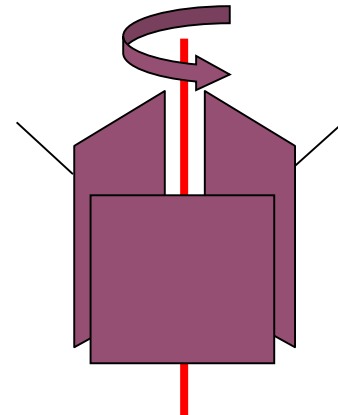
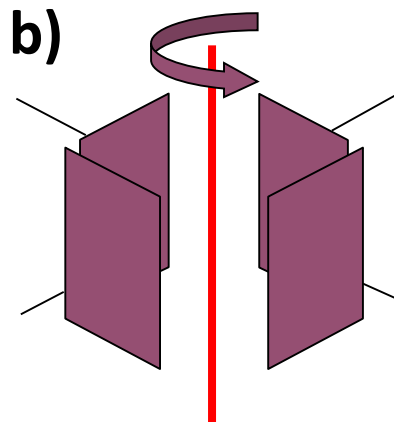
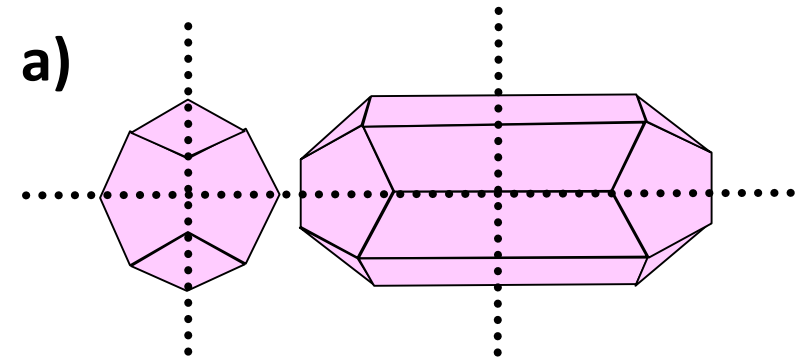


I.6. Elements of symmetry

Since the internal symmetry is reflected in the external form of perfect crystals, we are going to concentrate on repetition of crystal parts.

This Repetition could be in relation to:

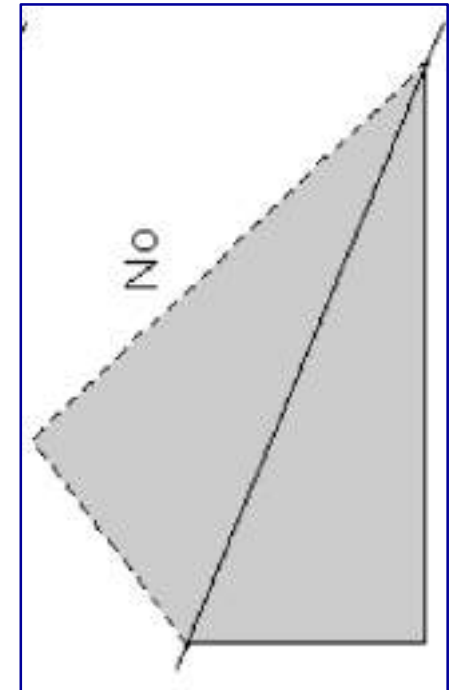
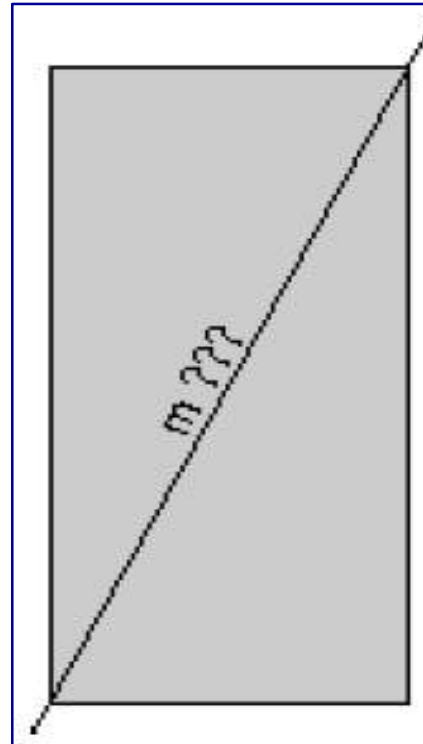
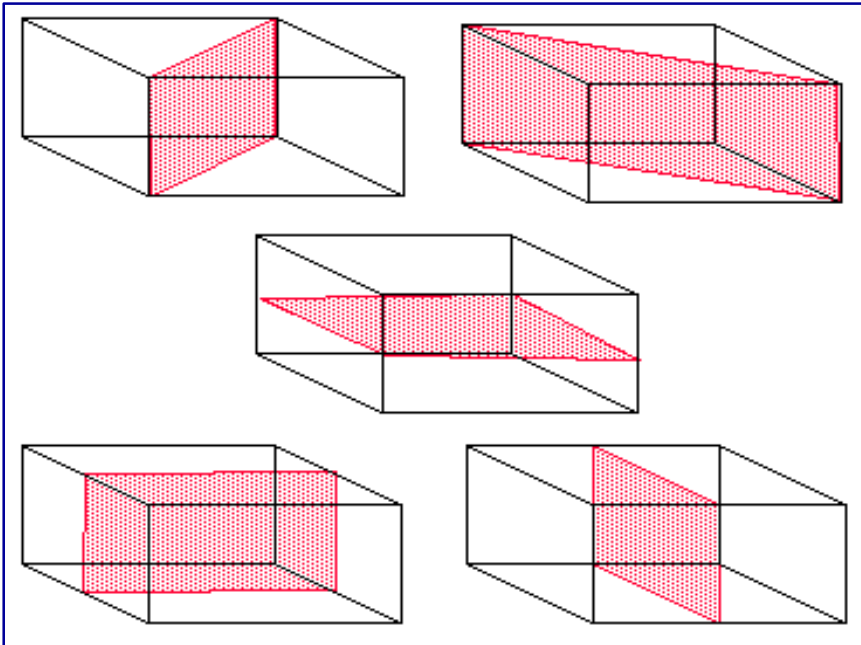
- a) Plane of Symmetry
- b) Rotational axes of symmetry
- b) Center of Symmetry



I.6. Elements of symmetry

a) Plane of Symmetry (P)

This is an imaginary plane which divides the crystal into 2 equal and identical halves each is a mirror image to the other. A crystal can have one or more planes of symmetry. Plane of symmetry is symbolized with the letter (P). A rectangle does not have mirror symmetry along the diagonal lines

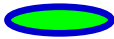


I.6. Elements of symmetry

b) Rotational axes of symmetry (L)

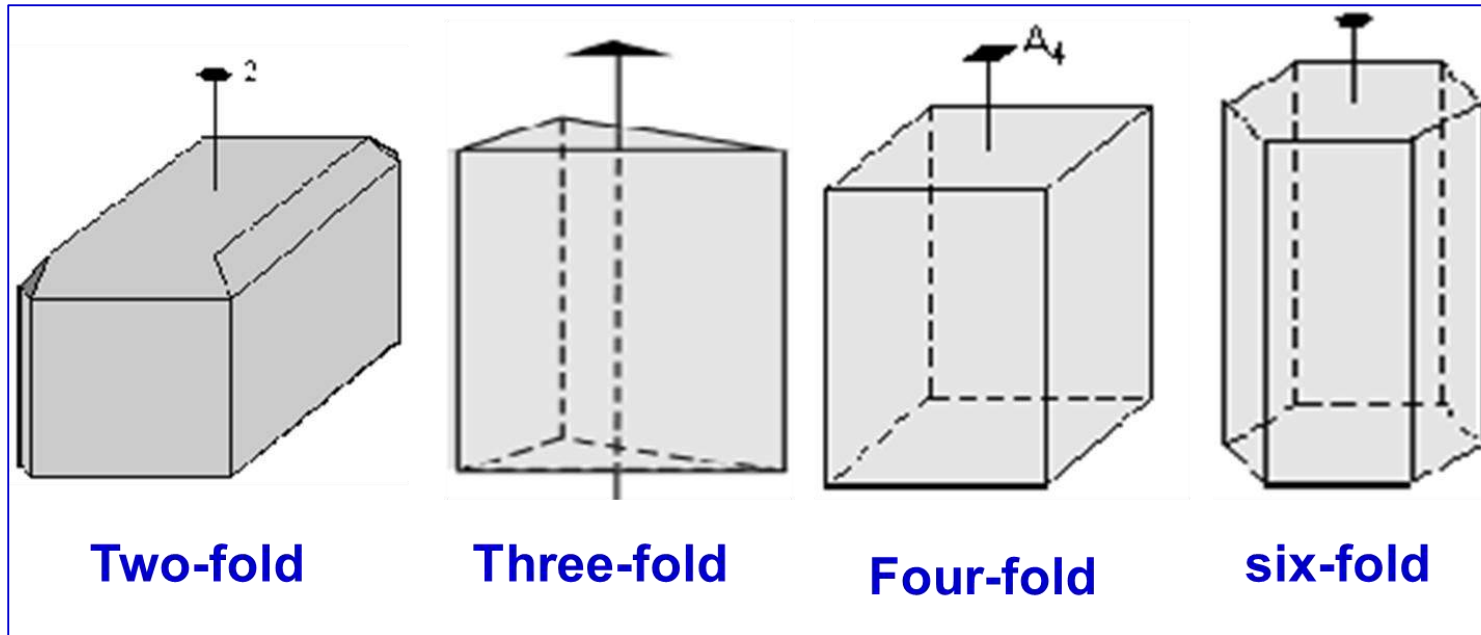
This is an imaginary lines passing through the center of the crystal around which the crystal may be rotated and similar face come to occupy the same position more than once in a complete rotation of 360° . It symbolizes with letter L.

➤ According to the number of times which similar faces appear in the same position during a complete rotation, we have four types of axes of symmetry:

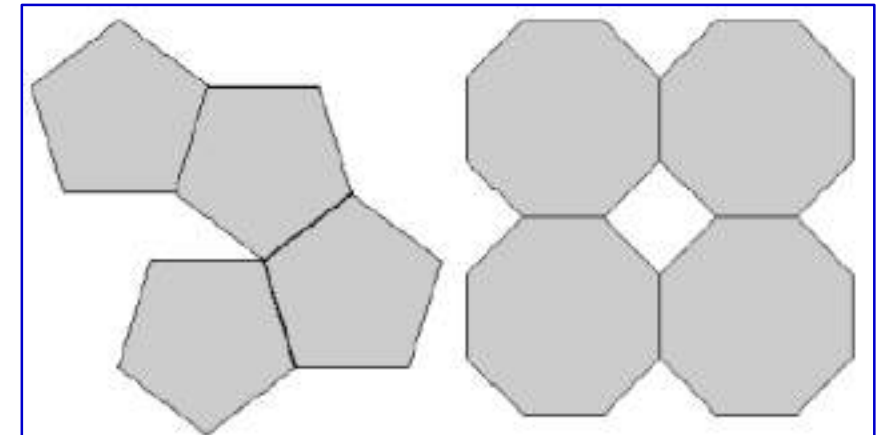
- **Two-fold (Diad) axis (L_2):** Crystal face repeats after a rotation of 180° 
- **Three-fold (Triad) axis (L_3):** Crystal face repeats after a rotation of 120° 
- **Four-fold (Tetrad) axis (L_4):** Crystal face repeats after a rotation of 90° 
- **Six-fold (Hexad) axis (L_6):** Crystal face repeats after a rotation of 60° 

I.6. Elements of symmetry

b) Rotational axes of symmetry



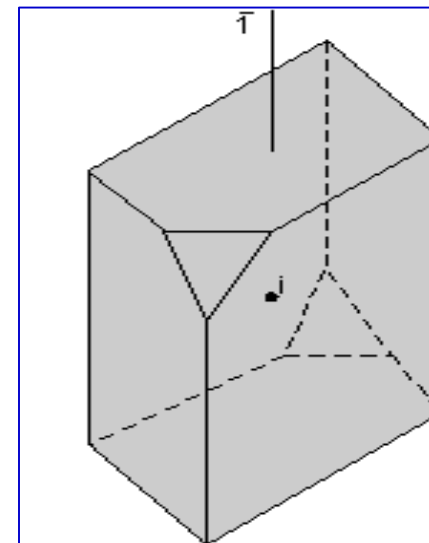
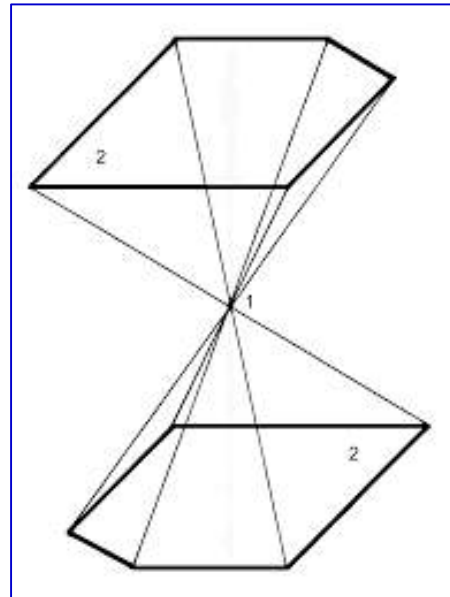
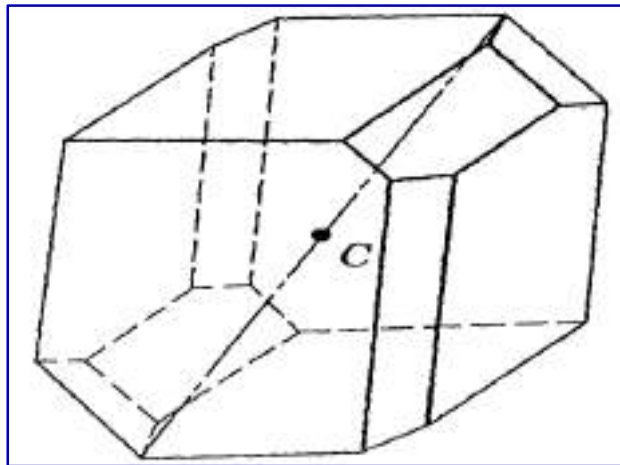
- 5-fold, 7-fold and other symmetries are not possible in crystals because you can't fill space with 5, 7 or 8 sided objects which is not consistent with the geometric arrangement of atoms in crystal.



I.6. Elements of symmetry

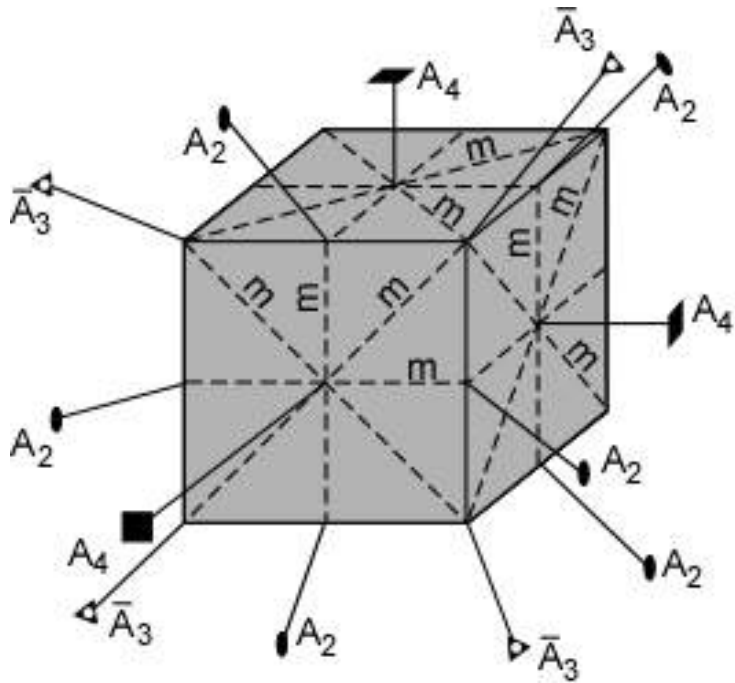
c) Center of symmetry (C)

Centre of symmetry is an inversion through a point, which is consistent with the center of crystal. If an imaginary line starts from any point (face, angle, and corner) on the surface of the crystal and passes through its center, a similar point on the opposite side should be met with at equal distance from the center. The symbol of center of symmetry is C

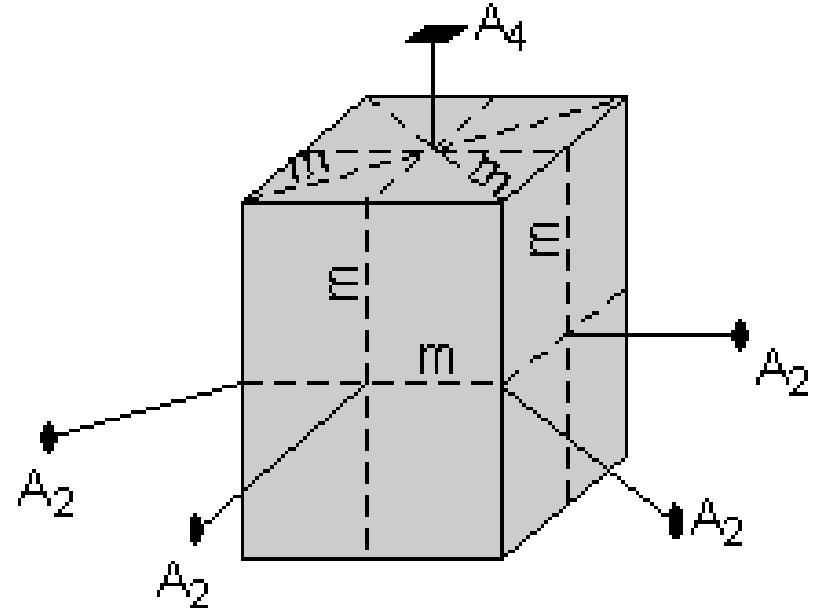


I.6. Elements of symmetry

- ✓ All elements of symmetry in crystal can be combined in what so called **complete symmetry formula (C.S.F)**
- ✓ **Note that:** Minimum symmetry is center of symmetry and Maximum symmetry is (13 axes, 9 plane, center)



3L₄ 4L₃ 6L₂ 9p C



1L₄ 4L₂ 5p C

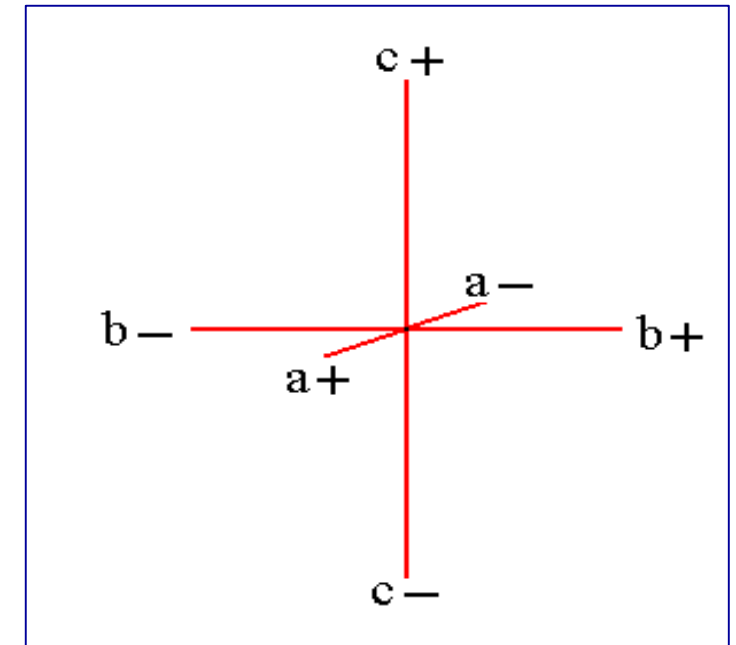
I.7. Elements of crystallization

a) Crystallographic axes

These are three or four imaginary lines intersect at the center of the crystal.

❑ In all types of crystals there are two or three of these axes running horizontal, whereas the 3rd or 4th axis is always vertical and called the c-axis

- **a-axis** : it runs mostly from the front to the back
- **b-axis**: it runs mostly from left to right side
- **c-axis**: it runs mostly from the top to bottom.

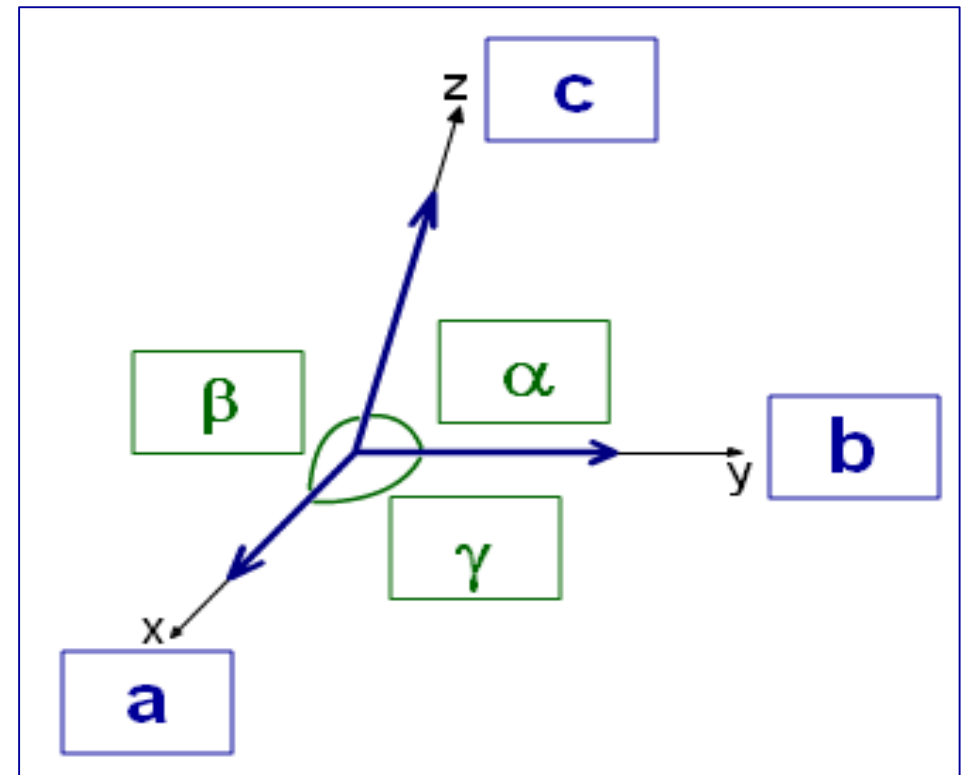


I.7. Elements of crystallization

b) Crystallographic angles

The intersections of the crystallographic axes at center of crystals give three angles called as α , β and γ

- alpha (α): lies between the b and c axes
- beta (β): lies between the a and c axes
- gamma (γ): lies between the a and b axes



I.8. Crystal form

- A crystal form is a set of crystal faces that are similar in size and shape
- There are two types of forms:
 - **Open form** is one or more crystal faces that cannot close the crystal in all directions alone such as pinacoid, prism.
 - **Closed form** is a set of crystal faces that completely close the crystal in all directions alone such as bipyramid and simple forms of cubic system.
- The crystal type can be classified based on type and number of crystal forms into:
 - **Simple crystal:** A crystal consists of only one closed form.
 - **Compound (complex) crystal:** A crystal have more than one form combined together in a regular arrangement. The compound crystal may be formed of open forms only, closed forms only or open plus closed forms. Complex closed forms are only recorded in cubic system.

1.8. Crystal systems

According to crystallographic axes and crystal symmetry, all known minerals can be classified into seven crystal systems. The classification is based on the following criteria:

- ❖ Number of crystallographic axes,
- ❖ Relative lengths of the crystallographic axes,
- ❖ Values of the interaxial angles, and
- ❖ Some essential element of symmetry.

- | | |
|------------------------|---------------|
| 1. Cubic (Isometric) | 6. Monoclinic |
| 2. Tetragonal system | 7. Triclinic |
| 3. Trigonal system | |
| 4. Hexagonal system | |
| 5. Orthorhombic system | |

1.8. Crystal systems

System	Crystallographic axes	Crystallographic angles	Elements of symmetry
1. Cubic	$a_1=a_2=a_3$	$\alpha=\beta=\gamma=90^\circ$	
2. Tetragonal	$a_1=a_2 \neq c$	$\alpha=\beta=\gamma=90^\circ$	
3. Orthorhombic	$a \neq b \neq c$	$\alpha=\beta=\gamma=90^\circ$	
4. Monoclinic	$a \neq b \neq c$	$\alpha=\gamma=90^\circ, \beta \neq 90^\circ$	
5. Triclinic	$a \neq b \neq c$	$\alpha \neq \beta \neq \gamma \neq 90^\circ$	
6. Hexagonal	$a_1=a_2=a_3 \neq c$	$\alpha=\beta=90^\circ, \gamma=120^\circ$	
7. Trigonal	$a_1=a_2=a_3 \neq c$	$\alpha=\beta=90^\circ, \gamma=120^\circ$	No horizontal plane of symmetry

Part 1: Crystallography

Lecture 2:

**Cubic system and
Tetragonal system**

Summary of previous lectures

- ❑ Crystal definition and crystal parts
- ❑ Elements of crystallization
- ❑ Elements of Symmetry
- ❑ Crystal form
- ❑ Crystal systems

Items of the Lecture-2

- 1) Cubic system
- 2) Tetragonal system

1.8. Crystal systems

System	Crystallographic axes	Crystallographic angles	Classes (32)
1. Cubic	$a_1=a_2=a_3$	$\alpha=\beta=\gamma=90^\circ$	5
2. Tetragonal	$a_1=a_2\neq c$	$\alpha=\beta=\gamma=90^\circ$	7
3. Orthorhombic	$a\neq b\neq c$	$\alpha=\beta=\gamma=90^\circ$	3
4. Monoclinic	$a\neq b\neq c$	$\alpha=\gamma=90^\circ, \beta\neq 90^\circ$	3
5. Triclinic	$a\neq b\neq c$	$\alpha\neq\beta\neq\gamma\neq 90^\circ$	2
6. Hexagonal	$a_1=a_2=a_3\neq c$	$\alpha=\beta=90^\circ, \gamma=120^\circ$	7
7. Trigonal	$a_1=a_2=a_3\neq c$	$\alpha=\beta=90^\circ, \gamma=120^\circ$	5

1.8. Crystal systems

- The seven crystal systems are classified into 32 crystal classes according to their elements of symmetry

The holosymmetrical class (normal class): a class in each crystal system that contains the highest number of elements of symmetry

General form: the form which have the largest number of crystal faces.

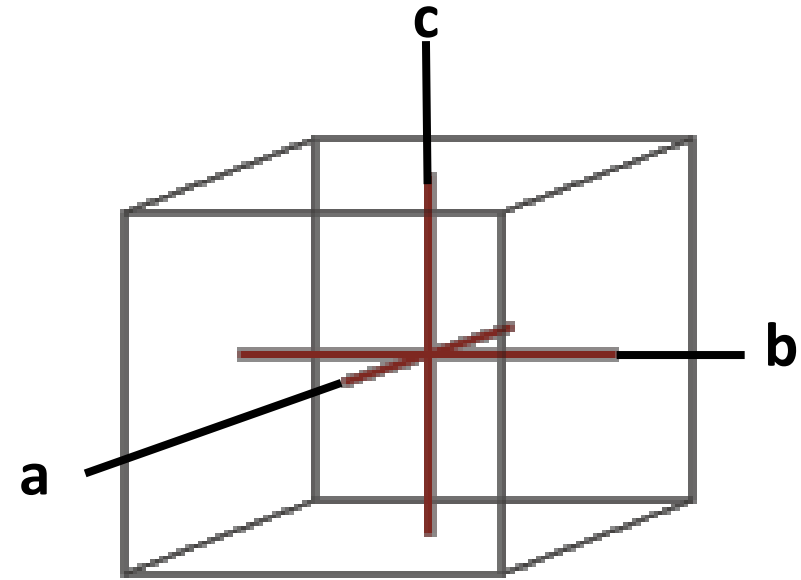
✓ The class can be named after its general form

2.1. Normal (holosymmetrical) class of Cubic system

➤ Elements of crystallization

Crystallographic axes: $a_1 = a_2 = a_3$

Crystallographic angles: $\alpha = \beta = \gamma = 90^\circ$



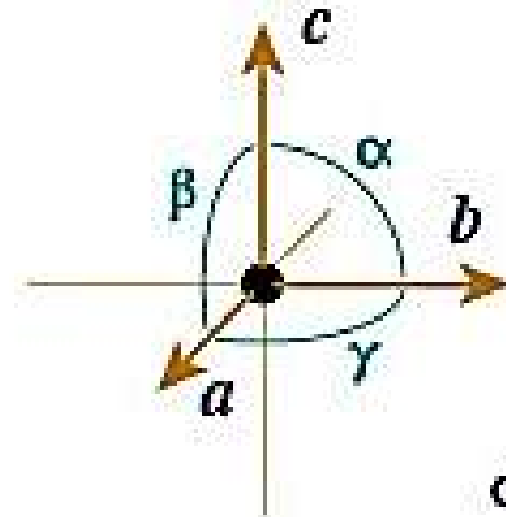
➤ Elements of symmetry

Axes: 13 (3 , 4 , 6 )

Plane: 9 (4 vertical, 1 horizontal, 4 diagonal)

Centre: +ve

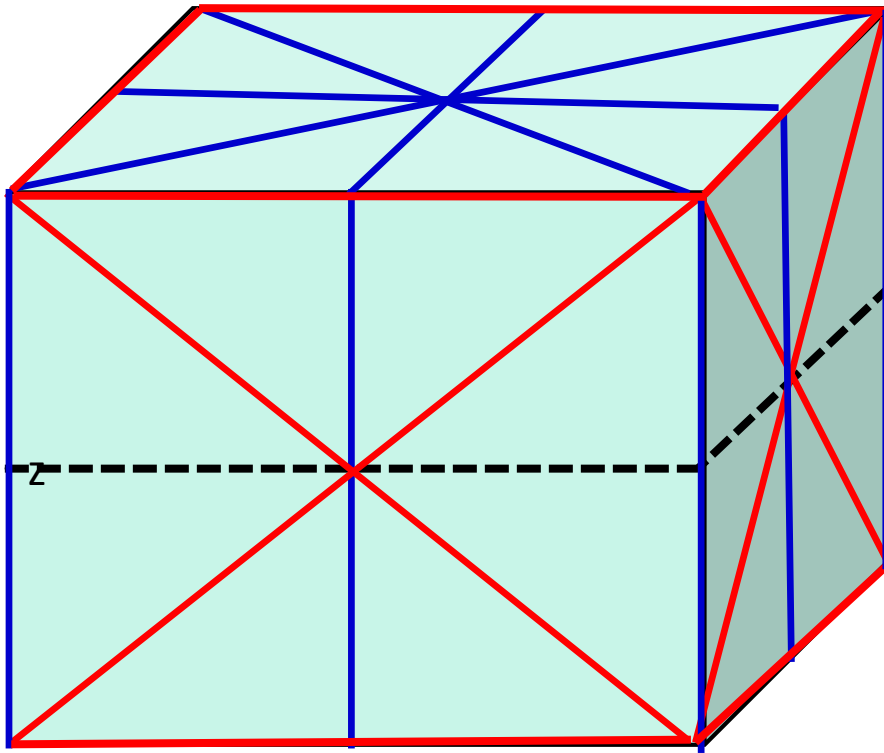
C.S.F: $3L_4$ $4L_3$ $6L_2$ $9P$ C



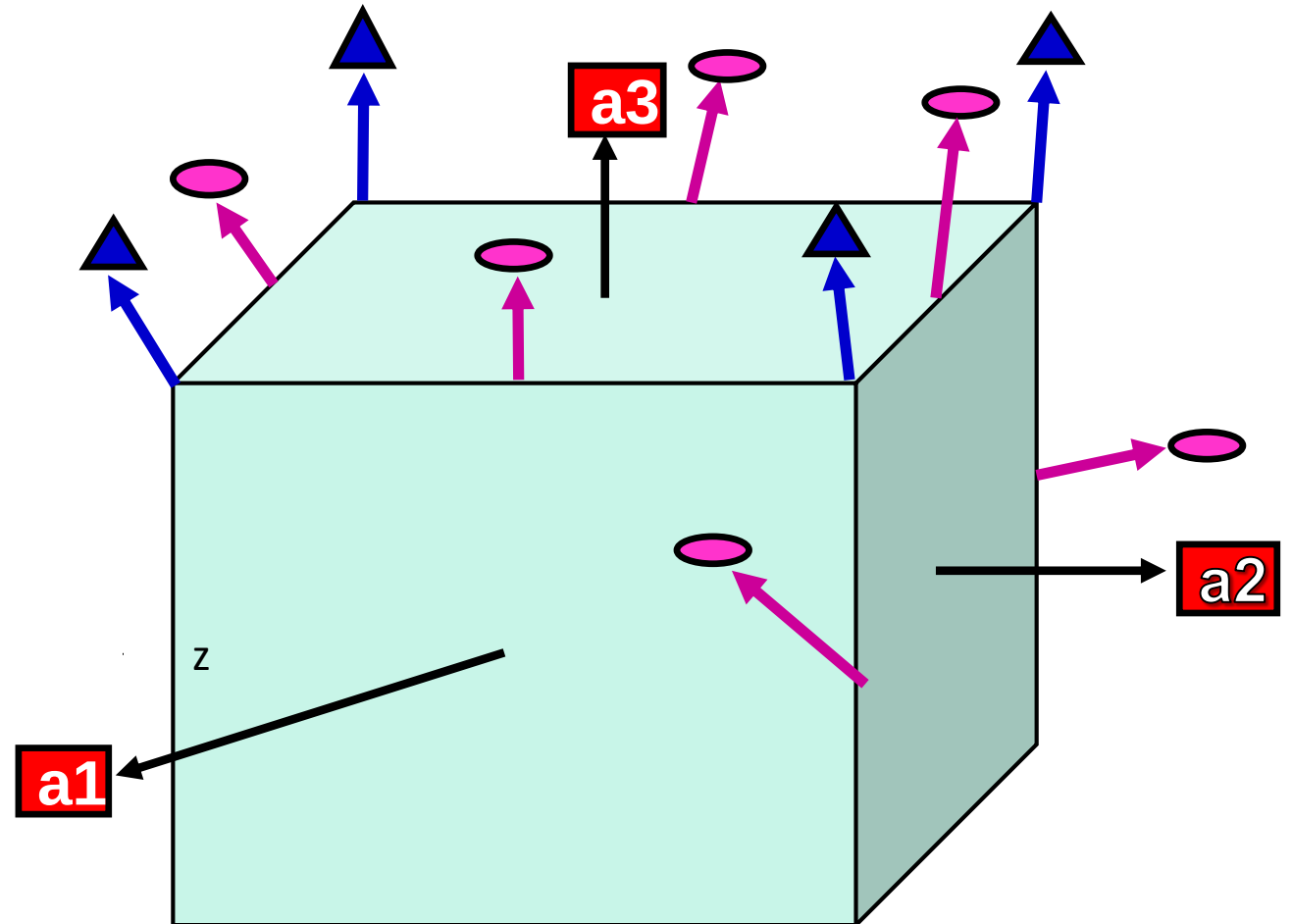
$$a=b=c$$
$$\alpha=\beta=\gamma=90^\circ$$

2.1. Normal class of Cubic system

Planes of symmetry



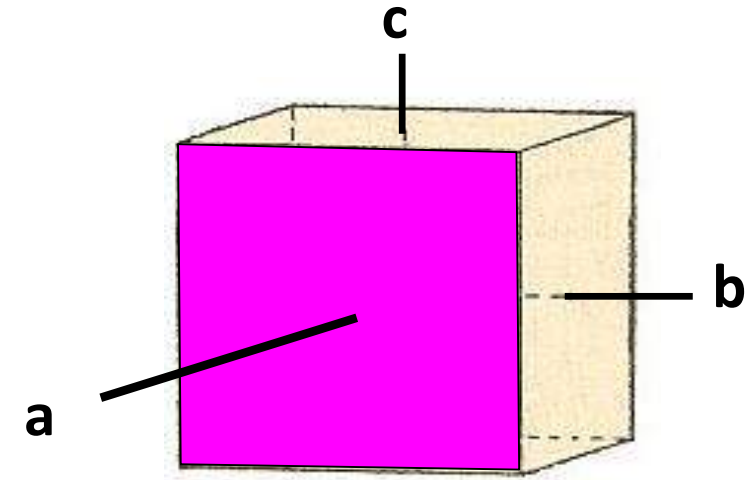
Axes of symmetry



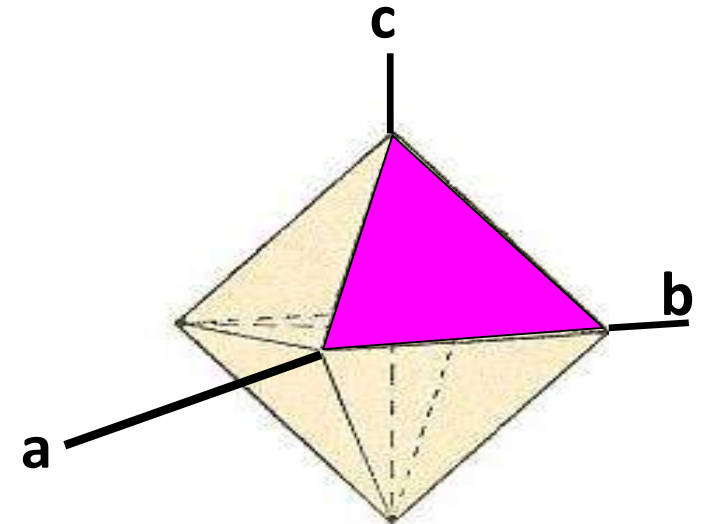
2.1. Normal class of Cubic system

➤ Crystal forms

1. **Cube (hexahedron)** : closed form, 6 square faces



2. **Octahedron**: closed form, 8 triangular faces

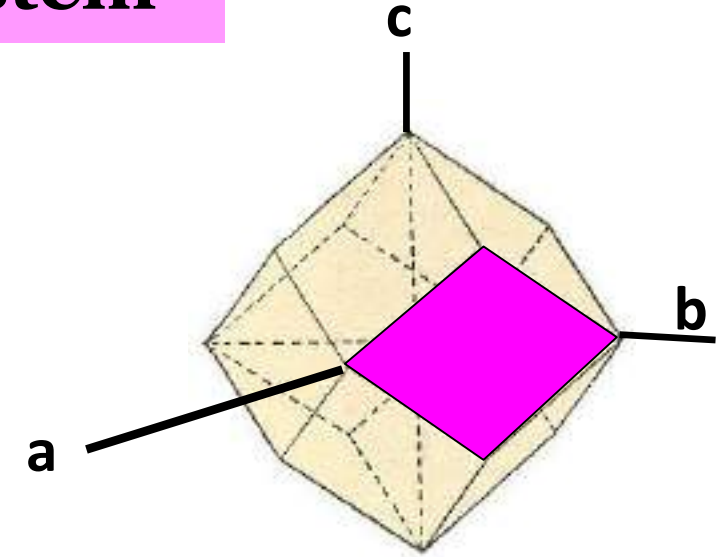


2.1. Normal class of Cubic system

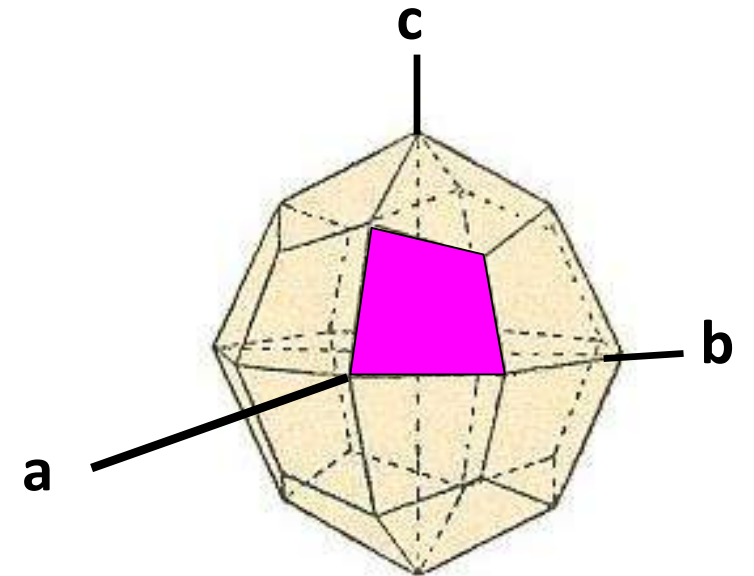
➤ Crystal forms

3. **Rhombic dodecahedron:** closed form, 12

Rhombic faces



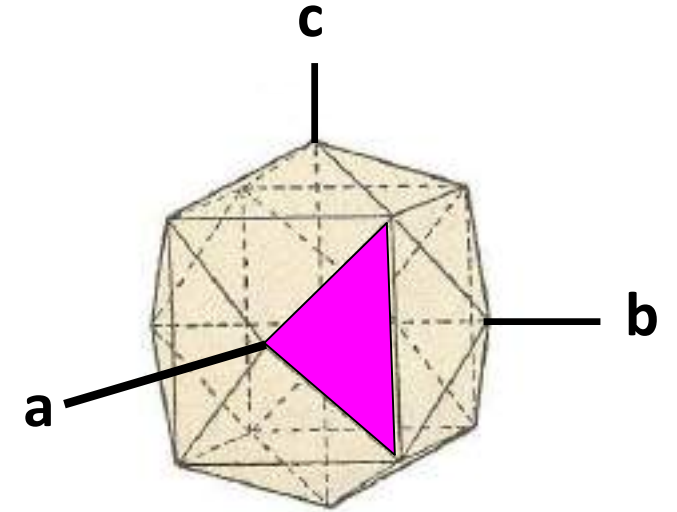
4. **Trapezohedron:** closed form, 24 trapezium faces,



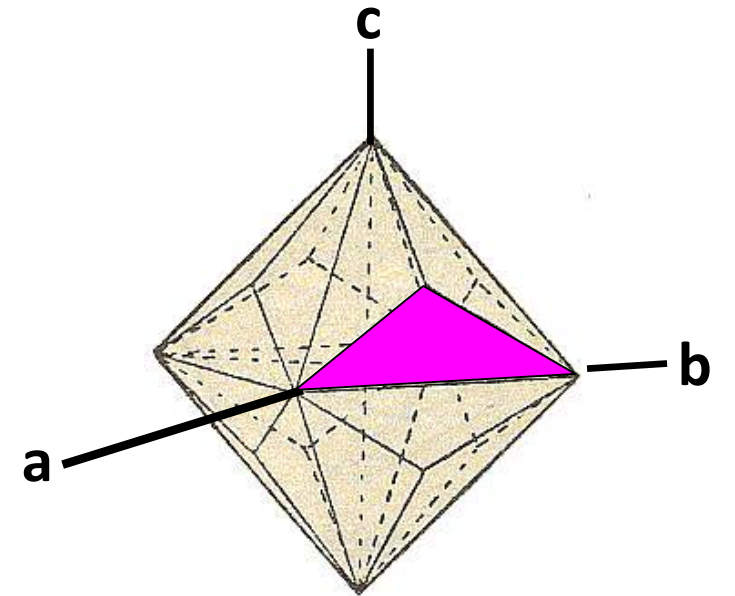
2.1. Normal class of Cubic system

➤ Crystal forms

5. **Tetrahexahedron:** closed form, 24 triangle faces



6. **Trisoctahedron:** closed form, 24 Triangular faces

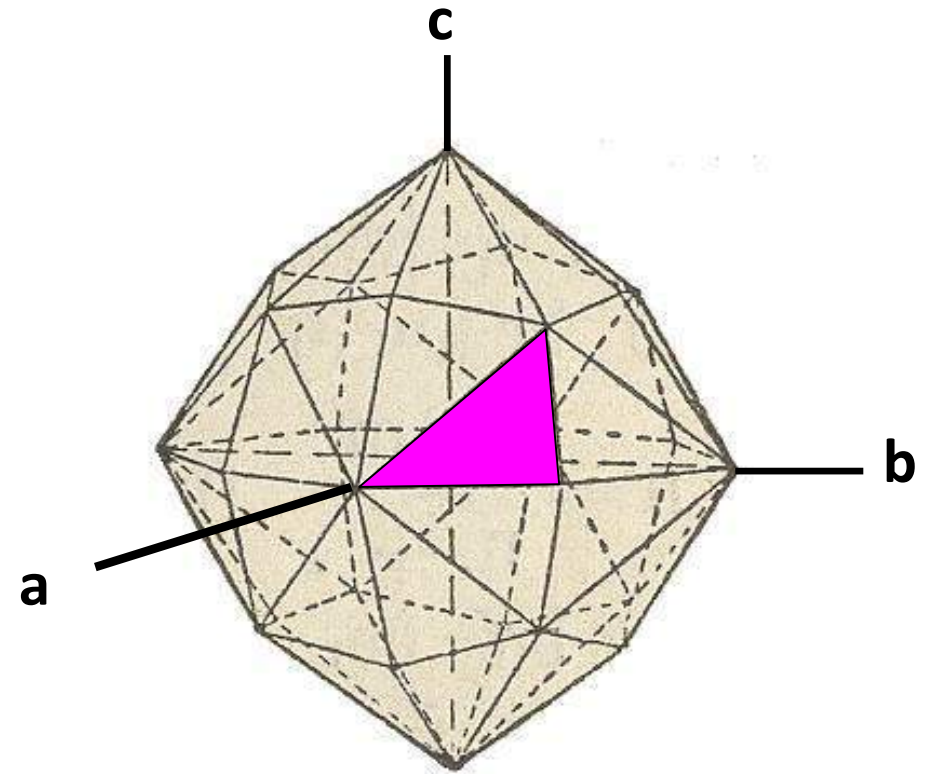


2.1. Normal class of Cubic system

➤ Crystal forms

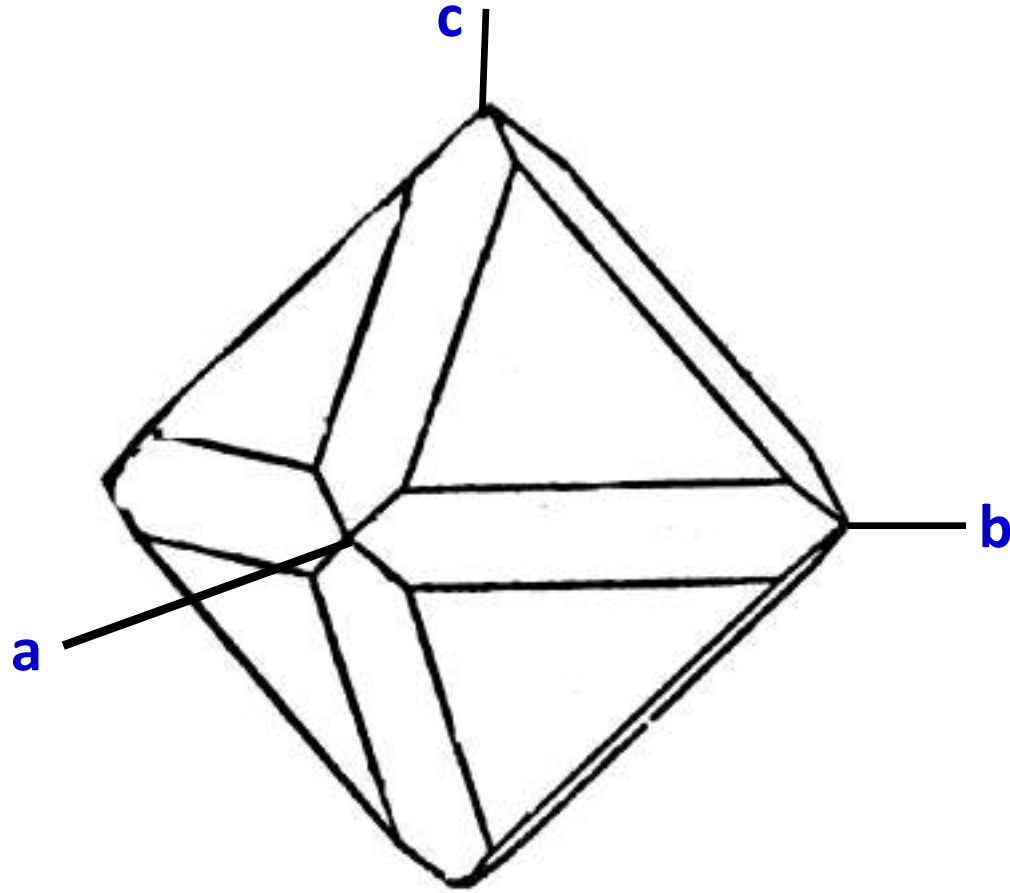
7. **Hexaoctahedron (General form):** closed form, 48 Triangular faces

✓ Normal class of Cubic system can be named as hexaoctahedral class



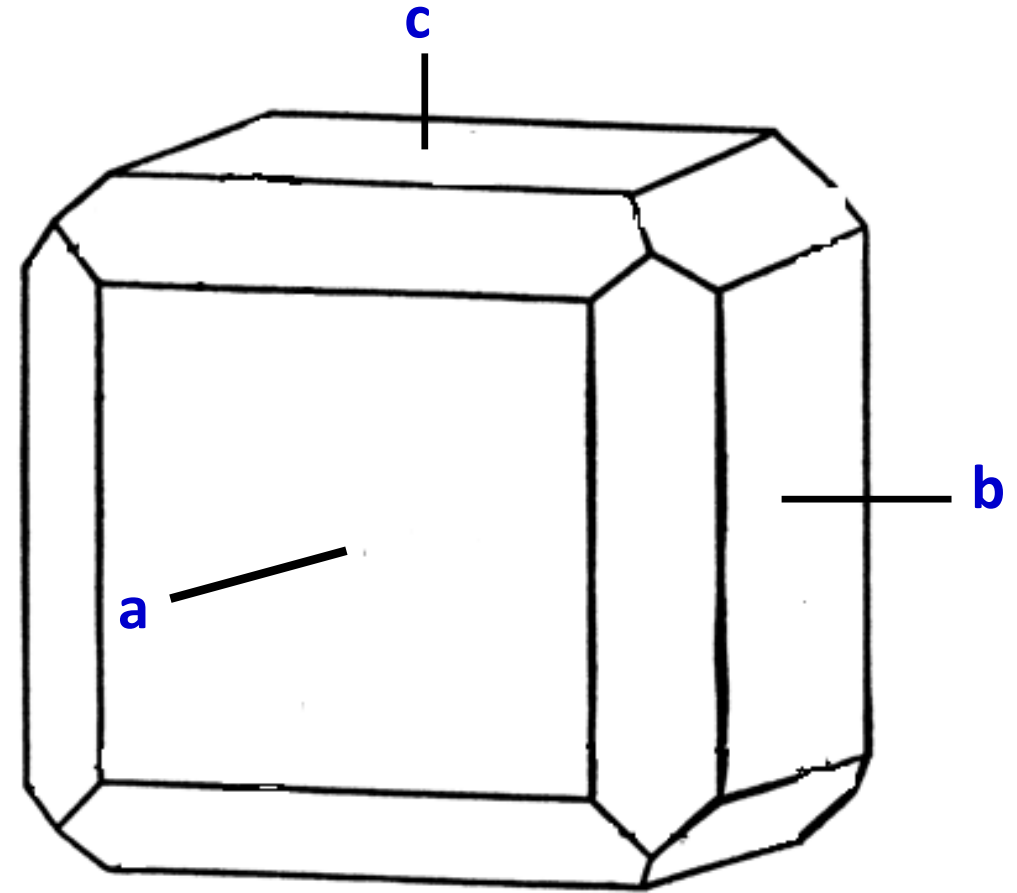
2.1. Normal class of Cubic system

➤ Combined (compound) crystal:



Octahedron

Rhombic dodecahedron

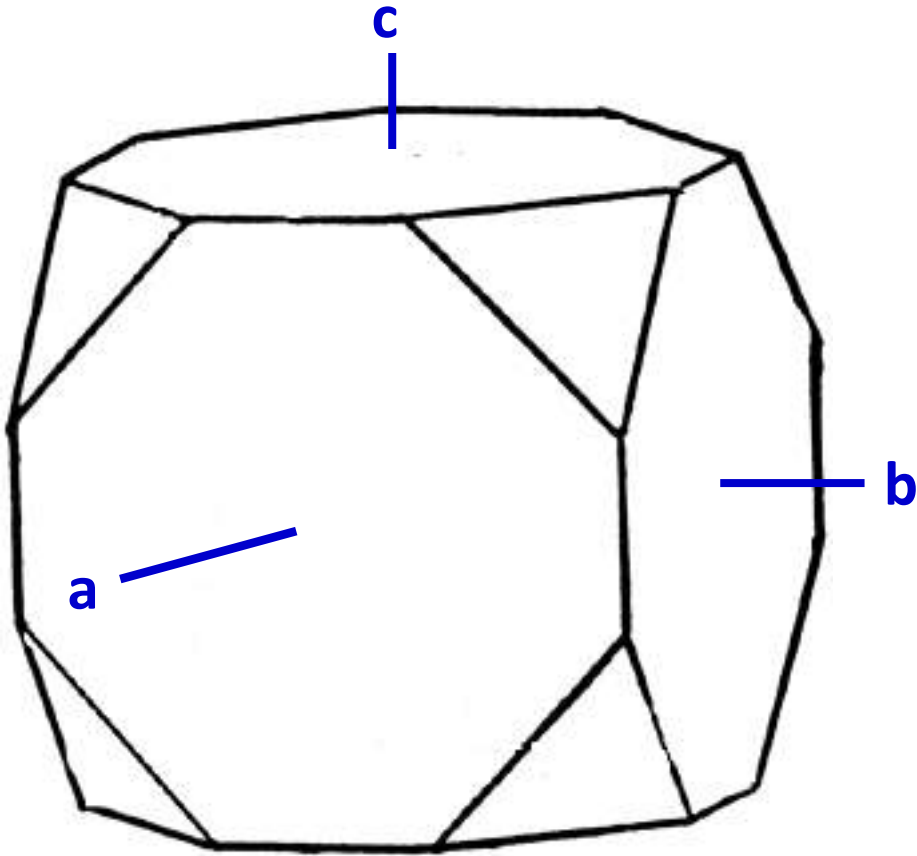


Cube

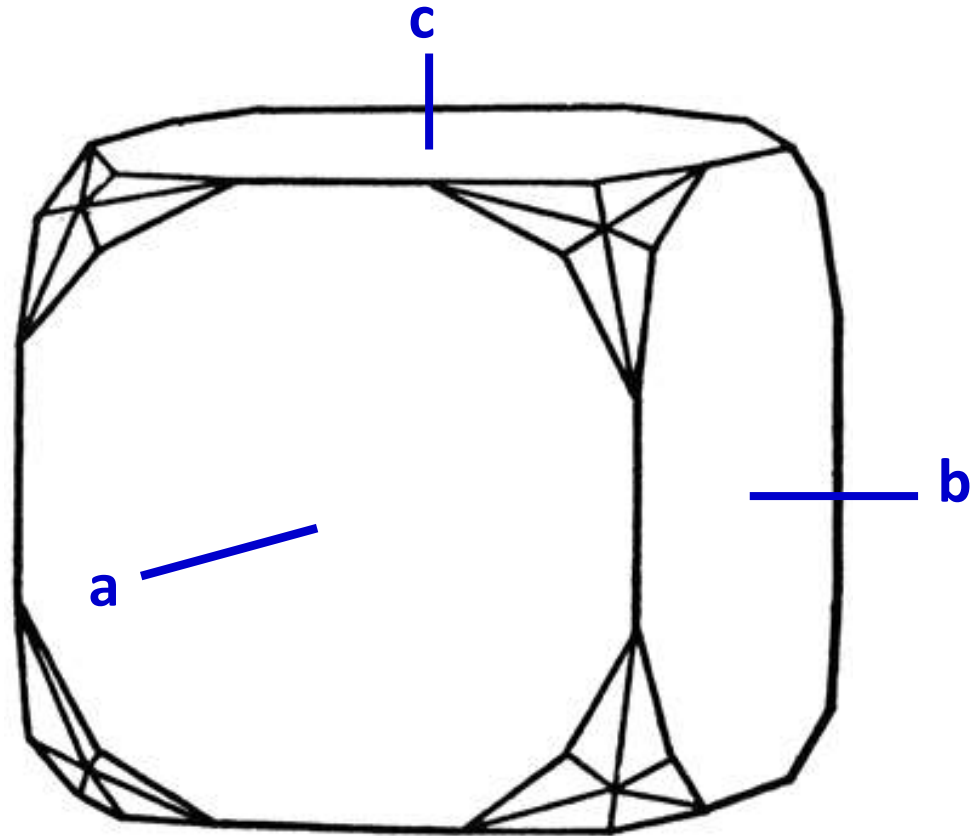
Rhombic dodecahedron

2.1. Normal class of Cubic system

➤ Complicated (compound) crystal:



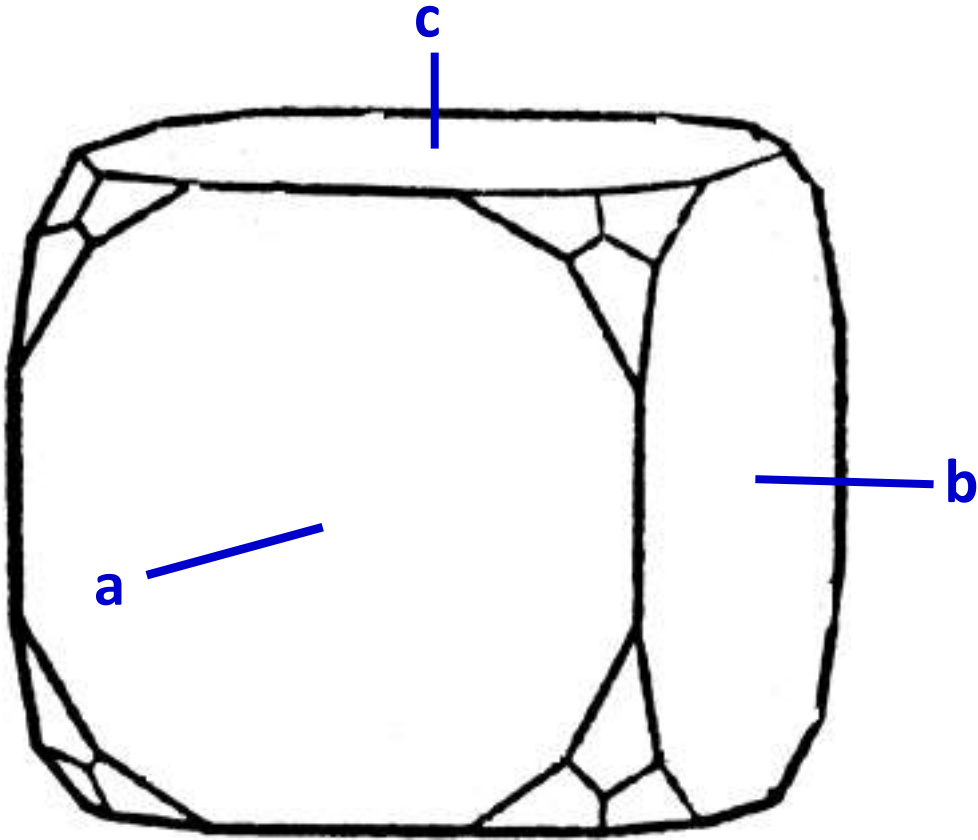
Cube
Octahedron



Cube
Hexaoctahedron

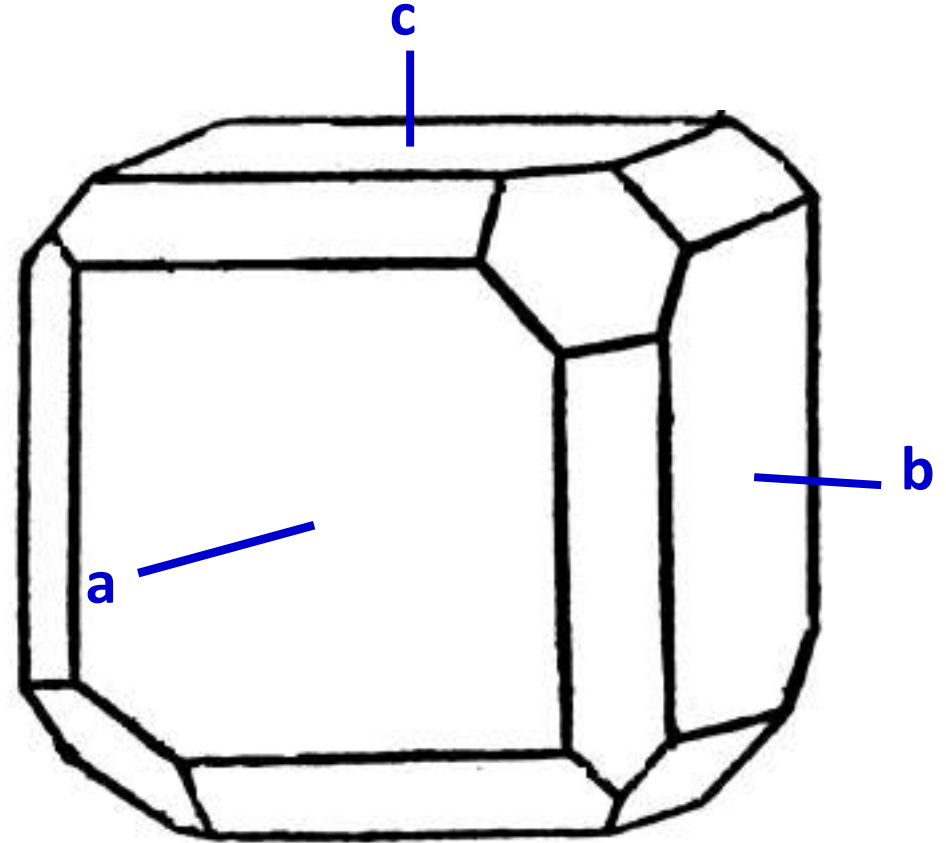
2.1. Normal class of Cubic system

➤ Complicated (compound) crystal:



Cube

Trisoctahedron



Cube

Octahedron

Rhombic dodecahedron

2.1. Normal class of Cubic system

➤ Crystal forms

Crystal Form	Number of Faces	Form type
1.Cube (Hexahedron)	6	closed
2. Octahedron	8	closed
3. Rhombic Dodecahedron	12	closed
4. Trapezohedron	24	closed
5. Tetrahexahedron	24	closed
6. Trisoctahedron	24	closed
7.Hexoctahedron	48	closed

2.2. Normal class of Tetragonal system

➤ Elements of crystallization

Crystallographic axes: $a_1 = a_2 \neq c$

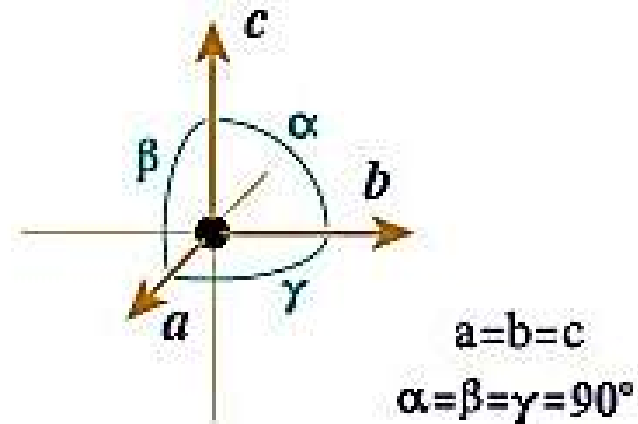
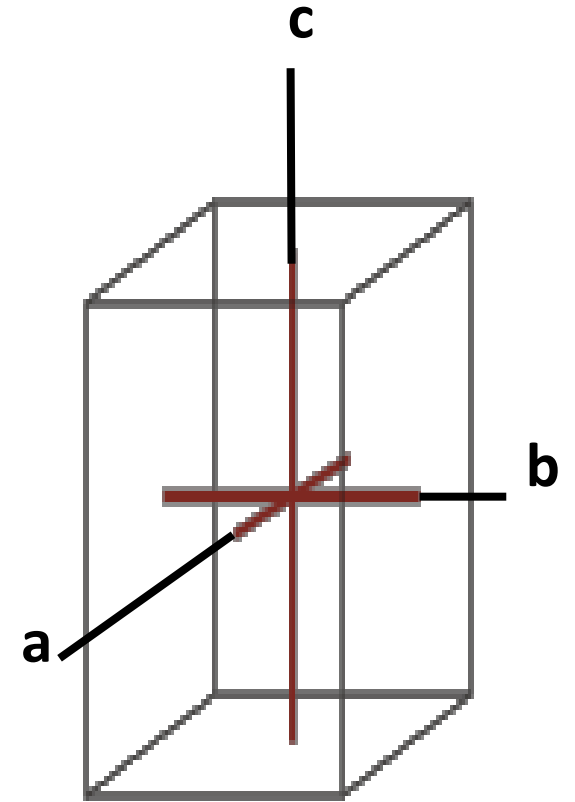
Crystallographic angles: $\alpha = \beta = \gamma = 90^\circ$

➤ Elements of symmetry

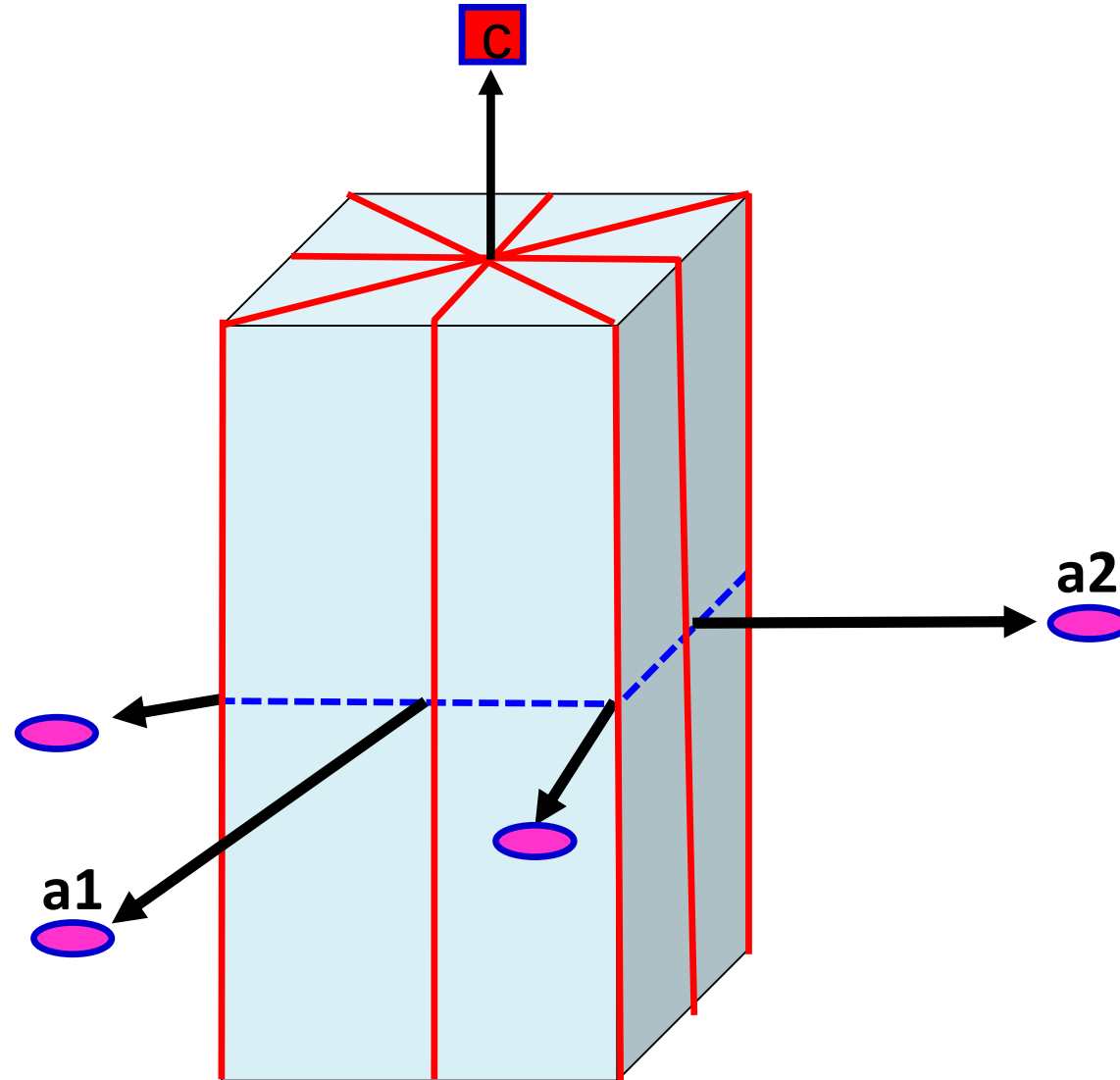
Axes: 5 (1 , 4 )

Plane: 5 (4 vertical, 1 horizontal)

Centre: +ve



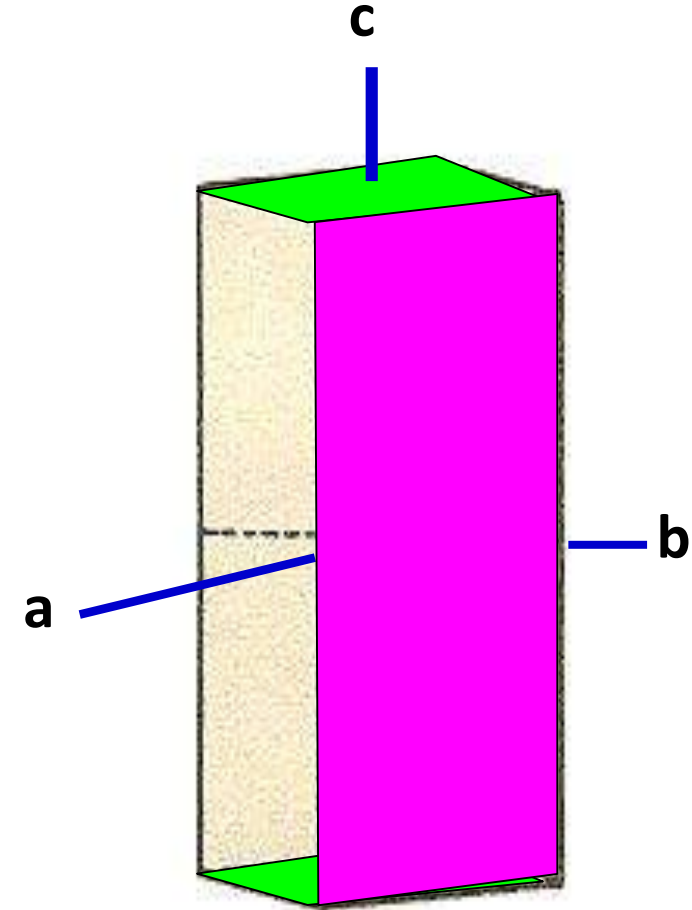
2.2. Normal class of Tetragonal system



2.2. Normal class of Tetragonal system

➤ Crystal forms

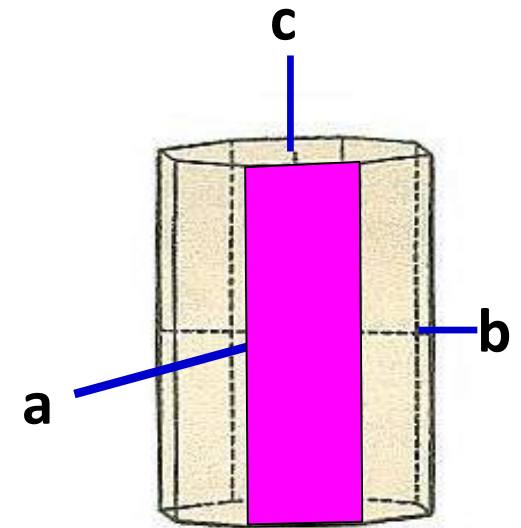
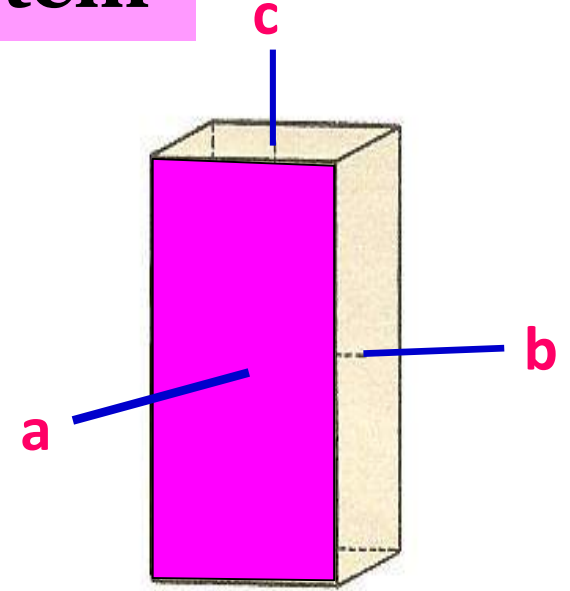
1. **Basal (c) Pinacoid** : an open form made up of two parallel faces that intercept the c axis and are parallel to the a and b axes.
2. **Tetragonal prism first order**: an open form, consists of 4 faces which are parallel to c axis and intersect the other two axes.



2.2. Normal class of Tetragonal system

➤ Crystal forms

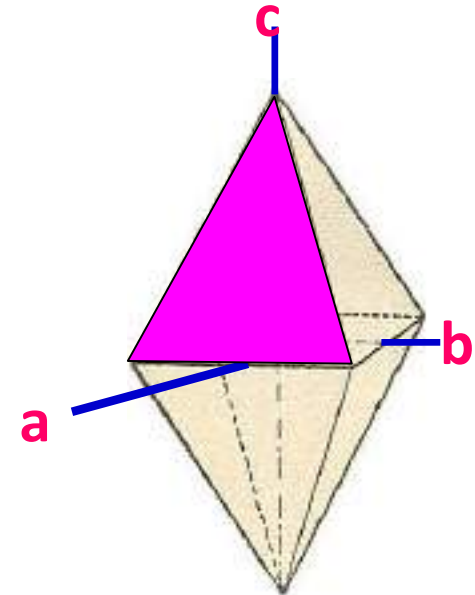
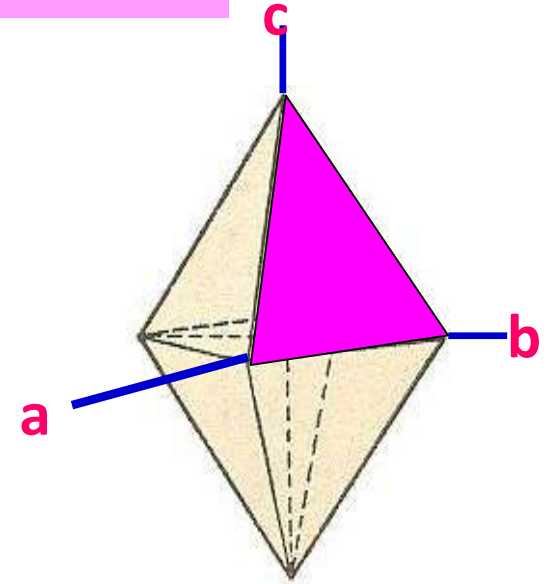
3. **Tetragonal prism second order:** an open form, consists of 4 faces which are parallel to c axis.
4. **Ditetragonal prism:** an open form, consists of 8 faces which are parallel to c axis



2.2. Normal class of Tetragonal system

➤ Crystal forms

5. **Tetragonal Bipyramid first order:** closed form consists of 8 isosceles triangular faces intersect all crystallographic axes. All faces intersect c-axis and both a & b axes
6. **Tetragonal Bipyramid second order:** closed form consists of 8 isosceles triangular faces, all intersect the c axis and either a or b axis



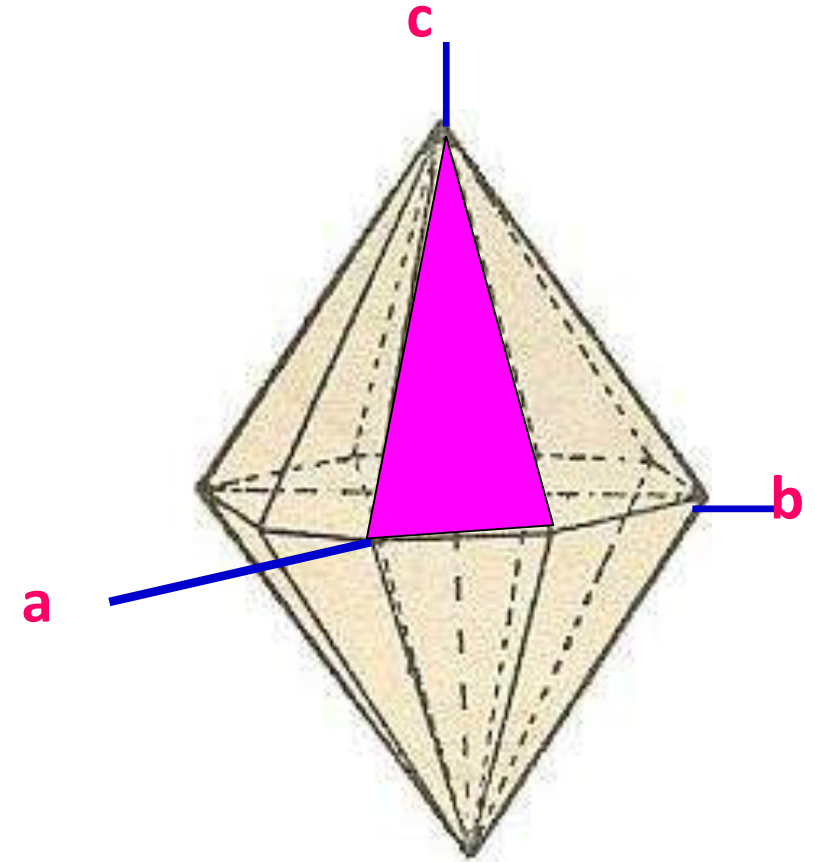
2.2. Normal class of Tetragonal system

➤ Crystal forms

7. Ditetragonal bipyramid (General form):

closed form consists of 16 isosceles triangular faces. All faces intersect the c axis and both a and b axes

- ✓ Normal class of tetragonal system can be named as Ditetragonal bipyramidal class



2.2. Normal class of Tetragonal system

➤ Crystal forms

Crystal Form	Number of Faces	Form
Basal Pinacoid	2	open
Tetragonal prism first order	4	open
Tetragonal prism second order	4	open
Ditetgagonal prism	8	open
Tetragonal Bipyramid first order	8	closed
Tetragonal Bipyramid second order	8	closed
Ditetgagonal Bipyramid	16	closed

Part 1: Crystallography

Lecture 3:
Orthorhombic system
and Hexagonal system

Summary of previous lecture

1) Cubic system

2) Tetragonal system

Items of the Lecture-3

3) Orthorhombic system

4) Hexagonal System

Normal class of orthorhombic system

➤ Elements of crystallization:

Crystallographic axes: $a \neq b \neq c$, ($c > b > a$)

Crystallographic angles: $\alpha = \beta = \gamma = 90^\circ$

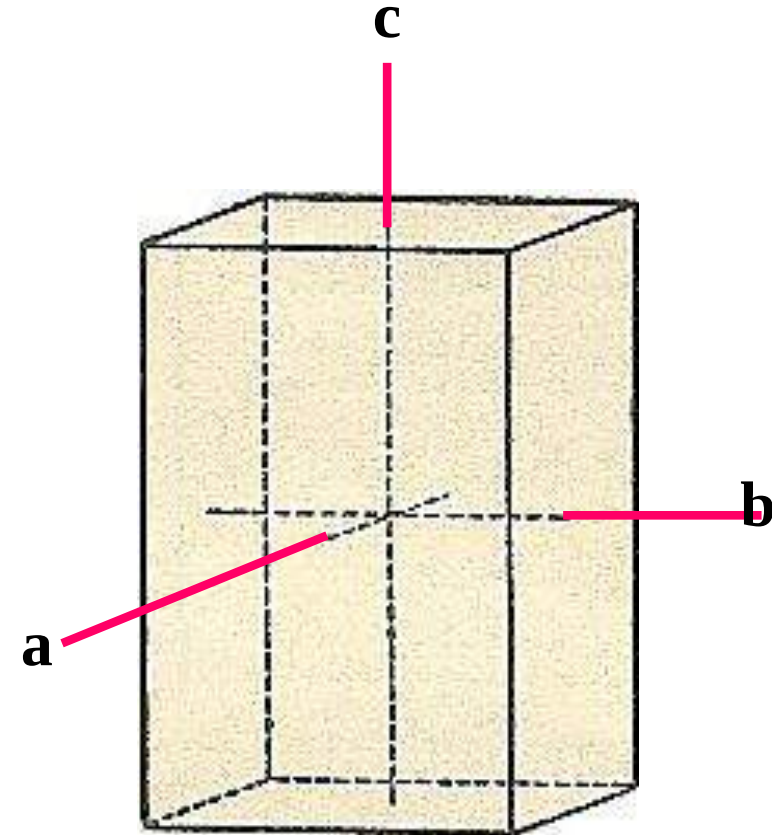
➤ Elements of symmetry

Planes: 3 (2 vertical, 1 horizontal)

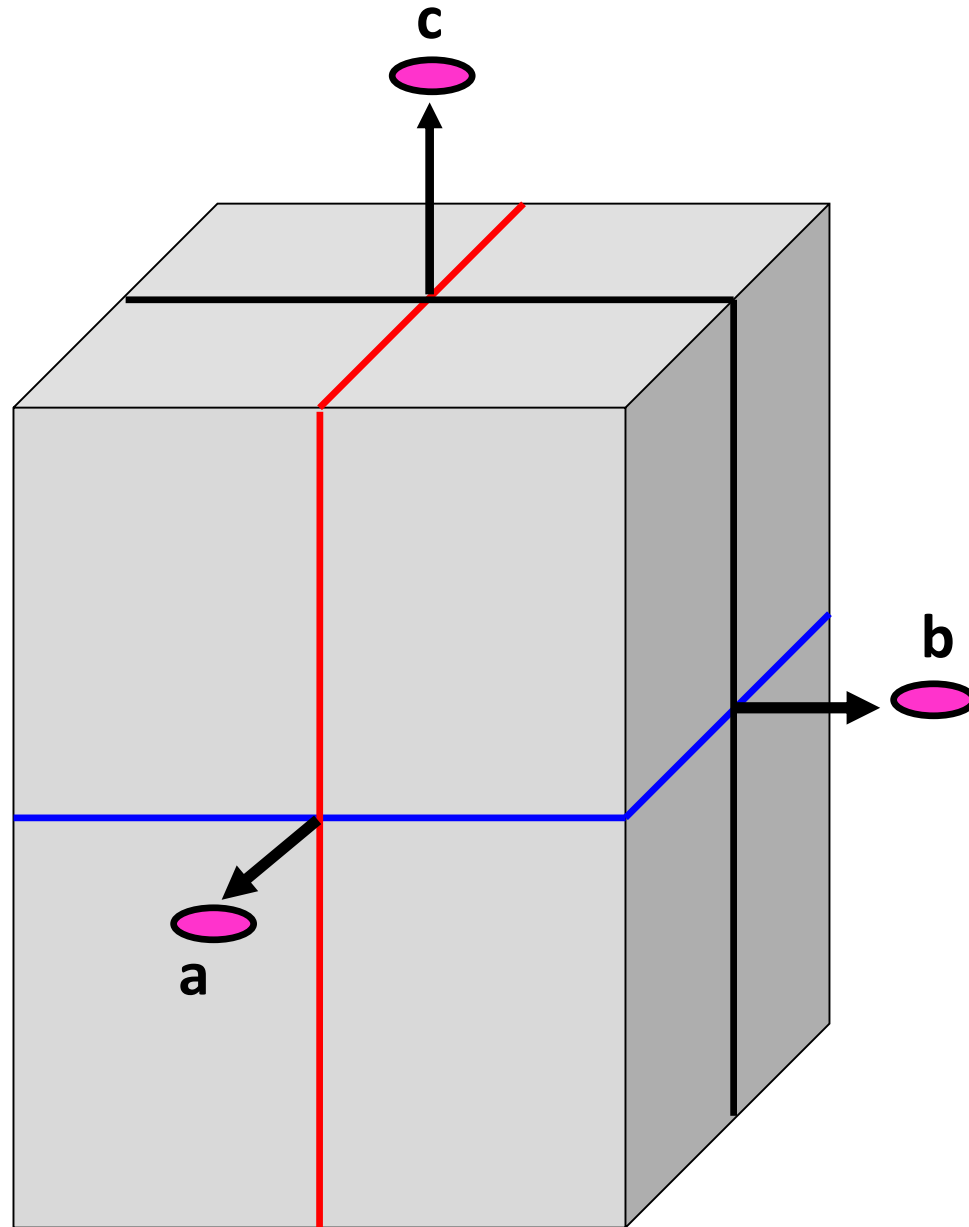
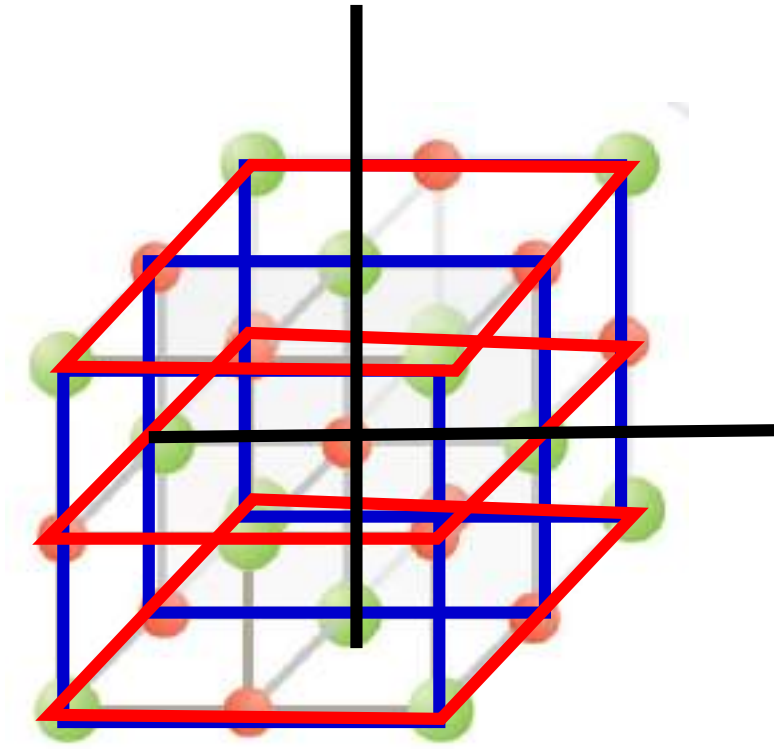
Axes: 3 

Centre: +ve

C.S.F: $3I_2 3P C$



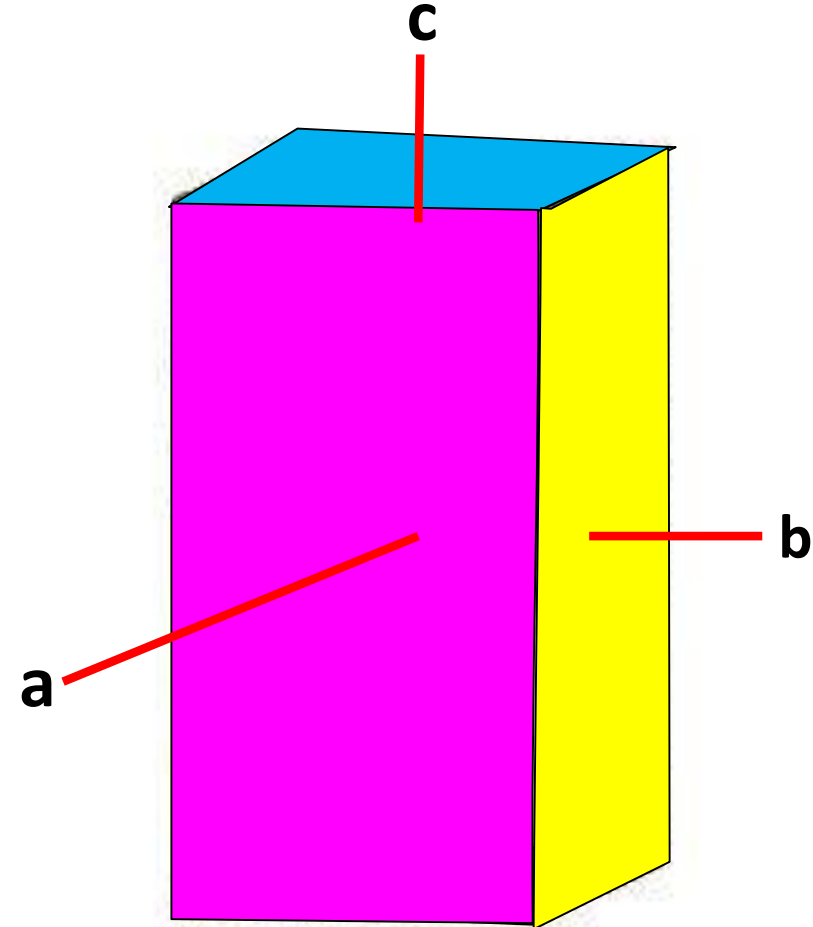
Normal class of orthorhombic system



Normal class of orthorhombic system

➤ Crystal forms

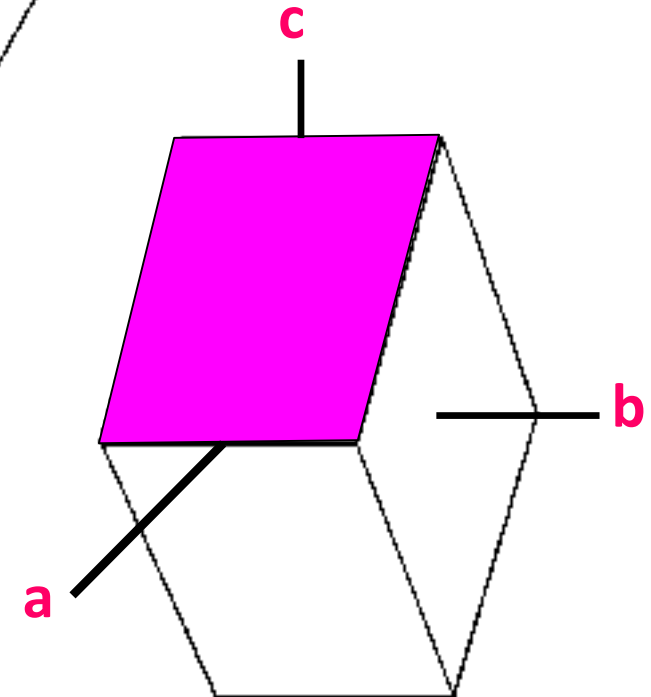
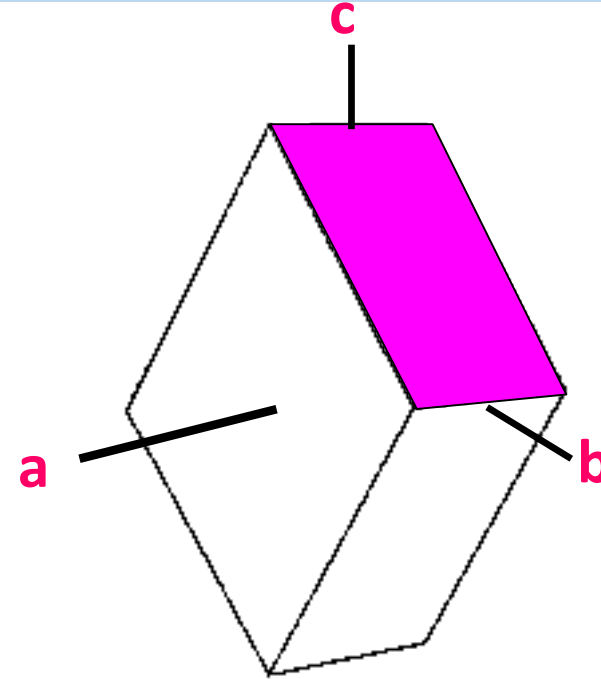
1. **Basal (c) Pinacoid** : an open form made up of two parallel faces that intercept the c axis and are parallel to the a and b axes.
2. **Front (a) Pinacoid** : an open form made up of two parallel faces that intercept the a axis and are parallel to the c and b axes.
3. **Side (b) Pinacoid** : an open form made up of two parallel faces that intercept the b axis and are parallel to the a and c axes.



Normal class of orthorhombic system

➤ Crystal forms

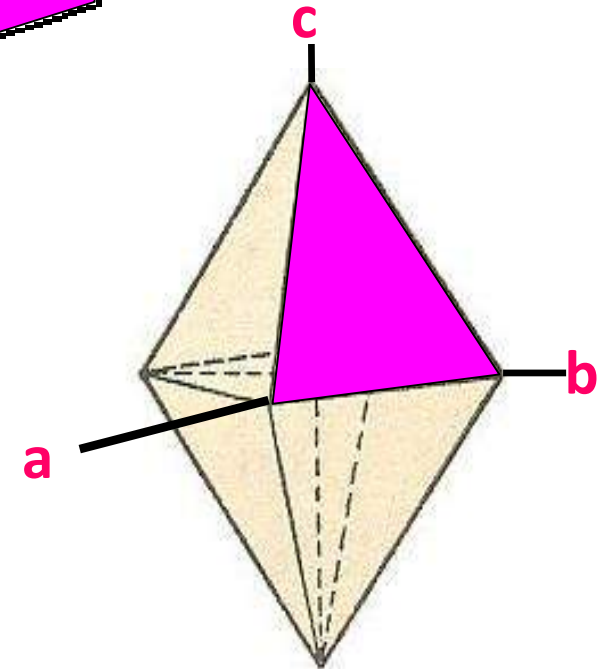
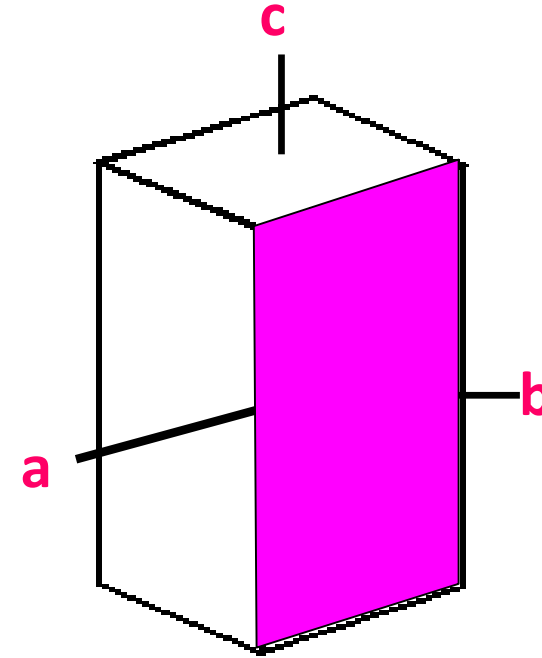
4. **(a) or Brachy dome:** It is an open form, consists of 2 faces parallel to a axis and intersect the other two axes (c, b).
5. **(b) or Macro dome:** It is an open form, consists of 2 faces parallel to b axis and intersect the other two axes (c, a) .



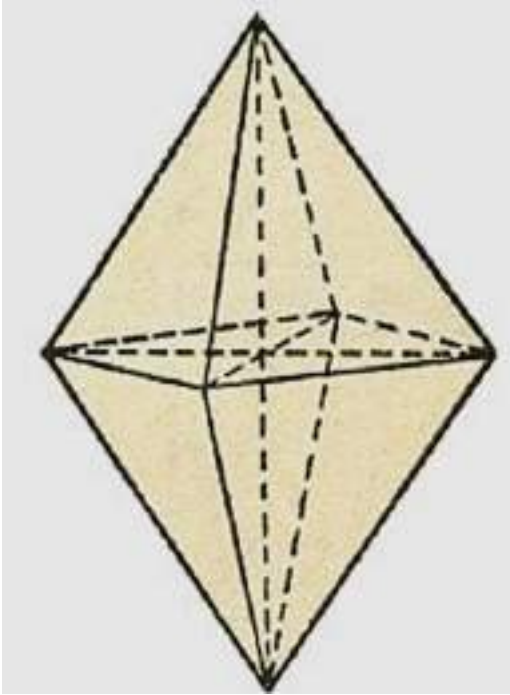
Normal class of orthorhombic system

➤ Crystal forms

6. **Orthorhombic prism:** It is an open form, consists of 4 vertical faces which are parallel to c axis and intersect the other two axes.
7. **Orthorhombic bipyramid (general form):** It is a closed form, consists of 8 triangular faces, each of them intersects all 3 crystallographic axes.



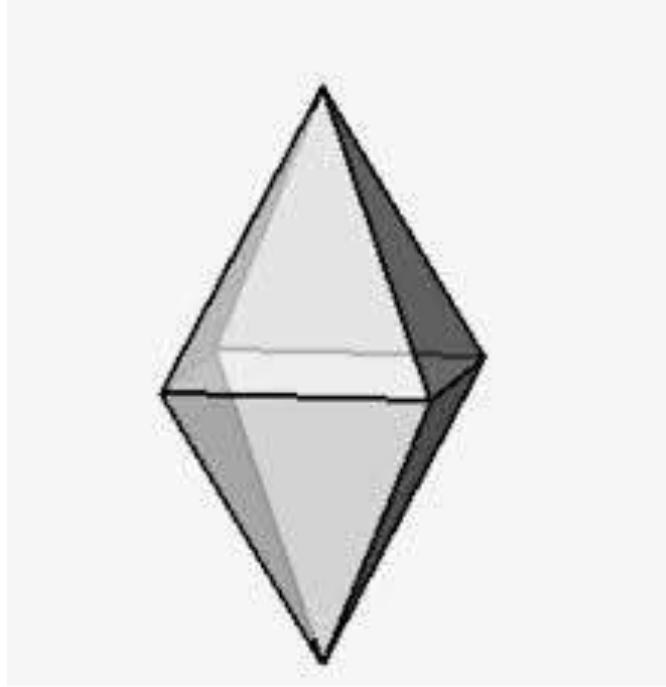
Orthorhombic system



Orthorhombic bipyramid

Scalene triangle

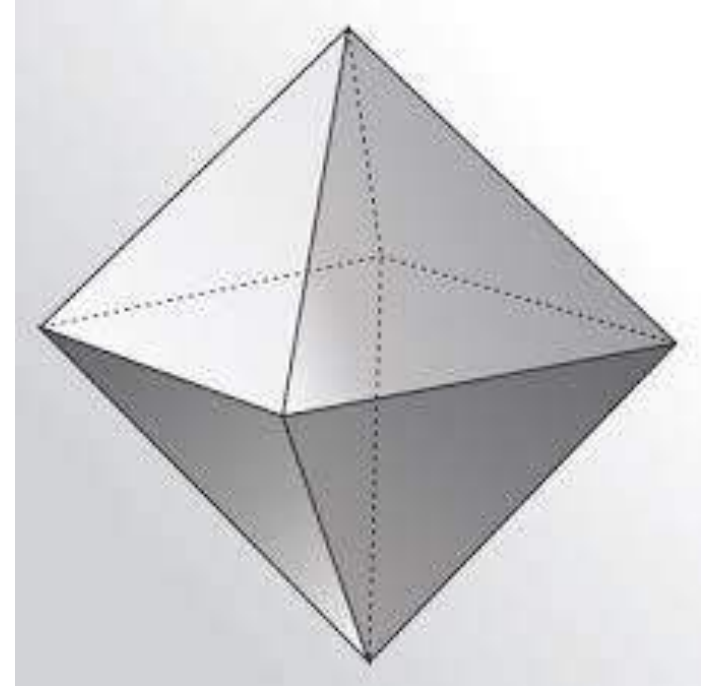
Tetragonal system



Tetragonal bipyramid

Isosceles triangle

Cubic system

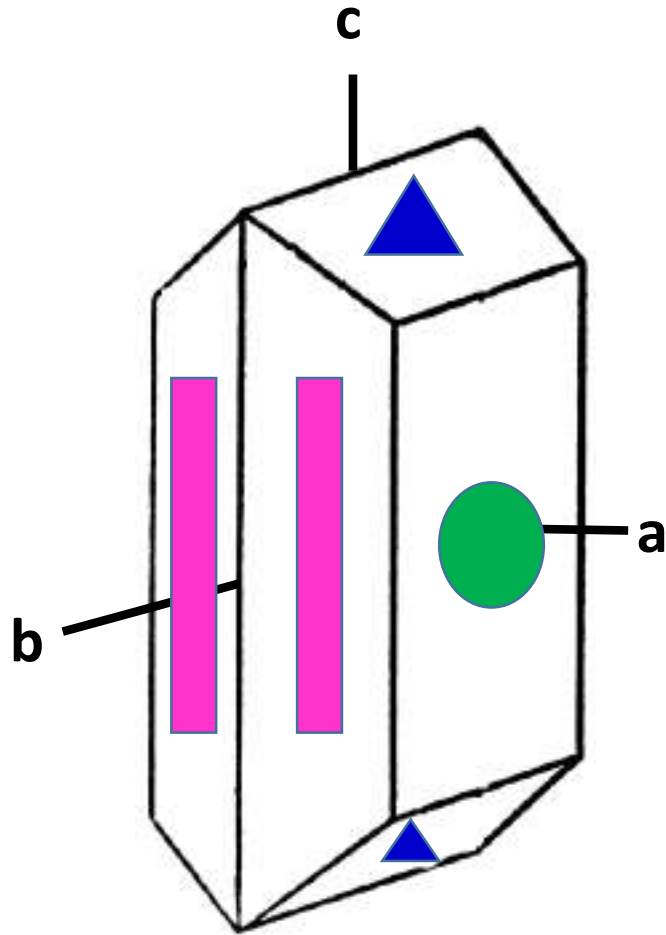


Octahedron

Equilateral triangle

Normal class of orthorhombic system

➤ Combined (compound) crystals:



✓ **Orthorhombic prism**

✓ **a- pinacoid**

✓ **b- dome**

Normal class of orthorhombic system

Crystal Form	Number of Faces	Form type
c-pinacoid	2	open
a-pinacoid	2	open
b-pinacoid	2	open
Orthorhombic prism	4	open
Orthorhombic bipyramid	8	closed
a-Dome	4	open
b-Dome	4	open

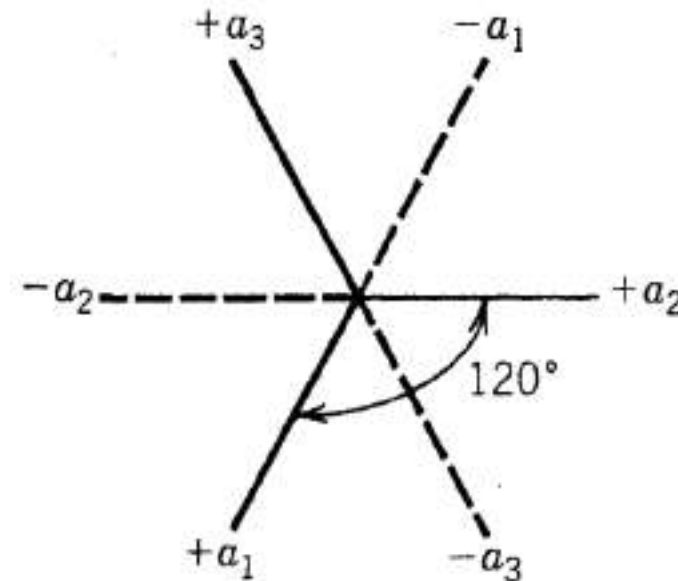
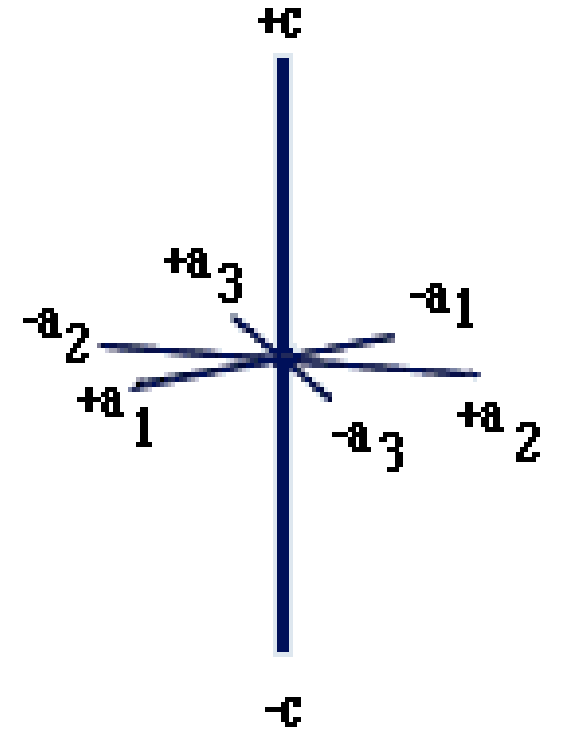
Normal class of hexagonal system

➤ Elements of crystallization:

Crystallographic axes: $a_1 = a_2 = a_3 \neq c$

Crystallographic angles: $\alpha = \beta = 90^\circ \neq \gamma = 120^\circ$

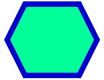
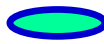
C-axis could be the shorter or the longer



Normal class of hexagonal system

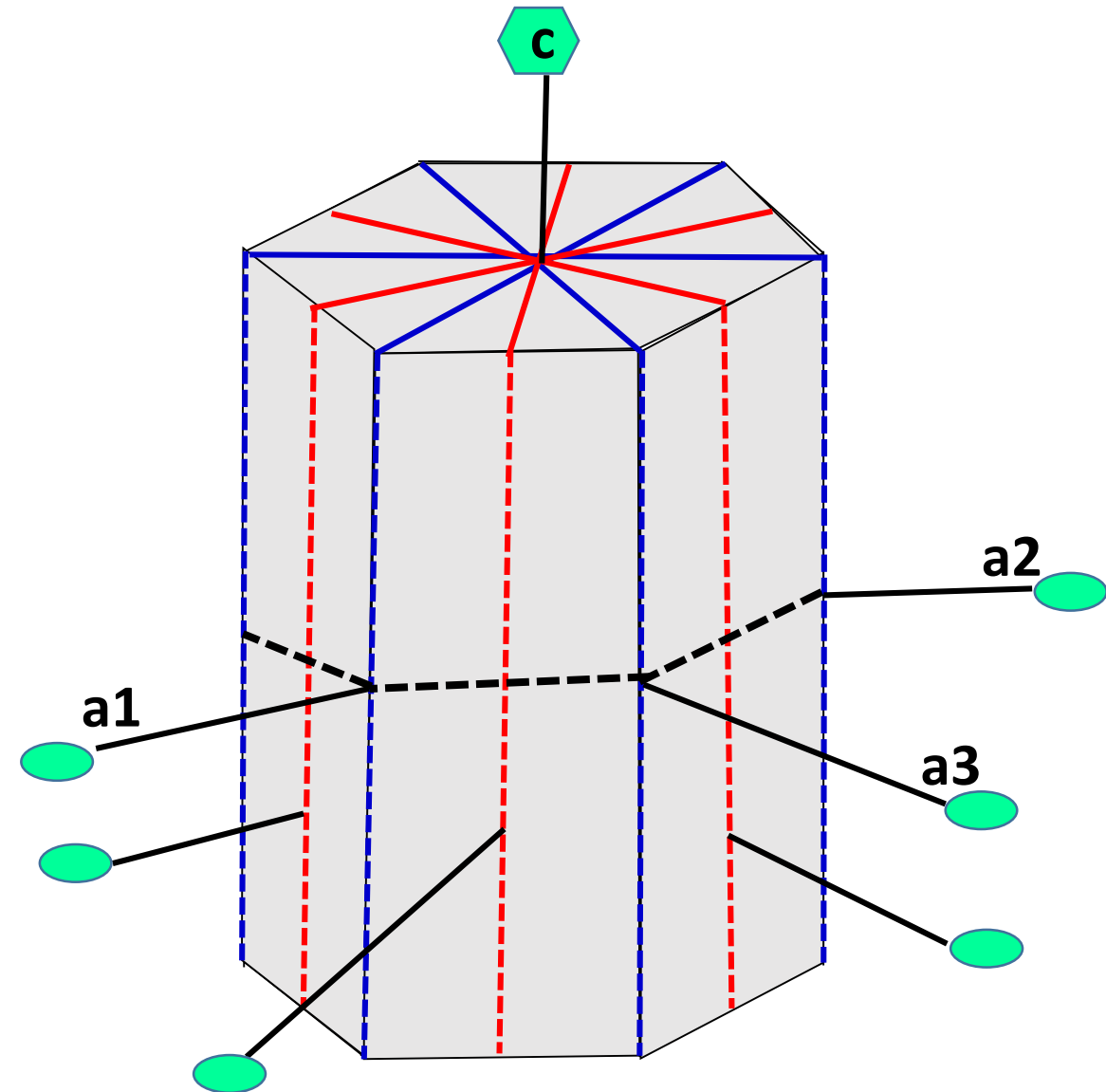
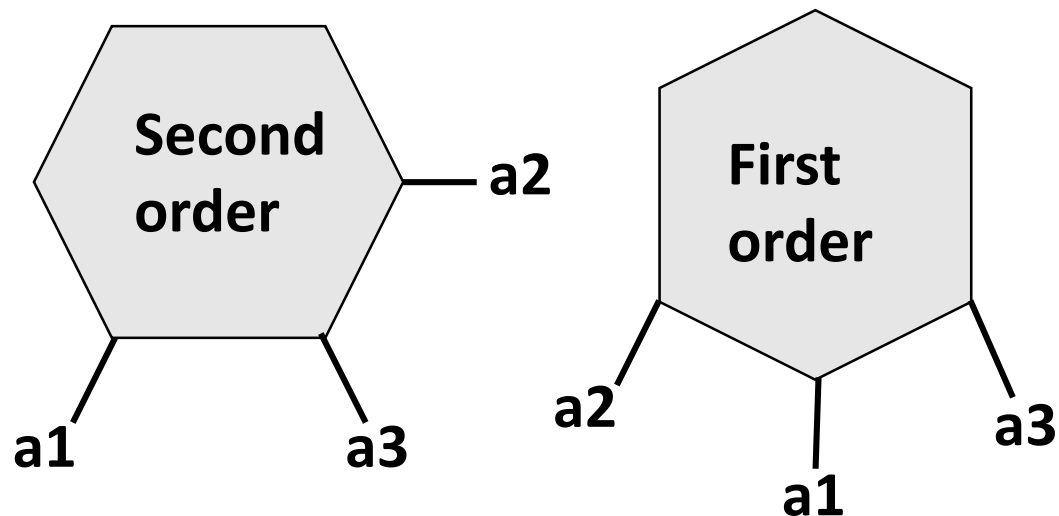
➤ Elements of symmetry

Plane: 7 (6 vertical, 1 horizontal)

Axes: 1 , 6 

Centre: +ve

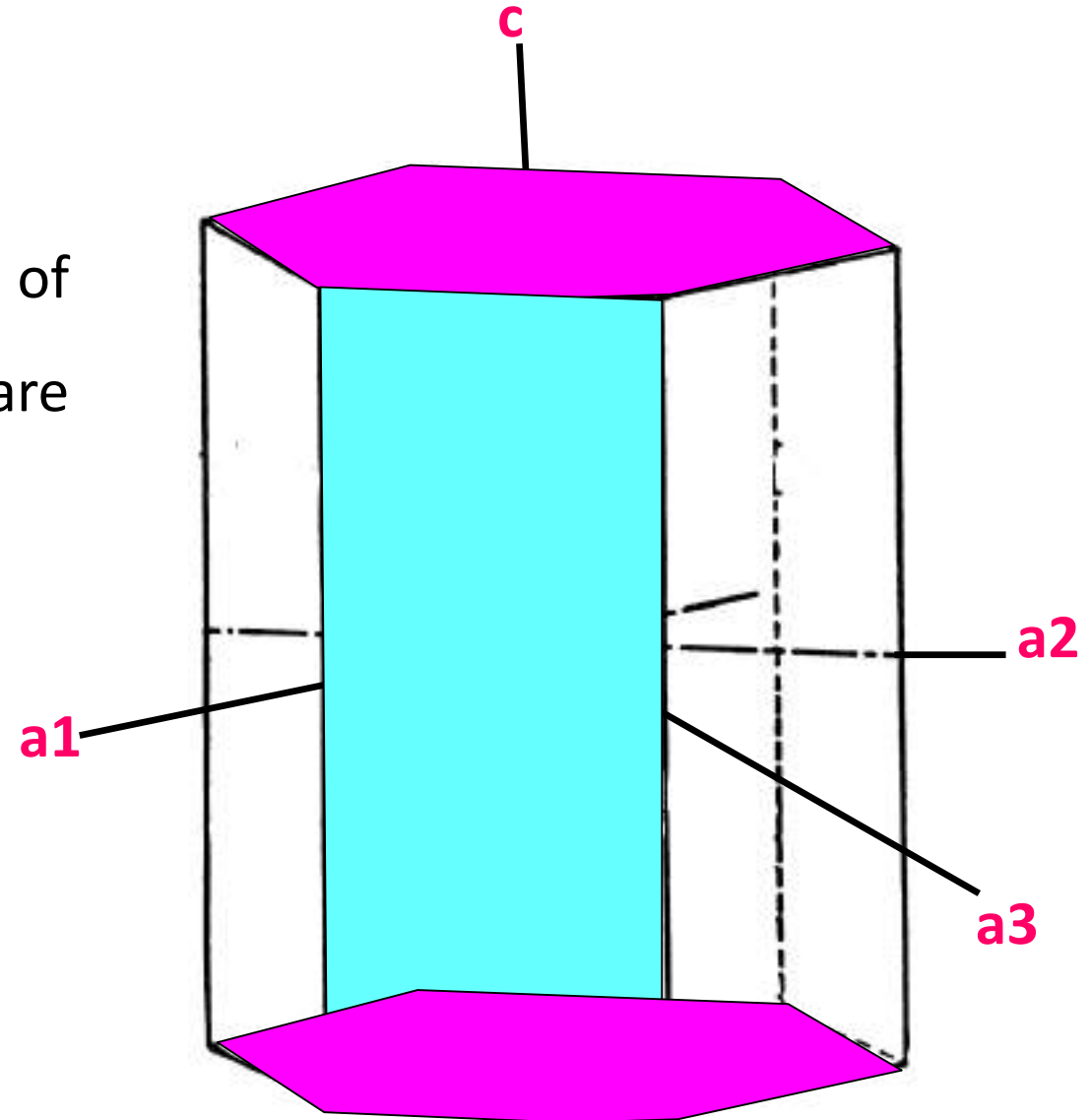
C.S.F: L_6 $6L_2$ $7P$ C



Normal class of hexagonal system

➤ Crystal forms

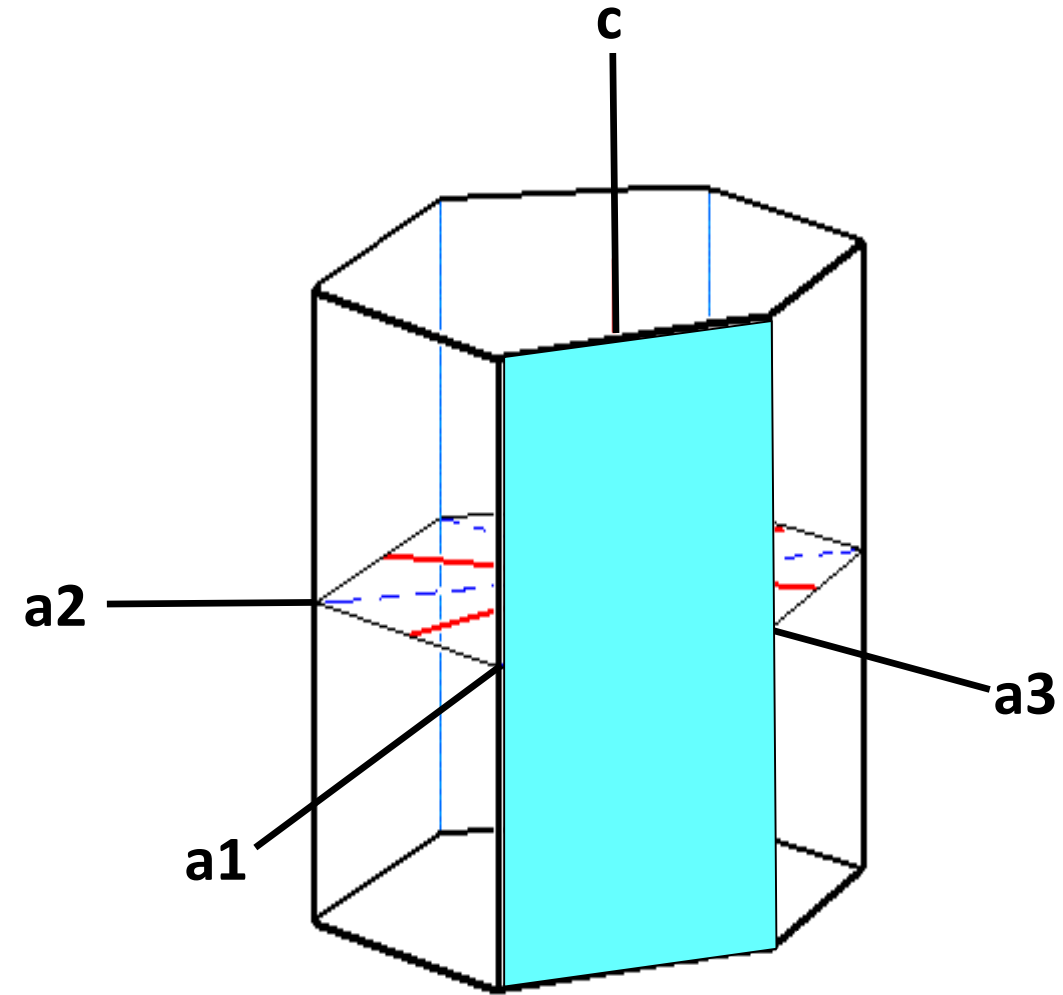
1. **Basal (c) Pinacoid:** an open form consisting of two parallel faces that intercept the c axis and are parallel to the other three horizontal axes.
2. **Hexagonal prism 2st order:** an open form having 6 faces parallel to c-axis and each face intersects two horizontal axes at the same distance (unity) and is parallel to the other horizontal axis



Normal class of hexagonal system

➤ Crystal forms

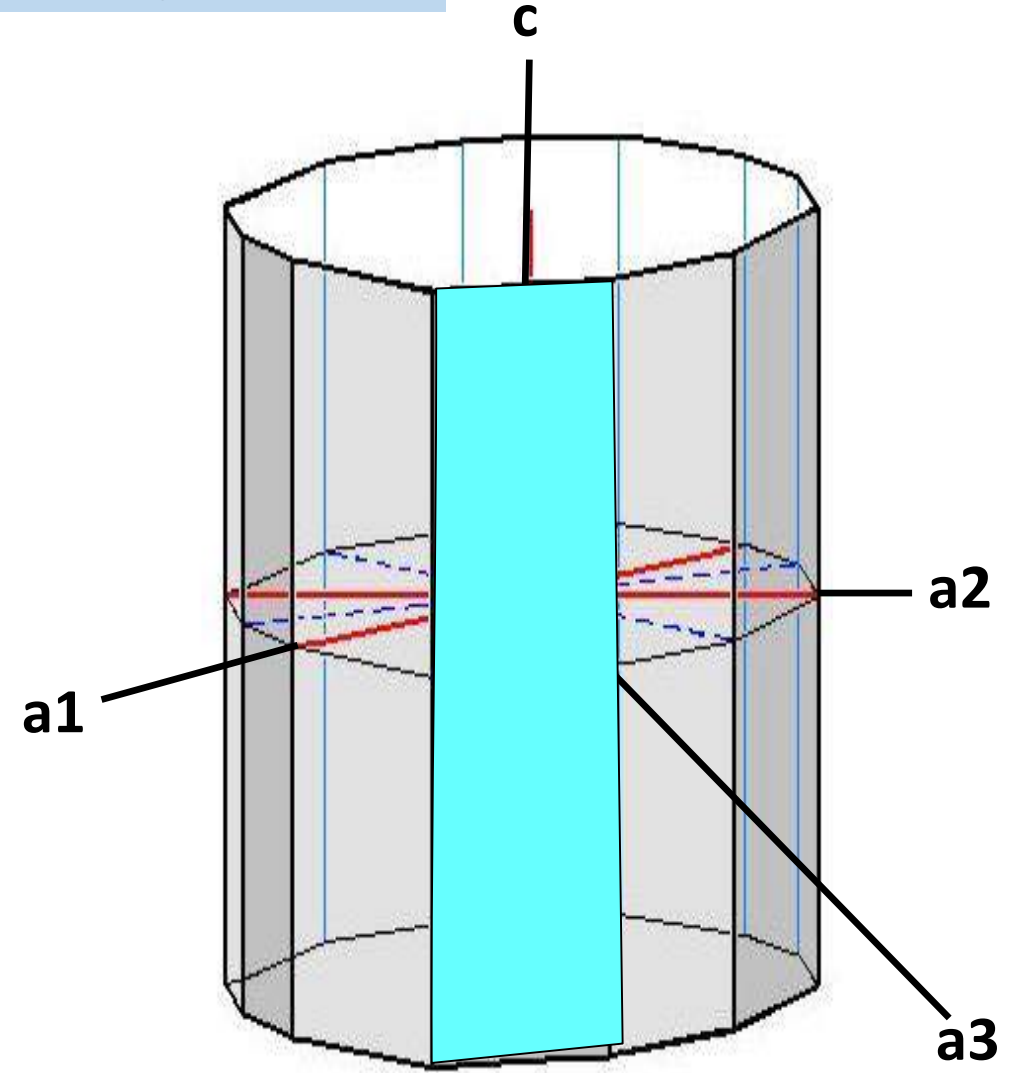
3. **Hexagonal prism 1st order:** It is an open form having 6 faces parallel to c-axis and each face intersects two horizontal axes at the same distance (unity) but intersect the other horizontal face axis at longer distance



Normal class of hexagonal system

➤ Crystal forms

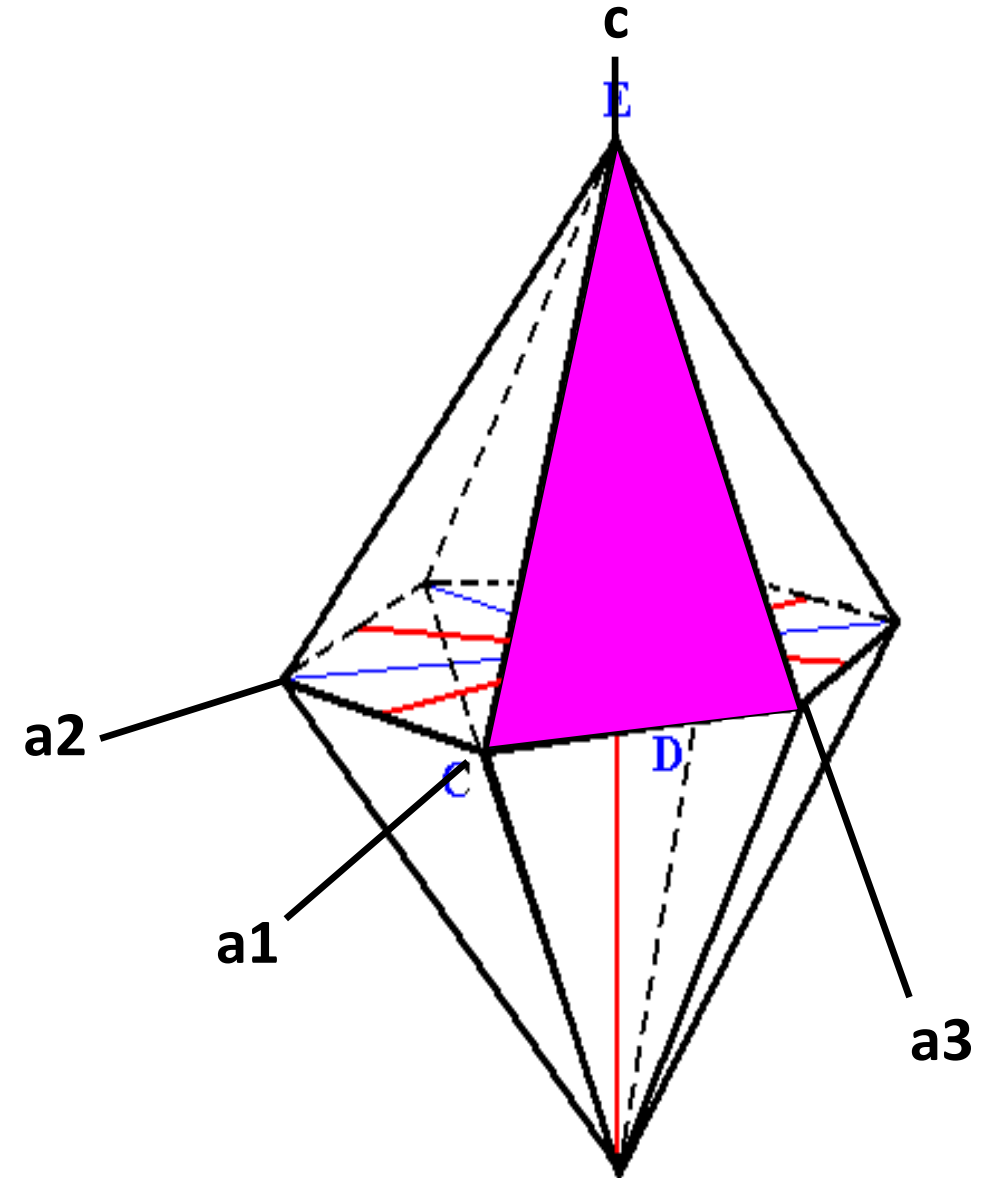
4. **Dihexagonal prism** : An open form consisting of twelve faces parallel to c axis and intersect the horizontal axes but at different distances.



Normal class of hexagonal system

➤ Crystal forms

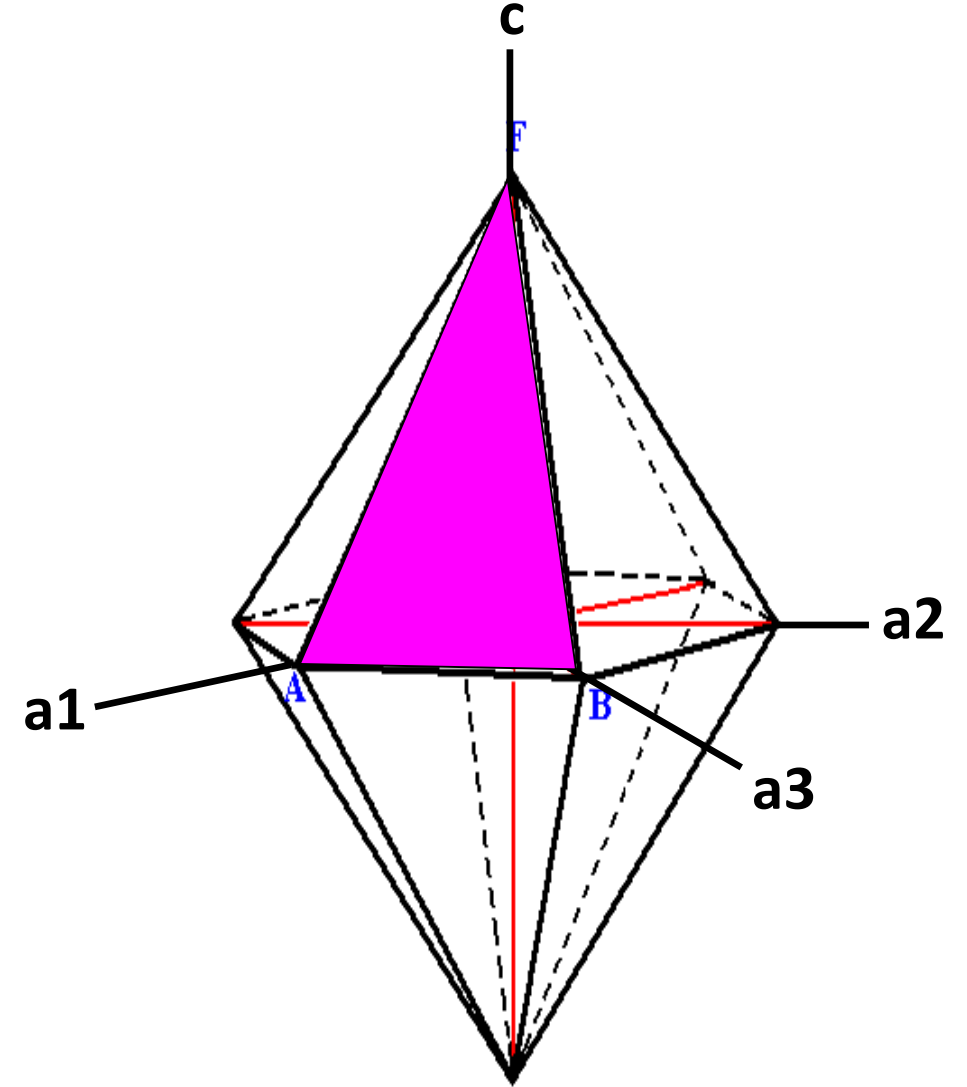
5. **Hexagonal bipyramid 1st order:** A closed form have 12 isosceles triangular faces, each face intersects two horizontal axes at the same distance (unity) but intersect the other horizontal face axis at longer distance. All faces intersect the c axis.



Normal class of hexagonal system

➤ Crystal forms

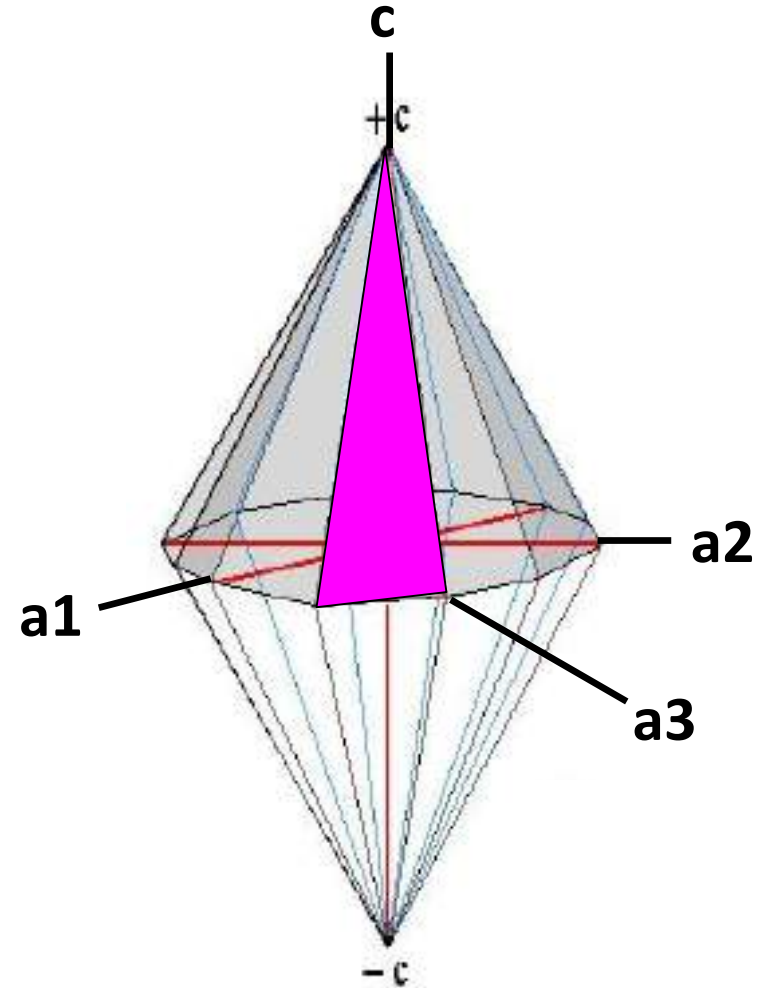
- 6. Hexagonal bipyramid 2nd order:** A closed form have 12 isosceles triangular faces, each face intersects two horizontal axes at the same distance (unity) and is parallel to the other horizontal axis. All faces intersect the c axis.



Normal class of hexagonal system

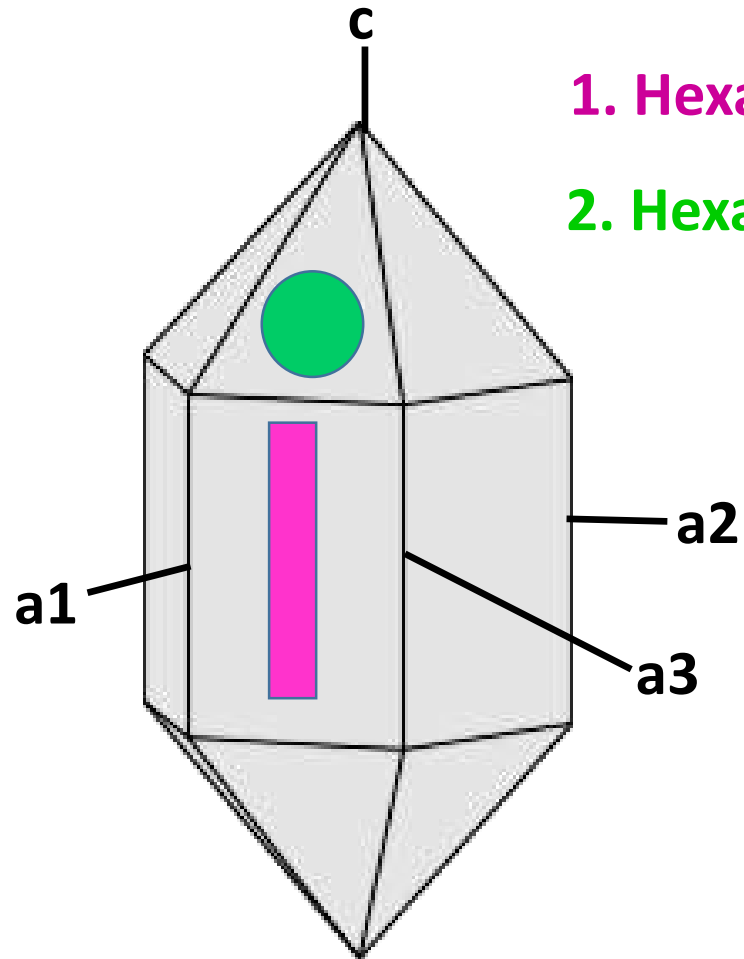
➤ Crystal forms

7. **Dihexagonal bipyramid (general form):** A closed form having 24 faces that intersect the horizontal axes but at different distances. All faces intersect the c axis.



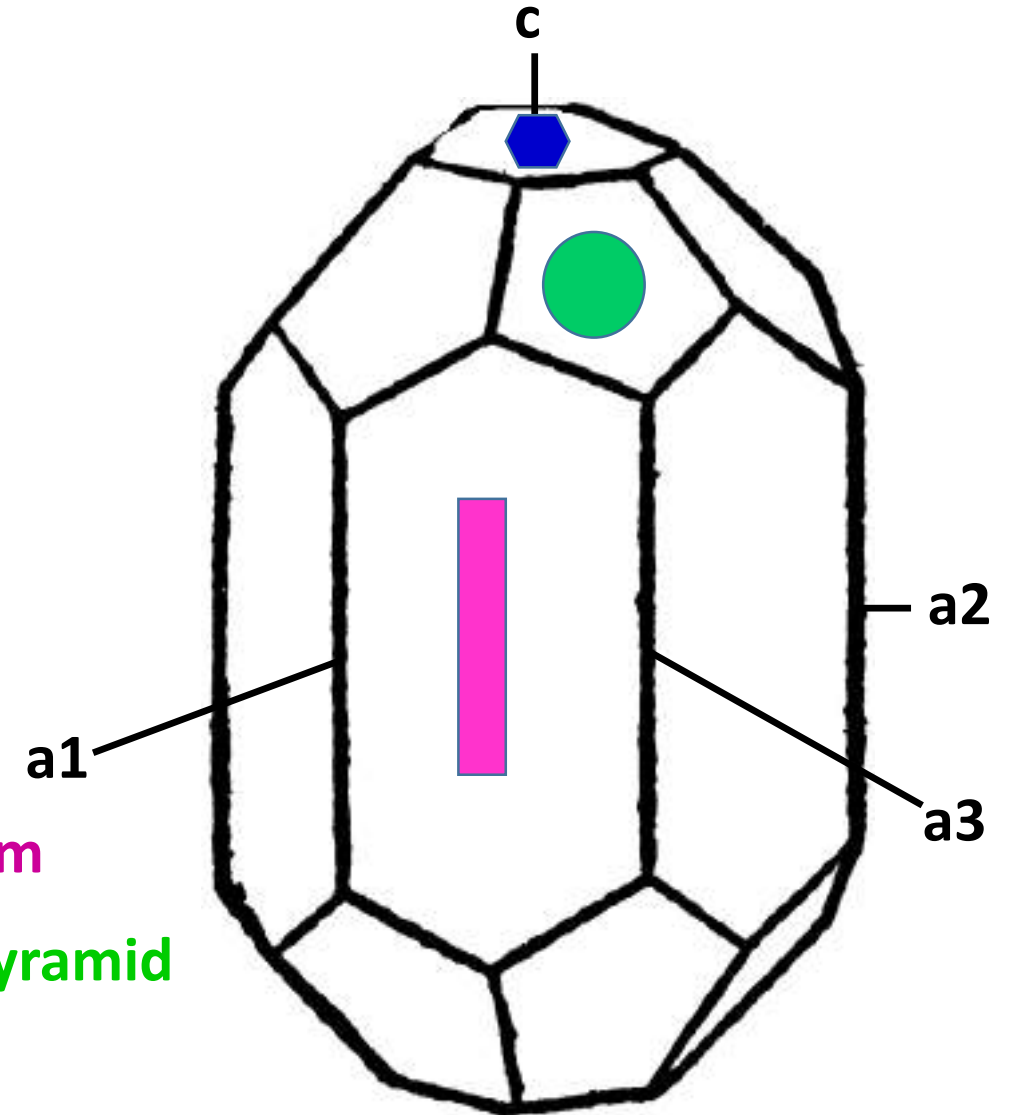
Normal class of hexagonal system

➤ Compound crystals



1. Hexagonal prism

2. Hexagonal bipyramid



1. Hexagonal prism

2. Hexagonal bipyramid

3. Basal pinacoid

Normal class of hexagonal system

Crystal Form	Number of Faces	Form type
Basal Pinacoid	2	open
Hexagonal prism first order	6	open
Hexagonal prism second order	6	open
Dihexagonal prism	12	open
Hexagonal Bipyramid first order	12	closed
Hexagonal Bipyramid second order	12	closed
Dihexagonal Bipyramid	24	closed

Mineralogy

What is a mineral?

The mineral is a homogeneous, naturally-occurring, solid, and generally inorganic substance with a definable chemical composition and an orderly internal arrangement of atoms

Homogeneous

- Mineral consists of single substance
- Cannot be broken into simpler components

Naturally Occurring

- Minerals are the result of natural geological processes
- Man-made minerals are called synthetic minerals (e.g. industrial diamonds)

Solid

- Minerals must be able to maintain a set shape nearly indefinitely
- liquids are not minerals

Definable Chemical Composition

- A mineral can be described by a chemical formula
 - Quartz: SiO_2
 - Diamond: C

Orderly Arrangement of Atoms

- Minerals have a fixed atomic pattern that repeats itself over a large region relative to the size of atoms
 - Crystal solid, or crystal lattice: The organized structure of a mineral
 - A glass is not a mineral; no organized structure

Generally Inorganic

- Organic: A substance composed of C bonded to H, with varying amounts of O, N and other elements. C, alone, is not organic!
- Only a few organic substances are considered minerals, all other minerals are inorganic

Nomenclature of minerals

Minerals may be given names on the basis of some physical properties or chemical aspects, or they may be named after a locality, a public figure, a mineralogist, or almost any other subject considered appropriate.

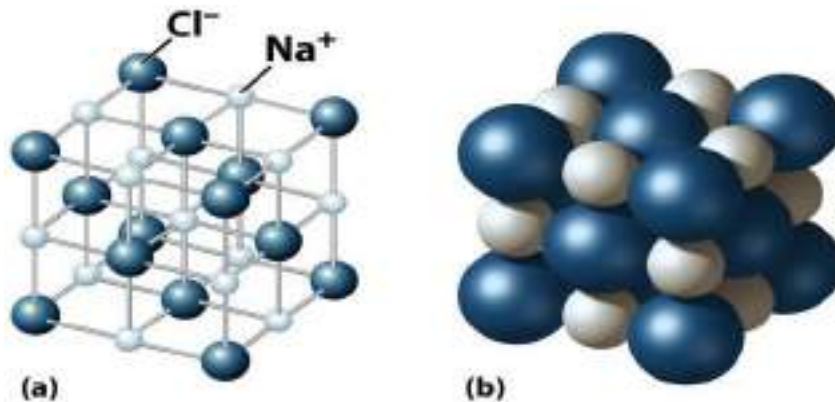
- **Albite ($\text{NaAlSi}_3\text{O}_8$):** from the Latin, albus (white), in allusion to its color.
- **Rhodonite (MnSiO_3):** from the Greek, rhodon (a rose), in allusion to its characteristically pink color.
- **Chromite (FeCr_2O_4):** because of the presence of a large amount of chromium in the mineral.
- **Magnetite (Fe_3O_4):** because of its magnetic Properties.
- **Franklinite (ZnFe_2O_4):** after a locality, Franklin, New Jersey, where it occurs as the dominant zinc mineral.
- **Sillimanite (Al_2SiO_5):** after Professor Benjamin Sillman of Yale University.

Structure of minerals

It is an ordered arrangement of atoms or ions which constitute mineral crystal.

Such as **Crystal lattice and Polymorphs**

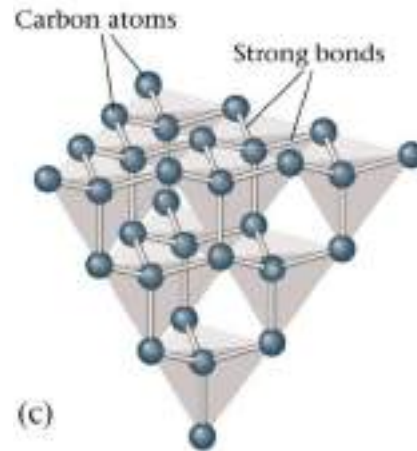
Crystal lattices are an imaginary three-dimensional framework and form a network of regularly spaced points without gaps. Lattice atoms are held in place by electrical bonds such as ionic, covalent, metallic, van der Waals and hydrogen bonds. Such bonds govern mineral properties.



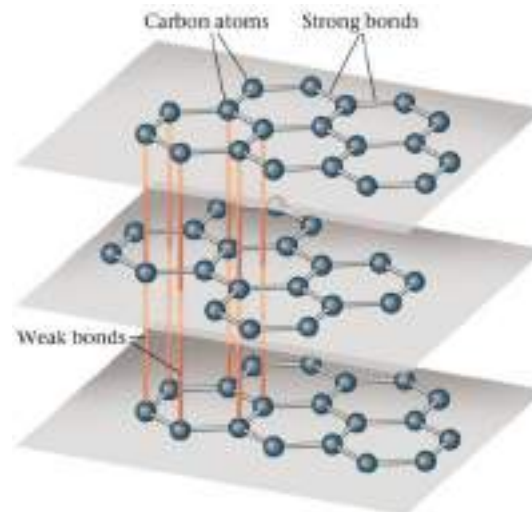
Crystal Structure (Lattice) of Halite mineral

: Two minerals that have the same composition but different crystal form

- Diamond: C



- Graphite: C



Diamond (C)

***Carbon atoms covalently bond in tetrahedral networks**

***Forms strong bonds that are hard to break, so diamonds are very hard**

***Diamonds are denser (3.5 g/cm³) than graphite (2.1 g/cm³) because of formation under great pressure.**

Graphite (C)

***Carbon atoms bond in planar sheets; sheets are weakly bonded**

***Sheets are easy to break; graphite is very soft**

Crystal systems

Based on the geometrical arrangement of the crystal lattice (crystallographic axes and angles), all minerals are classified into seven crystal systems

- **Cubic (isometric):** has three equal axes at right angles to each other.

Minerals that form in the isometric system such as : Garnet, Diamond, Fluorite, Gold, Silver

- **Tetragonal:** has three axes at right angles to each other. Two of them are horizontal and of equal length. The third vertical axis is different, shorter or longer than horizontal axes.

Minerals that form in the tetragonal system such as: Rutile and Zircon

- **Orthorhombic:** has three unequal axes at right angles to each other

- Minerals that form in the orthorhombic such as: Andalusite, Zoisite, Hypersthene, olivine, Sulfur and Topaz.

- **Monoclinic:** has three unequal axes, two at right angles, and the other is inclined (a/c , $\beta \neq 90$)

- Minerals that form in the monoclinic system such as: Azurite, Diopside, Malachite, Orthoclase feldspars (including albite) and Sphene.

- **Triclinic:** has 3 unequal axes and all are inclined to each other.

Minerals that form in the triclinic system such as: amblygonite, , kyanite, microcline feldspar, plagioclase and turquoise.

- **Hexagonal:** has four axes, three of them are horizontal and of equal length and the other is vertical and at right angles to the others.

- Minerals that form in the hexagonal system include Apatite, Beryl and Zincite.

- **Trigonal:** has the same crystallographic axes and angles as hexagonal system but the difference occur in vertical axis and horizontal plane.

- Mineralogists sometimes divide the hexagonal system into two crystal systems, the hexagonal and the trigonal, based on their external appearance. (Corundum, both ruby and sapphire, is sometimes described as trigonal). However, for gemological purposes, the above six categories are sufficient.

Mineral groups

Native elements are composed of a single, pure element (ex: Gold (Au), Silver (Ag) and Diamond (C)).

Oxides consist of metal cations bonded to oxygen anions like Quartz (SiO_2), Magnetite (Fe_3O_4), Chromite (FeCr_2O_4) and Pyrolusite (MnO_2).

Sulfides contain sulfide ion such as pyrite (FeS_2), sephalerite (ZnS), galena (PbS) and chalcopyrite (Cu Fe S_2). Oxides

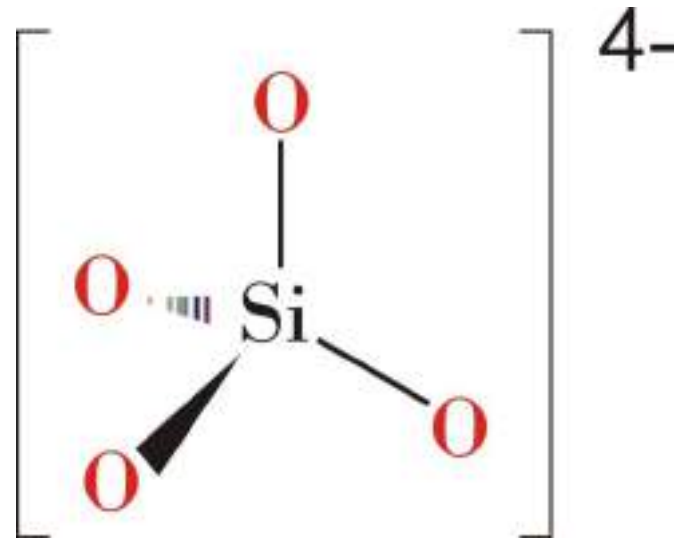
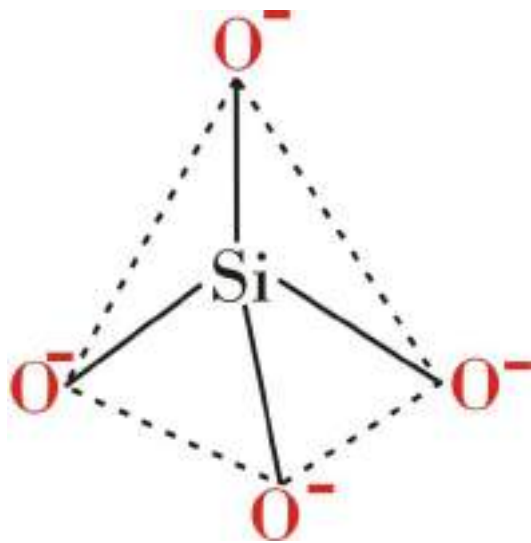
- **Halides** contain halogens (Cl^- , F^- , I^- , Br^-) as Halite (NaCl), and Fluorite (CaF_2)
- **Carbonates** which consist of carbonate groups (CO_3)⁻ such as Calcite (CaCO_3), Magnesite (MgCO_3) and Siderite (FeCO_3).
- **Sulfates** comprise the sulfate group (SO_4)⁻² like Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) and Barite (BaSO_4).
- **Phosphates** contain phosphate group (PO_4)⁻³ such as Apatite [$\text{Ca}_5\text{FeCl}_3(\text{OH})(\text{PO}_4)_2$]

- **Silicates group**

Basic unit: silica tetrahedral $(\text{SiO}_4)^{-4}$

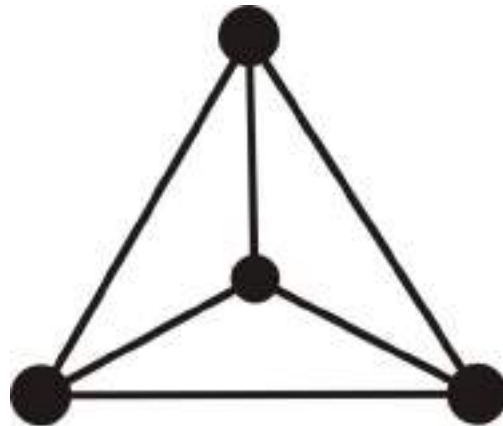
(one silica atom surrounded by four oxygen atoms)

Silicates are the most common mineral class in igneous rocks.

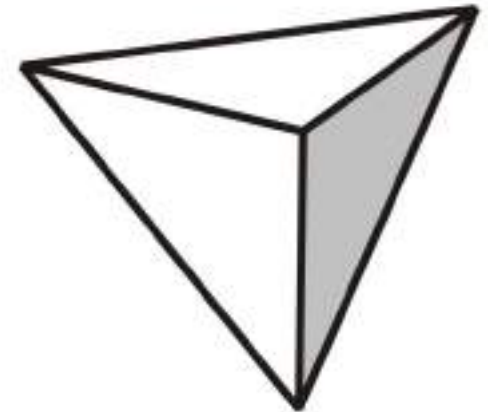


3-dimensional representation

Simplified
representation



2 D

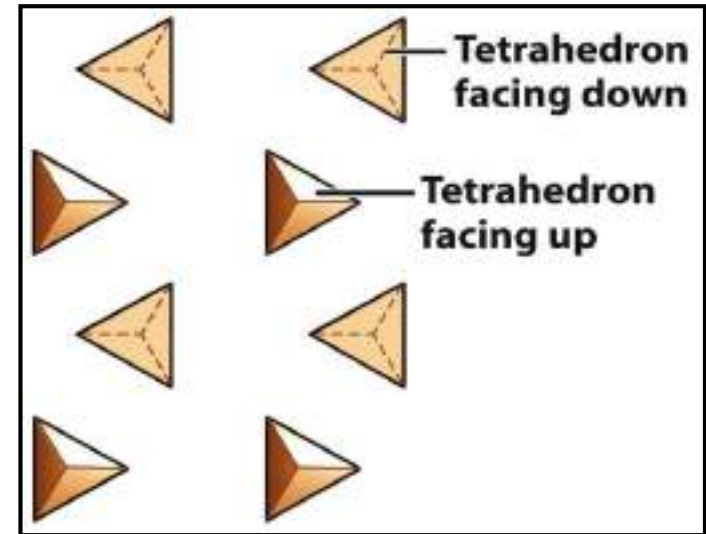


3 D

They show five different structural styles:

1- Isolated silicates

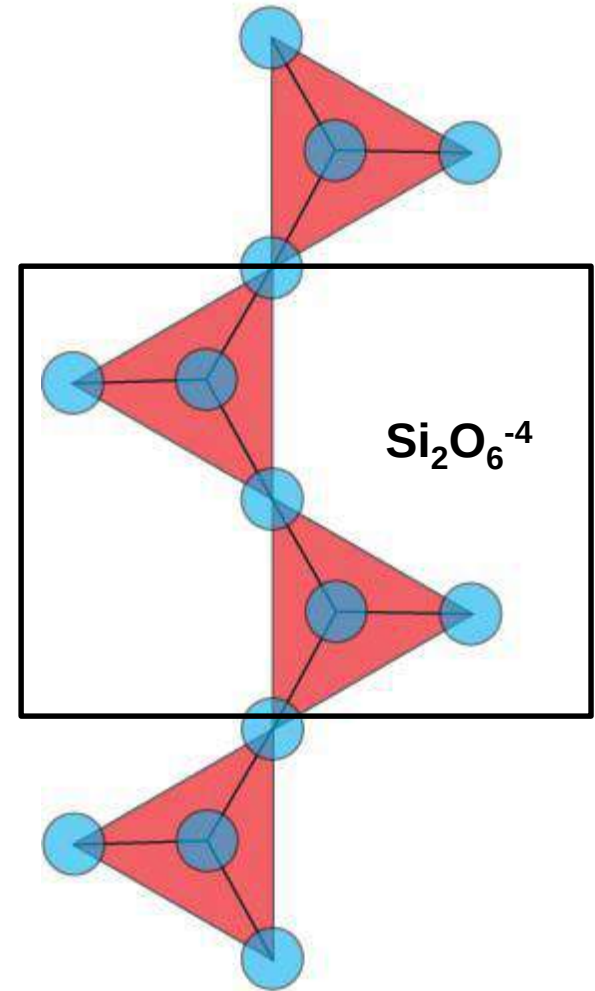
- Each tetrahedron will be isolated
- The basic structural unit is then SiO_4^{-4} .
- The mineral is held together by the attraction between silica tetrahedral and other positive ions such as Garnet



2- Single Chain Silicates

- Two of oxygen's are shared in a way to make long single chain.
- The basic structural unit is $\text{Si}_2\text{O}_6^{-4}$ or SiO_3

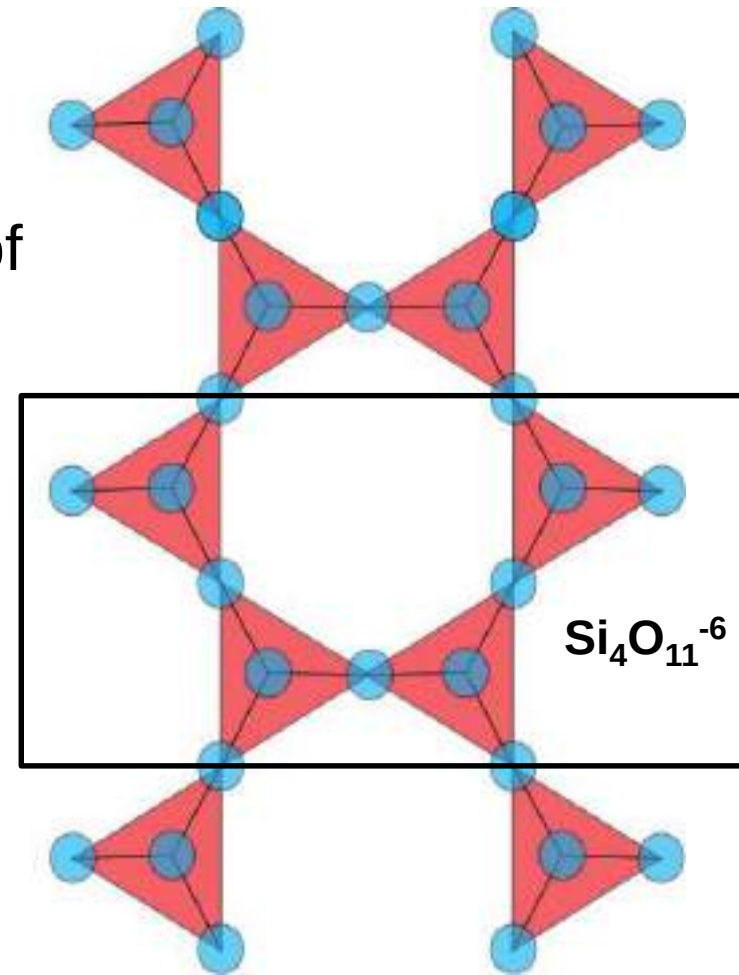
Pyroxene



3- Double chain silicates

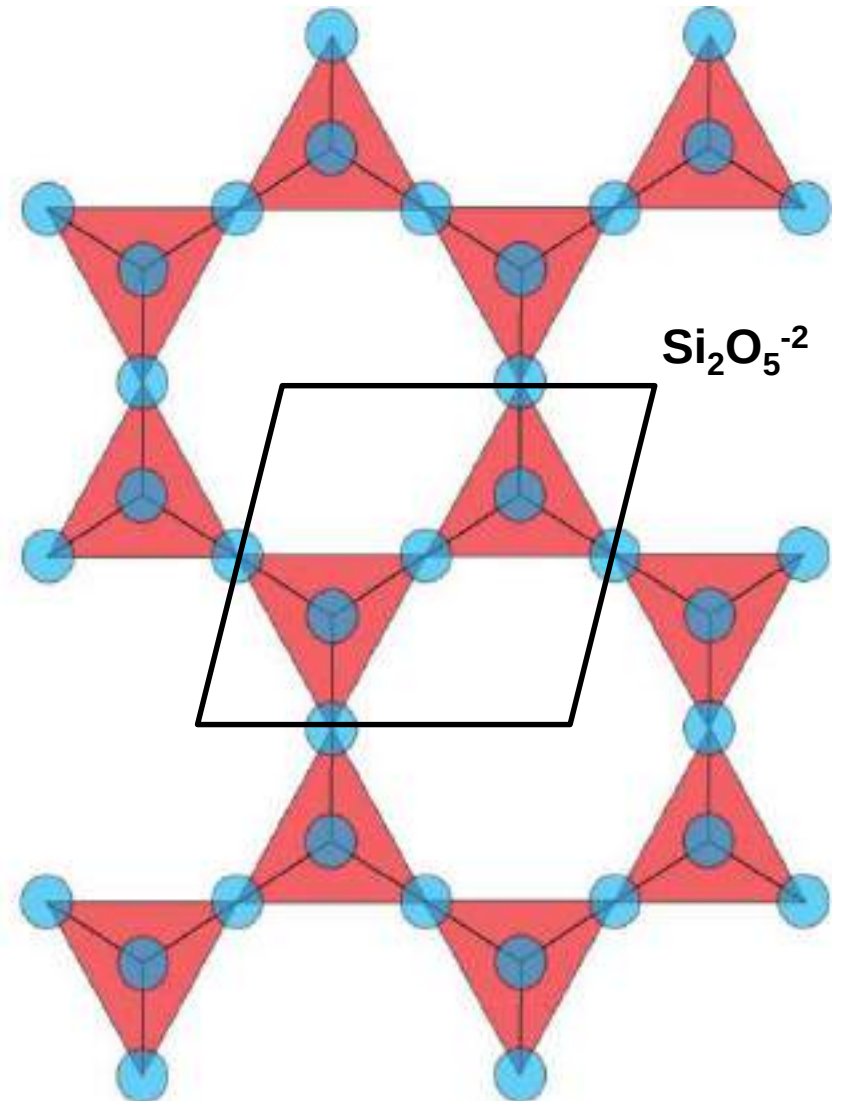
- Two chains are linked together so that each tetrahedral group shares 3 of its oxygen's
- The basic structural group being $\text{Si}_4\text{O}_{11}^{-6}$.

Hornblende



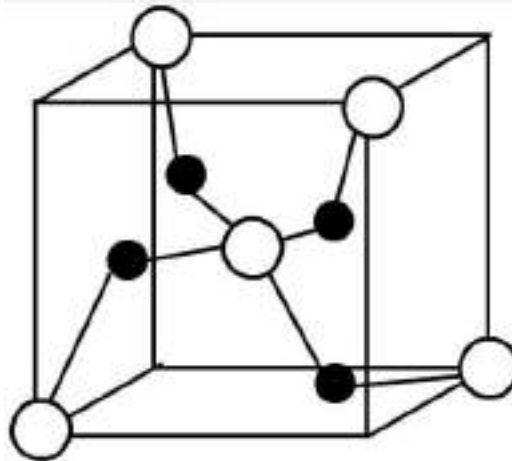
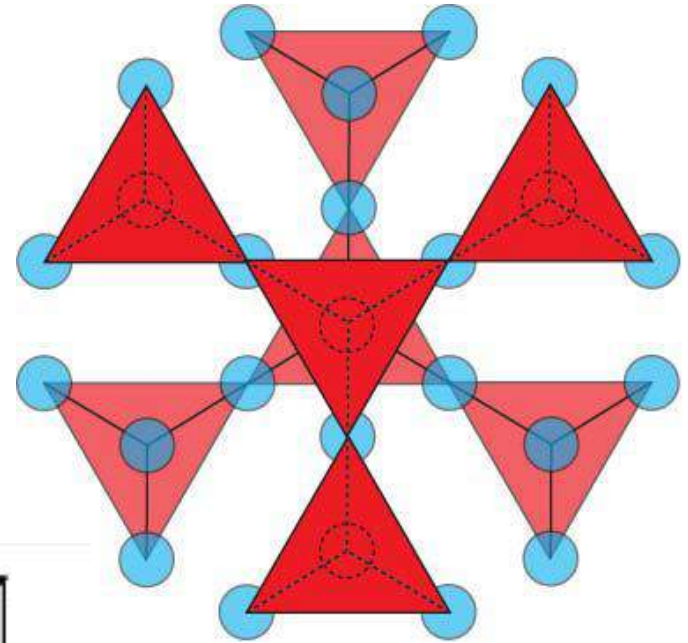
4- Sheet Silicates

- 3 of the oxygen's from each tetrahedral group are shared
- the basic structural group is $\text{Si}_2\text{O}_5^{-2}$.



5- Framework Silicates)

- All of the oxygens are shared with another SiO_4 tetrahedron
- The basic structural SiO_2 .



Quartz (SiO_2)_n

● – O atom

○ – Si atom

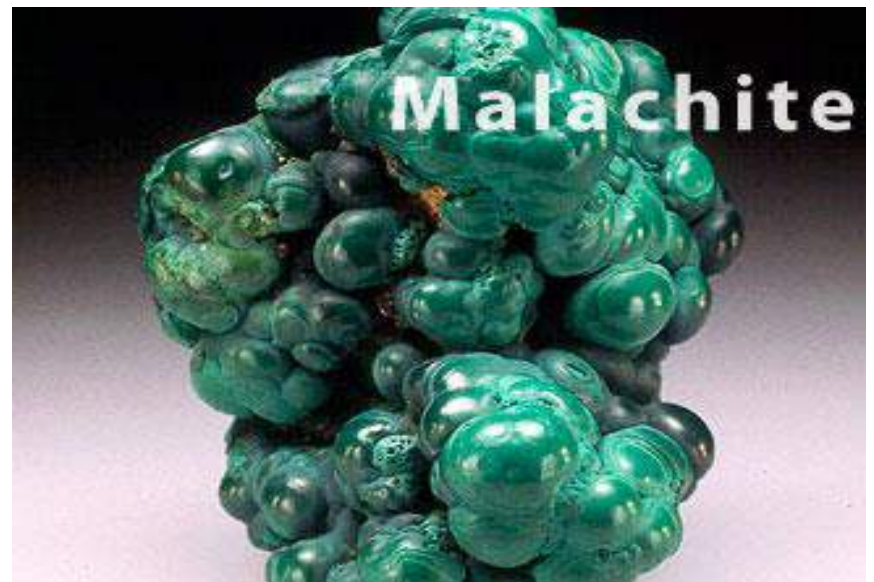
Physical properties of minerals

Optical properties (dependent upon light)

a) Colour

What causes colour in minerals? Minerals are coloured because certain wave lengths of light are absorbed, and the color results from a combination of those wave lengths that reach the eye.

Constant-coloured minerals



Constant-coloured minerals

- Malachite and olivine are always green, azurite is always blue, pyrite and chalcopyrite are always brass-yellow.

- **Varied-colored minerals (allochromatic):**

- in these types of minerals, the colour is not at all a diagnostic property.

Most minerals occur in more than one color (ex: quartz and fluorite).

- The diversity in colour depends on the impurities within the mineral.

- For example, pure quartz is colorless but when it contains small amount of red iron oxide (hematite), it gives rose quartz. Red quartz (jasper) contains large amount of hematite, yellow quartz (citrine) includes impurities of limonite, violet quartz (amethyst) includes impurities of Mn-oxide.

Moreover, smoky quartz contains traces of Al as a result of color centers whereas milky quartz contains inclusions of fluids and gases.

Varied-colored minerals

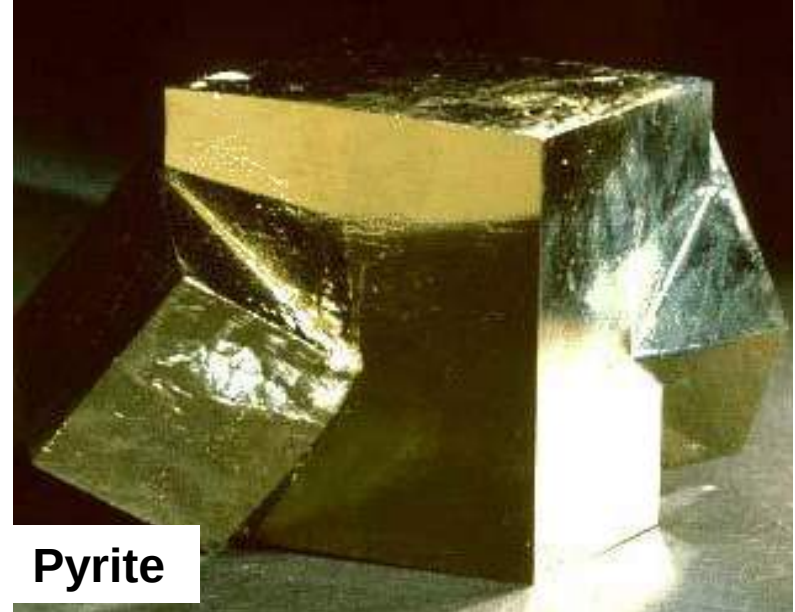


b) Luster

The appearance of mineral surface in reflected light. The two main types of luster are metallic and nonmetallic.

Minerals exhibiting metallic luster have a brilliant appearance and shine like polished metal, such as galena (silver appearance), pyrite (gold appearance) and magnetite (a flat piece of steel).

Metallic luster



Nonmetallic luster

Vitreous: luster of glass (Quartz)

Resinous : luster of resin (Sulphur)

Pearly : iridescence pearl-liked luster (Talc)

Greasy : as if covered with thin film of oil (Graphite)

Silky : silk like (Actinolite)

Adamantine: exceptionally brilliant luster due to unusual high refractive index (Diamond)

Dull (Earthy): dull like unglazed pottery (limonite and Kaolinite)





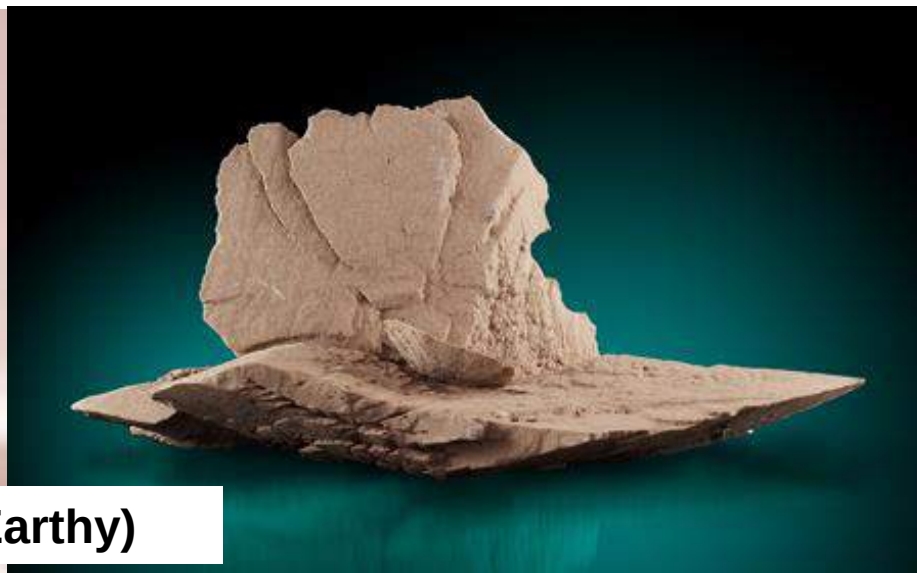
Silky



Adamantine



Dull (Earthy)



C. Streak

It is the colour of a mineral powder. The streak of mineral is determined by rubbing it on a streak plate.



The streak colour is usually consistent with apparent colour of mineral (Limonite)



**Different streak colour of mineral
than its colour**



**Sulphur has yellow colour and
white streak**



**Pyrite has brass-yellow colour
and black streak**

The streak is commonly more reliable than color for identification as the streak of a mineral is usually the same, no matter what the color of the mineral is. For example, Hematite can have various colors, but its streak is always red-brown

D. Transparency

It the ability of mineral to pass the light.



- Transparent:** light can pass through the mineral and images can be seen clearly as calcite, muscovite, pure quartz and gypsum

- Translucent:** light can pass through the mineral but it is diffused so images cannot be seen clearly such as talc, fluorite, orthoclase and barite.

- Opaque:** no light pass through the minerals such as galena.

Miscellaneous Features

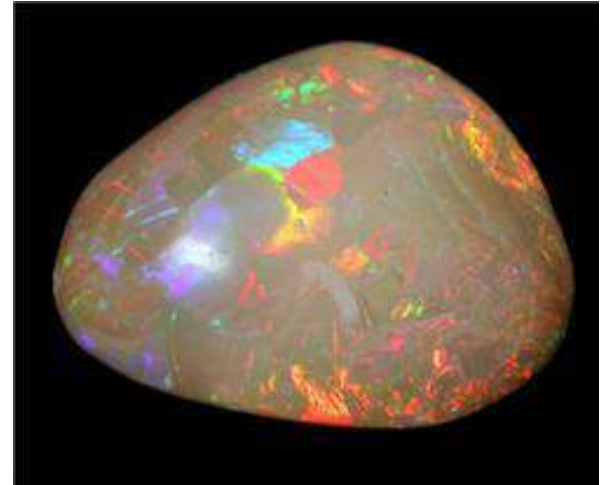
Play of colors: The mineral appear many colours when turned. Example, precious opal



Iridescence: It is a play of colours due to thin coating on the mineral surface or because of partially opened cleavages
Example, Goethite



Opalescence: Milky or pearly reflections from the interior of the specimen. Example: Opal displaying Opalescence



Chatoyancy: Silky appearance on reflected light result from closely packed parallel fibrous inclusions or cavities. Example tiger's eye quartz.



Asterism: similar to chatoyancy but inclusions arranged in three crystallographic directions at 120° to each other (six pointed star of light seen).

Star rose quartz



Pleochroism: the specimen appears variously colored when viewed in different directions as a result of selective absorption of light along different crystallographic directions. Example, tourmaline

• **Tarnish:** chemical reactions between the mineral and air often produce thin coatings of the reaction products. Usually these coatings dull the surface, but occasionally they are brilliantly colored. Examples, copper, bornite.



Bornite



Bornite when Tarnished

Luminescence: It is emission of light from non incandescent minerals.

Minerals that luminescent while exposing to UV or X-Ray or cathode ray are **Fluorescent**. If the luminescence continues after cut off exciting ray called **phosphorescent**.

Thermoluminescence: Mineral becomes luminous when heated. Example. Apatite and Calcite minerals

Triboluminescence: Mineral becomes luminous when scratched, rubbed, or crushed. Examples, fluorite, sphalerite.

Cohesive properties

Crystal Habit

Crystal habit is the characteristic external shape of an individual crystal or crystal group.

- complete faces is called euhedral,



- uncompleted faces is subhedral,



- no faces is called anhedral.



The names of crystal habits are derived from predominant crystal faces (prism-prismatic, pyramid – pyramidal and pinacoid–platy).

• Individual Crystal Terms

- ***Acicular***: Needle-like crystal (rutile).
- ***Bladed***: Elongated crystals flattened like a knife blade (actinolite, kyanite).
- ***Blocky***: Rectangular and box-like crystals (plagioclase).
- ***Equant***: Rounded and angular crystals (olivine, garnet).
- ***Fibrous***: Thinner acicular crystals parallel or radiating (okenite)
- ***Tabular***: Plate-like crystals (wulfenite).
- ***Prismatic***: Pencil-like, elongated crystals that are thicker than needles (tourmaline, beryl).
- ***Striated***: lines can grow on certain crystal faces of minerals (pyrite, quartz, sephalerite)

1) Aggregate Crystal Terms:

- ***Arborescent***: Tree-like clusters (native gold).
- ***Botryoidal (globular)***: Grape-like bunches with interlocking rounded masses (malachite, hematite).
- ***Dendritic***: Plant-like patterns (Sal ammoniac)
- ***Drusy***: A surface covered with a layer of small crystals (amethyst).
- ***Granular***: Crystals of a small size (less than 1 cm across) exhibit no really discernable crystal form (franklinite).
- ***Lamellar (Foliated or Micaceous)***: Layered masses like sheets of paper (muscovite).
- ***Massive***: Indiscernible masses of crystals usually too fine to see (Lazurite)

- ***Oolitic:*** A mineral aggregate formed of small spheres resembling fish roe (hematite).
- ***Radiating:*** Distinct crystals arranged in an orientation outward from a common point (atacamite).
- ***Rosette:*** Platy, radiating rose-like aggregate (barite).
- ***Stalactitic:*** Pendent cylinders or cones. Stalactites form by deposition from mineral bearing waters dripping from the roofs of caverns (calcite, goethite).
- ***Mammillary:*** Breast-like (malachite, hematite).
- ***Plumose:*** Fine, feather-like scales (aurichalcite, boulangerite, mottramite).
- ***Reticulated:*** Crystals forming net-like intergrowths (cerussite).



Acicular rutile



Striated sphalerite



Prismatic beryl



Bladed actinolite



Lamellar muscovite



Mammillary malachite



Botryoidal hematite



Reticulated cerussite



Stalactites



Rosette barite



Dendritic Sal ammoniac



Arborescent gold

Hardness

The hardness is a measure of mineral resistance to abrasion process (scratching).

Hardness	Mineral	Common Objects
1	Talc	Fingernail
2	Gypsum	Fingernail (2.5)
3	Calcite	Copper Penny (3)
4	Fluorite	knife blade (5)
5	Apatite	Glass (5.5) & Steel nail (6)
6	Orthoclase	Streak plate (6.5)
7	Quartz	
8	Topaz	
9	Corundum	
10	Diamond	

Cleavage and parting

Cleavage is the tendency of a mineral to split along planes of weak bonding (cleavage planes) producing flat, shiny surfaces.

there are three main types of cleavage:

- **Perfect cleavage:** cleavage planes are clear and can be easily distinguished (ex, mica).
- **Imperfect:** cleavage planes are present but less obscure like beryl and apatite.
- **Poor:** cleavage planes are absent.

Cleavage can be classified as the following:

- **One set of cleavage:**

- ex: Mica

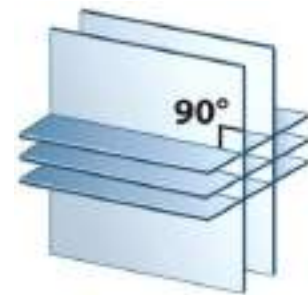


One set of cleavage

- **Two sets of cleavage:**

- Pyroxene two sets of cleavages at 90°

- Amphibole two sets of cleavages at 120° .



Two sets of cleavage

- **Three sets of cleavage:**

- Calcite three sets of cleavages

(Rhombohedral cleavage)



Three sets of cleavage
not at 90°

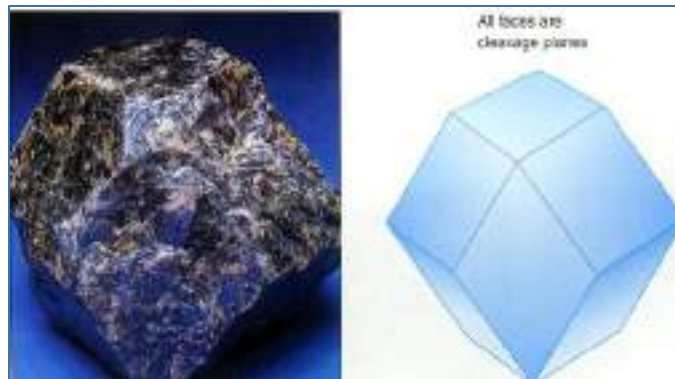
- **Four sets of cleavage:** the mineral breaks in four directions producing octahedrons

- Such as Fluorite



- **Six sets of cleavage:** the mineral breaks in six directions forming dodecahedrons

- Such as Sphalerite.



Parting

- *It* is also a plane of weakness in the crystal structure,
- They are weakened by some applied force,
- It may not be apparent in all specimens of the same mineral
- It may appear if the mineral has been subjected to the right stress conditions or when it is crystallographically twinned.
- **Corundum** shows parting due to twinning.
- **Pyroxene and Apatite** exhibit parting due to weakness.

Fracture

Fracture means description the way that mineral tends to break.

The quality of such surface is often further described as:

- **Conchoidal:** smooth curved lines (shell-like) such as quartz.



- Earthy:** looks like freshly broken soil such as Limonite and Kaolin



- Hackly:** jagged surface with sharp edges such as native metals (copper and silver).

- Uneven:** rough surface has random regularities such as pyrite and arsenopyrite.

- Fibrous:** surface show fibers or splinters similar to the way in which wood breaks such as chrysotile and asbestos



Additional characteristic features

Specific gravity

The specific gravity of a mineral is the weight of that mineral divided by the weight of an equal volume of water.

The rock-forming, minerals have specific gravities of 2.6 to 3.4 whereas, the ore minerals are usually heavier, with specific gravities of 5 to 8.

Some mineral show low specific gravity such as magnesite, kaolin, limonite and sulfur, some others show high specific gravity such as chromite, galena, and barite.

Sense properties (taste, odor and touch)

- Halite has saline taste
- Kaolin has astringent taste)
- Talc has soap touch,
- Graphite has greasy touch,
- Gold has cool touch
- By heating (sulfur- match odor and sulfides- H_2S odor),
- Breathing up on (kaolin-mud odor)
- Rubbing (phosphate-garlic odor).

Magnetism

Magnetism of mineral means its affinity to be attracted by magnet.

Paramagnetic minerals only show magnetic properties when subjected to an external magnetic field. When the magnetic field is removed, the minerals have no magnetism.

Ferromagnetic minerals have permanent magnetism if the temperature is below the Curie temperature. These materials will become magnetized when placed in a magnetic field, and will remain magnetic after the external field is removed. Examples of such minerals are magnetite and pyrrhotite.

Origin of Minerals

Mineral deposits have many different origins; magmatic, hydrothermal, metamorphic and sedimentary.

- a) **Magmatic origin**
- b) **Hydrothermal origin**
- c) **Metamorphic origin**
- d) **Sedimentary origin**

a) Magmatic origin

Magma is rock molten materials occur in the deep seated levels of the earth under very high temperature and pressure conditions, but when extruded on the earth's surface called lava.

Slow cooling of magma gives coarse crystals whereas
Rapid cooling gives fine crystals.

Sudden cooling give skeletal or amorphous substances (lava flow)

The chemical composition of magmatic minerals depends on the chemical composition of magma.

Acidic (rich in Si, O, Na, K, Al) produce feldspars, quartz and muscovite (felsic minerals),

basic magma (rich Si, O, Fe, Mg, Ca) produces the ferromagnesian minerals such as olivine, pyroxene, amphibole and biotite.

The alkaline magma (poor in O, Si and rich in Na and K) produces the feldspathoid minerals such as nepheline and Lucite.

b) Hydrothermal origin

Hydrothermal minerals that are formed by hot aqueous fluids flowing through fractures and pore spaces.

The temperature and pressure play the greatest role during the process of deposition

•**Hypothermal deposits:** They deposited from hot solutions of temperature ranging from 500-300°C and great pressure. Such conditions predominate in the deep places from the earth's surface. Examples are Wolframite and molybdenite.

•**Mesothermal deposits:** They deposited from hot solution of temperature ranging from 300-100°C and moderate pressure (i.e. moderate depth). Examples, metallic sulphides (chalcopyrite, sphalerite& galena), Sulphates (e.g Barite) and carbonates (e. g calcite).

•**Epithermal deposits:** They deposited from hot solution of temperature ranging from 100-50C and lower pressure (i.e. shallow depth) Examples Stibnite, marcasite, calcite, and fluorite.

c) Metamorphic origin

- Each mineral or rock must be formed under suitable conditions of temperature and pressure.
- When these conditions change, this solid matter changes also to be stable again at these new conditions.
- When the magma came in contact with a rock, the constituent minerals of this rock may fuse and recrystallize again forming new mineral phases.
- The original minerals are said to be metamorphosed to other minerals and process is called metamorphism.

- There are two types of metamorphic minerals; metamorphosed and metamorphogenic minerals.
- Metamorphosed minerals are formed by alteration of primary minerals in parent rock when it is exposed to agents of metamorphism (ex: Kaolin after feldspars and chlorite after mica and pyroxene).
- Metamorphogenic minerals resulted from chemical reaction between primary minerals in parent rock during metamorphism (ex: garnet, sphene, talc and graphite).
- Olivine + Anorthite → Garnet
- Ilmenite + Anorthite → Sphene

d) Sedimentary origin

i. Chemical precipitation from lake or sea. When the water becomes saturated in dissolved elements such as Fe, Al and Mg, it precipitates them in form of hydroxides, carbonates and oxides. (ex: Siderite, bauxite, hematite). Moreover, calcite can be formed by chemical precipitation

ii. Evaporation of lake or sea water lead to concentration of salts in these lakes to the degree that permits to crystallize some minerals in regular manner depending on the degree of solubility of these salts. The less soluble salt will first crystallize. Accordingly, carbonate salts crystallize first (e.g. calcite), then Magnesite, followed by Sulphates (e.g. gypsum and finally chlorides or halides (e.g. Halite).

iii. Biochemically where the minerals are formed as a result of organic activity of bacteria such as Sulfur, limonite and goethite. Sulfur is formed by the reduction action of bacteria to gypsum associated with salt domes whereas, limonite and goethite are precipitated as a result of bacteria activity in bogs and lake deposits.

Name	Hardness	Sp.Gr	Streak	Color	Group	Crystal Shape
Talc	1	2.58-2.83	White	Light to gray, green	Silicates	Monoclinic
Graphite	1-2	2.1-2.3	Gray	Grey	Native	Trigonal/ Hex
Bauxite	1-3	2.3-2.7	White	Yellow, brown	Hydroxides	N/A
Sulfur	1.5-2.5	2-2.1	White	Yellow	Native	Orthorhombic
Halite	2	2.1-2.2	White	Numerous	Halides	Cubic
Gypsum	2	2.32	White	Light medium	Sulfates	Monoclinic
Kaolinite	2-2.5	2.6-2.63	White	Light, medium	Silicates	Triclinic
Galena	2.5	7.58	Lead-gray	Lead gray	Sulfides	Cubic
Biotite	2.5-4	2.7-3.4	Colorless	Dark	Silicates	Monoclinic
Muscovite	2.5-4	2.77-2.88	Colorless	Light	Silicates	Monoclinic
Calcite	3	2.71	White grayish	Light medium	Carbonates	Trigonal/ Hex
Celestite	3-3.5	3.96-3.98	White	Light	Sulfates	Orthorhombic
Barite	3-3.5	4.5	White	Light medium	Sulfates	Orthorhombic
Dolomite	3.5-4	2.85	White	Light	Carbonates	Trigonal/ Hex
Azurite	3.5-4	3.77-3.78	Pale blue	Deep blue	Carbonates	Monoclinic
Sphalerite	3.5-4	3.9-4.1	Colorless-brown	Num. Esp. black	Sulfides	Cubic
Malachite	3.5-4	4	Pale green	Deep green	Carbonates	Monoclinic
Chalcopyrite	3.5-4	4.3-4.4	Green-black	Brassy yellow	Sulfides	Tetragonal
Fluorite	4	3.1-3.3	White	Numerous	Halides	Cubic
Goethite	5-5.5	3.3-4.3	Orange brownish	Black-brown light	Hydroxides	Orthorhombic
Hematite	5-6	5.26	Brown-red	Brown red, black	Oxides	Trigonal/ Hex
Opal	5.5-6.5	1.9-2.3	White	Many esp. dark	Silicates	N/A
Magnetite	5.5-6.5	5.2	Black	Black	Oxides	Cubic
Amazonite	6-6.5	2.55-2.63	White	Medium esp. green	Silicates	Triclinic
Feldspar	6-6.5	2.55-2.63	White	White red	Silicates	Monoclinic
Albite	6-6.5	2.6-2.63	White	Many Esp. Light	Silicates	Triclinic
Pyrite	6-6.5	5	Green-black	Pale yellow	Sulfides	Cubic
Epidote	6-7	3.35-3.5	Colorless-grayish	Dark or yellowish	Silicates	Monoclinic
Olivine	6.5-7	3.27-4.32	Colorless	Green brown	Silicates	Orthorhombic
Almandine (garnet)	6.5-7.5	4.1-4.3	White	Dark esp. brown	Silicates	Cubic
Quartz	7	2.65	Colorless-white	Numerous	Silicates	Trigonal/ Hex
Diamond	10	3.52	White	Numerous	Native	Cubic

IGNEOUS ROCKS





Outlines

- 1- Introduction on igneous petrology
- 2- Physical properties of magma
- 3- Processes of magma formation
- 4- Fractional crystallization of magma
- 5- Environments of magma formation
- 6- Classification of igneous rocks
- 7- Landforms of igneous rocks



1-Introduction

Petrology: the science deals with the study of different rock types

Rock: Hard natural material consists of one mineral (monomineralic rock) or more than one mineral (polymineralic rock).

Igneous rock: Any crystalline or amorphous rock that formed from cooling of magma or lava

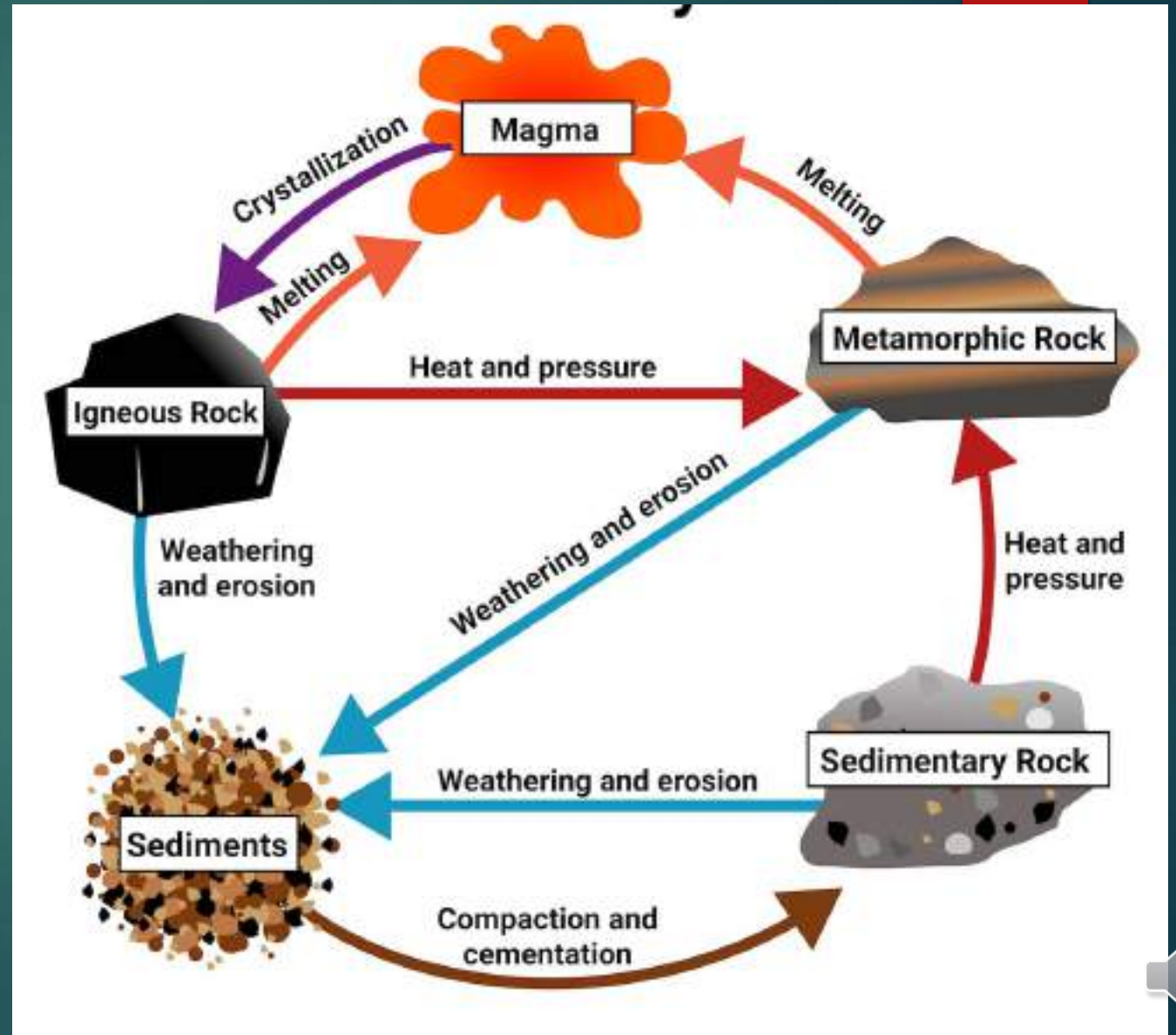
Magma: molten silicate material formed at great depth under the Earth's surface (about 100-350 km)

Lava: similar to magma but it is formed at the Earth's surface



1-Introduction

Rock cycle: The transformation from one rock type to another type over geologic time



2- Physical properties of magma



Type of magma	Chemical composition
Acidic (Rhyolitic)	> 65% silica, rich in Na & K and poor in Fe, Ca, Mg
Basic (Basaltic)	45-55% silica, rich in Fe, Ca, Mg and poor in Na & K
Intermediate (Andesitic)	55-65% silica, Fe, Ca, Mg ~ Na & K



2- Physical properties of magma

3.1 Temperature of Magmas

- Basaltic magma - 1000 to 1200°C
- Andesitic magma - 800 to 1000°C
- Rhyolitic magma - 650 to 800°C.

3.2. Viscosity of Magmas

It is the resistance to flow (opposite of fluidity) and depends on composition of magma and its temperature. Viscosity increase with increasing silica content and with decreasing temperature.

3.3. Gases (volatiles) in Magmas

The amount of gases of magma increase with increasing silica content of magma. The composition of these gases are mostly H₂O (water vapor) with some CO₂ + Minor amounts of S, Cl, and F gases. Explosive nature of magma depends on gas content and viscosity of magma



2- Physical properties of magma

Type of magma	Chemical composition	Temperature	Viscosity	Gas content
Acidic (Rhyolitic)	> 65% silica, rich in Na & K and poor in Fe, Ca, Mg	650-800	10^5 - 10^8 Pas	High
Intermediate (Andesitic)	55-65% silica, intermediate in Fe, Ca, Mg, Na & K	800-1000	10^3 - 10^5 Pas	Intermediate
Basic (Basaltic)	45-55% silica, rich in Fe, Ca, Mg and poor in Na & K	1000-1200	10 - 10^3 Pas	low



3- Processes of magma formation

Magma is formed as a result of partial melting of asthenosphere

Three different processes are responsible for melting of the asthenosphere:

- a- Rising Temperature
- b- Decreasing Pressure (pressure release)
- c- Flux melting (addition of water or CO₂)



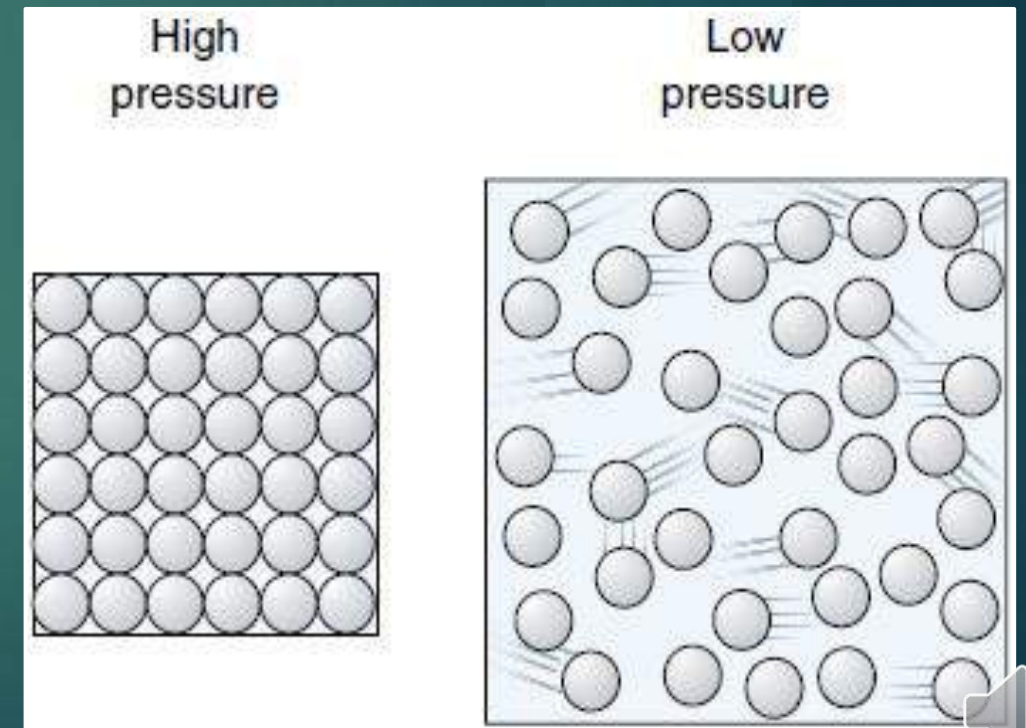
3- Processes of magma formation

a- Rising Temperature

- o An increase in temperature will melt a solid rock. However, increasing temperature is the least important cause of magma formation in the asthenosphere.

b- Decreasing Pressure

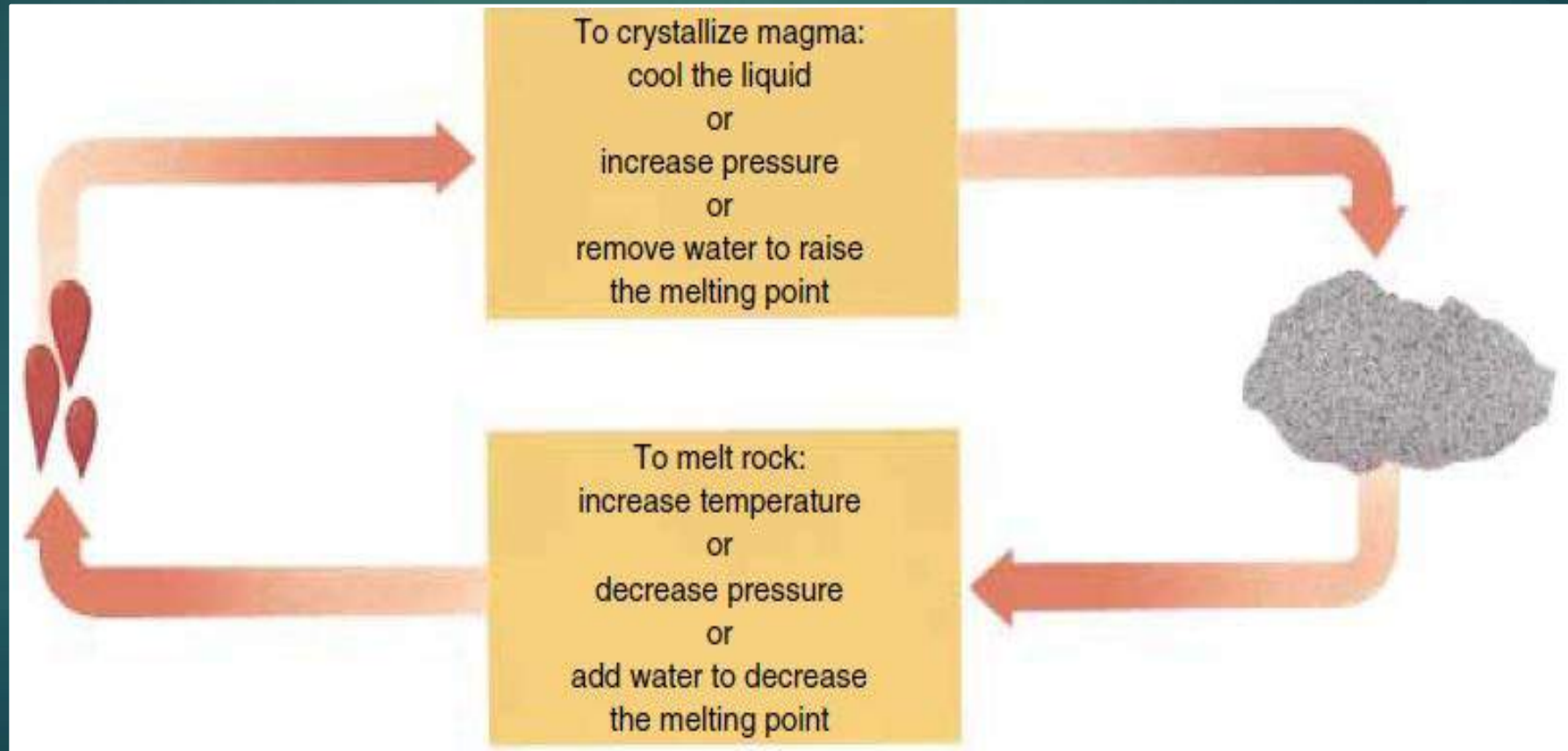
- If a rock is heated to its melting point on the Earth's surface, it melts readily because there is little pressure to keep it from expanding.
- Molten rock occupies about 10 percent more volume than the rock from which it melted
- When mineral melt, the atoms become disordered and move freely taking up more space than in solid rock



3- Processes of magma formation

c- Flux melting (addition of water or CO₂)

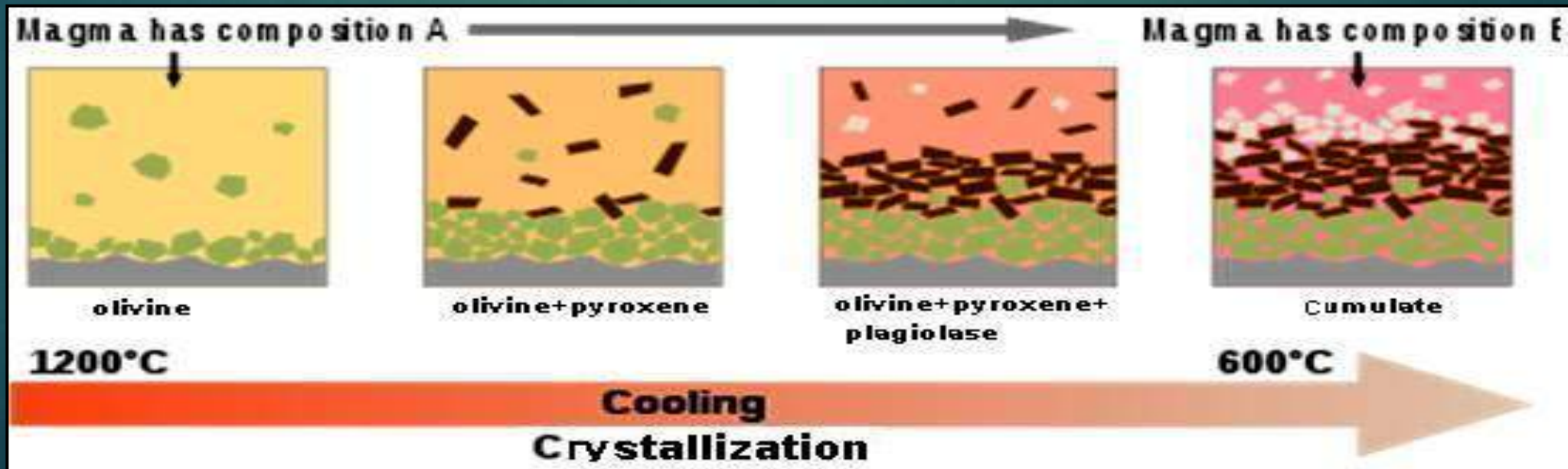
- When water or carbon dioxide are added to rock. These compounds cause the rock to melt at lower temperatures. Addition of water decrease the melting point of rock



4- Fractional crystallization of magma

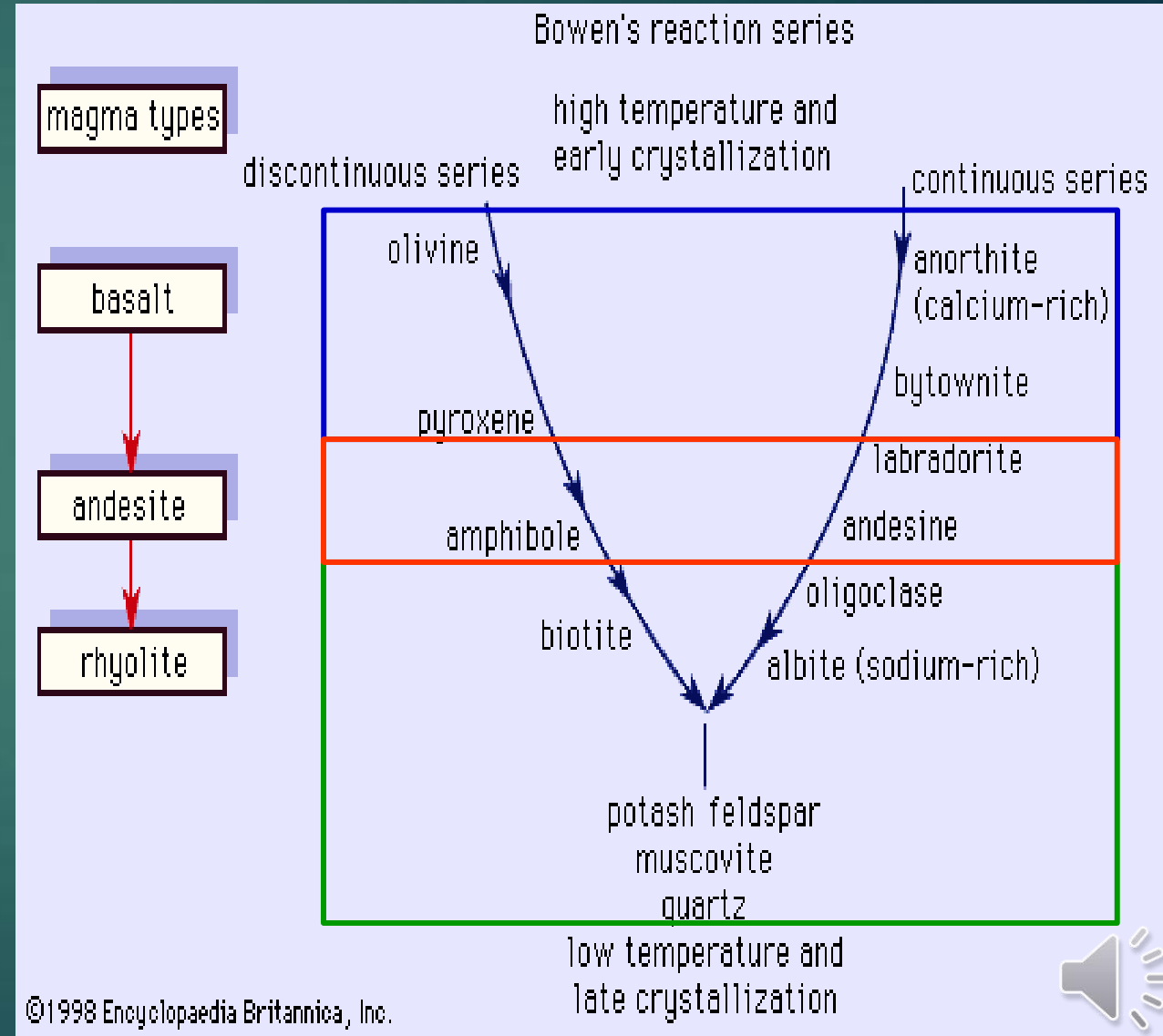
It is a natural mechanism means the change of magma composition up on cooling

- As magma cools, mineral crystallize from melt at different temperatures
- Basic magma can give residual melt of acidic magma if early crystallized mafic minerals are separated from magma.



4- Fractional crystallization of magma

- Bowen reaction series is a good example to understand fractional crystallization
- It is the sequence in which minerals crystallize from a magma up on cooling and can be arranged into two series:
 1. The continuous branch describes the evolution of the plagioclase feldspars as they begin with calcium-rich (anorthite) to more sodium rich (albite).
 2. The discontinuous branch describes the formation of the mafic minerals olivine, pyroxene, amphibole, and biotite mica.



5- Environments of magma formation

➤ Magma forms in three tectonic environments:

a- Spreading Centers (pressure-release)

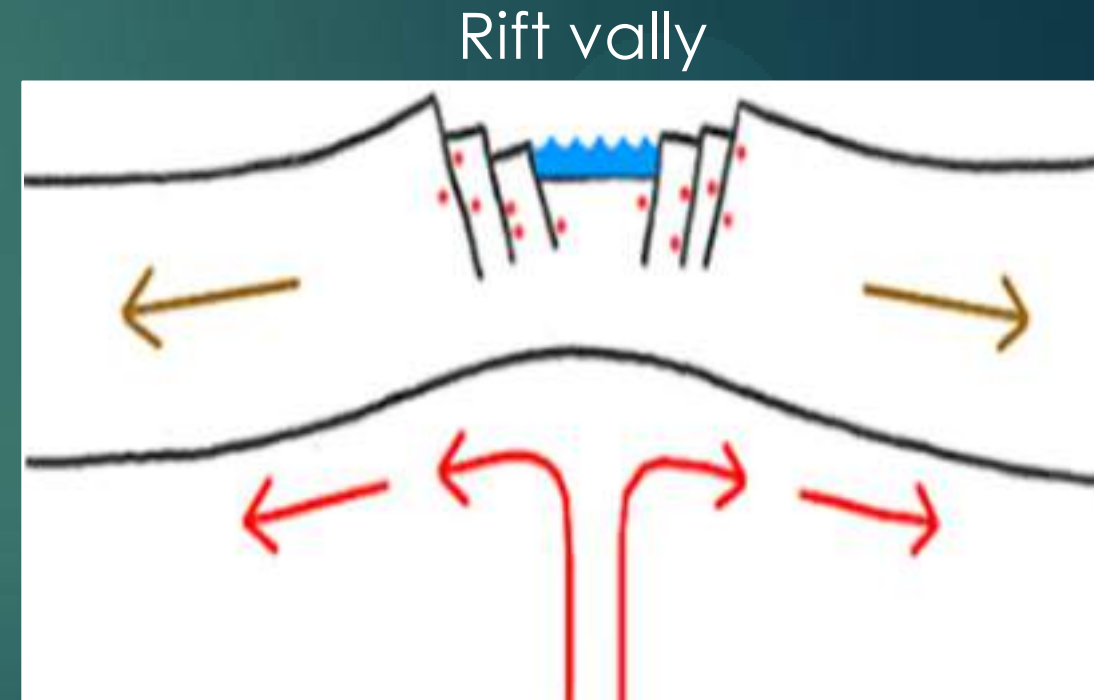
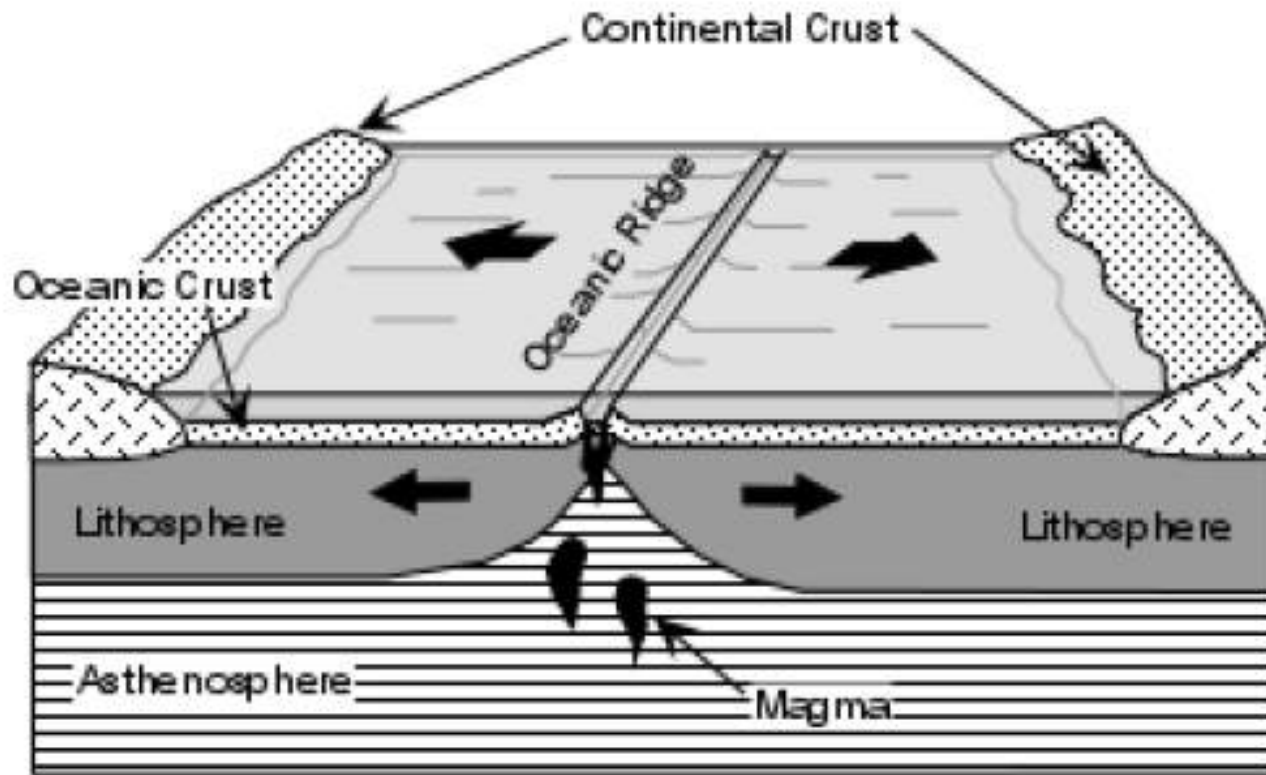
d- Subduction zones (Flux melting)

c- Hot spots (rising temperature)



5- Environments of magma formation

a- Spreading Centers (Divergent plate boundaries)

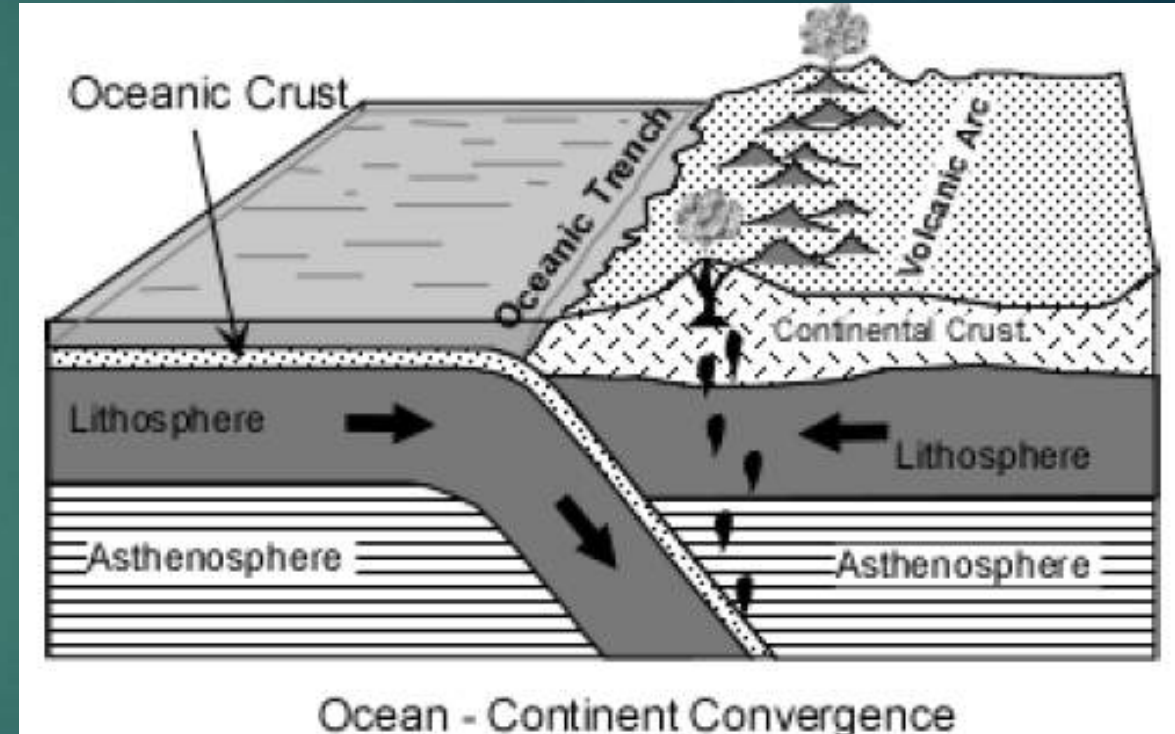


5- Environments of magma formation

b- Subduction zones (Convergent plate boundaries)

❖ Convergent plate boundaries are when two lithospheric plates move towards each other. The most common type where oceanic lithosphere subducts beneath continental one. The generation of magma in these environment is attributed to the following mechanisms:

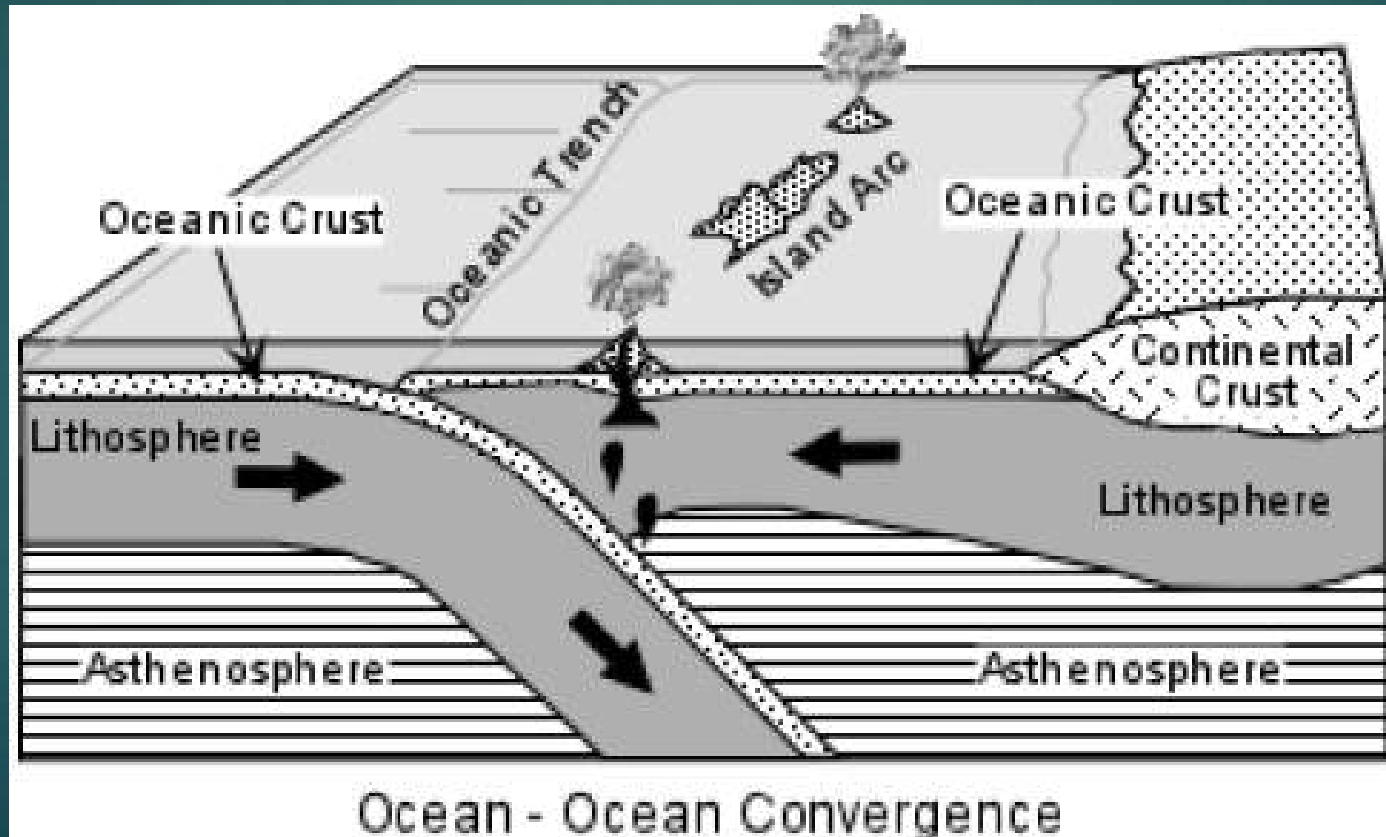
1. Frictional heat
2. Pressure release
3. Flux melting (the most important factor)



5- Environments of magma formation

b- Subduction zones (Convergent plate boundaries)

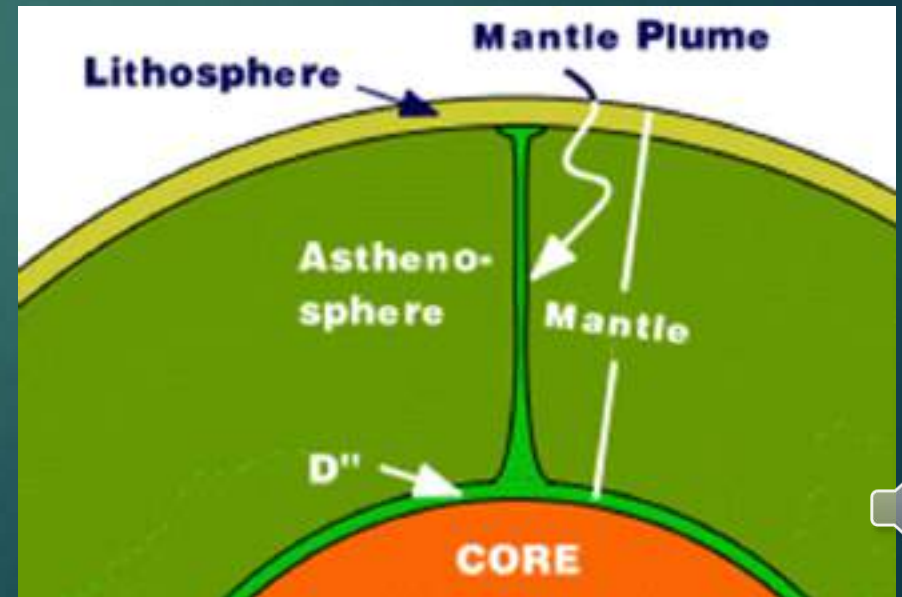
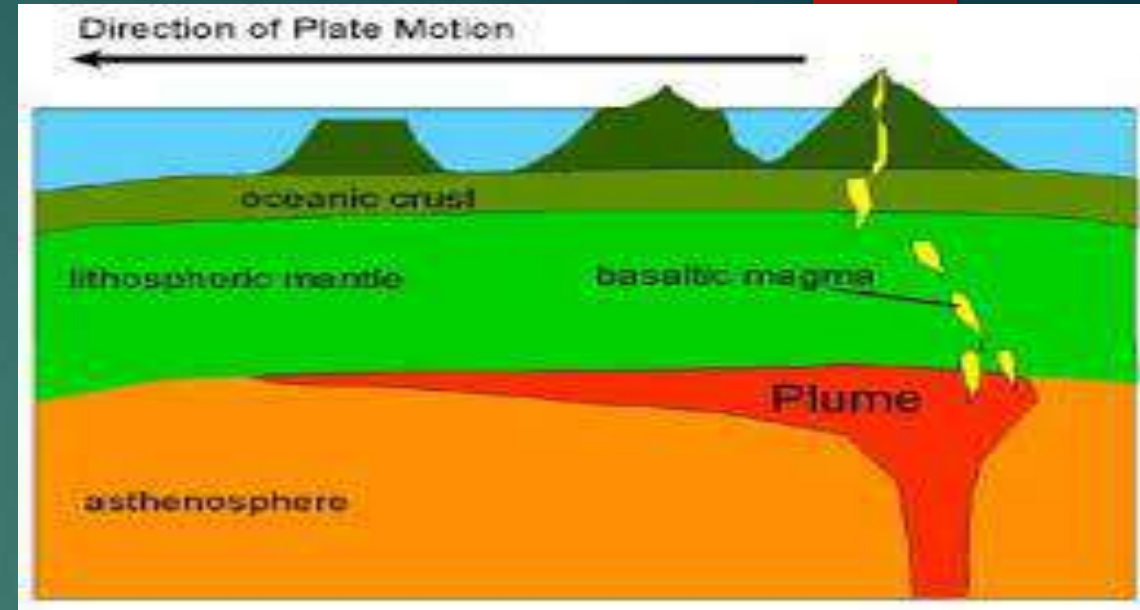
- If an oceanic lithospheric plate subducts beneath another oceanic lithospheric plate, we find island arcs on the surface above the subduction zone.



5- Environments of magma formation

c- Hot spot (Intraplate magmatism)

- ✓ A hot spot is a volcanically active place at the Earth's surface directly above a mantle plume. It occurs within a tectonic plate.
- ✓ A mantle plume is a large column of hot plastic rock rising through the mantle
- ✓ Mantle plume remains stationary at the core-mantle boundary, so hot spot does not shift in position while the plates move over mantle plume. The formation of chains of volcanoes is an evidence of mantle plume. If mantle plume rises beneath sea, volcanic islands are formed
- ✓ Type of magma is basic



6- Classifications of igneous rocks

Based on

Occurrence

Texture

Mineral
composition

Chemical
composition



6.1. classification based on occurrence

Occurrence is the place at which igneous rock is formed relative to earth's surface.

- I. Plutonic igneous rocks:*** which cooled at great depths under earth surface. They are characterized by slow rate of cooling giving rise to coarse-grained crystals. Ex: granite, diorite, gabbro and peridotite.
- II. Hypabyssal igneous rocks:*** which cooled at shallow depths beneath earth surface. They exhibit faster rate of cooling giving rise to medium-grained crystals. Ex: dolerite
- III. Volcanic igneous rocks*** formed when lava solidifies on the Earth's surface. They display rapid rate of cooling leading to fine-grained such as rhyolite, andesite, basalt, or glassy crystals such as obsidian.



6.2. Classification based on texture

Texture: Term describe size, shape, degree of crystallinity and mutual relationship between rock forming minerals

o Size of crystals

1. **Phaneritic rocks** : composed of crystals visible to naked eye or hand lens (> 1 mm). It includes coarse-grained, medium-grained and fine-grained
2. **Aphanitic rocks**: consist of crystals that are too small (< 1 mm) to be seen without polarized microscope.
3. **Glassy rocks**: the crystals are not visible even under the polarized microscope but can be distinguished using scanning electron microscope. It is formed as a result of sudden rapid cooling such as obsidian



6.2. Classification based on texture



Phaneritic



Aphanitic



Glassy



6.2. Classification based on texture

o Degree of crystallinity

1. **Holocrystalline rocks** : are entirely composed of crystals.
2. **Hypocrystalline rocks**: are composed of both crystals and glass
3. **Holohyaline (Glassy) rocks**: consist entirely of glass.



Holocrystalline Texture



Holohyaline texture



7.2. Classification based on texture

o Mutual relationship between crystals

Ex. Porphyritic rocks: formed of coarse-grained crystals (phynocrysts) embedded in a fine-grained matrix. This happens when slow cooling is followed by rapid cooling.



6.2. Classification based on texture

Vesicular rocks: the rock contains voids or cavities caused by trapped gas bubbles while cooling such as scoria and pumice.

Pumice



Scoria



6.3. Classification based on mineral composition

- ❖ Mineralogical classification is used to classify intrusive rocks (where all minerals are visible at least via microscope).
- ❖ Mineralogical classification of igneous rocks depends on association and percent of essential minerals

I) Primary minerals

a) **Essential minerals (95%)**

a) **Accessory minerals (5%)**

apatite, sphene, zircon, iron oxides, tourmaline, etc..

II) Secondary minerals

chlorite, epidote, clay minerals



7.3. Classification based on mineral composition

➤ The essential minerals include:

I) Felsic minerals (light-colored)

a) Quartz

b) K- feldspar (ex: orthoclase)

c) Na-plagioclase

d) Muscovite

II) Mafic minerals (dark-colored)

a) Ca-plagioclase

b) Pyroxene

c) Olivine

d) Hornblende

e) Biotite



7.3. Classification based on mineral composition

Based on abundance and association of these essential minerals, igneous rocks can be classified into:

1. Acidic igneous rocks (quartz, K-feldspar, Na-Plagioclase, muscovite)

Examples: Granite, Tonalite, Rhyolite and Dacite

2. Intermediate igneous rocks (K. feldspar, Na-Ca-Plag, hornblende, biotite, few quartz)

Examples: Diorite, Syenite, Andesite, Trachyte

3. Basic igneous rocks (Ca-plagioclase, pyroxene, olivine, no quartz)

Examples: Gabbro and Basalt

4. ultrabasic igneous rocks (pyroxene, olivine, hornblende $\pm$ Ca-plagioclase)

Examples: Dunite, Pyroxenite, Hornblendite, Peridotite, komatite



6.4. Classification based on chemical composition

Chemical classification of igneous rocks are needed for many volcanic rocks whose minerals are too fine-grained to be identified by microscope. It is based on the chemical composition obtained by XRF and ICP analyses

Shand's classification (SiO_2 content)

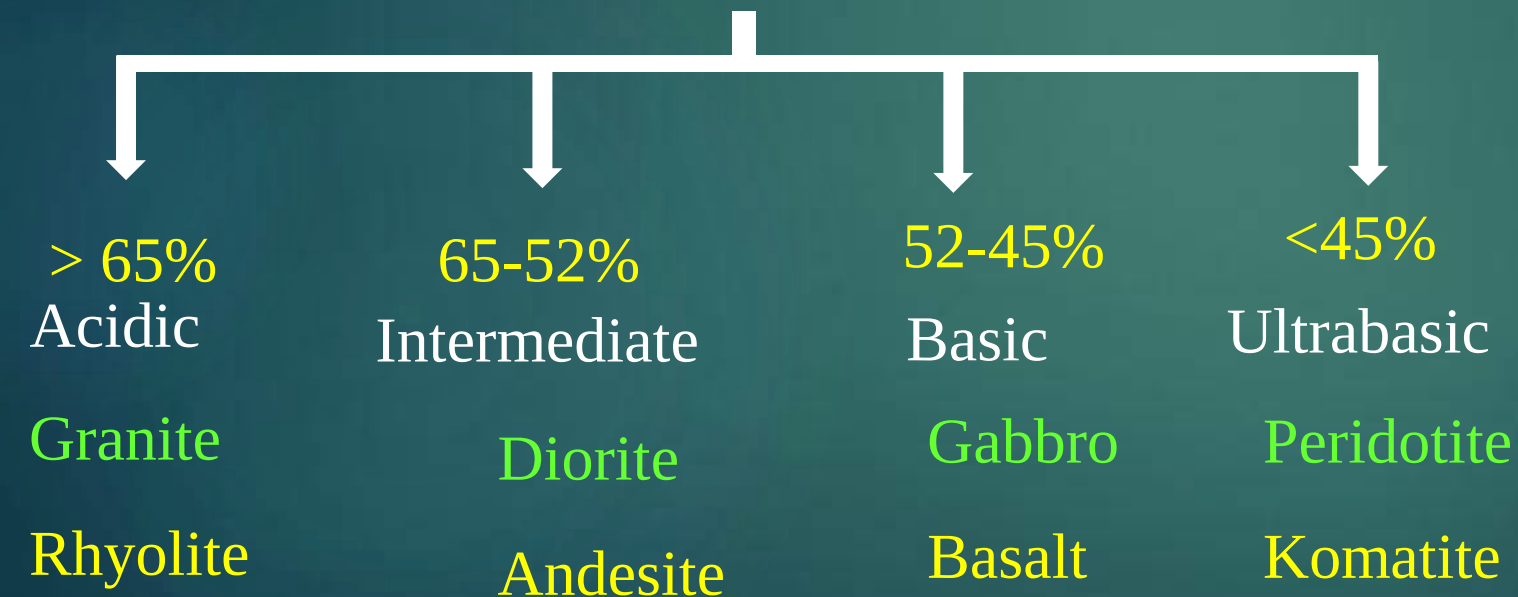


Table 8-3. Chemical analyses of some representative igneous rocks

	Peridotite	Basalt	Andesite	Rhyolite
SiO_2	42.26	49.20	57.94	72.82
TiO_2	0.63	1.84	0.87	0.28
Al_2O_3	4.23	15.74	17.02	13.27
Fe_2O_3	3.61	3.79	3.27	1.48
FeO	6.58	7.13	4.04	1.11
MnO	0.41	0.20	0.14	0.06
MgO	31.24	6.73	3.33	0.39
CaO	5.05	9.47	6.79	1.14
Na_2O	0.49	2.91	3.48	3.55
K_2O	0.34	1.10	1.62	4.30
H_2O^+	3.91	0.95	0.83	1.10
Total	98.75	99.06	99.3	99.50

7- Land forms of igneous rocks

I. Intrusive landforms



a) Plutonic

- **Batholiths (Plutons)**
- **Stocks**

b) Hypabyssal

- **Sills**
- **Laccolith**
- **Lopolith**
- **Dikes**

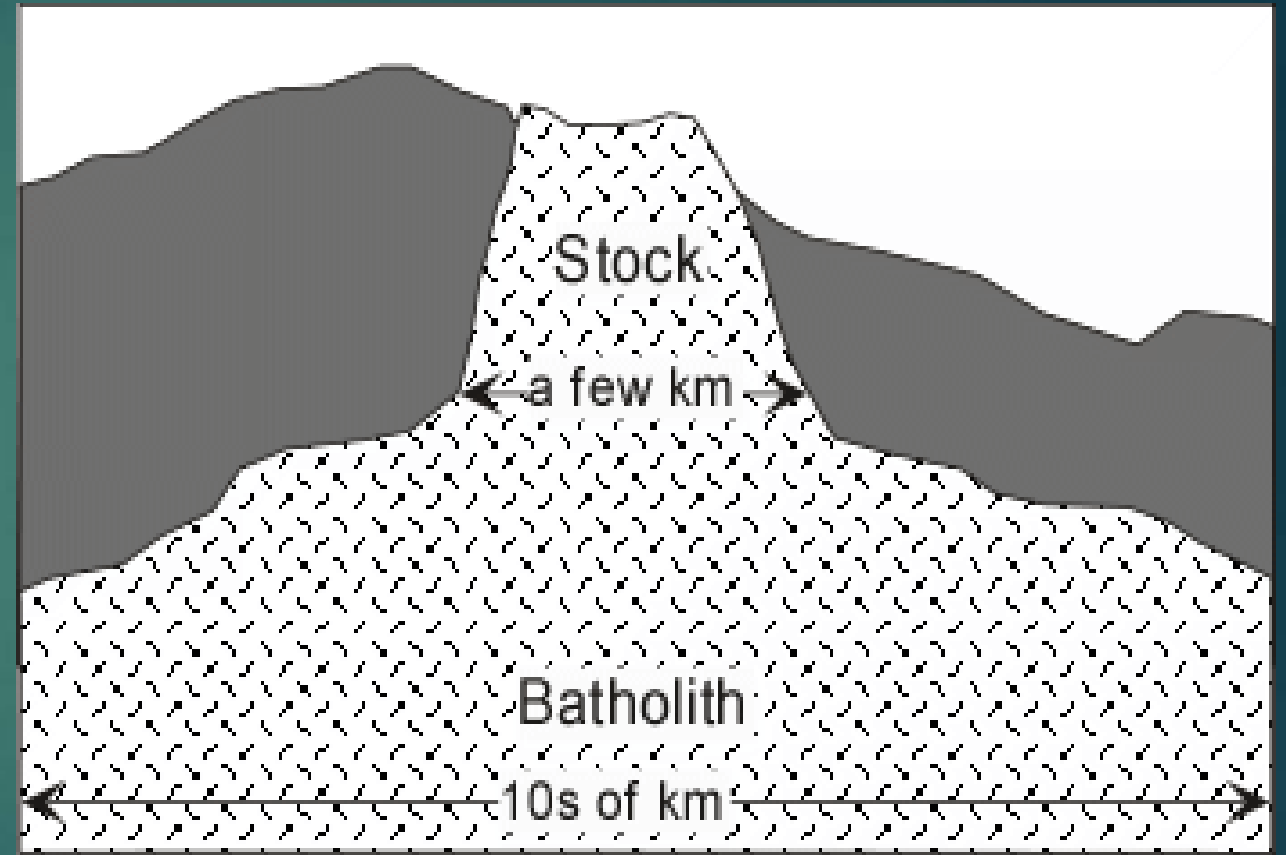
II. Extrusive landforms

- **Crater**
- **Volcanic cone**
- **Volcanic neck**
- **Lava dome**
- **Lava plateaus**



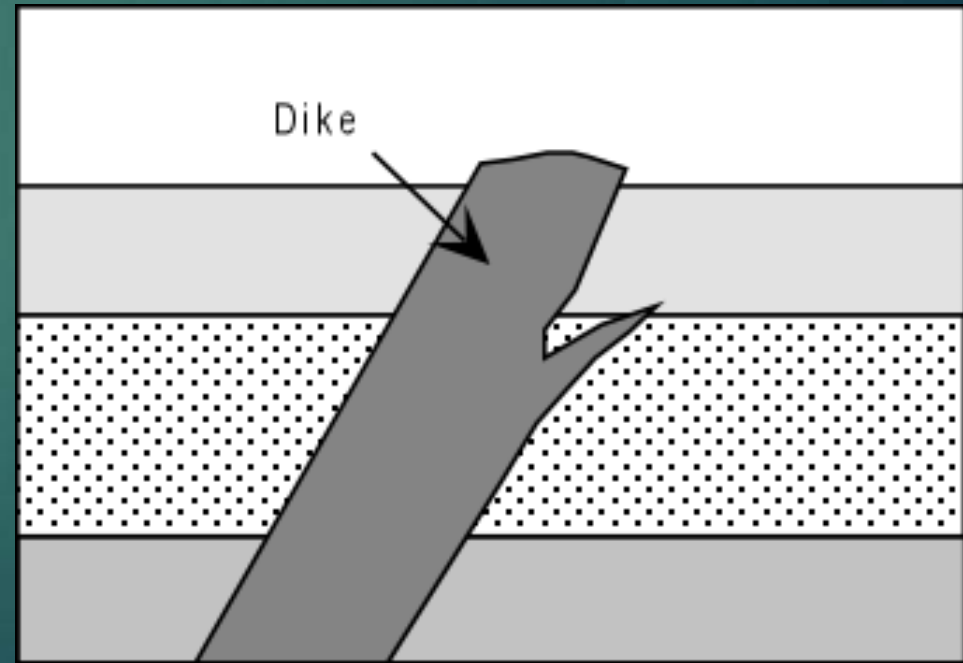
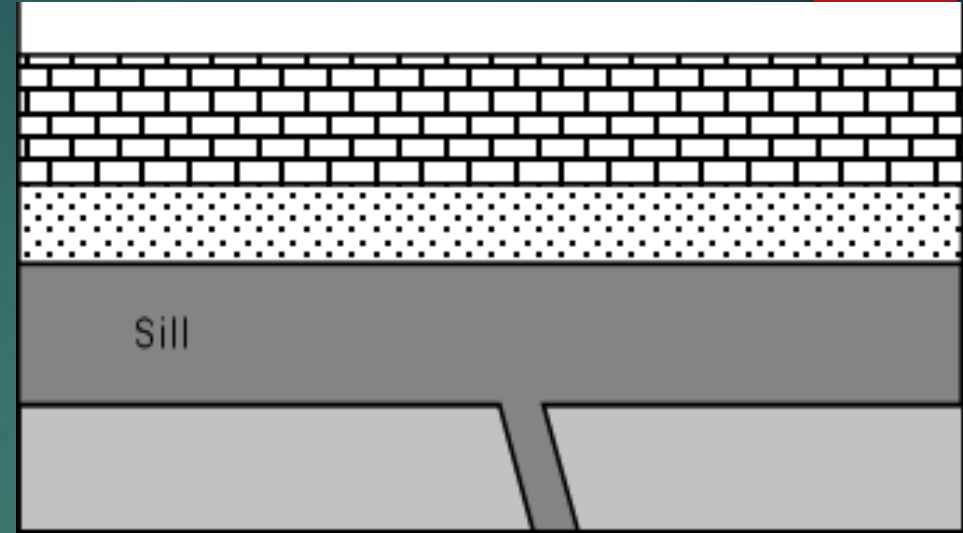
8- Land forms of igneous rocks

- ✓ **Batholith (Plutons)**: It is the largest emplacement of igneous rocks, irregular in shape and occupies large area (thousands of km²)
- ✓ **Stocks**: Are smaller irregular bodies with 10 km² maximum dimension, and are associated with batholiths.



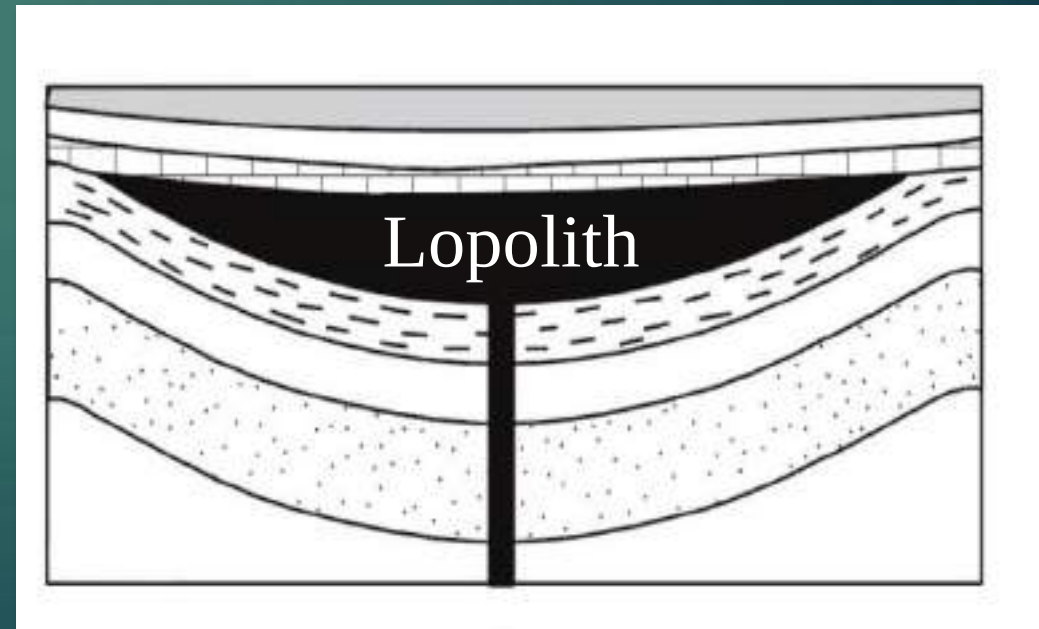
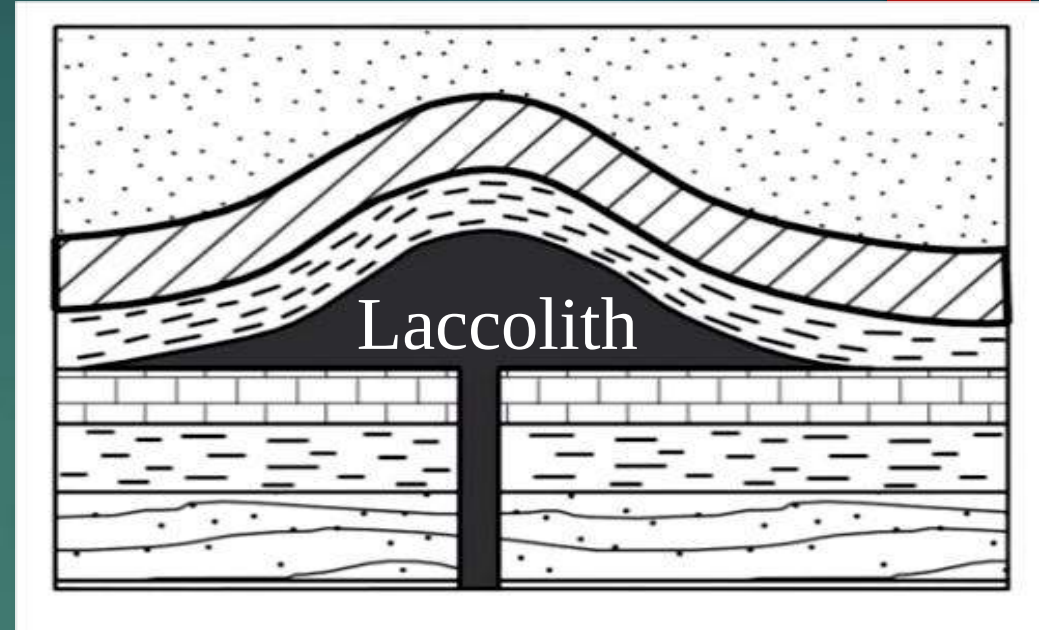
8- Land forms of igneous rocks

- ✓ **Sills** : concordant tabular sheet intrusion that penetrates between and parallel to the older layers of sedimentary rocks(Sills are fed by dikes)
- ✓ **Dykes** : discordant Vertical to inclined tabular sheet intrusion cut across the bedding of the older rocks in which they intrude.



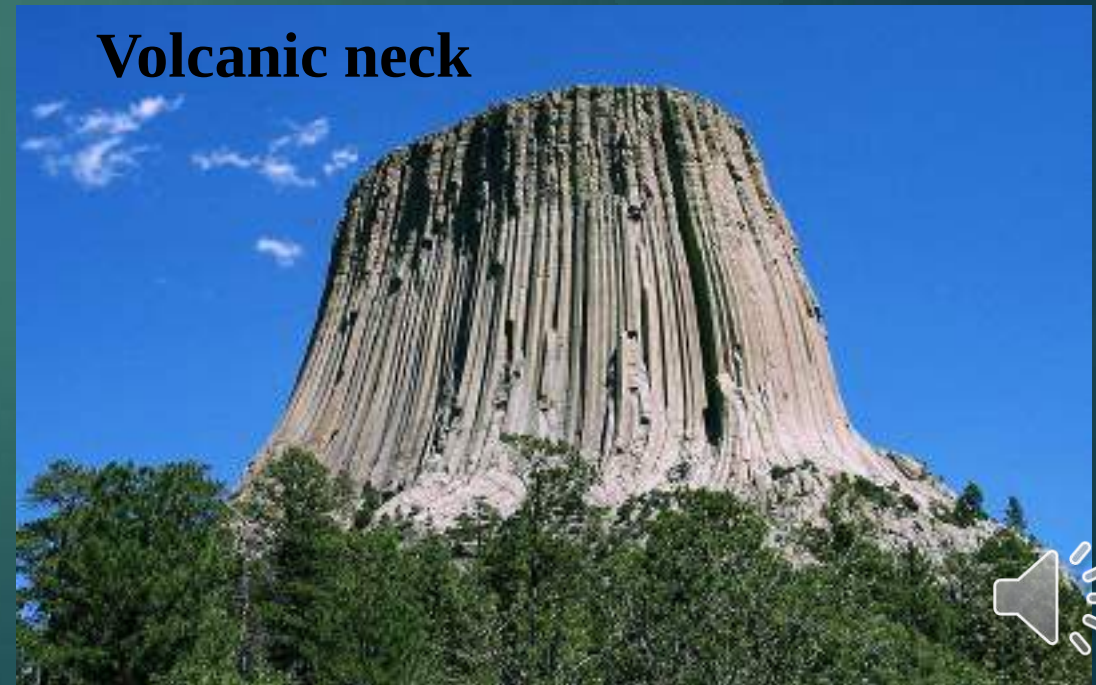
8- Land forms of igneous rocks

- ✓ **Laccolith** : It is a concordant pluton that has been injected between two layers of sedimentary rock. It has dome shape with flat bottom and convex top.
- ✓ **Lopolith** : It is a concordant pluton that has been injected between two layers of sedimentary rock. It has basin shape with concave bottom and flat top.



7- Land forms of igneous rocks

- ✓ **Volcanic cone:** Ejecta from a volcanic vent, piling up around the vent in the shape of a cone
- ✓ **Craters:** are circular depressions, usually less than 1 km in diameter, that form as a result of explosive eruptions
- ✓ **Volcanic necks:** are the exposed parts of volcanic pipes that stick out on the surface of the earth. They result from the differential erosion of the cone material, leaving behind the pipe which is more resistant to weathering and erosion.



7- Land forms of igneous rocks

- ✓ **Lava plateau:** are extremely large volume outpourings of low viscosity basaltic magma from fissure vents. The magma spread over huge areas of relatively low slope and build up plateaus.
- ✓ **Lava domes (volcanic dome):** result from the extrusion of highly viscous, gas poor andesitic and rhyolitic lava. Since the viscosity is so high, the lava does not flow away from the vent, but instead piles up over the vent.



Lava Plateau



Lava dome



Sedimentary and Metamorphic rocks



Sedimentary rocks

- 1- Introduction to sedimentary rocks
- 2- Types of sedimentary rocks
- 3- Textures of sedimentary rocks
- 4- Primary structures of sedimentary rocks

Metamorphic rocks

- 1- Introduction to metamorphism
- 2- Agents of metamorphism
- 3- Types and textures of metamorphism

Outlines



1. Introduction to sedimentary rocks

Sedimentary rock: rock formed by weathering, erosion (transportation), deposition and diagenesis of pre-existing continental rocks.

1- Weathering : it is the *process* of breaking down and fragmentation of rocks into smaller sizes

➤ **There are two types of weathering:**

- a) Mechanical weathering (no change in chemical composition) by rain water, winds and snow
- b) Chemical weathering (there is change in chemical composition) by rain water or acidic rains. It includes:

1. Hydrolysis

2. Hydration

3. Oxidation

4. Dissolution (carbonation)



Dissolution



Oxidation



Dissolution



1. Introduction to sedimentary rocks

2- Erosion : it is the process by which weathering products are transported to sedimentary basins (lakes, seas or oceans)

- Agents of erosion are the same as those of weathering (rain, snow or wind)

➤ Weathering products are transported in two different forms as the following:

- non dissolved fragmented mineralized materials (Detrital) by mechanical weathering
- dissolved mineralized materials by chemical weathering

3- Deposition :

➤ The deposition of sediments can occur mechanically, chemically or biochemically

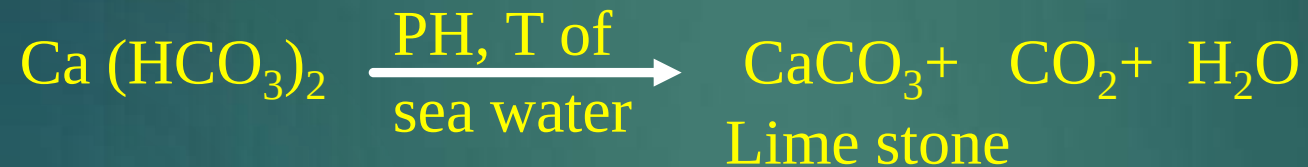
- a) **Mechanical deposition**: when running water carrying rock fragments starts to settle, it deposits its load in form of grains with varying size, where coarse grains are deposited near shore and fine grains far from shore.



1. Introduction to sedimentary rocks

b) Chemical deposition: is done by one of two ways:

- i. Chemical reaction between sea water and supersaturated solutions (solutions containing high concentrations of dissolved materials) [ex. Lime stone (Travertine) and dolostone]



- ii. Evaporation of sea water or lakes due to rising temperature or water abruption for long time which cause salts found in them to be concentrated and deposited in form of successive layers starting with low soluble salts (ex. Gypsum and Anhydrite) to more soluble salts (ex. Rock salt)



1. Introduction to sedimentary rocks

c) Biochemical deposition: there are many examples for biochemical deposition:

- i. Coal:** The accumulation of a large amount of plants in a warm, rainy environment, where a quick burial of plants occur before their decomposition. This was followed by deposition of a number of sedimentary layers where pressure and temperature increase and plants turn into coal
- ii. Phosphate:** it is formed by accumulation of the phosphorous skeletons and bones of large marine organisms and fishes.
- iii. Chalk:** is formed by accumulation of calcareous exoskeletons (CaCO_3 -rich) of micro marine organisms (nanofossils) after their death
- iv. Chert/Flint:** is formed by accumulation of siliceous skeletons (SiO_2 -rich) of planktons



1. Introduction to sedimentary rocks

v. Fossiliferous lime stone: it is formed by accumulation of calcareous exoskeletons and scales of macro marine organisms after their death. It includes coral reefs, coquina and oolite

Coral Reefs: limestone created by corals invertebrate animals which secrete a calcareous external skeleton.

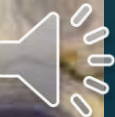


Coquina: poorly cemented, coarse-textured masses of easily discerned shells and shell fragments



1. Introduction to sedimentary rocks

Oolite: is lime stone formed from ooids (spherical grains composed of CaCO_3). Ooids form as a series of concentric layers around a nucleus of living or dead tissue of algae or sea grasses



1. Introduction to sedimentary rocks

4- Diagenesis: chemical, physical, and biological changes that take place after sediments are deposited. It occurs within the upper few kilometers of Earth's crust. It includes Recrystallization, cementation, compaction and Lithification.

- i. **Recrystallization** means the development of more stable minerals from less stable ones. It occurs during the formation of chemical sedimentary rocks
- ii. **Cementation** is done by calcite, silica, and iron oxide.
- iii. **Compaction** occurs when sediments are progressively deposited on top of one another, and over time the weight of the accumulated sediments compresses the buried sediments, as a result the closely packed individual grains begin to slowly compact into a solid rock.
- iv. **Lithification** occur as result of continued compression of buried sediments which reduces pore-spaces and removes excess water.



2. Types of sedimentary rocks

➤ According to mode of formation (method of deposition), two major groups of sedimentary rocks are distinguished: Clastic and non-clastic sedimentary rocks

a) **Clastic Sedimentary rocks:** are formed by mechanical deposition. They can be classified according to particle (grain) size into:

1. Rudaceous rocks (gravel size $\geq 2\text{mm}$) such as breccia and conglomerate

2. Arenaceous rocks (sand size $2\text{mm}-1/16\text{mm}$) such as sandstone

3. Mud rocks 
Silty size ($1/16\text{mm}-1/256\text{mm}$) such as siltstone
Clay size ($<1/256\text{ mm}$) such as claystone and shale



2. Types of sedimentary rocks

➤ **Mineral composition of clastic sedimentary rocks** : Quartz, mica, feldspar

❑ What is the difference between conglomerate and breccia?

Breccia found near source rock so it has angular grains but conglomerate found somewhat far from source rock so it has rounded grains

❑ What is the difference between shale and claystone?

Shale is characterized by fissility (layered laminations formed by compression forces exerted over long-time periods) where claystone does not contain fissility as it contains high amount of water (15%). when claystone loses water due to dryness or pressure it convert to shale



2. Types of sedimentary rocks

b) Non-clastic Sedimentary rocks: include chemical and biochemical sedimentary rocks

➤ Mineral composition of non-clastic sedimentary rocks:

1. Coal : no mineral composition
2. Phosphate: apatite
3. Chemical and biochemical limestone: calcite
4. Gypsum: gypsum
5. Rock salt: halite
6. Chert/flint: Quartz
7. Dolostone: dolomite



3. Textures of sedimentary rocks

Texture: is a term used to describe grain size, sorting and roundness

a) **Grain size:** is used to describe the size of the individual mineral grains, rock fragments, or organic material that are cemented together to form a clastic or non-clastic sedimentary rock.

In clastic sedimentary rocks, the texture is classified as coarse-grained in conglomerate and breccia, as fine-grained in sandstone, as very fine-grained in siltstone and as cryptocrystalline in shale and claystone

In non clastic sedimentary rocks, texture is described as crystalline in chemical sedimentary rocks and as organic in biochemical sedimentary rocks



3. Textures of sedimentary rocks

b) Sorting and roundness: are characterized for clastic sedimentary rocks only

Sorting is used to describe the range of grain size in a rock:

- Poorly sorted rocks contain a variety of grain sizes including fine, medium, and coarse.
- Well sorted rocks contain almost all grains of the same size.
- Moderately sorted rocks contain particles of relatively similar grain sizes (fine and medium grains, or medium and coarse grain).

Roundness is used to describe the relative shape of the grains:

- Well rounded grains are smooth with rounded edges.
- Poorly rounded grains may be sharp or angular.
- Moderately rounded grains are in-between the sharp, angular edges of a poorly rounded grain and the smooth roundness of a well-rounded grain.

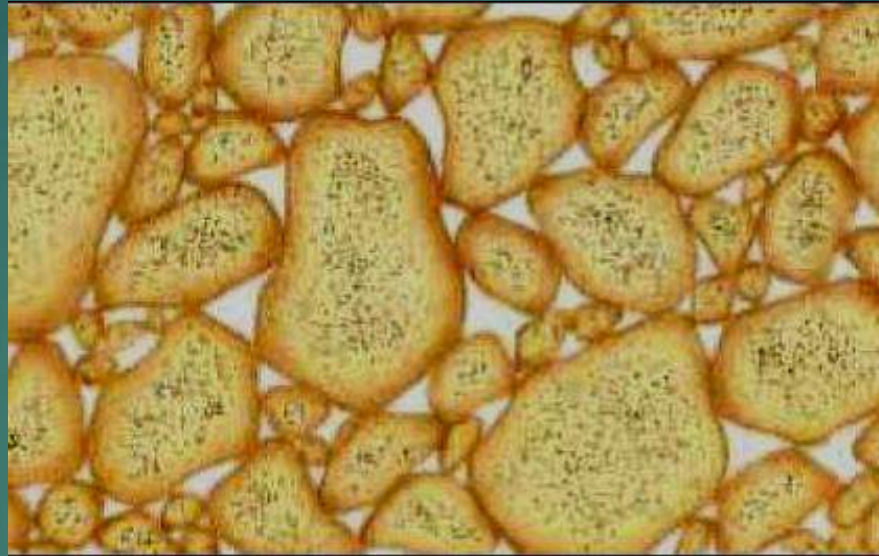


3. Textures of sedimentary rocks

Well-sorted



Poorly-sorted



Well-rounded



Poorly-rounded



Sorting

Roundness



4. Primary structures of sedimentary rocks

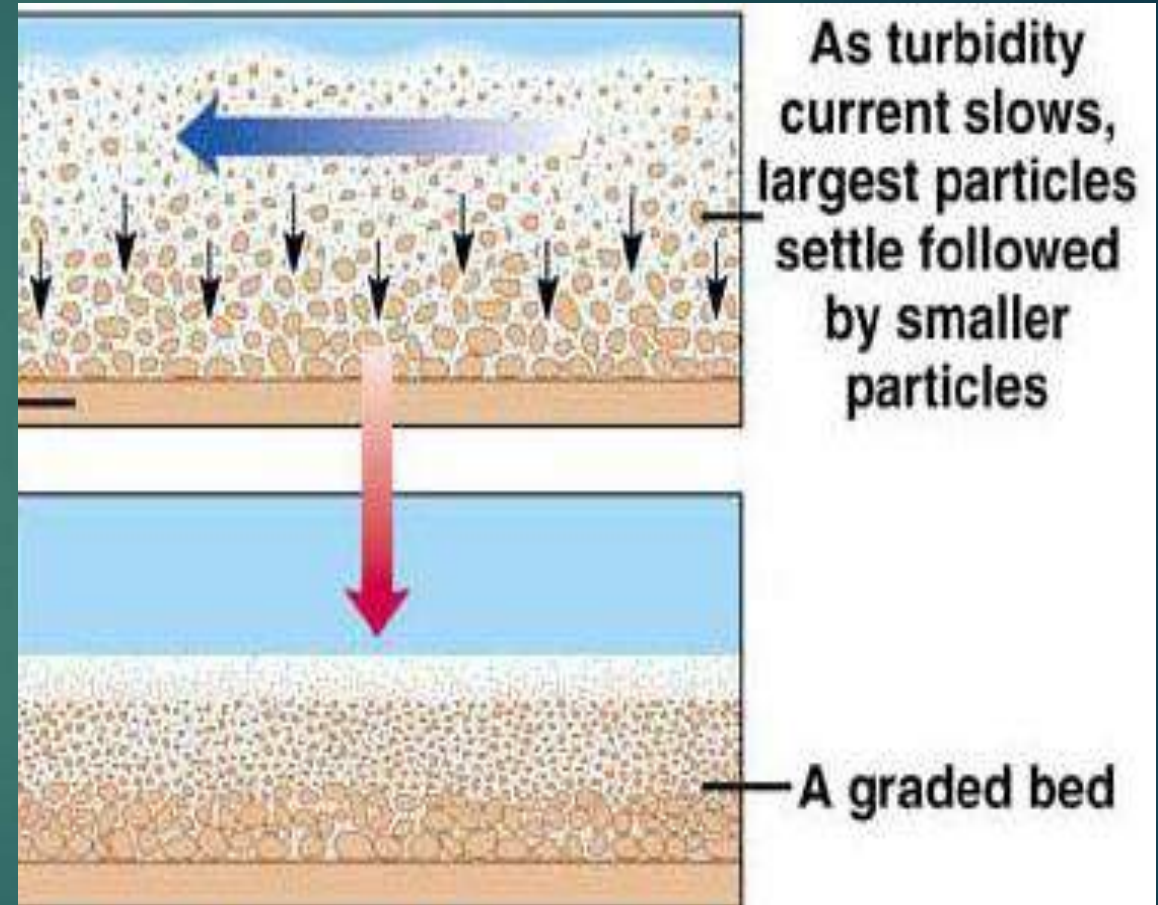
➤ Types of sedimentary structures:

- 1- Graded bedding
- 2- Cross-bedding
- 3- Ripple marks
- 4- Mud cracks



4. Structures of sedimentary rocks

1-Graded bedding: means that the grain size within a bed decreases upwards. This type of bedding is commonly associated with so called turbidity currents. Turbidity currents flow downslope along the seafloor or a lake bottom then the flow slowly and deposits progressively smaller particles, thus forming a graded bed.



4. Primary structures of sedimentary rocks

3-cross bedding (False bedding): takes place when the inner bedding planes (strata) within a bed are inclined to the main bedding planes (upper and lower bedding planes). It is formed as a result of change in speed and direction of currents flows. Most common in sandstones



4. Primary structures of sedimentary rocks

2-Ripple Marks: They are wave-like (undulating) structures produced in granular sediment such as sand by unidirectional wind and water currents or by oscillating wave currents.

➤ So two different types of ripple marks are identified:

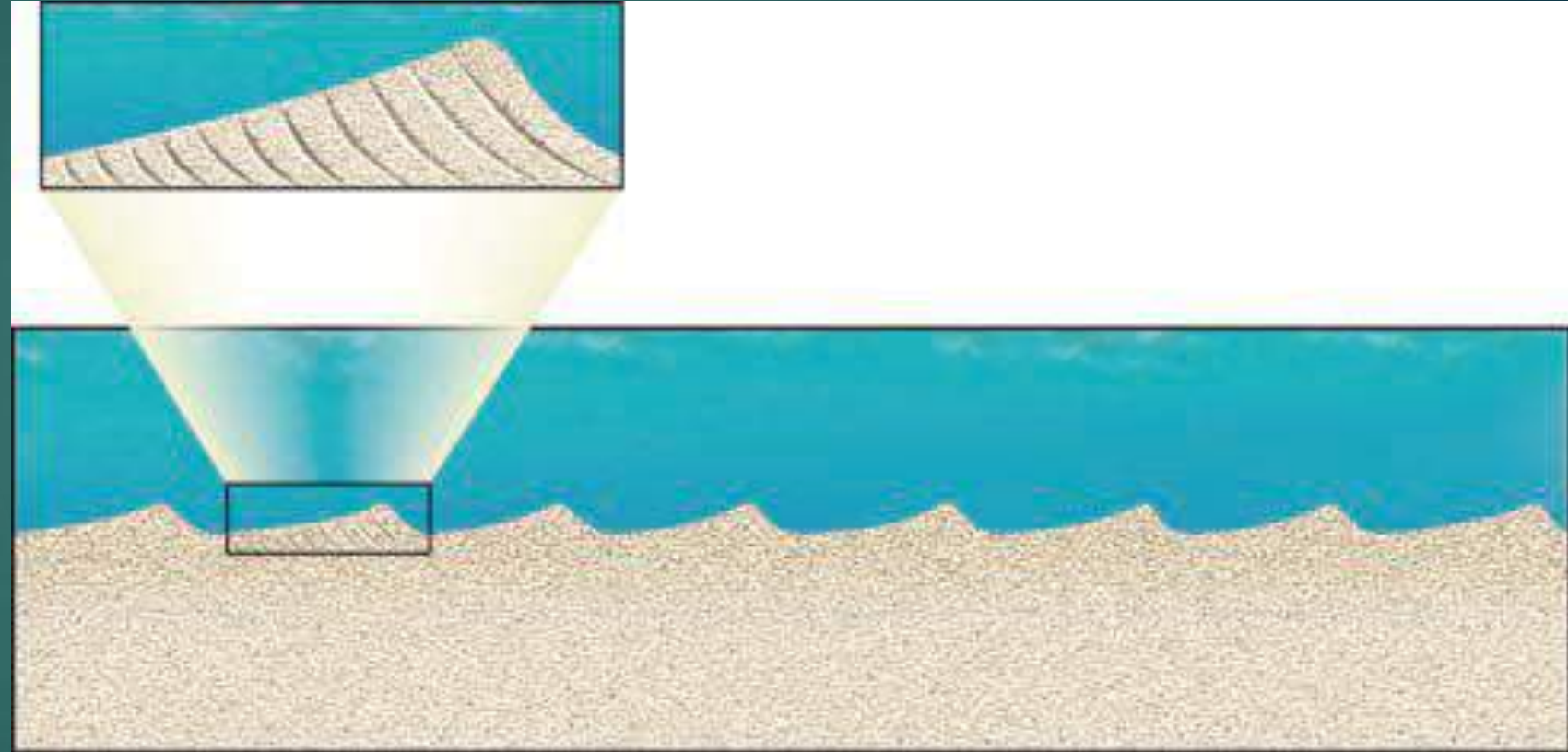
- Asymmetric (caused by unidirectional wind and water currents)
- Symmetric (caused by oscillating wave currents)

➤ Symmetric ripple marks by wave currents



4. Primary structures of sedimentary rocks

- Asymmetric ripple marks where water or wind flows in one direction over sand. The enlargement shows the internal structure of one ripple mark



4. Primary structures of sedimentary rocks

4-Mud cracks: cracks in clay-rich sediment that has dried out.



Mud cracks in a present-day
environment



Introduction to metamorphism

The word **Metamorphism** comes from the Greek: meta = change, morph= form,

- **Metamorphism:** Partial or complete change in a rock's mineralogy, texture, and/or chemical composition that occur in solid state before melting in response to change of environmental conditions.
- **Metamorphic rock:** Rock arises from change in form of the pre-existing igneous or sedimentary rock when subjected to agents of metamorphism
- **Metamorphic systems:**
 - **Closed system (Isochemical metamorphism):** No change in bulk chemical composition of the rock.
 - **Open system (Allochemical metamorphism):** there is change in chemical composition of the rock.



Introduction to metamorphism

The protolith of a metamorphic rock refers to the original rock prior to metamorphism.

- ✓ The protolith of schist may have been shale or mud rock
- ✓ The protolith of a marble must have been a limestone.
- ✓ The protolith of amphibolite may have been shale or a basalt
- The protolith of a metamorphic rock can be "guessed" based on the mineralogy, texture or chemical composition of this metamorphic rock. In low grade metamorphic rocks, original textures are often preserved allowing one to determine the likely protolith. As the grade of metamorphism increases, original textures are replaced with metamorphic textures and other clues, such as bulk chemical composition of the rock, are used to determine the protolith. For example, if a rock contains abundant muscovite, it must be rich in K_2O and Al_2O_3 , and the protolith was most likely a shale.



2- Agents of metamorphism

The agents of metamorphism are:

a- Temperature (T)

b- Stress

c- Chemically active fluids (Hydrothermal solutions)



2- Agents of metamorphism

a- Temperature (T)

- o Change in temperature is probably the most common cause of metamorphism. Increasing temperature may promotes recrystallization (change in mineral size and shape) or causes formation of new minerals . This depends on stability range of forming minerals
- o The lower limit is 100 - 200 °C whereas, the maximum is 700 - 900 °C.
- o Temperature increases with depth in the Earth (Geothermal Gradient). Thus higher temperature can occur by burial of rock. But, in this case, metamorphism does not only depends on T but other many things as how the pressure is applied, the time over which the rock is subjected to the higher pressure and temperature, and whether or not there is a fluid phase present during metamorphism.



2- Agents of metamorphism

a- Temperature (T)

❖ The main sources of temperature for metamorphism are the following:

- Heat related to burial effect and geothermal gradient.
- Heat associated with magmatic intrusions in the crust.
- Heat generated by the movements of crustal blocks along fault planes.
- Heat generated from the decay of radioactive elements (U and Th) in earth's crust and mantle.
- Heat flowing into the base of the crust from the mantle.



2- Agents of metamorphism

a- Temperature (T)

Geothermal gradient

The geothermal gradient is the increase in temperature with depth. it is measured in degrees Celsius per kilometer (i.e. $T^{\circ}\text{C km}^{-1}$). The temperature gradient varies from place to place in the crust, depending on the geological environment.

Table 2.5 Geothermal gradient in various crustal environments.

Type of crust	Geothermal gradient ($^{\circ}\text{C km}^{-1}$)
Gulf Coast, USA (oil wells)	30
Middle East (oil wells)	50
active volcanic zones (modern)	100
oceanic trenches (subduction zones)	10
Precambrian shields today	20–25
sialic crust in the Archaean	50



2- Agents of metamorphism

b- Stress

There are two types of stress: a) lithostatic stress (pressure) b) differential shear stress

Pressure : a measure of the force per unit area acting on rock surface

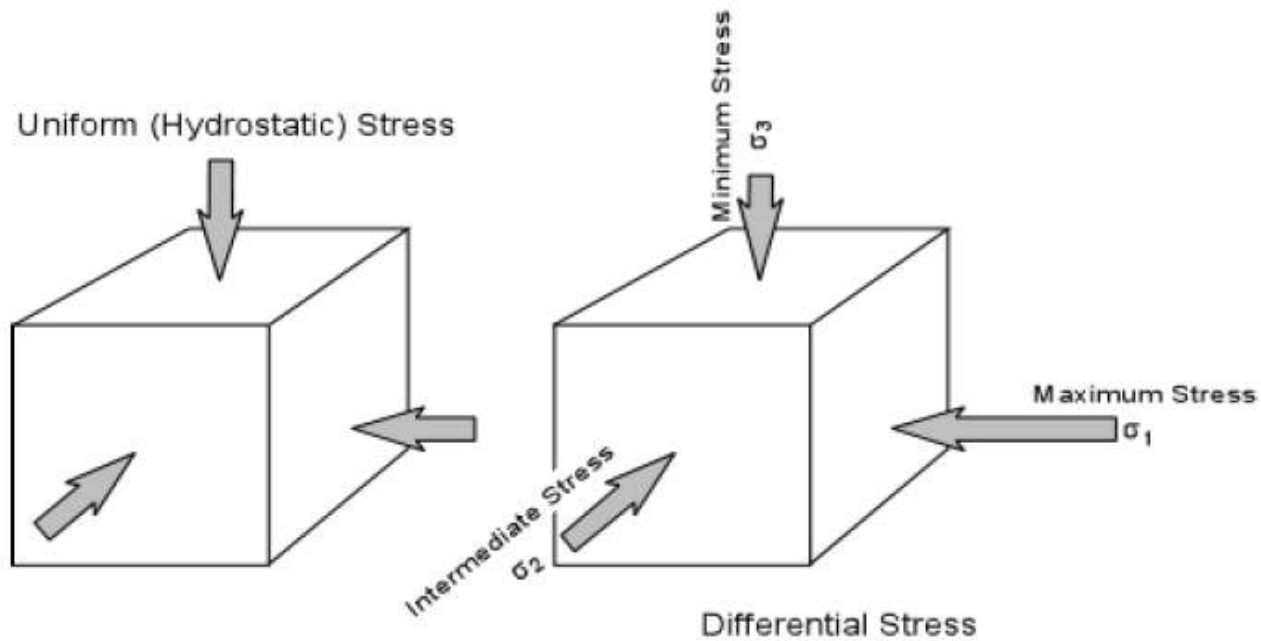
Lithostatic stress	Differential shear stress
Vertical stress	Horizontal stress
Uniform (Non directive) stress	Non uniform (Directive) stress
Does not cause deformation	Causes deformation
Depends on the (weight) of overlying rock (depth)	Depends on tectonic movement caused by decollement along fault planes



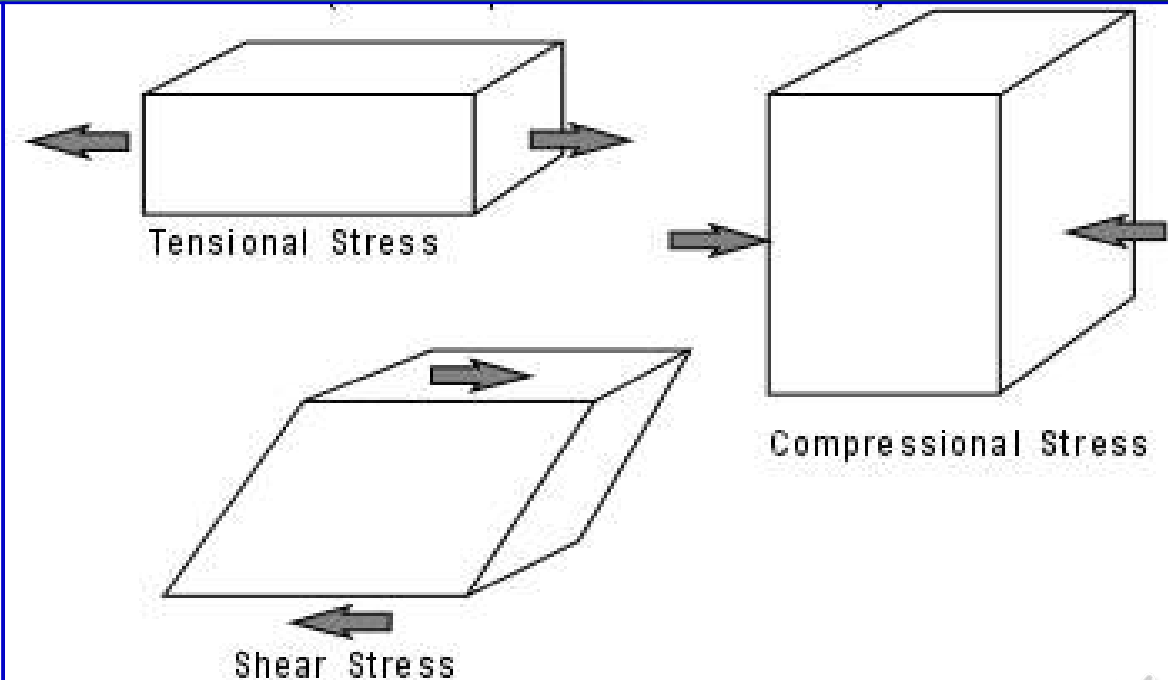
2- Agents of metamorphism

b- Stress

Two types of stress



Types of differential stress



2- Agents of metamorphism

c- Chemically active fluids (Hydrothermal solutions) (liquids and gases)

❖ Source of hydrothermal fluids

- 1- Sedimentary (descending fluids of the meteoric water).
- 2- Magmatic (ascending fluids from magma chamber)
- 3- Metamorphic (fluids released from rocks during metamorphism of hydrous minerals)

❖ The Main chemical composition of hydrothermal fluids is (H_2O , CO_2 and CH_4) the same in different sources except for magmatic fluids which are enriched in halogens (H_2O , CO_2 , CH_4 , Cl, F, B, S). Mixing of the fluids of two different origins is often possible, and their solidified product may be economic.



2- Agents of metamorphism

c- Chemically active fluids (Hydrothermal solutions) (liquids and gases)

- o The presence of fluids makes metamorphism easier (speed up the chemical reactions taking place)
- o The chemically active fluids move forward through the spaces between open spaces between grains in a sedimentary rock and the tiny fractures in igneous rocks . At high temperature , this fluid dissolve relatively mobile atoms and ions, such as K, Na, Ca and Mg. Al and Si remain because they have low solubilities.
- o The fluid and dissolved ions react with rock and change its mineral and chemical composition



4- Types of metamorphism

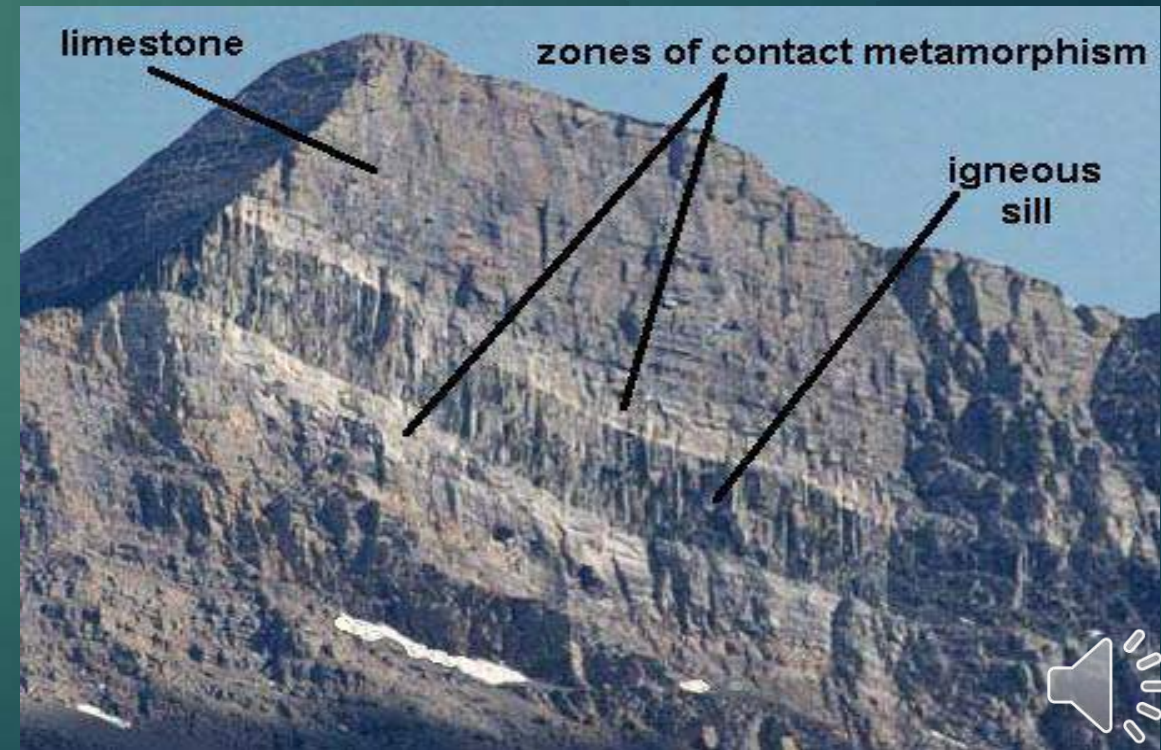
Based on agents of metamorphism, there are five types of metamorphism:

1. **Contact metamorphism (T)**
2. **Regional metamorphism (T + P)**
3. **Dynamic metamorphism (Shear stress)**
4. **Metasomatic metamorphism (Hydrothermal solutions)**
5. **Burial metamorphism (T + lithostatic P)**



4.1. Contact metamorphism (T)

- occurs where hot magma intrudes cooler country rock (may be sedimentary or igneous rock).
- The degree of metamorphism decrease as we far from intrusion



4.1. Contact metamorphism (T)

- The metamorphic haloe around pluton is referred to as contact aureole which can range in width from less than a meter to hundreds of meters
- The width of contact aureole depends up on:
 - 1- Volume of the magmatic intrusion
 - 2- Nature of the magmatic bodies (basaltic or granitic composition)
 - 3- Type of country rocks (Shale, limestones or igneous rocks)
 - 4- depth of magmatic intrusions
- Examples of contact metamorphic rocks are: Quartizite (after sandstone), Marble (after limestone) and Hornfelse (after shale or basic igneous rocks)
- Contact metamorphism is isochemical low grade metamorphism



4.1. Texture of contact metamorphism

- ❑ **Texture (fabric):** is used to describe the orientation and arrangement of minerals in the rock. It contains foliated texture (minerals with preferred orientation) and non-foliated (no preferred orientation)
- **Rocks formed by contact metamorphism are characterized by non-foliated texture (Granoblastic or Mosaic):** all the crystals are approximately the same size and equidimensional.

Marble



Quartzite



4.2. Regional metamorphism (T & P)

- ❖ It is the most common and widespread type of metamorphism and affects broad regions of the Earth's crust. It is associated with mountains building process
- ❖ Regional metamorphism is isochemical metamorphism occur at temperature range from 200-800° C and starts at pressure from 5 kbar and at depth from 10 or 15 km
- ❖ Regionally metamorphosed rocks are classified based on grade of metamorphism into low grade low P-T like slate, phyllite), medium grade (medium P-T like schist and amphibolite), high grade (high P-T like gneiss and migmatite)
- ❖ All regionally metamorphosed rocks are originated from sedimentary rocks (ex. Shale). Some can be originated from igneous rocks also (ex. gneiss and migmatite after Granite and Amphibolite after mafic igneous rocks such as basalt and gabbro)



4.2. Regional metamorphism

1. Shale is the most abundant sedimentary rock. It consists of clay minerals, quartz, and feldspar. As regional metamorphism begins (at 200° c to 250°c), the clay minerals break down and are replaced by mica and chlorite where quartz and feldspars are recrystallized. These new minerals grow and arranged in parallel alignment perpendicular to the direction of pressure. As a result, the rock develops foliated texture and the rock formed is called slate.
2. With rising temperature (from 250° c to 300°c), the micas, chlorite, quartz and feldspars grow larger giving rise to phyllite rock
3. As temperature continues to rise (from 300° c to 500°c), phyllite minerals grow large enough to be seen by the hand lens, amphibole start to grow. Foliation becomes very well developed forming schist rock



4.2. Regional metamorphism

4. At high metamorphic grades (from 500° c to 700°c), dark-colored minerals (biotite mica & amphibole) tend to separate from light-colored ones (Qz, feldspar) into distinct bands a rock called gneiss is formed.
5. At higher metamorphic grades (from 700° c to 800°c), light bands collected together and the same occur for dark-colored minerals forming thick bands in a rock called migmatite
6. All regionally metamorphosed rock are characterized by foliated texture. Micas and other platy minerals may define planer foliation, whereas elongate minerals such as hornblende may define linear foliation.



4.2. Regional metamorphism

Slate



Phyllite



Schist



Gneiss



Migmatite



4.4. Metasomatic metamorphism (hydrothermal solutions)

- ❖ Metasomatism is the term used to describe metamorphic processes in which substantial amounts of 'foreign' components are added to a host rock, usually with the aid of fluids
- Hydrothermal metamorphism is Allochemical high grade metamorphism
- ❖ The most common rocks formed by hydrothermal metamorphism are skarn (after limestone or dolostone) and serpentinite (after peridotite)
- ❖ Texture of hydrothermal metamorphosed rocks is non-foliated

