

**ZAGAZIG UNIVERSITY  
FACULTY OF SCIENCE  
GEOLOGY DEPARTMENT**



# **LECTURE NOTES PRINCIPLES OF GEOLOGY (2)**



**First Level**

**2025-2026**



**Collected by:  
Faculty members, Geology  
Department, Faculty of  
Science, Zagazig University**



## Course specification

### A- Basic Information

Program (s) on which the course is given: **Geology**

Major or Selective element of Program: **Major**

Department offering the Program: **Geology**

Department offering the course: **Geology**

Academic level: **First year**

**Credit hour**

**First semester**

Academic year: 2025-2026

Date of specification approval: 3/12/2025

Title: **Principles of Geology 2**

Code: **G 102**

Lecture: **2h/ w**

Practical: **1h/ w**

Total: **3h/ w**

### B- Professional Information

#### 1 - Overall Aims of Course

The main aim of the course is to ensure that the student has the necessary

Knowledge and understanding of the following:

- Elements of crystallization and crystal systems
- Physical properties and origin of minerals
- Origin of magma and classification of igneous rocks.
- Classification of sedimentary rocks and sedimentary structures
- Agents and types of metamorphism and textures of metamorphic rocks

#### 2-Intended Learning Outcomes of Course (ILOs)

##### *a-Knowledge and Understanding:*

By the end of course, the student should be able to

- a.1- Define crystal, crystallographic axes and crystal form
- a.2- List different forms in each crystal system
- a.3- Recognize origin of minerals
- a.4- Describe physical properties of minerals
- a.5- write on the processes of magma formation and related tectonic environment
- a.6- Identify types, textures and primary structures of sedimentary rocks
- a.7- List agents and types of metamorphism

##### *b- Intellectual Skills*

By the end of course, the student should be able to

- b.1- Differentiate between seven crystal system based on elements of crystallization
- b.2- Distinguish between open and closed form
- b.3- Classify mineral groups based on their chemical composition
- b.4- Determine the characteristic physical properties in a number of minerals
- b.5- Assess different concepts of classification of igneous rocks
- b.6- Compare between clastic and non-clastic sedimentary rocks
- b.7. Differentiate between allochemical and isochemical metamorphism

### ***c- Professional and Practical Skills***

By the end of course, the student should be able to

- c.1- Deduce different forms in a combined crystal
- c.2- Distinguish between crystal systems with the same number of crystallographic axes
- c.3- Differentiate between transparent and translucent minerals
- c.4- Detect the relative hardness and streak of unknown minerals
- c.5- Show how to identify acidic and basic igneous rocks
- c.6- Distinguish between chemical and biochemical limestone
- c.7- Use texture to differentiate between metamorphic rocks

### ***d- General and Transferable Skills***

By the end of course, the student should be able to

- d.1- Communicate different knowledge resources.
- d.2-Continue self learning.
- d.3-Train different methods of the information technology.

### **3- Contents**

| <b>Topic</b>                                                       | <b>No. of hours</b> | <b>Lecture</b> | <b>Practical</b> |
|--------------------------------------------------------------------|---------------------|----------------|------------------|
| Elements of Crystallization and crystal systems                    | 9                   | 6              | 3                |
| Mineral groups and origin of minerals                              | 3                   | 2              | 1                |
| Physical properties of minerals and other characteristic features. | 9                   | 6              | 3                |
| Origin and tectonic environments of magma                          | 3                   | 2              | 1                |
| Classification of igneous rocks and igneous landforms              | 6                   | 4              | 2                |
| Types, textures and primary structures of sedimentary rocks        | 6                   | 4              | 2                |
| Agents, types and textures of metamorphic rocks                    | 6                   | 4              | 2                |

### **4-Teaching and Learning Methods**

| <b>Teaching and Learning Methods</b> | <b>ILOs</b>                                 |
|--------------------------------------|---------------------------------------------|
| 4.1-Teaching across the classroom    | a.1, a.4, a.7, c.1, c.2, c.3, c.4, c.5, c.6 |
| 4.2- Self learning methods           | d.1, d.2, d.3                               |
| 4.3- Preparing some essay            | a.5, b.3, b.6                               |

### **5- Student Assessment Methods**

| <b>Student Assessment Methods</b>        | <b>ILOs</b>                         |
|------------------------------------------|-------------------------------------|
| 5.1- Written examinations (essay or MCQ) | a.2, a.6, b.5,a.1, a.3, a.4         |
| 5.2- Practical examination               | b.1, b.2, b.4, c.1,c.2, c.3,c.5,c.7 |
| 5.3- Oral examination                    | a.4, a.5, b.3                       |
| 5.4- Research report                     | a.3, b.5, b.7                       |

### **Assessment Schedule**

Assessment 1: Through the lecture, at the end of each topics (written exercises). Week 13

Assessment 2: Mid-term examination (written examination) week 7.

Assessment 3: Final first semester examination (written, oral and practical) week 14-17.

### **Weighting of Assessments**

|                               |             |
|-------------------------------|-------------|
| Semester work                 | 10 %        |
| Mid-term examination          | 10 %        |
| Practical& oral examination.  | 20 %        |
| <u>Final-term examination</u> | <u>60 %</u> |
| Total                         | 100%        |

## **6- List of References**

### **6.1- Course notes**

Stuff members of geology, 2017: Principals of Geology (2)

### **6.2- Recommended books**

- Hefferan, K, O'Brein, J., 2010: Earth materials, text book.
- Klein, C, philpotts, A., 2016: Earth Materials 2nd Edition: Introduction to Mineralogy and Petrology, Cambridge University Press, 650p.
- philpotts, A., Argue, J., 2009: Principles of Igneous and Metamorphic Petrology, 2nd edition, Cambridge University Press, 644p.
- Plummer, C. C., McGeary, D., Carlson, D.H. (2001): Physical geology, Updated 8<sup>th</sup> edition. WCB/McGraw-Hill, 578 p. ISBN: 0072904437 and Thompson, G.R., Turk, J. (1997): Introduction to Physical Geology. 13th edition, Brooks Cole, USA, 371p, ISBN 13: 9780030243486

### **6.3- Websites**

- <http://www.tulane.edu/~sanelson/eens211/>.
- [www.wiley.com/go/hefferan/earthmaterials](http://www.wiley.com/go/hefferan/earthmaterials),
- [https://www.mediafire.com/folder/no1agm22h5dob/Geo\\_Pedia\\_E-Geological\\_Library](https://www.mediafire.com/folder/no1agm22h5dob/Geo_Pedia_E-Geological_Library) - المكتبة الجيولوجية الالكترونية
- Periodicals, Web Sites: [www.planetdiary.com](http://www.planetdiary.com)

## **7- Facilities Required for Teaching and Learning**

Data show, white board, models for crystals and hand specimens for minerals and rocks

**Course Coordinator:** Assis. Prof. Waheed Ibrahim Elwan

Assis. Prof. Amr Amin El-Awady

**Head of Department:** Prof. Dr. Abeer abdel Reheem El-Kenawy

**Date of department council:** 3/12/2025

**Course matrix (Principals of geology-G 102)**

| Topics                                                                    | Knowledge and Understanding |    |    |    |    |    |    | Intellectual Skills |    |    |    |    |    |    | Professional and Practical Skills |    |    |    |    |    |    | General and Transferable Skills |    |    |
|---------------------------------------------------------------------------|-----------------------------|----|----|----|----|----|----|---------------------|----|----|----|----|----|----|-----------------------------------|----|----|----|----|----|----|---------------------------------|----|----|
|                                                                           | a1                          | a2 | a3 | a4 | a5 | a6 | a7 | b1                  | b2 | b3 | b4 | b5 | b6 | b7 | c1                                | c2 | c3 | c4 | c5 | c6 | c7 | d1                              | d2 | d3 |
| <b>Elements of Crystallization and crystal systems</b>                    | x                           | x  |    |    |    |    |    | x                   | x  |    |    |    |    |    | x                                 | x  |    |    |    |    |    |                                 |    |    |
| <b>Mineral groups and origin of minerals</b>                              |                             |    | x  |    |    |    |    |                     |    | x  |    |    |    |    |                                   |    |    |    |    |    |    | x                               |    |    |
| <b>Physical properties of minerals and other characteristic features.</b> |                             |    |    | x  |    |    |    |                     |    |    | x  |    |    |    |                                   |    | x  |    |    |    |    |                                 | x  |    |
| <b>Origin and tectonic environments of magma</b>                          |                             |    |    |    | x  |    |    |                     |    |    |    |    |    |    |                                   |    |    |    | x  |    |    | x                               | x  |    |
| <b>Classification of igneous rocks and igneous landforms</b>              |                             |    |    |    |    |    |    |                     |    |    |    | x  |    |    |                                   |    |    |    | x  |    |    |                                 |    | x  |
| <b>Types , textures and primary structures of sedimentary rocks</b>       |                             |    |    |    |    | x  |    |                     |    |    |    |    | x  |    |                                   |    |    |    |    | x  |    | x                               | x  |    |
| <b>Agents, types and textures of metamorphic rocks</b>                    |                             |    |    |    |    |    | x  |                     |    |    |    |    |    | x  |                                   |    |    |    |    |    | x  |                                 | x  |    |



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# Chapter 1

## CRYSTALLOGRAPHY

### Goals

***By the end of this chapter, you should be able to:***

- 1. Describe various elements of crystallography in terms of crystal structure, classification, and symmetry in crystals.*
- 2. State the Law of Constancy of interfacial angles in crystals and how to measure those angles using a goniometer.*
- 3. Differentiate between crystal systems.*

**Crystallography** is the science deals with the study of crystal morphology (external form of crystal). It determines the arrangement of atoms in the crystalline solids. The word "crystallography" derives from the Greek words *crystallon* (cold/frozen drop) and *grapho* (write).

### 1.1. What is the Crystal

A crystal is a solid material whose constituent atoms, molecules, or ions are arranged in an orderly repeating pattern extending in all three spatial dimensions.

Based on the atomic arrangement in a substance, solids can be broadly classified as either crystalline or non-crystalline. In a crystalline solid (Fig.

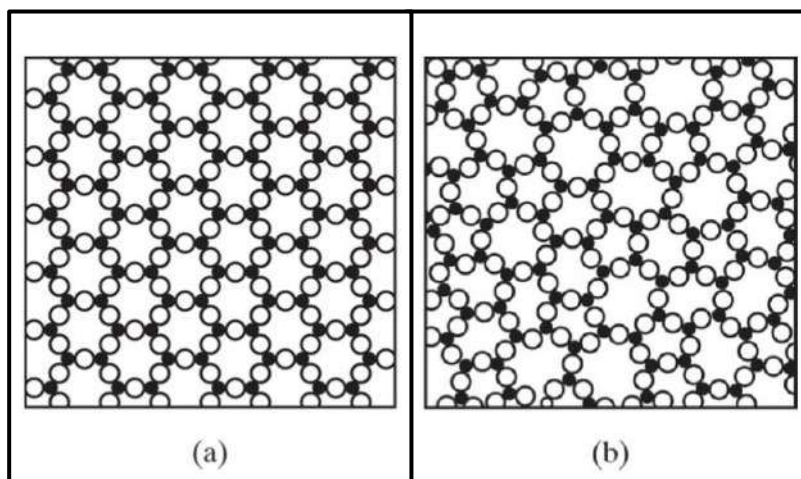


**Fig. 1.1: (a) a crystalline quartz, (b) non crystalline quartz**

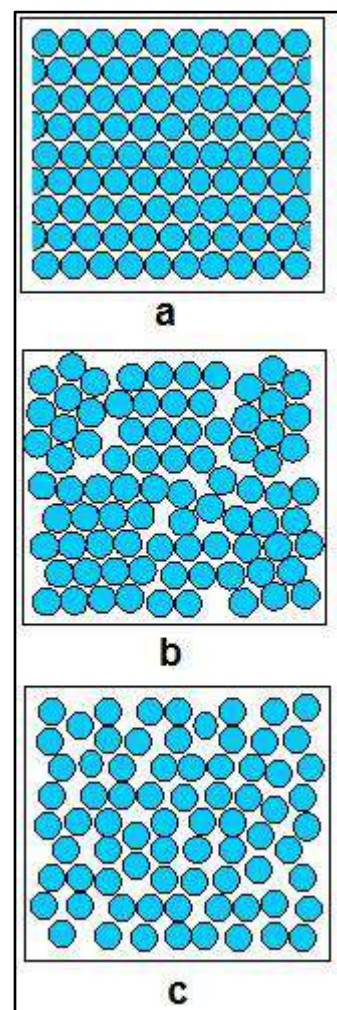
1-1a), all the atoms are arranged in a periodic manner in all three dimensions where as in a non-crystalline solid (Fig. 1-1b) the atomic arrangement is random or nonperiodic in nature. Some more differences between crystalline solids and amorphous solids are listed in Table 1-1.

Table 1-1 Distinction between crystalline and amorphous solids

| Crystalline solids                                                                                                                                                                                                              | Amorphous (non-crystalline) solids                                                                                               |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------|
| 1. The atoms or molecules of the crystalline solids are periodic in space.                                                                                                                                                      | 1. The atoms or molecules of the amorphous solids are not periodic in space.                                                     |
| 2. Some crystalline solids are anisotropic i.e., the magnitude of physical properties [such as refractive index, electrical conductivity, thermal conductivity, etc.,] are different along different directions of the crystal. | 2. Amorphous solids are isotropic i.e., the magnitude of the physical properties are the same along all directions of the solid. |
| 3. Crystalline solids have sharp melting points.                                                                                                                                                                                | 3. Amorphous solids do not possess sharp melting points.                                                                         |
| 4. Breaks are observed in the cooling curve of a crystalline solid.                                                                                                                                                             | 4. Breaks are not observed in the cooling curve.                                                                                 |
| 5. A crystal breaks along certain crystallographic planes.                                                                                                                                                                      | 5. When an amorphous solid breaks, the broken surface is irregular because it has no crystal planes.                             |

A crystalline solid can either be a single crystalline or a polycrystalline. In the case of single crystal the entire solid consists of only one crystal and hence, periodic arrangement of atoms continues throughout the entire material (Fig. 1-2a). A polycrystalline material is an aggregate of many small crystals separated by well-defined grain boundaries and hence periodic arrangement of atoms is limited to small regions of the material called as grain boundaries (Fig. 1-2a and b). The non-crystalline substances are also called as amorphous substances materials. Single crystalline materials exhibit long range as well as short range periodicities while long range periodicity is absent in case of poly-crystalline materials and non-crystalline materials.

Figure 1-2 (a) single crystal (b) polycrystalline, (c) amorphous materials.



The majority of materials like minerals, alloys, metals, organic and inorganic salts, etc. in their natural forms normally exist as polycrystalline solids. However some organic materials made up of large sized molecules (polymers) mostly exist in non-crystalline form. Among inorganic materials, ordinary glass (soda lime glass) is a typical example of a non-crystalline solid. It requires great effort and skill to make single crystal specimens of these polycrystalline or non-crystalline materials. Table 1-2 lists examples of some common single crystals, polycrystalline and non-crystalline materials.

**Table 1-2 Examples for different categories of solid materials.**

| Type                              | Examples                                                                                                                                                                            |
|-----------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Single crystals</b>            | Silicon chips used in integrated circuits, quartz crystal used in watches, ruby rods used in ruby lasers, gallium arsenide crystals used in light-emitting diodes, etc.             |
| <b>Poly crystalline materials</b> | Metals like copper, steel, aluminum, brass etc., used in ordinary engineering and household appliances. Organic and inorganic materials used in powder form like sugar, salts, etc. |
| <b>Non-crystalline materials</b>  | Soda lime glass (ordinary window glass), polymers (plastics like polyethylene, polyvinylchloride, polytetrafluoroethylene (Teflon), plexiglass, polyurethane foam, bakelite, etc.)  |

## 1.2. Crystal structure

Crystal structure is a description of the ordered arrangement of atoms, ions or molecules in a crystalline material. The properties of some materials are directly related to their crystal structures. For example, pure and undeformed magnesium and beryllium, having one crystal structure, are much more brittle (i.e., fracture at lower degrees of deformation) than pure and undeformed metals such as gold and silver that have yet another crystal structure. Furthermore, significant property differences exist between

crystalline and non-crystalline materials having the same composition. For example, non-crystalline ceramics and polymers normally are optically transparent; the same materials in crystalline (or semi-crystalline) form tend to be opaque or, at best, translucent.

The smallest group of particles in the material that constitutes the repeating pattern is the **unit cell** of the structure (Fig. 1-3a). The unit cell completely defines the symmetry and structure of the entire **crystal lattice**, which is built up by repetitive translation of the unit cell along its principal axes (Fig. 1-3b).

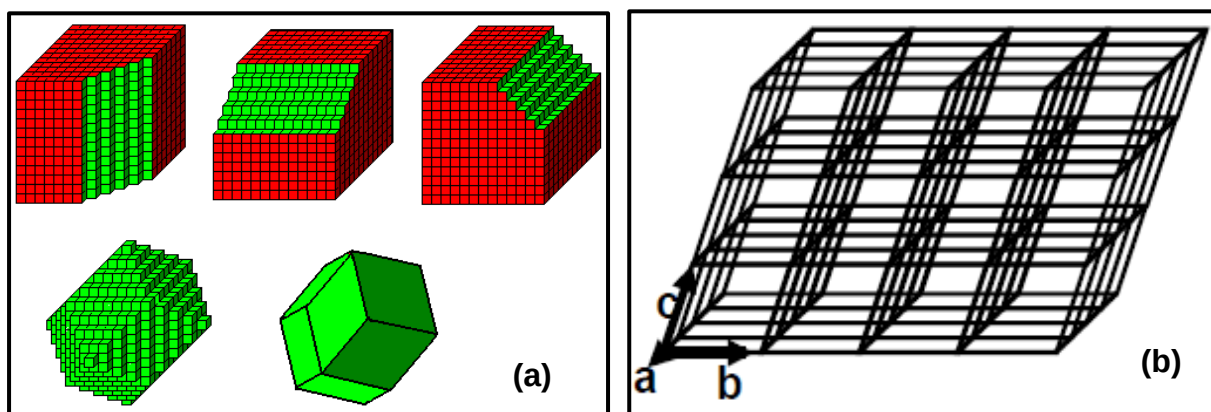


Figure 1-3 (a) Unit cell of cubic system, (b) Crystal lattice.

By studying the crystal structure and bonding nature of different materials, we can investigate the reasons for the similar or dissimilar nature of the selected materials in terms of different properties or different parameters. The crystal structure and symmetry of a material play a vital role in determining many of its physical properties, such as cleavage, electronic band structure, and optical transparency, etc.

### 1.2.1. Crystal lattice

In a solid crystalline material, the atoms or molecules are arranged regularly and periodically in all three dimensions. The atomic arrangement in a crystal is called crystal structure. To explain crystal symmetries easily, it is convenient to represent an atom or a group of atoms that repeats in three dimensions in the crystal as a unit. If each such atom or unit of atoms in a

crystal 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** and each atom or unit of atoms is called **basis or pattern**. A space lattice represents the geometrical pattern of crystal in which the surroundings of each lattice point is the same. If the surroundings of each lattice point is same or if the atom or all the atoms at lattice points are identical, then such a lattice is called **Bravais lattice**. On the other hand, if the atom or the atoms at lattice points are not same, then it is said to be a **non-Bravais lattice** (Fig. 1-4).

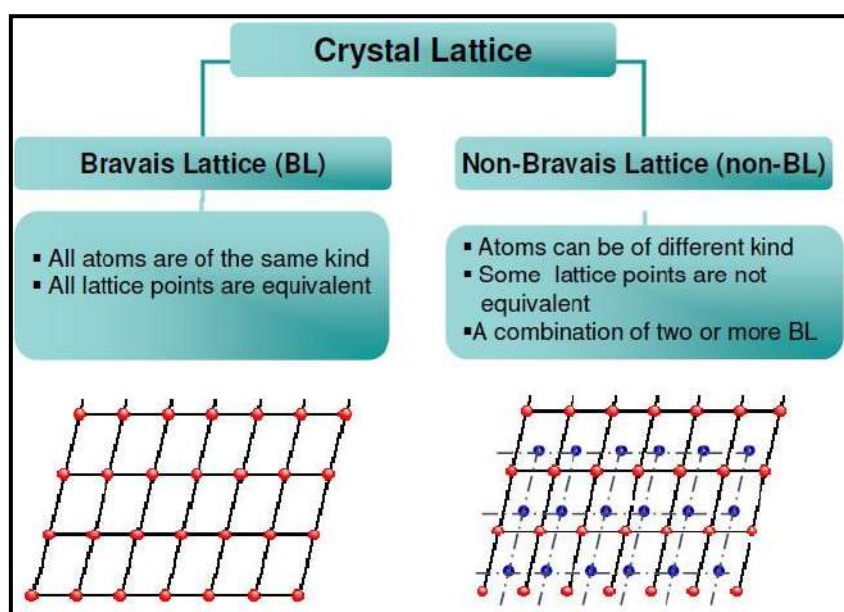


Figure 1-4 Bravais and non-Bravais Lattice.

### 1.2.2. Unit cell and lattice parameters

A unit cell is the basic structural unit or building block of the crystal. A unit cell is defined as the smallest component (geometric figure) of the crystal (group of atoms, ions or molecules), which when stacked together with pure translational repetition along the crystallographic axes reproduces the whole crystal. The choice of a unit cell is not unique but it can be constructed in a number of ways; (Fig. 1-5a and b) shows different ways of representing unit cells in a two-dimensional lattice. A unit cell can be represented as ABCD or A'B'C'D' or A''B''C''D'', etc.

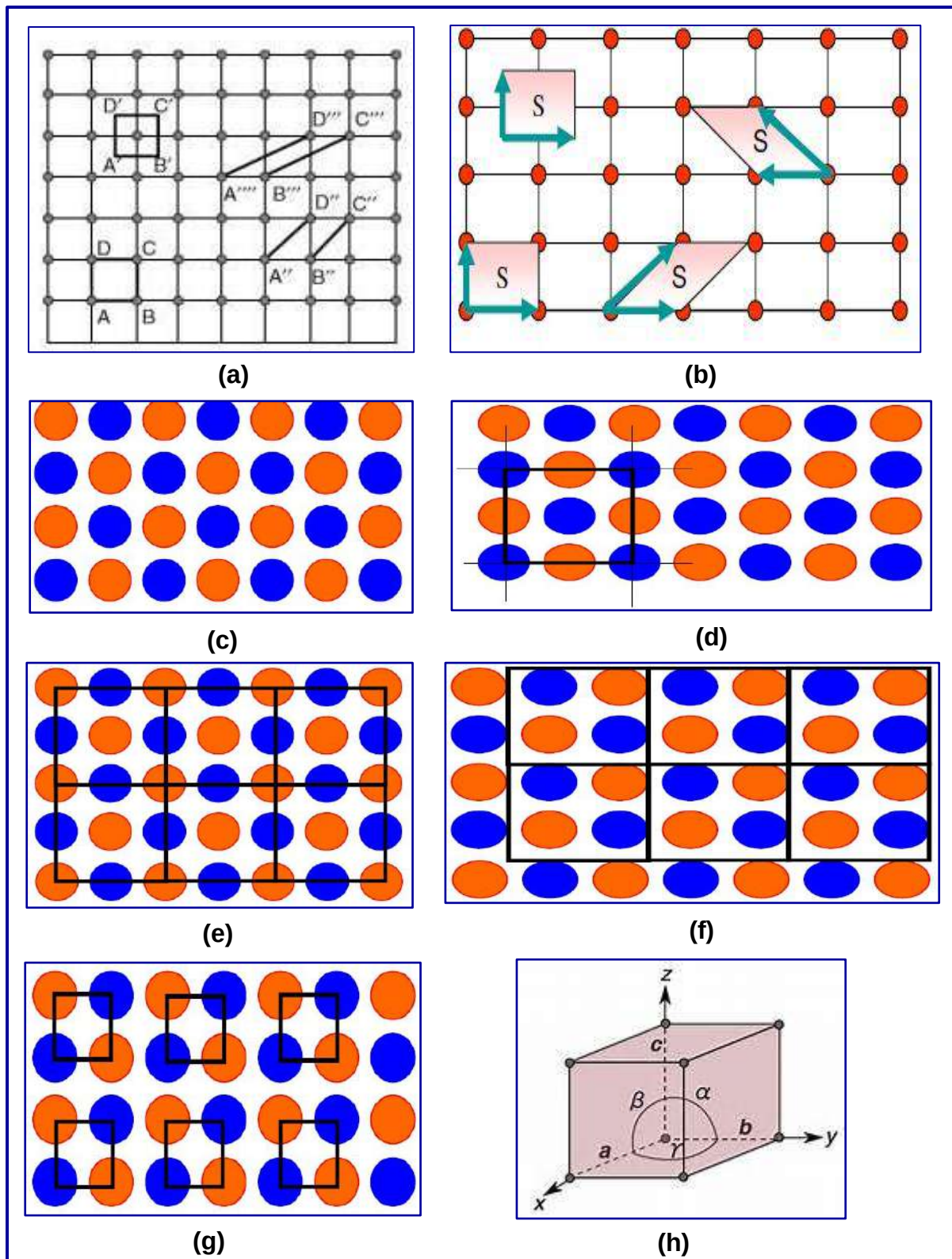


Figure 1-5 Unit cells in crystal lattice. The choice of unit cell is not unique.

Lattice points are points with *identical environments* (Fig. 1-5 c). The choice of origin is arbitrary - lattice points need not be atoms - but unit cell size should always be the same. It doesn't matter if you start from Na or Cl (Fig. 1-5 d, e and f). Figure (1-5 g) is not a unit cell even though they are all the same - empty space is not allowed.

To define the lattice parameters, first we define crystallographic axes. These axes are obtained by the intersection of the three non-coplanar faces of the unit cell. The angle between these faces or crystallographic axes are known as interfacial or interaxial angles. The angles between the axes Y and Z is  $\alpha$ , between Z and X is  $\beta$  and between X and Y is  $\gamma$ . The translational vectors or primitives a, b, c of a unit cell along X, Y, Z axes and interaxial angles  $\alpha$ ,  $\beta$ ,  $\gamma$  are called lattice constants or lattice parameters. These cell parameters are shown in Figure (1-5 h). The cell parameters determine the actual size and shape of the unit cell.

### 1.3. Crystal growth

The directions of growth start always from a center nucleus (the minute crystal) and follow in all cases several directions, which are at right angle to the individual faces shown by the crystal. In this respect, we have two types of crystals:

- **Isotropic crystals:** These are crystals in which the velocity of growth is the same in all directions i.e. all faces of the crystal are regularly distributed around the center and are at equal distance from it (e.g. crystals belonging to cubic system).
- **Anisotropic crystals:** These are crystals in which the velocity of growth is not the same (i.e. different in all directions). All faces of the crystal are not situated at equal distance from its center (e.g. crystals belonging to all systems other than cubic system).

The crystallization from melt, solution, gases and solids give mineral with internal structure. When crystal has crystal faces described as euhedral, when

lacking some crystals named as subhedral. The crystals without faces described as anhedral.

The crystal shape and habits are affected by variation in temperature during growth, impurities and cooling rate. Ex. (NaCl, Halite) can crystallized into cube when the solution is pure or into octahedron when 10% urea is added to the solution. Cassiterite mineral crystallized from granitic melt give pyramidal habit but from hydrothermal give prismatic shape.

The growth defects happen when some ions of the same mineral are lacking giving a hole or some foreign ions are added. This result in some coloration of the mineral as coloration of quartz and fluorite minerals. The post growth defects are found in minerals having some radioactive elements ex. Zircon may contain some U and /or Th radioactive elements. The decay of these elements destructs the internal structure of zircon giving amorphous substances. This process is called metamictization.

## 1.4 Polymorphism and isomorphism

**Polymorphism** means a substance can crystallize into more than one crystal system under different conditions of crystallization. Ex.  $\text{SiO}_2$  can give low quartz (tetragonal), high quartz (hexagonal, or stishovite tetragonal) under high pressure.  $\text{CaCO}_3$  can crystallize into calcite at high temperature or aragonite at high pressure. Also C give graphite (hexagonal) at low T and give diamond under high pressure. The high pressure minerals characterized by closely backed atoms and high density than the corresponding high temperature minerals with expanded structure.

**Isomorphism** means different minerals with the same chemical formula and the same crystal system. Ex, plagioclase minerals are all triclinic and their chemical formula is  $\text{Na, Ca, Al SiO}_3$ . the first mineral crystallized at high temperature is anorthite 100% Ca, the latest mineral is albite 100% Na as a result of Na substitution during growth.

## 1.5. Crystal components

- a) Crystal faces: External smooth surfaces reflect the whole shape of the crystal.
- b) Crystal edge: The line that results from the meeting of two neighboring faces
- c) Solid angles: Angles result from meeting of more than two faces (Fig.1-6).

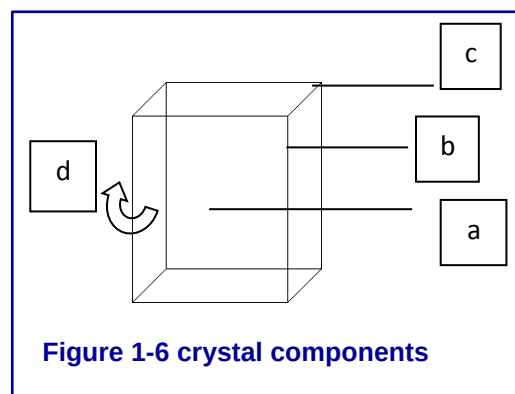


Figure 1-6 crystal components

- d) Interfacial angles: The angles between corresponding faces. By measuring the interfacial angles, it is possible to determine the symmetry and characterize the substance. This was the basis of geometrical crystallography. The measurement of the interfacial angles in crystal is done using an instrument termed as a goniometer.

## 1.6. Crystal form

A crystal form is a set of crystal faces that are related to each other by symmetry. An important point to note is that a form refers to a face or set of faces that have the same arrangement of atoms. Thus, the number of faces in a form depends on the symmetry of the crystal. There are two types:

**Open form** is one or more crystal faces that cannot close the crystal in all directions alone such as, pedion, 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.

- Pedion is a single faced form. Since there is only one face in the form a pedion cannot completely enclose space. Thus, a crystal that has only pedions, must have at least 3 different pedions to completely enclose space.
- Pinacoid is two faced form parallel to each other. When the faces are parallel then they cannot completely enclose space.

- A prism is a 3 or more faced form also parallel to the same line. Thus, crystals that have prisms must also have at least one additional form in order to completely enclose space.
- A bipyramid has at least 6 faces that meet in points at opposite ends of the crystal. These faces can completely enclose space, so a bipyramid is closed form. Although a crystal may be made up of a single bipyramid form, it may also have other forms present.

Based on the abundance of crystal forms in the crystal, the crystal can be described as the following:

- ❖ **Simple crystal:** This is a crystal containing one close form with its similar faces enclosing the crystal from all direction.
- ❖ **Compound (combined) crystal:** This is a crystal containing more than one form combined together in a regular arrangement to enclose the room of this individual crystal. The compound crystal may be formed of open forms, closed forms or open with closed forms. Combined closed forms are mostly recorded in cubic system.

## 1.7. Elements of crystallization

### 1.7.1. Crystallographic axes

These are imaginary lines passing through the center of the crystal and are always taken as a basis to describe different crystal systems. Such crystallographic are four axes only in crystals belonging to the hexagonal and trigonal systems whereas, in other crystal systems they are only three axes.

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 corresponding to the length or height of the crystal (Fig. 1-7a).

- 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.

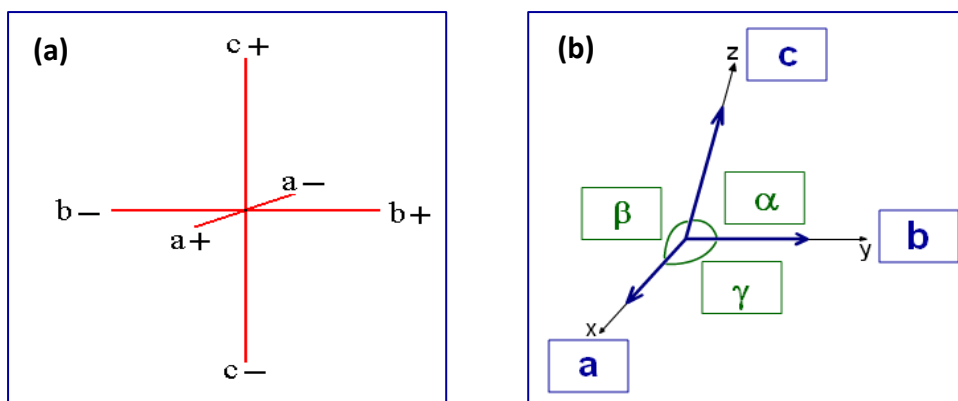


Figure 1-7 (a) crystallographic axes, (b) crystallographic angles

### 1.7.2. Crystallographic angles

The intersections of the crystallographic axes at center of crystals give three angles called as  $\alpha$ ,  $\beta$  and  $\gamma$  (Fig. 1-7b).

- alpha ( $\alpha$ ): lies between the b and c axes
- beta ( $\beta$ ): lies between the a and c axes
- gamma ( $\gamma$ ): lies between the a and b axes

## 1.8. Elements of symmetry

Symmetry is the most important of all properties in the identification of crystalline substances. In this section we shall be concerned with the symmetrical arrangement of crystal faces, an arrangement which reflects the internal symmetry of the lattice. Symmetry may be described by reference to symmetry planes, axes, and the center of symmetry as discussed here below.

### 1.8.1. Plane of Symmetry

This is an imaginary plane which divide the crystal into 2 equal and identical halves each or which is a mirror image to the other. A crystal can have one or more planes of symmetry. A sphere for example has infinite planes of symmetry.

### 1.8.2 Axis of Symmetry

This is an imaginary axis or line passing through the center of the crystal. Around this line the crystal can be rotated and similar face come to occupy the same position more than once in a complete rotation of  $360^\circ$ .

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

- **Hexad (six-fold) axis:** When rotation repeats form every 60 degrees.
- **Tetrad (four-fold) axis:** When rotation repeats form every 90 degrees.
- **Triad (three-fold) axis:** When rotation repeats form every 120 degrees.
- **Diad (two-fold) axis:** When rotation repeats form every 180 degrees.

### 1.8.3 Center of Symmetry

This is an imaginary point, which lies inside the crystal exactly in its center. Now it should be also added that 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 should be met with at equal distance beyond the center of the other side of this line. In this case only, the concerned crystal is said to possess a center of symmetry.

The elements of symmetry may be or may not be combined in the same crystal. Indeed, we will find that one crystal class or system has only one of these elements!

## 1.9. Crystal systems

Based on elements of crystallization and elements of symmetry, crystals can be classified into 7 systems; cubic, tetragonal, orthorhombic, monoclinic, triclinic, hexagonal and trigonal systems. These seven systems include 32 classes.

### 1.9.1. Cubic (Isometric) system

Cubic system includes five different crystalline classes. We will focus only on the hexaoctahedral class which is called as the holosymmetrical (normal) class.

### Crystallographic axes

Cubic system has three equal axes ( $a_1 = a_2 = a_3$ ) at right angles to each other (Fig. 1-8).

- $a_3$  is vertical axis [from top is (+ve) to bottom (-ve)].
- $a_2$  is horizontal [from right (+ve) to left (-ve)].
- $a_1$  is horizontal [from front (+ve) to back (-ve)].

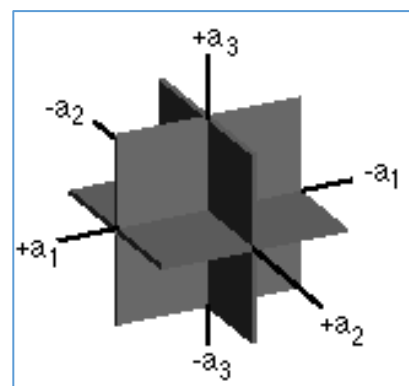


Figure 1-8 crystallographic axes of cubic system.

### Crystallographic angles

The angles between intersections of the crystallographic axes are represented by  $\alpha$ ,  $\beta$  and  $\gamma$  (Fig. 1-9). All of three angles are equal to  $90^\circ$  ( $\alpha = \beta = \gamma = 90^\circ$ ).

- $\alpha$  – angle between the  $a_2+$  and  $a_3+$  axis.
- $\beta$  – angle between the  $a_1+$  and  $a_3+$  axis.
- $\gamma$  – angle between the  $a_1+$  and  $a_2+$  axis

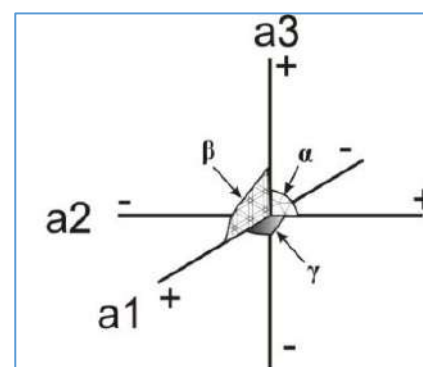


Figure 1-9 crystallographic angles of cubic system.

### Planes of symmetry

There are nine planes of symmetry in the holosymmetrical class, four of them are vertical, one is horizontal and the other four planes are inclined (Fig. 1.10).

### Axes of symmetry

The normal class of cubic system has 13 axes of symmetry described as following (Fig. 1.10):

- Three tetrad axes perpendicular to three planes (3■)
- Four triad axes not perpendicular to any plane (4▲)
- Six diad axes perpendicular to six planes (6●)

### Center of symmetry

There is only one center of symmetry in this class, where each face in the crystal corresponds to another equivalent parallel face.

### Crystal forms

There are seven forms in cubic system (Fig. 1-10):

- **Cube (Hexahedron):** It is composed of 6 square faces at 90 degree angles to each other. Each two parallel faces intersects one of the crystallographic axes. This form is one of the easiest to recognize and many minerals display such as galena, pyrite, fluorite, or halite cubes.
- **Octahedron:** This form composed of 8 equilateral triangles. These triangle shaped faces intersect all 3 crystallographic axes at the same distance. Minerals commonly exhibiting the simple octahedral form are magnetite, chromite, gold, and diamond. Sometimes fluorite, pyrite, and galena take this form.
- **Rhombic Dodecahedron:** This form is composed of 12 rhomb-shaped faces. Four of these rhomb-shaped faces are parallel to  $a_3$  axis while the other eight faces are inclined to  $a_3$  axis. The different mineral species of the garnet group often display this form. Magnetite and sodalite sometimes exhibit this form.
- **Tetrahexahedron:** This form has 24 isosceles triangular faces. The easiest way to understand this shape is dividing each face of a cube to 4 equal-sized triangular faces. The tetrahexahedron is rarely the dominant form on natural crystals. However, fluorite sometimes, exhibit this form.
- **Trapezohedron:** This form has 24 similar trapezium-shaped faces. Firstly, think of an octahedron then each octahedral face is divided into 4 trapezium faces. Two silicate minerals, analcime and leucite, usually crystallize as simple trapezohedrons.
- **Trisoctahedron:** This is another 24-faced form, but the faces are isosceles triangles. Firstly, think of an octahedron then each octahedral

face is divided into 3 isosceles triangles. As a dominant form, the trisoctahedron is scarce, most commonly being reported for diamond, usually as a subordinant form

- **Hexoctahedron:** This form has 48 triangular faces, 6 faces appearing to be raised from each face of a simple octahedron. Just like the trisoctahedral form, this form is most often seen on diamond.

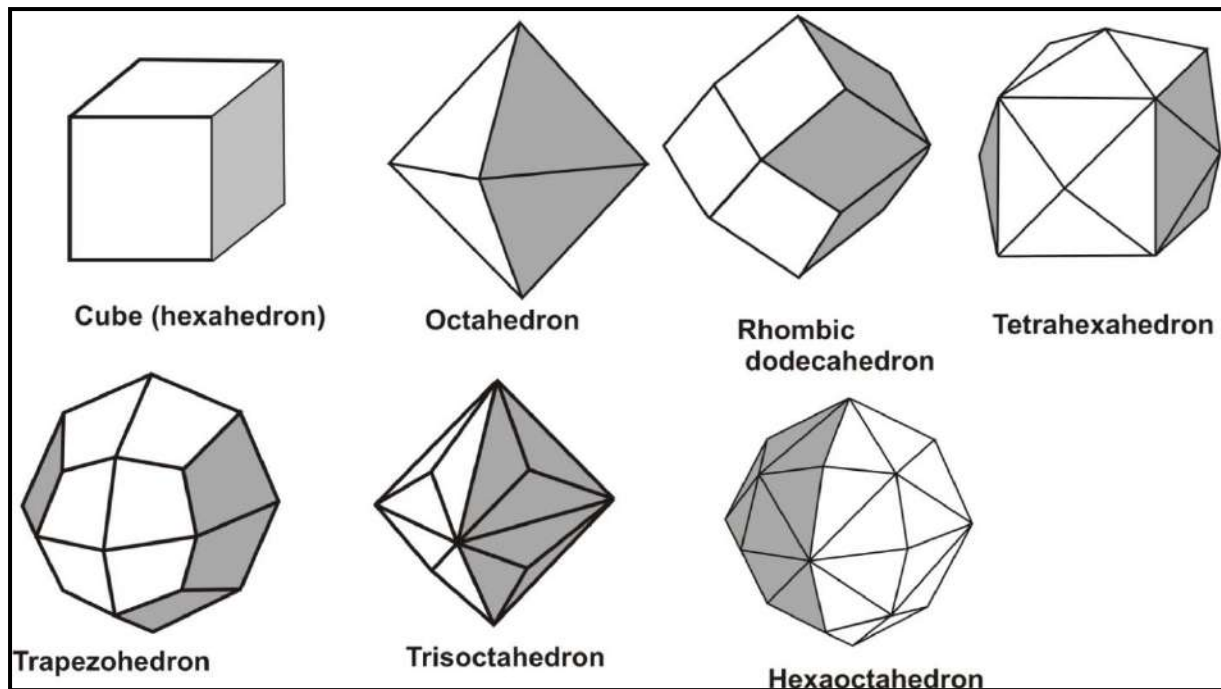


Figure 1-10 Crystal forms of cubic system

### 1.9.2. Tetragonal system

Tetragonal system includes seven different crystalline classes. We will focus only on the ditetragonal bipyramidal class which is called as the holosymmetrical (normal) class.

#### Crystallographic axes

Tetragonal system has three axes at right angles to each other. Two of them are horizontal and of equal length ( $a_1 = a_2$ ). The third vertical axis ( $c$ ) is different, either shorter or longer than horizontal axes (Fig. 1-11).

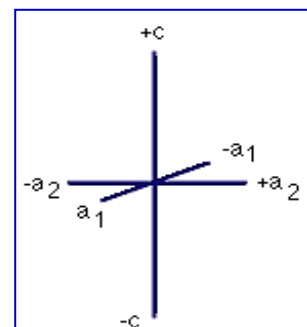


Figure 1-11: crystallographic axes of tetragonal system.

### Crystallographic angles

As in cubic system, the crystallographic axes in tetragonal system intersect at three angles equal to  $90^\circ$  ( $\alpha = \beta = \gamma = 90^\circ$ )

### Planes of symmetry

There are five planes of symmetry in the holosymmetrical class, one of them is horizontal and the other four planes are vertical (Fig. 1.12).

### Axes of symmetry

The normal class of tetragonal system has 5 axes of symmetry described as following (Fig. 1-12):

- one tetrad axis perpendicular to one planes (1  $\blacksquare$ )
- four diad axes perpendicular to four planes (6  $\bullet$ )

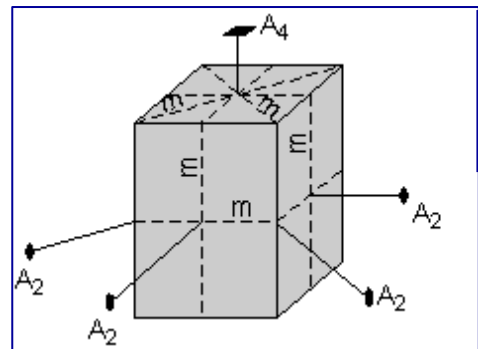


Figure 1-12 Axes and planes of symmetry in tetragonal system.

### Center of symmetry

Only one center of symmetry is observed in this normal class.

### Crystal forms

Tetragonal system includes seven forms (Fig. 1-13):

- **Basal (c) pinacoid:** It is an open form composed of two faces parallel to each other and intersects only the c axis.
- **Tetragonal prism 1<sup>st</sup> order:** It is an open form having 4 faces that are parallel to the c axis and having each face intersect the a<sub>1</sub> and a<sub>2</sub> axes at the same distance (unity).
- **Tetragonal prism 2<sup>nd</sup> order:** This form is essentially identical to the first order prism, but here two faces intersect the a<sub>1</sub> and are parallel to a<sub>2</sub> while the other two faces are parallel to a<sub>1</sub> and intersects a<sub>1</sub>. It is apparent that the faces of both prisms are identical, and their letter designation is only dependent on how they are oriented to the two horizontal axes (a<sub>1</sub>, a<sub>2</sub>).

- **Ditetragonal prism:** This form consists of eight faces parallel to  $c$  axis and intersect the horizontal axes but at different distances. It is formed when tetragonal prism is equally developed.
- **Tetragonal bipyramid 1<sup>st</sup> order:** it is a closed form have 8 isosceles triangular faces intersect all crystallographic axes but not at the same distance as we already defined that form as an octahedron in the isometric. So, in this form, the faces intersect the  $c$  axis either at a longer or shorter distance than that of  $a$  axes.
- **Tetragonal bipyramid 2<sup>nd</sup> order:** It has the basic shape as the form of the 1st order bipyramid, differing only in its orientation to horizontal axes ( $a_1, a_2$ ).
- **0 Ditetragonal bipyramid:** It is a closed termination form having 16 faces. Think of this form as a double 8-sided pyramid whose 16 similar faces meet the 3 axes at unequal distances. This form is rarely dominant, but is common enough as a subordinant form on zircon to be nicknamed a zirconoid.

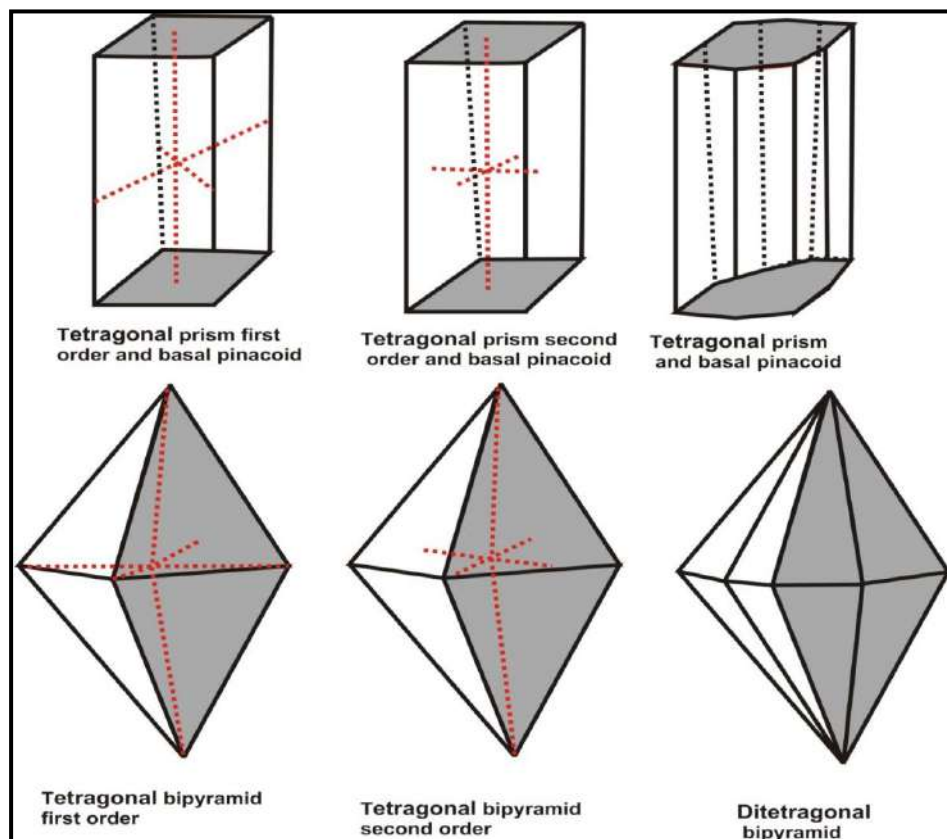


Figure 1-13 Crystal forms of tetragonal system

### 1.9.3. Hexagonal system

Tetragonal system includes seven different crystalline classes. We will focus only on the dihexagonal bipyramidal class which is called as the holosymmetrical (normal) class.

#### Crystallographic axes

Hexagonal system has four axes, three of them are horizontal and of equal length ( $a_1=a_2=a_3$ ) and the other axis is vertical (c-axis) at right angles to the others. The vertical axis (c) is different, either shorter or longer than horizontal axes (Fig. 1-14).

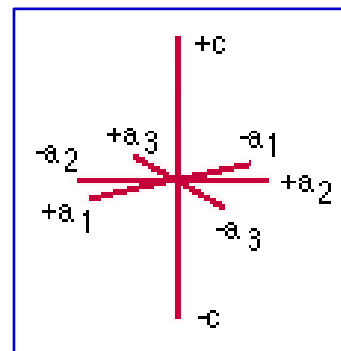


Figure 1-14 Crystallographic axes of hexagonal system.

#### Crystallographic angles

In hexagonal system, c-axis is vertical to horizontal axes, so alpha ( $\alpha$ ) and beta ( $\beta$ ) angles are equal to  $90^\circ$ . On the other hand,  $a_1$ -axis is inclined to  $a_2$ -axis, then gamma angle ( $\gamma$ ) will be greater than  $90^\circ$  ( $\approx 120^\circ$ ).

#### Planes of symmetry

There are seven planes of symmetry in the holosymmetrical class, one of them is horizontal and the other six planes are vertical (Fig. 1-15a).

#### Axes of symmetry

The normal class of hexagonal system has 7 axes of symmetry described as following (Fig. 1-15b):

- one hexad axis perpendicular to one planes (1 )
- six diad axes perpendicular to four planes (6 )

#### Center of symmetry

Only one center of symmetry is observed in this normal class.

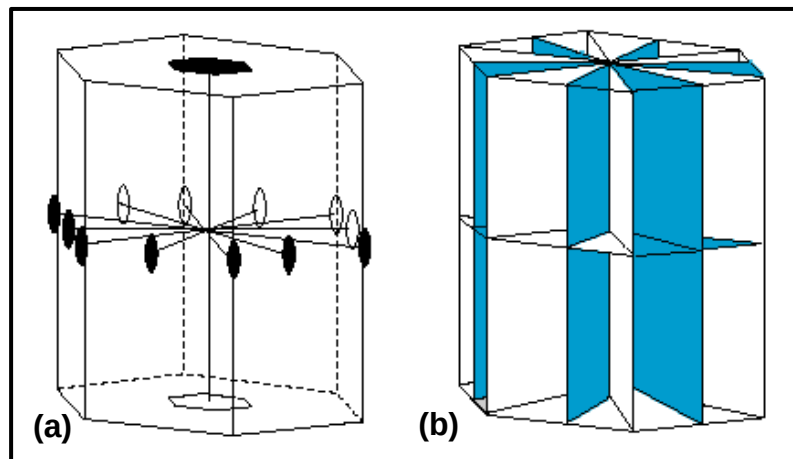


Figure 1-15 (a) axes of symmetry (b) planes of symmetry of hexagonal system

### Crystal forms

There are seven crystal forms in hexagonal system (Fig. 1-16):

- **Basal (c) pinacoid:** It is an open form composed of two faces parallel to each other and intersects only the c axis.
- **Hexagonal prism 1<sup>st</sup> order:** It is an open form having 6 faces that are parallel to the c axis and having each face intersect the  $a_1$ ,  $a_2$  and  $a_3$  axes at the same distance (unity).
- **Hexagonal prism 2<sup>nd</sup> order:** This form is essentially identical to the first order prism, but here two faces intersect the  $a_1$  and are parallel to  $a_2$  while the other two faces are parallel to  $a_1$  and intersects  $a_2$ . It is apparent that the faces of both prisms are identical, and their letter designation is only dependent on how they are oriented to the two horizontal axes ( $a_1$ ,  $a_2$ ,  $a_3$ ).
- **Dihexagonal prism:** This form consists of twelve faces parallel to c axis and intersect the horizontal axes but at different distances. It is formed when hexagonal prism is equally developed.
- **Hexagonal bipyramid 1<sup>st</sup> order:** it is a closed form have 12 isosceles triangular faces intersect all crystallographic axes but not at the same distance. The faces intersect the c axis either at a longer or shorter distance than that of a axes.

- **Hexagonal bipyramid 2<sup>nd</sup> order:** It has the basic shape as the form of the 1st order bipyramid, differing only in its orientation to horizontal axes ( $a_1, a_2, a_3$ ).
- **Dihexagonal bipyramid:** It is a closed termination form having 24 faces. Think of this form as a double 12-sided pyramid whose 24 similar faces meet the 4 axes at unequal distances.

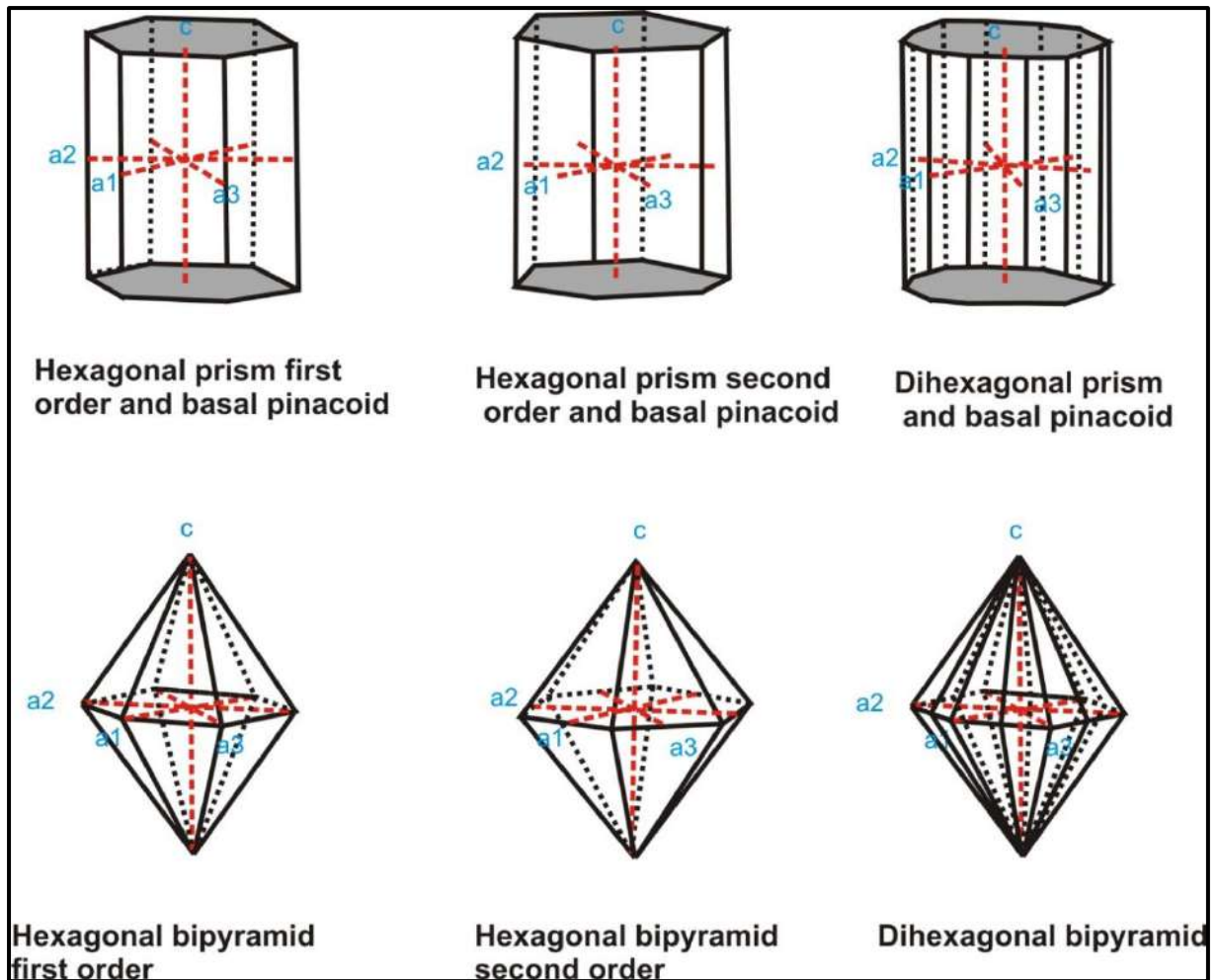


Figure 1-16 Crystal forms of Hexagonal system

#### 1.9.4. Trigonal system

Tetragonal system includes five different crystalline classes. We will focus only on the ditrigonal scalenohedral class which is called as the holosymmetrical (normal) class.

### Crystallographic axes and angles

Trigonal system has the same crystallographic axes and angles as in hexagonal system.

### Planes of symmetry

There are three planes of symmetry in the normal class of trigonal system, all are vertical (Fig. 1-20). No horizontal plane is observed in trigonal system.

### Axes of symmetry

The normal class of trigonal system has 4 axes of symmetry described as following:

- one triad rotoinversion axis ( $1 \Delta$ )
- three diad axes perpendicular to 3 planes ( $3 \bullet$ )

### Center of symmetry

Only one center of symmetry is observed in this normal class.

### Crystal forms

Trigonal system include 7 crystal forms:

- **Basal (c) pinacoid**
- **Trigonal (Hexagonal) prism 1<sup>st</sup> order**
- **Trigonal (Hexagonal) prism 2<sup>nd</sup> order**
- **Ditrigonal (dihexagonal) prism**
- **Trigonal (Hexagonal) bipyramid 2<sup>nd</sup> order**

The above five forms are the same as those of hexagonal. On the other hand, there are two principal forms characteristic to normal class of trigonal system described as the following:

- a) Rhombohedron:** It is a closed form having 6 rhombohedral faces, 3 faces above and 3 faces below the center of the

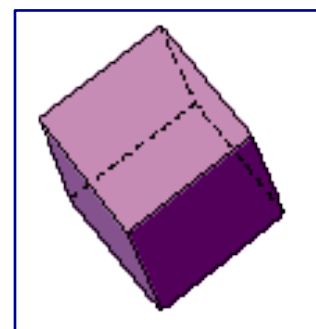


Figure 1-17 Rhombohedron form

crystal. In this form two faces above meet one face below forming y-shape (Fig. 1.17).

**b) Ditrigonal scalenohedron:** It is a closed form, consists of 12 inequilaterally triangle faces, 6 faces above and 6 faces below the center of the crystal. The upper faces are not placed directly on the lower faces due the absence of horizontal plane, hence the meeting points between faces giving zigzag line (Fig. 1-18).

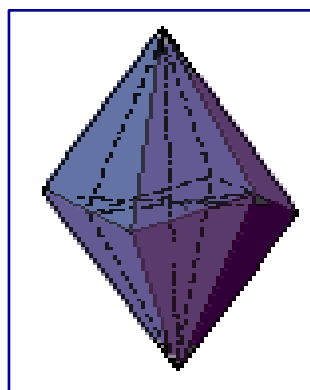


Figure 1-18 Scalenohedron form

### 1.9.5. Orthorhombic system

Orthorhombic system includes three different crystalline classes. We will focus only on the orthorhombic bipyramidal class which is called as the holosymmetrical (normal) class.

#### Crystallographic axes

Orthorhombic system has three unequal axes ( $a \neq b \neq c$ ) at right angles to each other, where  $c > b > a$  (Fig. 1-19).

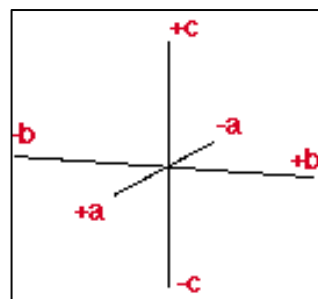


Figure 1-19 Crystallographic axes of orthorhombic system.

#### Crystallographic angles

As in cubic and tetragonal systems, the crystallographic axes in orthorhombic system intersect at three angles equal to  $90^\circ$  ( $\alpha = \beta = \gamma = 90^\circ$ )

#### Planes of symmetry

There are three planes of symmetry in the holosymmetrical class, one of them is horizontal and the other two planes are vertical.

#### Axes of symmetry

The normal class of orthorhombic system has three diagonal axes (3  $\bullet$ ) in the same places of crystallographic axes. Each axis is perpendicular to one of the three planes.

### Center of symmetry

Only one center of symmetry is observed in this normal class.

### Crystal forms

There are seven forms in orthorhombic system (Fig. 1-20):

- **Basal (c) pinacoid:** It is an open form composed of two parallel faces that intercept the c axis and are parallel to the a and b axes.
- **(a) Pinacoid:** It is an open form composed of two parallel faces that intercept the a axis and are parallel to the c and b axes.
- **(b) Pinacoid:** It is an open form composed of two parallel faces that intercept the b axis and are parallel to the a and c axes.
- **Orthorhombic prism:** It is an open form, consists of 4 faces which are parallel to c axis and intersect the other two axes.
- **Orthorhombic bipyramid:** It is a closed form, consists of 8 triangular faces, each of them intersects all 3 crystallographic axes. This pyramid may have several different appearances due to the variability of the axial lengths.
- **(a) or Brachy dome:** It is an open form, consists of 4 faces parallel to a axis and intersect the other two axes (c, b).
- **(b) or Macro dome:** It is an open form, consists of 4 faces parallel to b axis and intersect the other two axes (c, a). It is apparent that the dome form either (a) or (b) is always intersects the c axis. So there is no c-dome.

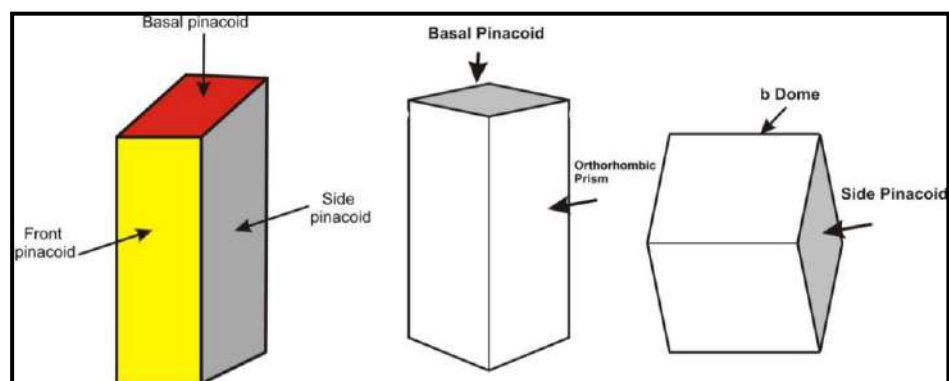


Figure 1-20 Crystal forms of tetragonal system

### 1.9.6. Monoclinic system

Monoclinic system includes three different crystalline classes. We will focus only on the prismatic class which is called as the holosymmetrical (normal) class.

#### Crystallographic axes

Monoclinic system has three unequal axes ( $a \neq b \neq c$ ), two at right angles ( $c, b$ ), and the other ( $a$ ) is inclined (Fig. 1-21). As in orthorhombic system,  $c > b > a$  in monoclinic system.

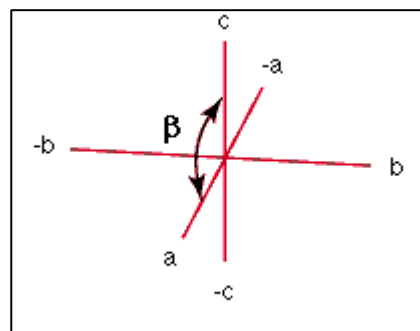


Figure 1-21 crystallographic axes and angles of monoclinic system.

#### Crystallographic angles

In monoclinic system,  $\alpha$  and  $\gamma$  remain  $90^\circ$  whereas, the angle between  $c$  and  $a$  axes ( $\beta$ -angle) will vary (Fig. 1-21). It will be greater than  $90^\circ$  towards the viewer and lower than  $90^\circ$  in the opposite side.

#### Planes of symmetry

There is only one vertical plane of symmetry which is perpendicular to  $b$ -axis.

#### Axes of symmetry

The prismatic class of monoclinic system has only one diagonal axis ( $b$ -axis) which is perpendicular to present vertical plane.

#### Center of symmetry

Only one center of symmetry is recorded in this normal class.

#### Crystal forms

The most common crystalline forms in prismatic class of monoclinic system are seven forms:

- **Basal (c) pinacoid:** It is an open form composed of two parallel faces that intercept the c axis and are parallel to the a and b axes.
- **(a) Pinacoid:** It is an open form composed of two parallel faces that intercept the a axis and are parallel to the c and b axes.
- **(b) Pinacoid:** It is an open form composed of two parallel faces that intercept the b axis and are parallel to the a and c axes.
- **Monoclinic prism:** It is an open form, consists of 4 faces which are parallel to the vertical c axis and intersect the other two horizontal axes.
- **Hemibipyramid:** It is an open form, consists of 4 faces, each of them intersects all 3 crystallographic axes. It is called as +ve hemi-bipyramid at obtuse  $\beta$ -angle and as -ve hemi-bipyramid at acute  $\beta$ -angle.
- **(a) or clino-dome:** It is an open form, consists of 4 faces parallel to a axis and intersect the other two axes (c, b). It is called clino-dome because it is parallel to clino-axis (a).
- **(b) or ortho-(hemi)dome:** It is an open form, consists of only two faces parallel to b axis and intersect the other two axes (c, a). As in hemi-bipyramid, hemi-dome can be distinguished as +ve type at obtuse  $\beta$ -angle and as -ve type at acute  $\beta$ -angle

### 1.9.7. Triclinic system

Triclinic system includes two different crystalline classes. We will focus only on the pinacoidal class which is called as the holosymmetrical (normal) class.

#### Crystallographic axes

Triclinic system has three unequal axes ( $a \neq b \neq c$ ), all are inclined to each other (Fig. 1-23).

#### Crystallographic angles

This crystal system include three unequal angles ( $\alpha \neq \beta \neq \gamma \neq 90^\circ$ ) (Fig. 1.23).

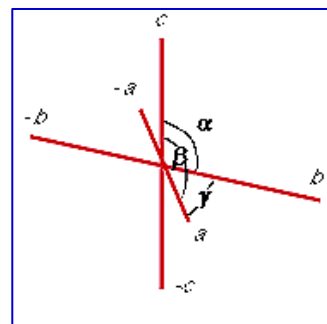


Figure 1-22 crystallographic axes and angles of triclinic

### Planes of symmetry

No planes of symmetry are observed in the pinacoidal class of monoclinic system.

### Axes of symmetry

No axes of symmetry are observed in the pinacoidal class of monoclinic system.

### Center of symmetry

Only one center of symmetry is recorded in this normal class.

### Crystal forms

Triclinic system have seven characteristic forms:

- **Basal (c) pinacoid:** It is an open form composed of two parallel faces that intercept the c axis and are parallel to the a and b axes.
- **(a) Pinacoid:** It is an open form composed of two parallel faces that intercept the a axis and are parallel to the c and b axes.
- **(b) Pinacoid:** It is an open form composed of two parallel faces that intercept the b axis and are parallel to the a and c axes.
- **Hemiprism:** It is an open form, consists of 2 faces parallel to c axis, one face in the right side and the other is in the left side.
- **Tetrato (quarter) bipyramid:** It is an open form, consists of 2 faces, each of them intersects all 3 crystallographic axes.
- **(a) or hemi-brachy-dome:** It is an open form, consists of 2 faces parallel to a axis and intersect the other two axes (c, b). The two faces appear in opposite sides, one in the left and the other in the right.
- **(b) or hemi-macro-dome:** It is an open form, consists of only two faces parallel to b axis and intersect the other two axes (c, a). The two faces appear in opposite sides, one is above and the other is below.

# Chapter 2

## MINERALOGY

### Goals

*By the end of this chapter, you should be able to:*

1. Define mineral and how to identify it.
2. Knew the classification of minerals according to its chemical composition.
3. Knew the basis of mineral nomenclature.
4. Differentiate between minerals according to their physical properties.

The term **Mineralogy** means the study of minerals “the rock building units”

### 2.1 What is a mineral?

**A mineral is a naturally occurring inorganic solid with a characteristic chemical composition and a crystalline structure.** Chemical composition and crystalline structure are the two most important properties of a mineral: They distinguish any mineral from all others. Before discussing them, however, let us briefly consider the other properties of minerals described by this definition.

- **Natural occurrence** It means that minerals are formed as a result of natural geological processes such as pressure and temperature. So man-made substances such as steel, glass, concrete, synthetic diamonds, rubies and emeralds are not minerals.
- **Inorganic solid** means that minerals are not formed by anything that was ever alive. Therefore, materials such as: Ivory, Amber, Coal, Pearls are not minerals (Fig. 2-1). Moreover, sulfur and iron oxides formed by bacterial action are not minerals. However, in some places, coal beds have been subjected to high temperatures which cause volatile hydrocarbons to be driven off and the remaining carbon to be crystallized into graphite.

**Amber****Pearl****Ivory**

Figure 3-1 Solids (*not Minerals*) with a characteristic chemical composition.

- **Homogeneous** means that mineral consists of single substance that cannot be physically broken into simpler components.
- **Solid** means that minerals must be able to maintain a set shape nearly indefinitely. Thus H<sub>2</sub>O as ice in a glacier is a mineral, but water is not.
- **Crystalline** means that minerals have an internal ordered atomic structure in which the atoms (or ions) arranged in a regular repeated geometric pattern with or without crystal faces. Crystalline minerals are easy to see in the big specimens as quartz, hematite and olivine. Solids that lack an ordered atomic **arrangement** are called amorphous or mineraloids such as glass (Fig. 2-2). The substances which cooled rapidly such as obsidian and opal are also called amorphous substances. They are solidified without regular arrangement of atoms are, so they have neither internal structure nor external form (no crystal faces).

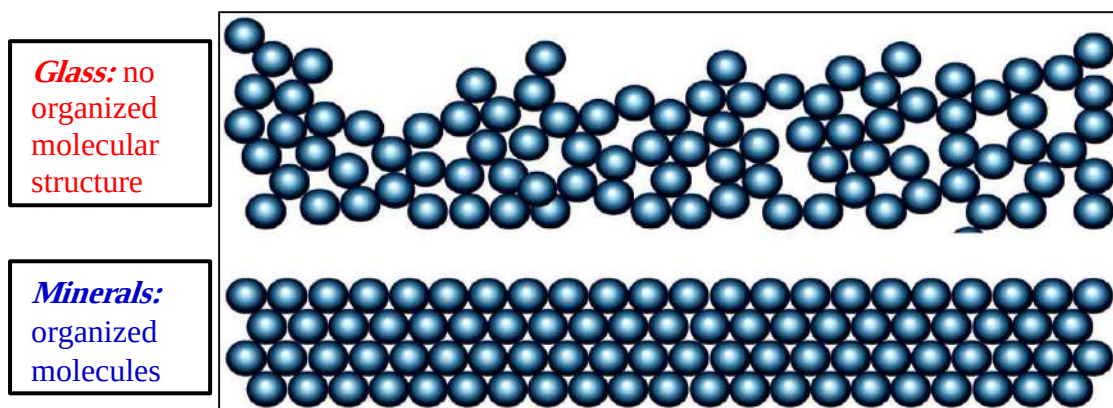


Figure 2-2 Organized crystal lattice showing differences between amorphous solids and crystalline solids

- **A definite chemical composition** implies that minerals can be expressed by a specific chemical formula. For example, the chemical composition of quartz is expressed as  $\text{SiO}_2$ . Because quartz contains no chemical elements other than silicon and oxygen, its formula is definite. However, most minerals do not have such well-defined compositions. Dolomite is not always a pure Ca-Mg-carbonate. It may contain considerable amounts of Fe and Mn in place of Mg. As these amounts vary, the composition of dolomite is said to range between certain limits and is, therefore, not fixed.

## 2.2 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. Some examples of mineral names and their derivations are as follows:

- **Albite ( $\text{NaAlSi}_3\text{O}_8$ ):** from the Latin, albus (white), in allusion to its color.
- **Rhodonite ( $\text{MnSiO}_3$ ):** from the Greek, rhodon (a rose), in allusion to its characteristically pink color.
- **Chromite ( $\text{FeCr}_2\text{O}_4$ ):** because of the presence of a large amount of chromium in the mineral.
- **Magnetite ( $\text{Fe}_3\text{O}_4$ ):** because of its magnetic Properties.
- **Franklinite ( $\text{ZnFe}_2\text{O}_4$ ):** after a locality, Franklin, New Jersey, where it occurs as the dominant zinc mineral.
- **Sillimanite ( $\text{Al}_2\text{SiO}_5$ ):** after Professor Benjamin Sillman of Yale University.

## 2.3 Structure of minerals

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

### 2.3.1 Crystal lattice

These 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 (Fig. 2-3). Such bonds govern mineral properties.

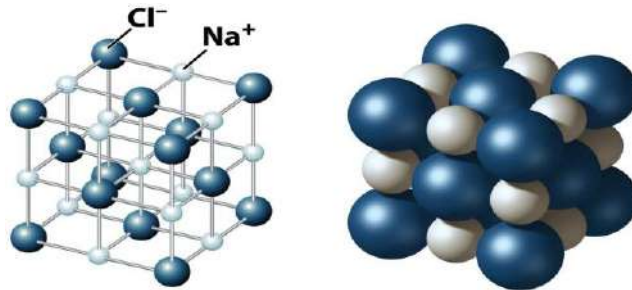


Figure 2-3 Crystal Structure (Lattice) of Halite mineral

### 2.3.2 Polymorphs

Polymorphs are minerals with the same chemical composition but different crystalline structures such as diamond and graphite (Fig. 2-4).

#### **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/cm<sup>3</sup>) than graphite (2.1 g/cm<sup>3</sup>) 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

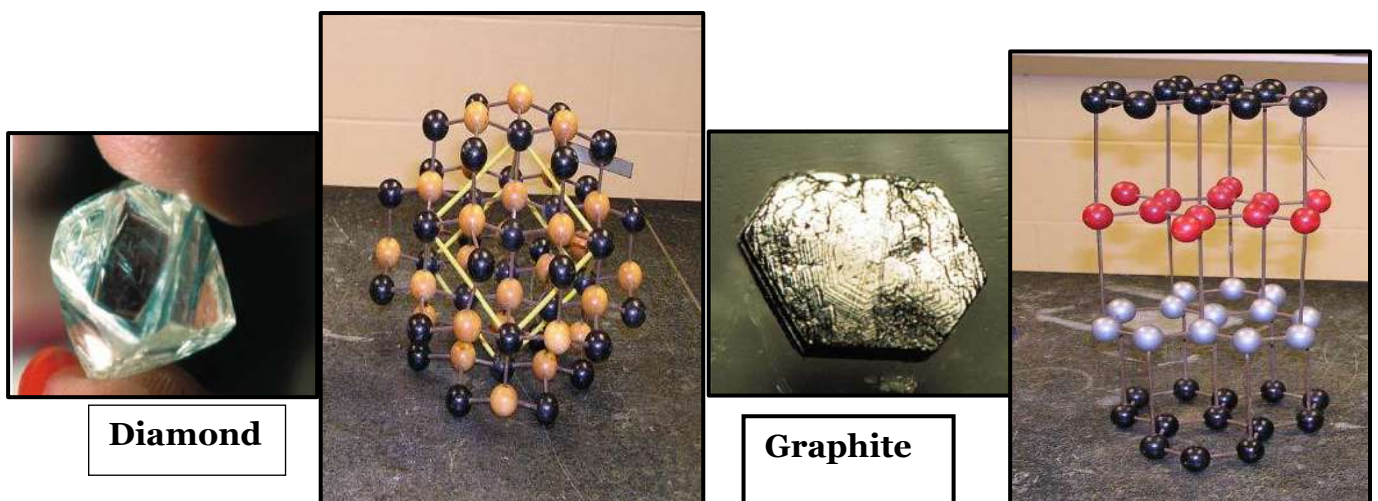


Figure 2-4 Polymorphs of two minerals (Diamond and Graphite) that have the same composition but different crystal form

### 2.3.3 Crystal systems

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

1. **Cubic (isometric):** has three equal axes at right angles to each other.
2. **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.
3. **Orthorhombic:** has three unequal axes at right angles to each other
4. **Monoclinic:** has three unequal axes, two at right angles, and the other is inclined ( $a/c$ ,  $\beta \neq 90^\circ$ )
5. **Triclinic:** has 3 unequal axes and all are inclined to each other.
6. **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.
7. **Trigonal:** has the same crystallographic axes and angles as hexagonal system but the difference occur in vertical axis and horizontal plane. In trigonal system, the vertical axis is three fold (repeat the face 3 times through  $360^\circ$ ) whereas, in hexagonal the c- axes is six fold in symmetry (the face is repeated 6 times through 360 degree). Moreover, in hexagonal system, there is a horizontal plane of symmetry which is not achieved in trigonal system.

### 3.4 Mineral groups

There are 92 naturally-occurring elements. Only 8 elements (O, Si, Fe, Al, Na, K, Ca, Mg) make up most of the minerals. Minerals are classified according to their chemical composition into the following 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 ( $\text{SiO}_2$ ), Magnetite ( $\text{Fe}_3\text{O}_4$ ), Chromite ( $\text{FeCr}_2\text{O}_4$ ) and Pyrolusite ( $\text{MnO}_2$ ).
- ❖ **Sulfides** contain sulfide ion such as pyrite ( $\text{FeS}_2$ ), sephalerite ( $\text{ZnS}$ ), galena ( $\text{PbS}$ ) and chalcopyrite ( $\text{Cu Fe S}_2$ ). Oxides

- ❖ **Halides** contain halogens ( $\text{Cl}^-$ ,  $\text{F}^-$ ,  $\text{I}^-$ ,  $\text{Br}^-$ ) as Halite ( $\text{NaCl}$ ), and Fluorite ( $\text{CaF}_2$ )
- ❖ **Carbonates** which consist of carbonate groups ( $\text{CO}_3$ ) - such as Calcite ( $\text{CaCO}_3$ ), Magnesite ( $\text{MgCO}_3$ ) and Siderite ( $\text{FeCO}_3$ ).
- ❖ **Sulfates** comprise the sulfate group ( $\text{SO}_4$ )<sup>-2</sup> like Gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) and Barite ( $\text{BaSO}_4$ ).
- ❖ **Phosphates** contain phosphate group ( $\text{PO}_4$ )<sup>-3</sup> such as Apatite [ $\text{Ca}_5\text{FeCl}_3(\text{OH})(\text{PO}_4)_2$ ]
- ❖ **Silicates** contain the silica tetrahedral ( $\text{SiO}_4$ )<sup>-4</sup>. The silica tetrahedral is composed of one silica atom surrounded by four oxygen atoms. Silicates are the most common mineral class in igneous rocks. They show five different structural styles:

1. **Isolated silicates** ( $\text{SiO}_4$ ) have crystal structures where no oxygen is shared between tetrahedra. In this group the mineral is held together by the attraction between silica tetrahedra and other positive ions such as Olivine and Garnet (Fig. 2-5).

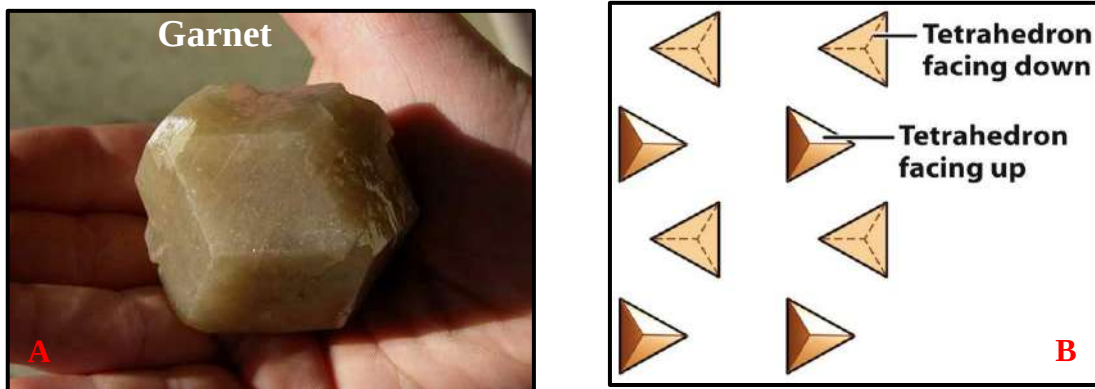


Figure 2-5 A) Dodecahedral (12 sided) crystal of garnet mineral and B) Tetrahedra share no oxygens - linked by cations

2. **Single chain silicates** ( $\text{SiO}_3$ ) contain silica tetrahedra that are linked up in a chain by sharing two oxygen atoms. The most common single chain



Figure 2-6 A) Black to green color of pyroxene mineral and B) Single-Chain Silicates

silicate is pyroxene (Fig. 2-6).

3. **Double chain silicates** ( $\text{Si}_4\text{O}_{11}$ ) form by sharing either two or three oxygen as hornblende (Fig. 2-7).

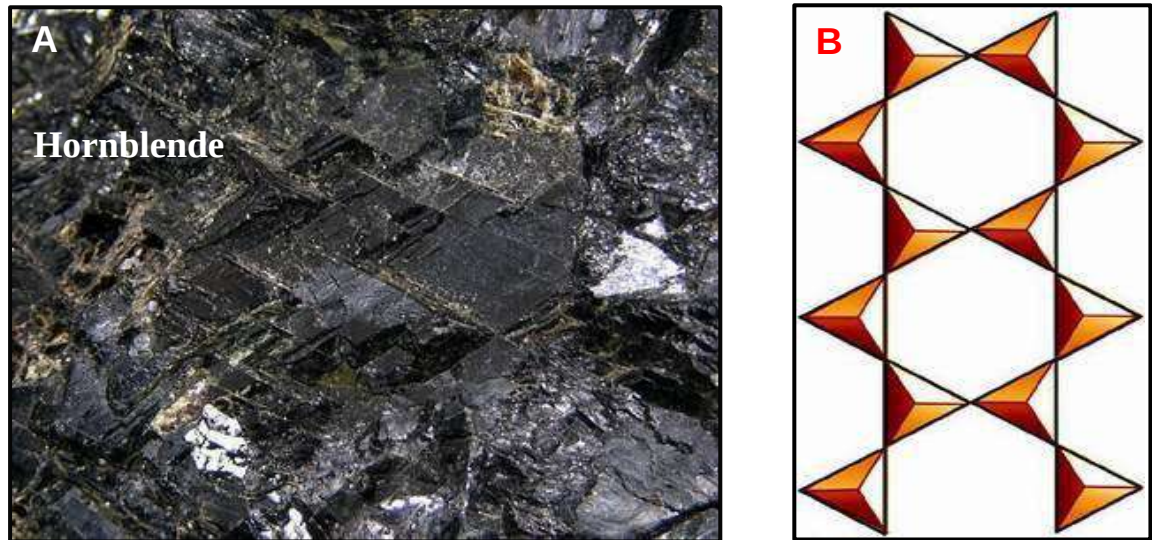


Figure 2-7 A) Elongate crystals of hornblende showing two perfect cleavages and B) Double chain of silica tetrahedra bonded together

4. **Sheet Silicates** ( $\text{Si}_2\text{O}_5$ ) in which, three oxygens of the silica tetrahedra share and form two-dimension sheets of silica. Other ions or even water molecules fit between the sheets to bond individual sheets together. Because of their structure sheet silicates tend to have excellent cleavage in one plane. Muscovite and Talc are examples of sheet silicates (Fig. 2-8).

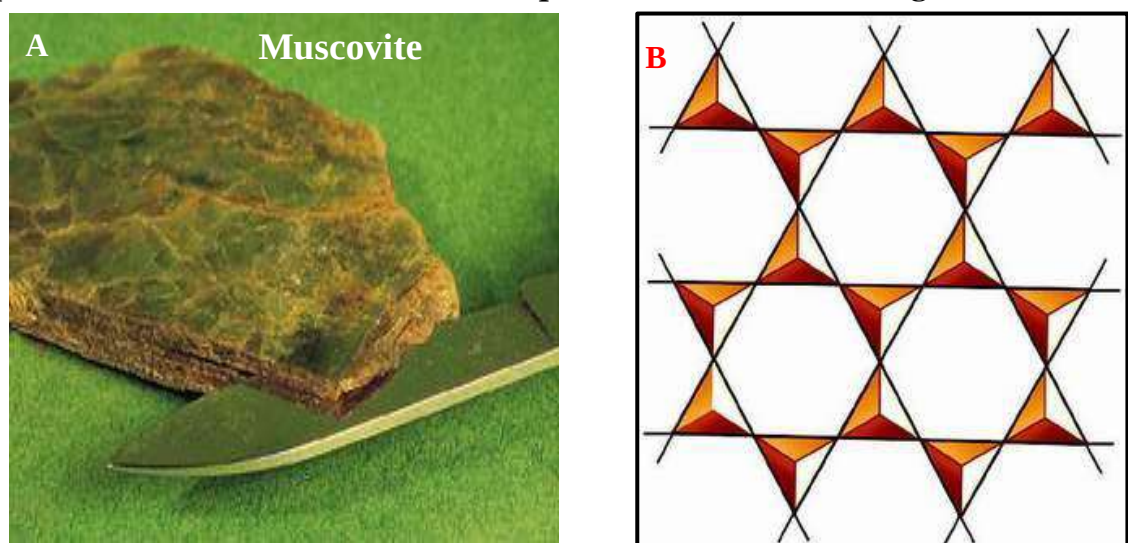


Figure 2-8 A) Muscovite mineral showing one direction of perfect cleavage and B) Two-dimensional sheets of linked tetrahedra

**5. Framework Silicates** ( $\text{SiO}_2$ ) are formed when all four oxygen of a silica tetrahedra are shared with adjacent tetrahedra to produce a three-dimensional network of tetrahedra. The most common framework silicates are quartz and feldspar (Orthoclase) (Fig. 2-9).

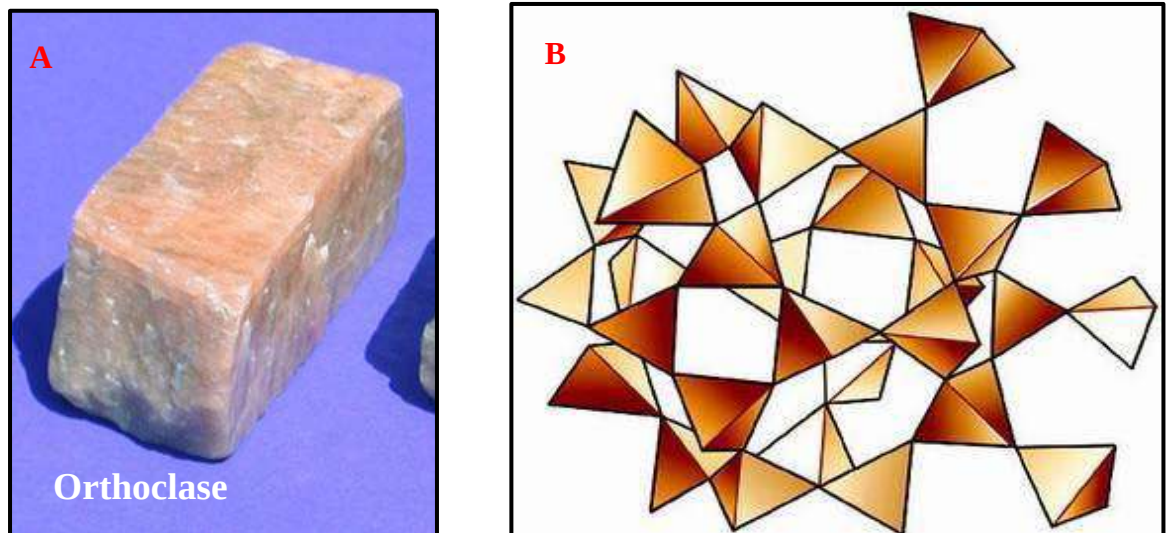


Figure 2-9 A) Crystals of orthoclase mineral and B) Silica tetrahedra are shared all 4 oxygens in the framework silicates.

## 2.5 Physical properties of minerals

The Physical properties of minerals reflect the internal arrangement of atoms. They are applicable to identify the hand-specimen of different minerals. Although some properties are more useful than others to identify the mineral, one physical property is rarely enough to determine what a mineral is. The following are the main physical properties used to identify minerals:

### 2.5.1 Optical properties (dependent upon light)

#### a) Colour

Color represents the least useful physical property as more than one mineral can have the same colour. Moreover, the same mineral can have samples with different colours (Fig. 3-10).

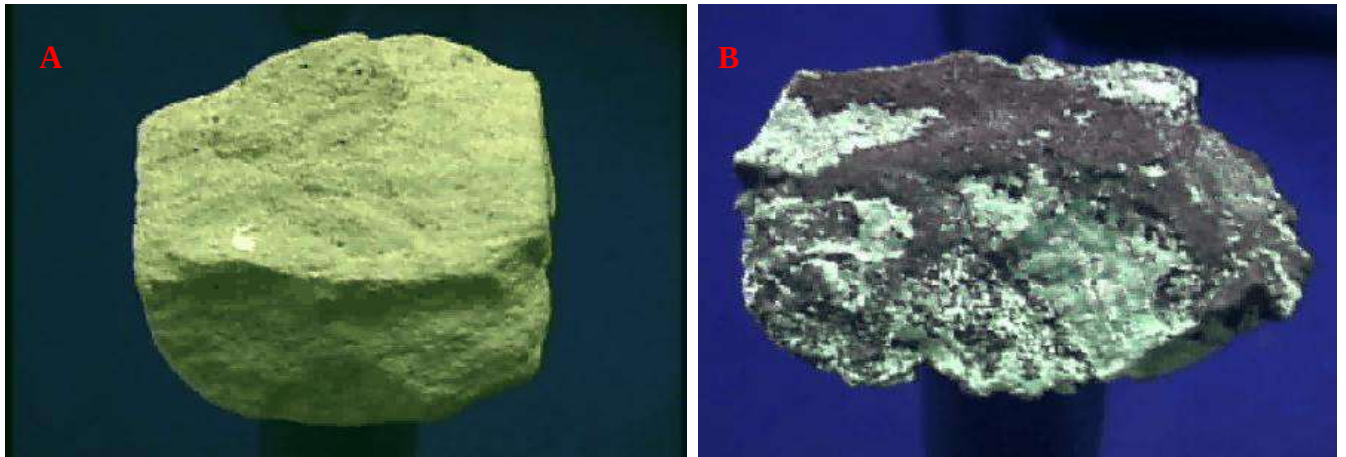


Figure 3-10 A) Olivine (green-colored ) and B) Malachite (green-colored).

Colorless minerals (ex: pure quartz, calcite and gypsum) reveal that all wave lengths of light are reflected whereas, in opaque minerals (ex: magnetite, ilmenite, galena, pyrolusite) all wave lengths of light are absorbed. In Colored minerals, certain wave lengths of light are absorbed, and the color reaching eye results from the combination of those wave lengths.

### ***Types of colored minerals:***

- a) **Constant-colored minerals:** the color is directly related to one of the major elements and can be and can be characteristic and serving as a means of identification. Malachite and olivine are always green, azurite is always blue, pyrite and chalcopyrite are always brass-yellow.
- b) **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 (Fig. 3-11).



### b) Luster

It is the intensity of light reflected from mineral surface. 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) (Fig. 3-12) and magnetite (a flat piece of steel).

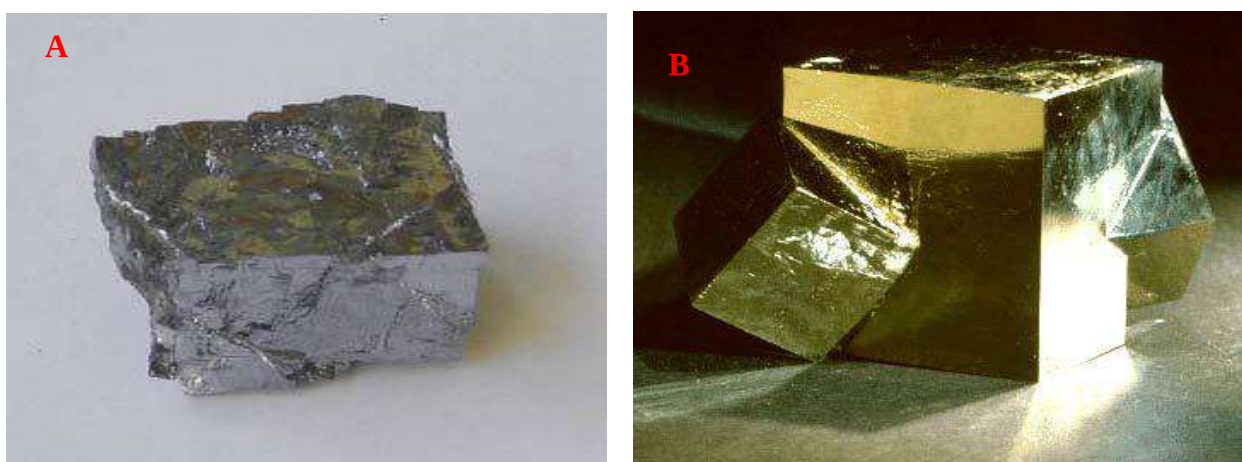
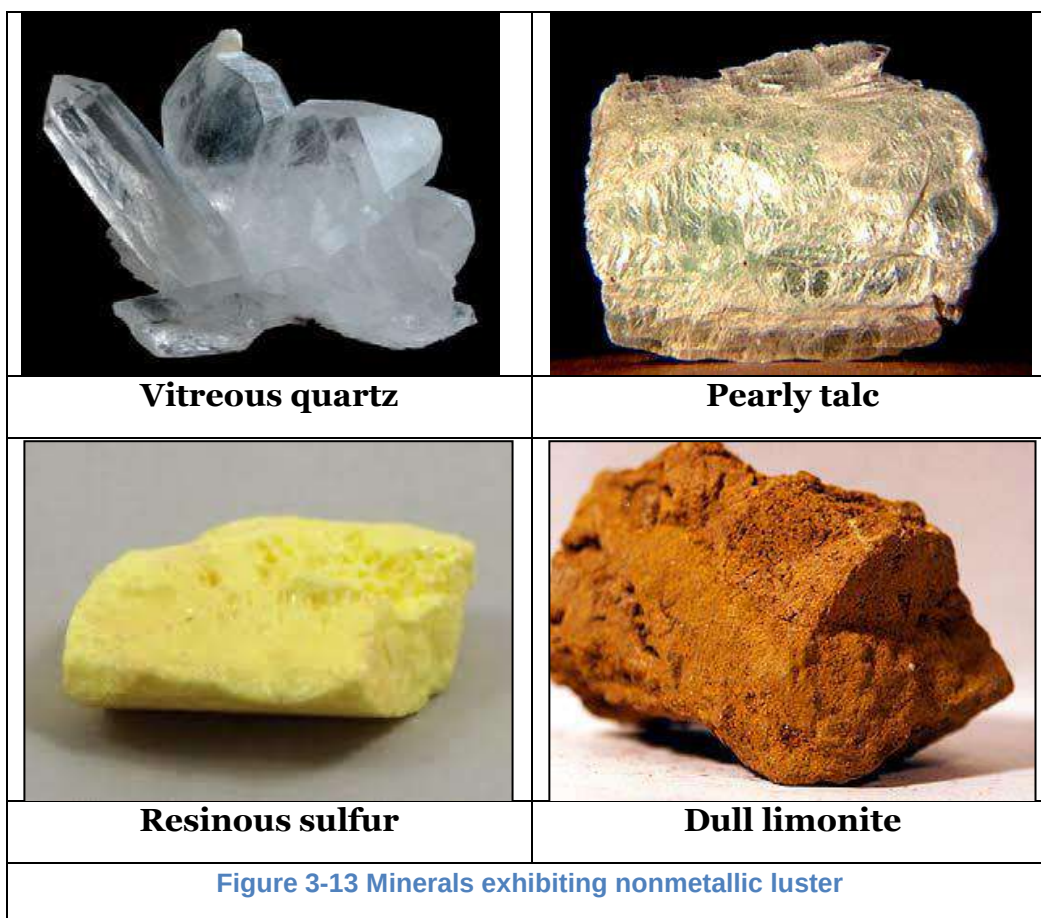


**Figure 3-12 Minerals exhibiting metallic luster A) Galena (Silver appearance) and B) Pyrite (Gold appearance).**

Nonmetallic minerals (Fig. 3-13) do not shine like polished metal, and are sometimes described as:

- **Vitreous:** have the luster of glass. Examples quartz, calcite, barite, orthoclase, gypsum and fluorite.
- **Resinous:** have the luster of resin. Examples sphalerite and sulfur.
- **Pearly:** have the luster of an iridescent pearl. Examples talc and mica.
- **Greasy:** have the appearance of being coated with oil. Examples graphite
- **Silky:** have silk like appearance. Examples-fibrous gypsum and serpentine (chrysotile),
- **Adamantine:** A hard, brilliant luster like that of a diamond.
- **Dull (Earthy):** dull like unglazed pottery. Examples Kaolin, hematite and limonite.



### c) Streak

It is the colour of mineral in its powdered form. The streak of mineral is determined by rubbing it on a streak plate (an unglazed plate of white porcelain). Powder when it is rubbed on unglazed plate of white porcelain (streak plate). The streak plate is harder than most minerals so rubbing the mineral across it produces a powder of that mineral. The streak colour is usually consistent with apparent colour of mineral but some metallic minerals may have very distinctive streaks. For example, pyrite has brass yellow colour but its streak is greenish black on the other hand, most pale colored or transparent to translucent minerals have white streak (ex: buff-colored orthoclase has white streak) (Fig. 3-14 A).

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 (Fig. 3-14 B).

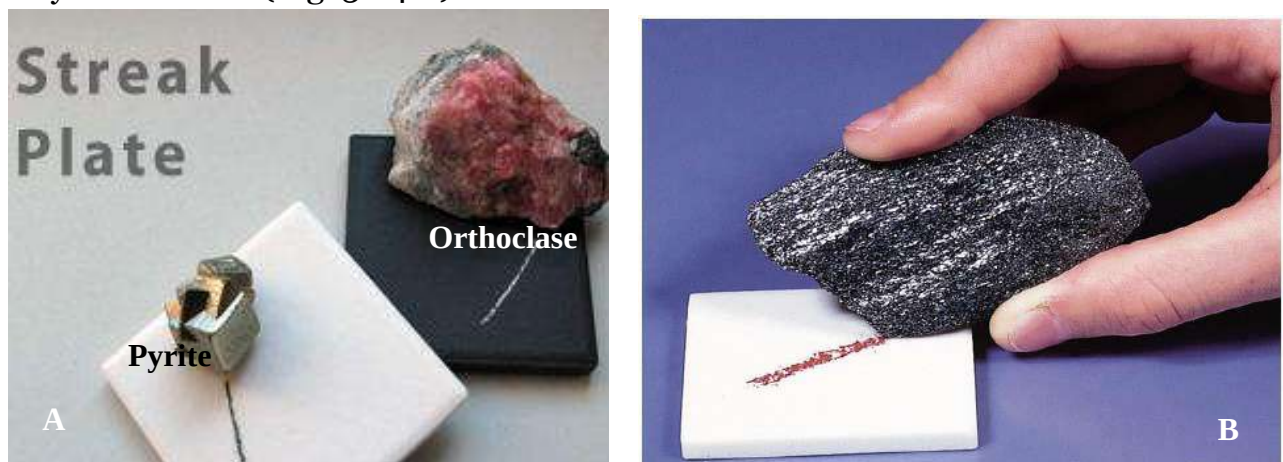


Figure 3-14 A) Pyrite show greenish black streak and orthoclase show white streak and B) Dark grey hematite has reddish brown streak

### d) Transparency (Diaphaneity)

It the ability of mineral to pass light through it. The mineral is described as the following:

- 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.

#### e) Miscellaneous Features

- **Play of colors:** different radiant colors observed as the mineral is turned. Example, precious opal, labradorite.
- **Iridescence:** is the production of a rainbow of colors caused by interference of light in thin films of different refractive indices and varying thickness. Minerals with metallic luster, such as bornite and chalcopyrite are good examples of minerals which exhibit iridescence. A couple of cases where it does not involve metallic minerals are the way fracture surfaces in quartz may show it, and the way some fluorite crystals may exhibit it on the surfaces of their faces.
- **Opalescence:** milky or pearly reflections from the interior of the specimen. Example, moonstone. Reflections off the mineral producing flashes of color that may appear somewhat like a patch-work of different "grains" of color that aren't really there. The color disappears immediately by moving sample from that spot.
- **Chatoyancy:** is the play of light off closely packed parallel fibers or parallel inclusions in cavities. The light reflects along lines – which may be straight or curved – giving the mineral a somewhat silky appearance. This characteristic is seen in such minerals as "satin spar" gypsum, "tiger's eye" (fibrous crocidolite replaced by quartz), and chrysoberyl.
- **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.
- **Asterism:** a six-pointed star of light seen in reflected or transmitted light. Examples, star sapphire, phlogopite.

- **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.
- **Luminescence:** is the emission of light by a mineral other than the reflected light of the sun or a lamp – the mineral "glows" due to some other reason. The usual reason is reaction to ultraviolet light, though X-rays and electrons may produce it as well. The types of luminescence seen in minerals are fluorescence and phosphorescence – two closely related phenomena. Minerals that light up when exposed to ultraviolet light, x-rays, or cathode rays are called **fluorescent**. If the emission of light continues after the light is cut off, they are said to be **phosphorescent**. Some specimens of the same mineral show fluorescence while others don't. For example some crystals of fluorite ( $\text{CaF}_2$ ) show fluorescence and others do not. Other minerals show fluorescence frequently, but not always. These include - calcite ( $\text{CaCO}_3$ ) and diamond (C). material becomes luminous during exposure to X- rays or ultraviolet light Example, scheelite.
- **Thermoluminescence:** material becomes luminous when heated.
- **Triboluminescence:** material becomes luminous when scratched, rubbed, or crushed. Examples, fluorite, sphalerite.

## 2.5.2 Cohesive properties

### a) Crystal Habit

Crystal habit is the characteristic external shape of an individual crystal or crystal group. A single crystal's habit is a description of its general shape and its crystallographic forms. Recognizing the habit may help in identifying a mineral. When the faces are well-developed due to uncrowded growth a crystal is called euhedral, one with partially developed faces is subhedral, and one with undeveloped crystal faces is called anhedral. The names of crystal habits are derived from predominant crystal faces (prism-prismatic, pyramid – pyramidal and pinacoid–platy). Crystal forms (cubic, octahedral,

dodecahedral). Aggregation of crystals or aggregates (fibrous, botryoidal, radiating, massive). Crystal appearance (foliated/lamellar, dendritic, bladed, acicular, lenticular, tabular).

These are some of the more common descriptive terms used to portray certain crystal habits of both individual and aggregate crystal varieties (Fig. 3-15):

### 1) 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)

### 2) 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).

## b) Hardness

The hardness is a measure of mineral resistance to abrasion process (scratching). This is one of the key means of identifying a mineral and it can also help to determine how quickly a mineral is broken up by weathering. The hardness of a mineral is tested using Mohs' Hardness scale or by using the hardness of some common objects such as finger nail, copper penny, knife blade, steel nail, glass plate and steak plate (Table 2-1). Mohs' scale include ten mineral starting from the softest (Talc) to the hardest (Diamond) with a relative values. This doesn't mean that diamonds are 10 times harder than talc; that's why we call this a qualitative measure, not quantitative measure. Each mineral in the scale scratches the one above it but not the one below it.

Table 2-1 The minerals of the Mohs hardness scale

| 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    |                              |

### C) Cleavage and parting

**Cleavage** is the tendency of a mineral to split along planes of weak bonding (cleavage planes) producing flat, shiny surfaces. Cleavage can be described through the direction of cleavage planes and the resulting geometric shapes. We should not be confused between cleavage shape and crystal habit as crystal habit is only applied for external surfaces. Generally, there are three main types of cleavage:

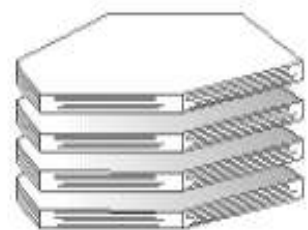
- i. **Perfect cleavage:** cleavage planes are clear and can be easily distinguished (ex, mica).
- ii. **Imperfect:** cleavage planes are present but less obscure like beryl and apatite.
- iii. **Poor:** cleavage planes are absent.

According to the direction of cleavage planes and the resulting geometric shapes, cleavage can be classified as the following:

- i. **One set of cleavage:** the mineral peels into parallel basal sheets (ex: Mica and Graphite) (Fig. 3-16).



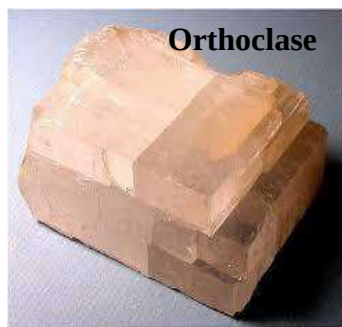
One set of cleavage



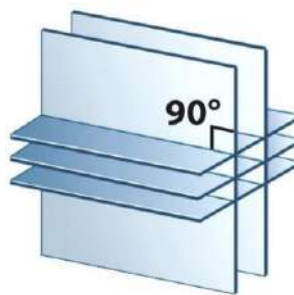
Basal cleavage

Figure 3-16 One set of cleavage in Mica mineral

- ii. **Two sets of cleavage:** the mineral breaks in two prismatic sometimes at right angles to each other ( $90^\circ$ ) such as Orthoclase (Fig. 3-17) and Pyroxene or not at  $90^\circ$  like amphibole ( $120^\circ$ ). The resulting shape in both cases is prismatic.



Orthoclase



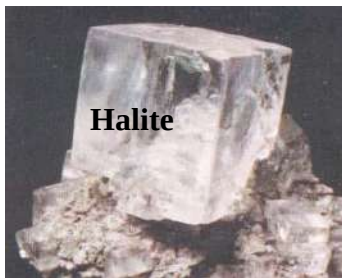
Two sets of cleavage



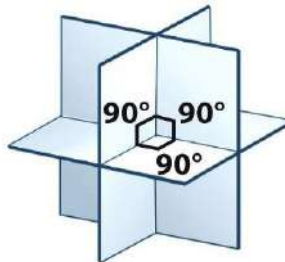
Prismatic cleavage

Figure 3-17 Two sets of cleavage (at  $90^\circ$ ) in orthoclase mineral

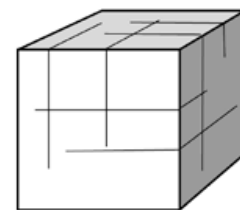
- iii. Three sets of cleavage:** the mineral breaks in three directions sometimes at right angles to each other giving cubes such as Halite, and Galena or not at  $90^\circ$  forming rhombohedrons like calcite (Fig. 3-18).



Halite



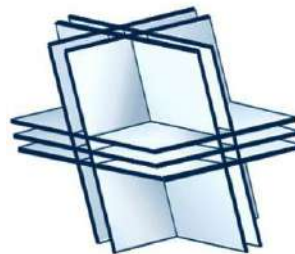
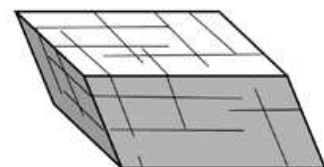
Three sets of cleavage



Cubic cleavage



Calcite

Three sets of cleavage  
not at  $90^\circ$ 

Rhombohedral cleavage

Figure 3-18 three sets of cleavage (at  $90^\circ$  and oblique) in Halite and Calcite minerals.

- iv. Four sets of cleavage:** the mineral breaks in four directions producing octahedrons such as Fluorite (Fig. 3-19A) and Diamond.
- v. Six sets of cleavage:** the mineral breaks in six directions forming dodecahedrons such as Sphalerite (Fig. 3-19 B).



Figure 3-19 A) octahedral cleavage in fluorite and B) dodecahedral cleavage in sephalerite

**Parting** is also a plane of weakness in the crystal structure, but they are weakened by some applied force, therefore, 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.

#### d) Fracture

Fracture means description the way that mineral tends to break. If the mineral does not contain cleavage planes, it will break along random directions called fracture. Several different kinds of fracture patterns are observed. The quality of such surface is often further described as:

- **Conchoidal:** smooth curved lines (shell-like) such as quartz (Fig. 3-20 A).
- **Earthy:** looks like freshly broken soil such as Limonite and Kaolin (Fig. 3-20 B).
- **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 (Fig. 3-20 C).

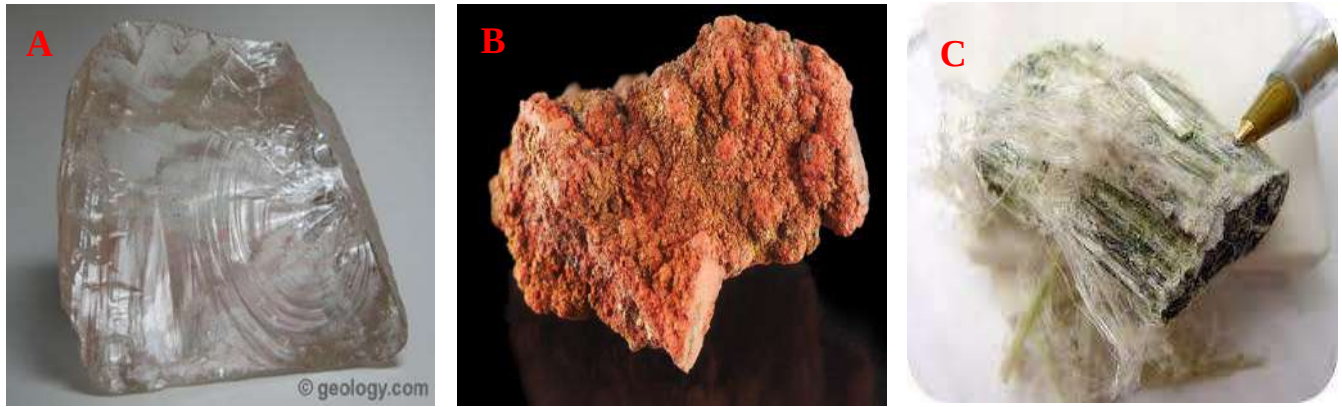


Figure 3-20 A) conchoidal fracture in quartz, B) earthy fracture in limonite and C) splintery fracture in chrysotile

### e) Tenacity

Tenacity is the resistance of a mineral to breaking, crushing, or bending. Tenacity can be described by the following terms.

- **Brittle:** A mineral that breaks or powders easily.
- **Malleable:** A mineral that can be hammer out into thin sheets
- **Sectile:** A mineral that can be cut into thin shavings with a knife.
- **Ductile:** A mineral that can be drawn into wire. It bends easily and does not return to its original shape.
- **Flexible:** A mineral that bends but does not resume its original shape when the pressure is released.
- **Elastic:** A mineral that, after being bent, will resume its original position upon the release of the pressure.

## 2.6 Additional characteristic features

### a) 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. If you compare similar-sized samples of two different minerals, the one with the higher specific gravity will feel the heaviest; it has a greater heft.

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.

### **b) Sense properties (taste, odor and touch)**

Some minerals have a distinctive taste (halite has saline taste and kaolin has astringent taste) and some have a distinctive feel (talc has soap touch, graphite has greasy touch, gold has cool touch and limonite has rough touch). Moreover, some minerals have a distinctive odor. These minerals do not exhibit a direct odor. The odors of minerals can be smelt either by heating (sulfur- match odor and sulfides- $\text{H}_2\text{S}$  odor), breathing up on (kaolin-mud odor) or rubbing (phosphate-garlic odor).

### **c) Magnetism**

Magnetism of mineral means its affinity to be attracted by magnet. All minerals contain Fe are attracted to magnet as Fe is a paramagnetic elements. However, magnetite ( $\text{Fe}_3\text{O}_4$ ), is the only common mineral attracted to a small hand magnet. Other Fe-bearing minerals are attracted to magnet only when they are heated in open air. Paramagnetic elements like Ti, Cr, V, Mn, Fe, Co, Ni, and Cu can sometimes result in weak magnetism. Minerals that do not have these elements have no magnetism, and thus are called **diamagnetic**.

**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.

### **d) Reaction with acid**

Reaction to acids is a property that can be used to help identify some carbonate minerals. Carbonate minerals especially calcite react with a dilute

hydrochloric acid (HCl). When a drop of dilute hydrochloric acid is placed on calcite, it readily bubbles or effervesces, releasing carbon dioxide. Other carbonate minerals such as magnesite does not react directly with diluted HCl .it needs to be heated or concentrated HCl is used. The bond between Mg and  $\text{CO}_3$  is stronger than that between Ca and  $\text{CO}_3$  as Mg precede Ca in electrochemical series.

### e) Electrical properties

There are two uncommon types of electrical properties found in minerals; piezoelectricity and pyroelectricity.

**Piezoelectricity** appears in quartz and tourmaline when pressure is exerted at the ends of a polar axis where a flow of electrons toward one end produces a negative electrical charge, while a positive charge is induced at the opposite end. In 1921, the piezoelectric property of quartz was first used to Control radio frequencies. By placing a quartz plate in the electric field generated by radio circuit, the frequency of transmission or reception is controlled when the frequency of the quartz coincides with the oscillations of the circuit. The tiny quartz plate used in digital quartz watches serves the same function as quartz oscillators used to control radio frequencies. The piezoelectric property of tourmaline has been known almost as long as that of quartz, but compared to quartz, tourmaline is a less effective radio oscillator and is rare in occurrence.

**Pyroelectricity** appears in quartz when it is heated to about  $100^\circ\text{C}$ . On cooling, quartz develops positive and negative charges alternate the prismatic edges. These charges have been called secondary pyroelectric polarization.

## 2.7 Origin of Minerals

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

**a) Magmatic origin**

Magma is a rock molten material 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. Magmatic minerals are directly crystallized from magma. Slow cooling of magma gives coarse crystals whereas, rapid cooling gives fine crystals. A melt under sudden cooling give skeletal or amorphous substances as occur in 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. (Si, O, Na, Al, Mg, Ca). Quartz, orthoclase, magnetite and chromite are examples of magmatic minerals. 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. There are many sources for hydrothermal solutions; residual liquid in magma chamber, fluid phase in metamorphic process or surface water. Calcite, fluorite and galena are examples of hydrothermal minerals.

The temperature and pressure play the greatest role during the process of deposition. Accordingly, the mineral deposits of these hot solutions can be classified into the following:

**a) 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.

**b) 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).

**c) 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

Generally, each mineral or rock must be formed under suitable conditions of temperature and pressure. When these conditions changes, 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).

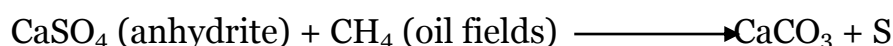
Olivine + Anorthite  $\longrightarrow$  Garnet

Ilmenite + Anorthite  $\longrightarrow$  Sphene

### d) Sedimentary origin

The surface solution include all the soluble constituents in the seas, lakes, oceans, river and ground water that formed principally from the rains that penetrate the rocks bearing the dissolvable constituents from the rocks. The minerals of these solutions may precipitate due to changing of the physical conditions i.e. pressure and temperature. The types of minerals are called sedimentary ore-mineral. These are the ways, by one of them mineral can be precipitated.

- 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.  $\text{CO}_2$  dissolves in water rains forming  $\text{H}_2\text{CO}_3$  which reacts with calcareous rocks they penetrate forming calcium bicarbonate (can be easily soluble in water) but it is unstable. When PH of water becomes lower than 7, calcium bicarbonate loses  $\text{CO}_2$  and changes into  $\text{CaCO}_3$  (not soluble in  $\text{H}_2\text{O}$ ). Finally  $\text{CaCO}_3$  precipitates forming calcite. One of the most interesting features of this process is the formation of stalactites (columns of calcite grow downwards through caves within the calcareous rocks) and stalagmites (the same as stalactite but grow upwards from the floor of caves).
- 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.
- iv. Sublimation process:** as the deposition of sulfur from gaseous state.



### Mineral Description

| 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         |

### REVIEW QUESTIONS

1. What properties distinguish minerals from other substances?
2. Explain why oil and coal are not minerals.
3. What does the chemical formula for quartz,  $\text{SiO}_2$ , tell you about its chemical composition? What does  $\text{KAlSi}_3\text{O}_8$  tell you about orthoclase feldspar?
4. What is an atom? An ion? A cation? An anion? What roles do they play in minerals?
5. What is a chemical bond? What role do chemical bonds play in minerals?
6. Every mineral has a crystalline structure. What does this mean?
7. What factors control the shape of a well-formed crystal?
8. What is a crystal face?
9. What conditions allow minerals to grow well-formed crystals? What conditions prevent their growth?
10. List and explain the physical properties of minerals most useful for identification.
11. Why do some minerals have cleavage and others do not?  
Why do some minerals have more than one set of cleavage planes?
12. Why is color often an unreliable property for mineral identification?
13. List the rock-forming mineral groups. Why are they called “rock-forming”?  
Which are silicates? Why are so many of them silicates?
14. Draw a three-dimensional view of a single silicate tetrahedron. Draw the five different arrangements of tetrahedral found in the rock-forming silicate minerals. How many oxygen ions are shared between adjacent tetrahedral in each of the five configurations?
15. Make a table with two columns. In the left column list the basic silicate structures. In the right column list one or more rock-forming minerals with each structure.

### DISCUSSION QUESTION

1. Diamond and graphite are two minerals with identical chemical compositions, pure carbon (C). Diamond is the hardest of all minerals, and

- graphite is one of the softest. If their compositions are identical, why do they have such profound differences in physical properties?
2. List the eight most abundant chemical elements in the Earth's crust. Are any unfamiliar to you? List familiar elements that are not among the eight. Why are they familiar?
  3. Table 3–1 shows that silicon and oxygen together make up nearly 75 percent by weight of the Earth's crust. But silicate minerals make up more than 95 percent of the crust. Explain the apparent discrepancy.
  4. Quartz is  $\text{SiO}_2$ . Why does no mineral exist with the composition  $\text{SiO}_3$ ?
  5. If you were given a crystal of diamond and another of quartz, how would you tell which is diamond?
  6. Would you expect minerals found on the Moon, Mars, or Venus to be different from those of the Earth's crust? Explain your answer.

### Miscellaneous Questions

- 1-Define the following terms:  
Cleavage, fracture, hardness, luster, streak, crystal habit, fluorescence.
- 2- What is your opinion about color as a distinctive physical property for a mineral and give reasons for your answer?
- 3- Write on: a) mineral groups and b) sedimentary mineral deposits.
- 4- Find the difference between the following items:
  - a) Diamagnetic and ferromagnetic
  - b) Mineral and mineraloid
  - c) Diamond and graphite
- 5- Complete the following sentences:
  - a) From minerals used in electrical conductivity ----- and -----.
  - b) You can get the streak of quartz using -----, while in fluorite we may use -----.
  - c) Luster can be generally classified into ----- and -----.
  - d) ----- and ----- are minerals of high specific gravity.
  - e) Pyrite has-----streak and quartz has-----fracture.
  - f) Halite exhibit-----cleavage and -----luster.

10- Write true or false with corrections.

- a) Coal and glass are minerals.
- b) Orthoclase has buff streak and calcite has white streak.
- c) Sulfur and sephalerite have resinous luster.
- d) Orthoclase can be scratched by flourite.
- e) The streak is more reliable than color for identification
- f) Calcite has three sets of cleavage at right angles to each other.
- g) Heated magnesite effervescences directly with dil.HCl

# Chapter 3

## IGNEOUS ROCKS

### Goals

1. *Knew Terms and definition of Igneous rocks*
2. *Identify the important of Igneous rocks*
3. *Interpret the modes of occurrence ( Intrusive, Extrusive and Hypabyssal)*
4. *Knew the Classification of igneous rocks (Texture, Chemical classification and Mineralogical classification)*
5. *Explain the magma generation ( Decompression, Effects of water and carbon dioxide)*
6. *Explicit Crystallization and magma evolution.*

### 3.1 Rocks and The Rock Cycle

Geologists group rocks into three categories on the basis of how they form: **igneous rocks**, **sedimentary rocks**, and **metamorphic rocks**. Under certain conditions, rocks of the upper mantle and lower crust melt, forming a hot liquid called **magma** (Fig. 3–1). An igneous rock forms when magma solidifies. About 95 percent of the Earth's crust consists of igneous rock and metamorphosed

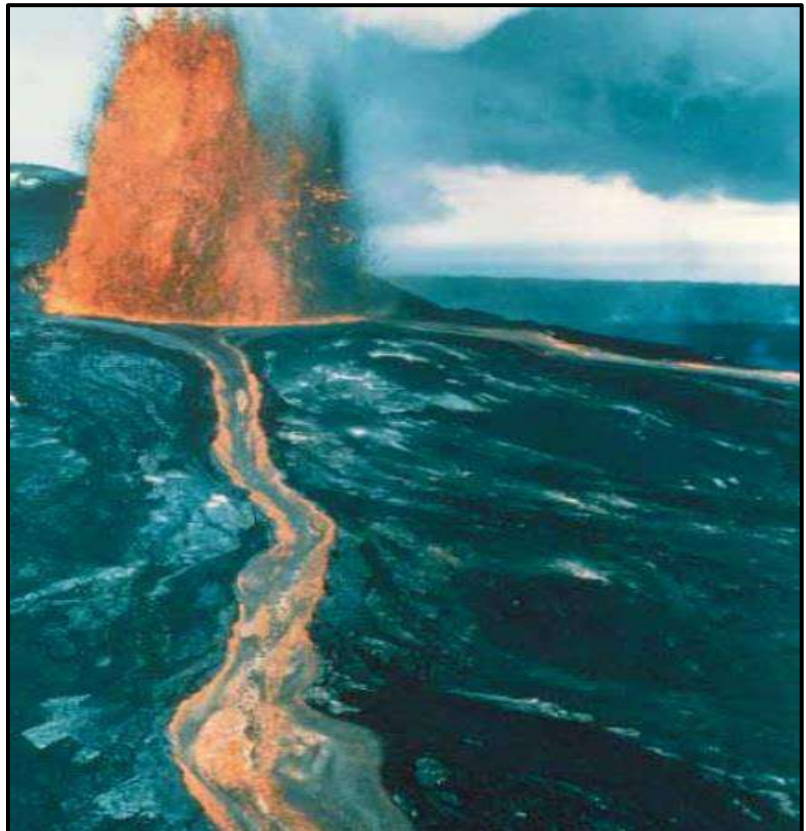


Figure 3–1 Magma rises from Pu'u O'o vent during an eruption in June 1986. (U.S. Geological Survey, J. D. Griggs)

igneous rock. Although much of this igneous foundation is buried by a relatively thin layer of sedimentary rock, igneous rocks are conspicuous

because they make up some of the world's most spectacular mountains. **Granite** and **basalt** are two common and familiar igneous rocks.

Rocks of all kinds decompose, or weather, at the Earth's surface. Weathering breaks rocks into smaller fragments such as gravel, sand, and clay. At the same time, rainwater may dissolve some of the rock. Streams, wind, glaciers, and gravity then erode the weathered particles, carry them downhill, and deposit them at lower elevations. All such particles, formed by weathering and then eroded, transported, and deposited in layers, are called sediment. The sand on a beach and mud on a mud flat are examples of sediment that accumulated by these processes.

A sedimentary rock forms when sediment becomes cemented or compacted into solid rock. When the beach sand is cemented, it becomes **sandstone**; the mud becomes **shale**. Sedimentary rocks make up less than 5 percent of the Earth's crust. However, because sediment accumulates on the Earth's surface, sedimentary rocks form a thin layer over about 80 percent of all land. For this reason, sedimentary rocks seem more abundant than they really are.

A metamorphic rock forms when any preexisting rock is altered by heating, increased pressure, or tectonic deformation. Tectonic processes can depress the Earth's surface to form a basin that may be hundreds of kilometers in diameter and thousands of meters deep. Sediment accumulates in the depression, burying the lowermost layers to great depths. When a rock is buried, its temperature and pressure increase, causing changes in both the minerals and the texture of the rock. These changes are called metamorphism, and the rock formed by these processes is a metamorphic rock. Metamorphism also occurs when magma heats nearby rock, or when tectonic forces deform rocks. Schist, gneiss, and marble are common metamorphic rocks.

No rock is permanent over geologic time; instead, all rocks change slowly from one of the three rock types to another. This continuous process is called the **rock** cycle (Fig. 3–2). The transformations from one rock type to another can follow many different paths. For example, weathering may reduce a

metamorphic rock to sediment, which then becomes cemented to form a sedimentary rock. An igneous rock may be metamorphosed. The rock cycle simply expresses the idea that rock is not permanent but changes over geologic time.

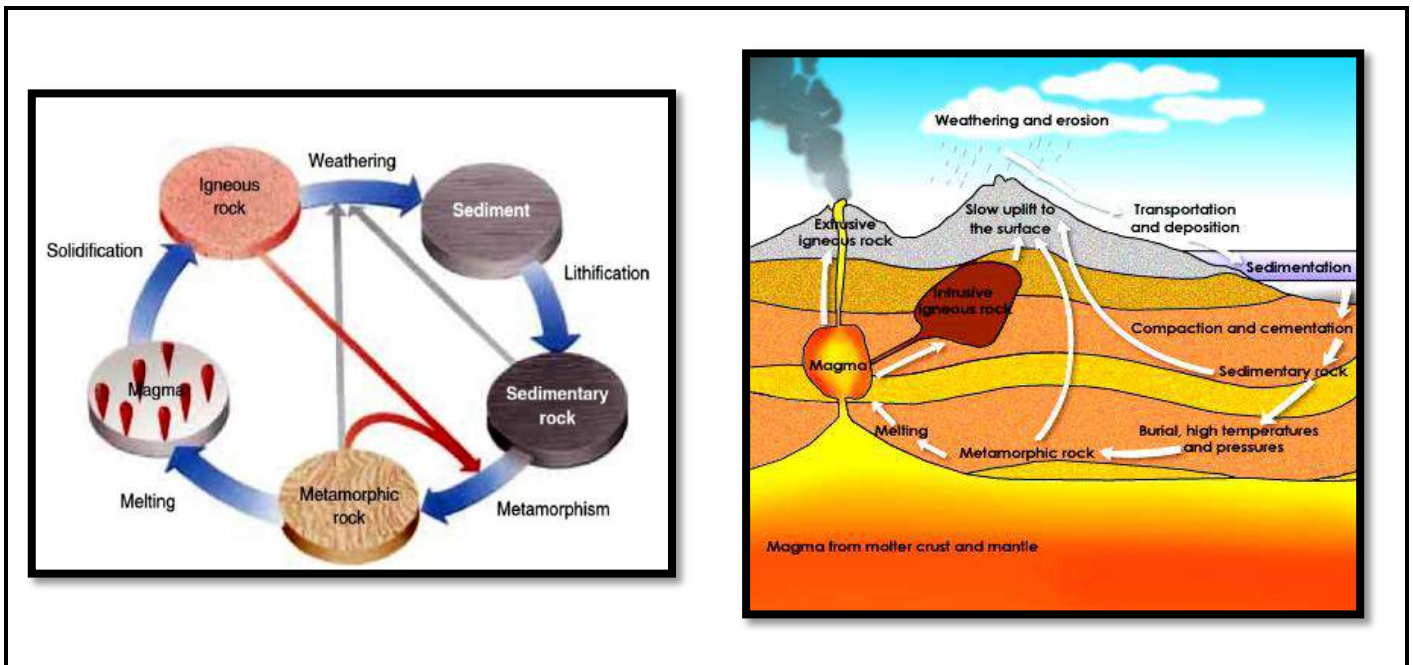


Figure 3-2 The rock cycle shows that rocks change continuously over geologic time. The arrows show paths that rocks can follow as they change.

## 3.2 Igneous Rocks: The Origins of Magma

If you drilled a well deep into the crust, you would find that Earth temperature rises about 30°C for every kilometer of depth. Below the crust, temperature continues to rise, but not as rapidly. In the asthenosphere (between depths of about 100 to 350 kilometers), the temperature is so high that rocks melt in certain environments to form magma.

### 3.2.1 Processes that form magma

Three different processes melt the asthenosphere: rising temperature, decreasing pressure, and addition of water (Fig. 3-3). We will consider these processes and then look at the tectonic environments in which they generate magma.

#### a. Rising Temperature

Everyone knows that a solid melts when it becomes hot enough. Butter melts in a frying pan, and snow melts under the spring sun. For similar

reasons, an increase in temperature will melt a hot rock. Oddly, however, increasing temperature is the least important cause of magma formation in the asthenosphere.

### b. Decreasing Pressure

A mineral is composed of an ordered array of atoms bonded together. When a mineral melts, the atoms become disordered and move freely, taking up more space than when they were in the solid mineral. Consequently, magma occupies about 10 percent more volume than the rock that melted to form it. As an analogy, think of a crowd of people sitting in an auditorium listening to a concert. At first, they sit in closely packed, orderly rows. But if everyone gets up to dance, they need more room because spaces open up between the dancers as they move.

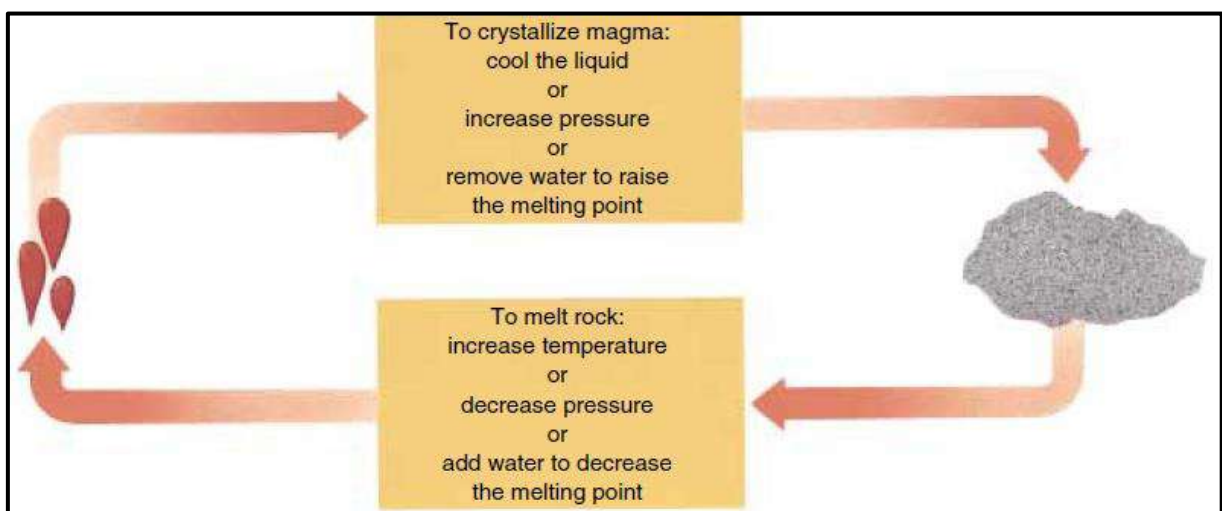


Figure 3-3 The lower box shows that increasing temperature, addition of water, and decreasing pressure all melt rock to form magma. The upper box shows that cooling, increasing pressure, and water loss all solidify magma to form an igneous rock.

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. The temperature in the asthenosphere is more than hot enough to melt rock, but there, the high pressure prevents the rock from expanding, and it cannot melt (Fig. 3-4). However, if the pressure were to decrease, large volumes of the asthenosphere would melt. Melting caused by decreasing pressure is called pressure-release melting. In the section entitled "Environments of Magma Formation" we will see how certain tectonic processes decrease pressure on

parts of the asthenosphere and cause large-scale melting and magma formation.

### c. Addition of Water

A wet rock generally melts at a lower temperature than an otherwise identical dry rock. Thus, addition of water to rock that is near its melting temperature can melt the rock.

Certain tectonic processes add water to the hot rock of the asthenosphere to form magma.

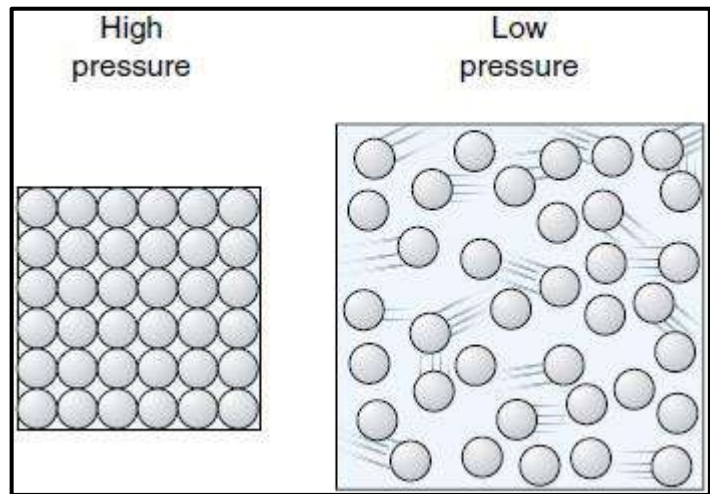


**Figure 3-4** When most minerals melt, the volume increases. If a deeply buried mineral is near its melting point, high pressure prevents expansion and it doesn't melt. If the pressure decreases, the mineral can expand more easily and it melts, even though the temperature remains constant.

## 3.2.2 Environments of magma formation

Magma forms in three tectonic environments: spreading centers, mantle plumes, and subduction zones. Let us consider each environment to see how the three aforementioned processes melt the asthenosphere to create magma.

### a. Magma Production in a Spreading Center

As lithospheric plates separate at a spreading center, hot, plastic asthenosphere oozes upward to fill the gap (Fig. 3-5). As the asthenosphere rises, pressure drops and pressure-release melting forms basaltic magma

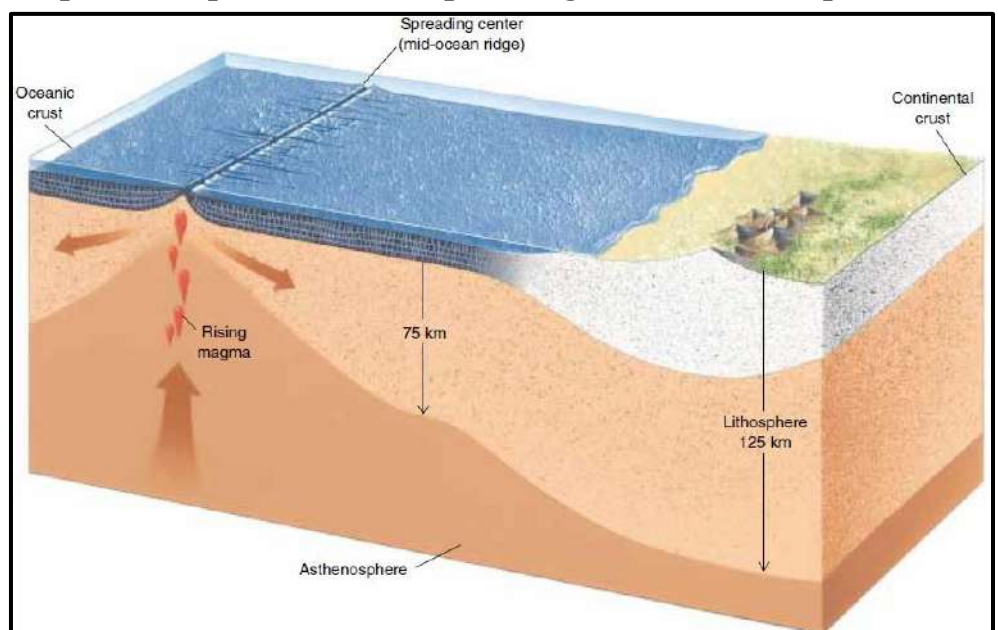


**Figure 3-5** Pressure-release melting occurs where hot asthenosphere rises beneath a spreading center.

(the terms

basaltic and granitic refer to magmas with the chemical compositions of basalt and granite, respectively). Because the magma is of lower density than the surrounding rock, it rises toward the surface.

Most of the world's spreading centers are in the ocean basins, where they form the mid-oceanic ridge. The magma created by pressure-release melting forms new oceanic crust at the ridge. The oceanic crust then spreads outward, riding atop the separating tectonic plates. Nearly all of the Earth's oceanic crust is created in this way at the mid-oceanic ridge. Some spreading centers, like the East African rift, occur in continents, and here, too, basaltic magma erupts onto the Earth's surface.

### b. Magma Production at a Hot Spot

A mantle plume is a rising column of hot, plastic mantle rock that originates deep within the mantle. The plume rises because it is hotter than the surrounding mantle and, consequently, is buoyant. As a mantle plume rises, pressure-release melting forms magma that erupts onto the Earth's surface (Fig. 3-6). A hot spot is a volcanically active place at the Earth's surface directly above a mantle plume. Because mantle plumes form below the asthenosphere, hot spots can occur within a tectonic plate. For example, the Yellowstone hot spot, responsible for the

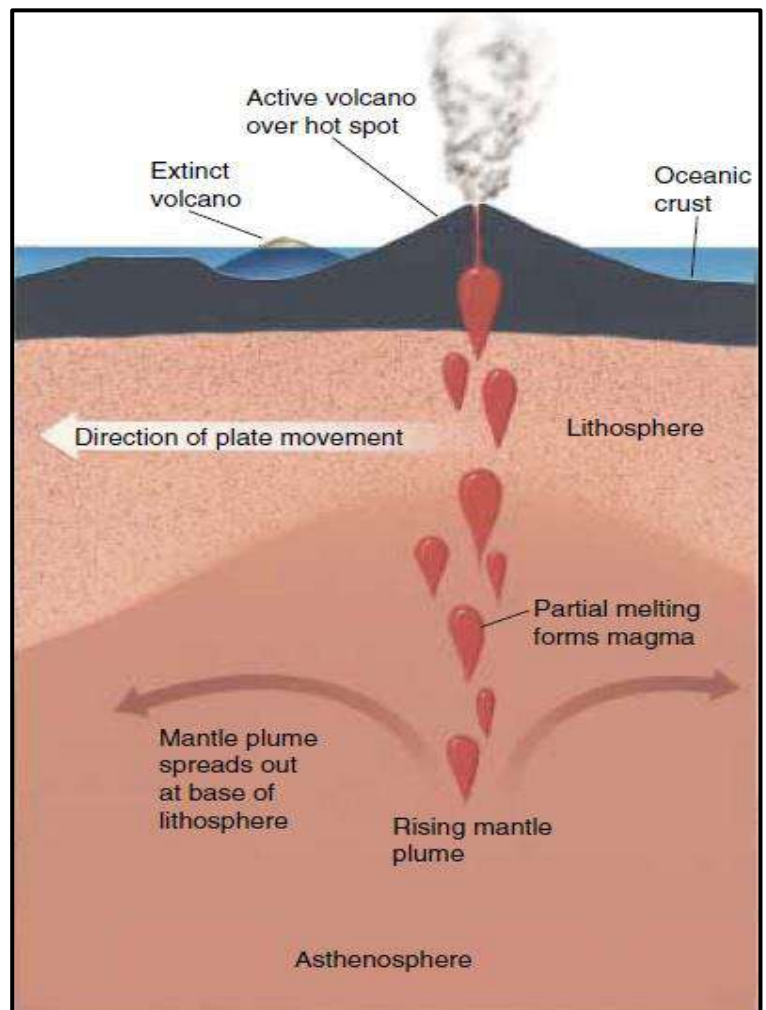


Figure 3-6 Pressure-release melting occurs in a rising mantle plume, and magma rises to form a volcanic hot spot.

volcanoes and hot springs in Yellowstone National Park, lies far from the nearest plate boundary. If a mantle plume rises beneath the sea, volcanic eruptions build submarine volcanoes and volcanic islands.

### c. Magma Production in a Subduction Zone

At a subduction zone, a lithospheric plate sinks hundreds of kilometers into the mantle (Fig. 3–7). A subducting plate is covered by oceanic crust, which, in turn, is saturated with seawater. As the wet rock dives into the mantle, rising temperature drives off the water, which ascends into the hot asthenosphere directly above the sinking plate.

As the subducting plate descends, it drags plastic asthenosphere rock down with it, as shown by the elliptical arrows in Figure 3–7. Rock from deeper in the asthenosphere then flows upward to replace the sinking rock. Pressure decreases as this hot rock rises.

Finally, friction generates heat in a subduction zone as one plate scrapes past the opposite plate. Figure 3–7 shows that addition of water, pressure release, and frictional heating combine to melt portions of the asthenosphere, at a depth of about 100 kilometers,

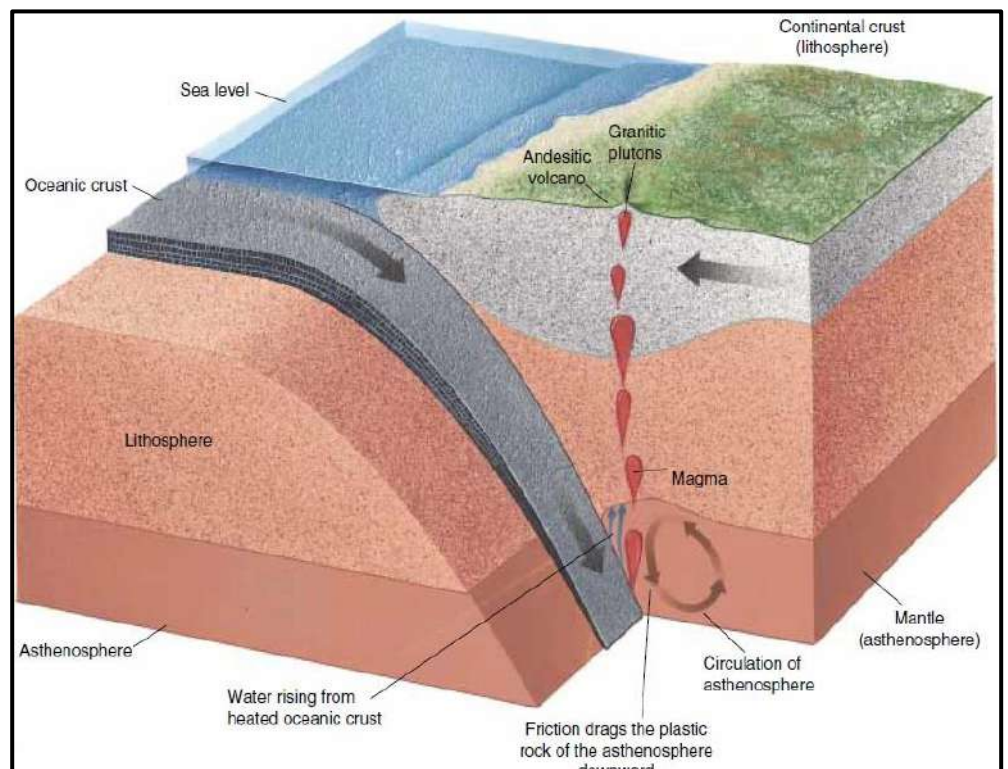


Figure 3–7 Three factors contribute to melting of the asthenosphere and production of magma at a subduction zone: (1) Friction heats rocks in the subduction zone; (2) water rises from oceanic crust on top of the subducting plate; and (3) circulation in the asthenosphere decreases pressure on hot rock.

asthenosphere. Addition of water is probably the most important factor in

magma production in a subduction zone, and frictional heating is probably the least important.

### 3.2.3 Characteristics of magma

We have just described how, why, and where magma forms. Now we consider its properties and behavior.

#### a. Temperature

The temperature of magma varies from about 600 to 1400°C, depending on its chemical composition and the depth at which it forms. Generally, basaltic magma forms at great depth and has a temperature near the high end of this scale. Granitic magmas, which form at shallower depths, tend to lie near the cooler end of the scale. As a comparison, an iron bar turns red hot at about 600°C and melts at slightly over 1500°C.

#### b. Chemical Composition

Because oxygen and silicon are the two most abundant elements in the crust and mantle, nearly all magmas are silicate magmas. In addition to oxygen and silicon, they also contain lesser amounts of the six other common elements of the Earth's crust: aluminum, iron, magnesium, calcium, potassium, and sodium. The main variations among different types of magmas are differences in the relative proportions of these eight elements. For example, basaltic magma contains more iron and magnesium than granitic magma, but granitic magma is richer in silicon, potassium, and sodium. A few rare magmas are of carbonate composition. The rocks that form from these are called carbonatites and contain carbonate minerals such as calcite and dolomite.

#### c. Behavior

When a silicate rock melts, the resulting magma expands by about 10 percent. It is then of lower density than the rock around it, so magma rises as it forms—much as a hot air balloon ascends in the atmosphere. When magma rises, it enters the cooler, lower-pressure environment near the Earth's surface. When temperature and pressure drop sufficiently, it solidifies to form solid igneous rock.

### 3.2.4 Crystallization and magma evolution

Schematic diagrams showing the principles of crystallisation in magma (Fig. 3-8). While cooling, the magma changes in composition because different minerals crystallize from the melt.

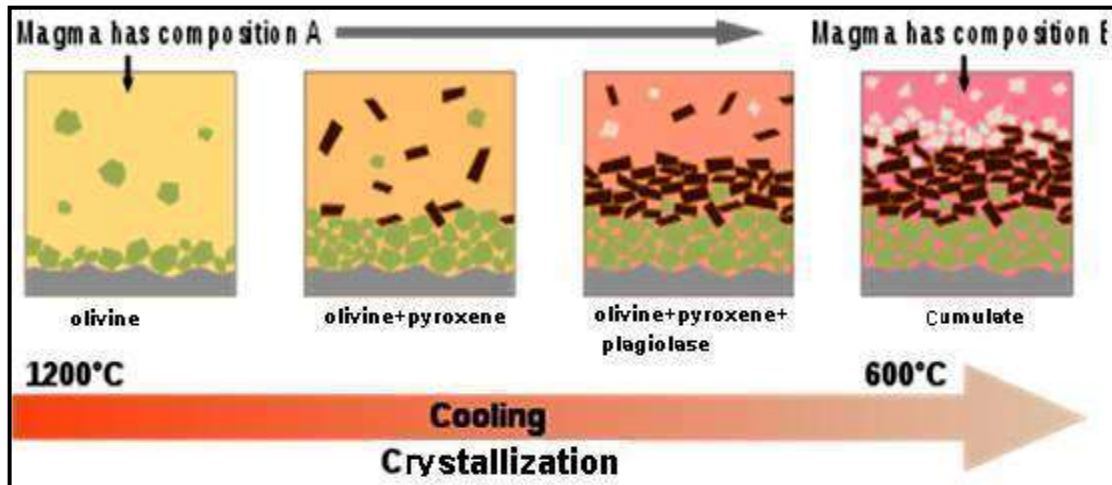


Figure 3-8 Diagrams showing the principles of crystallization of magma.

Most magma only entirely melts for small parts of their histories. More typically, they are mixes of melt and crystals, and sometimes also of gas bubbles. Melt, crystals, and bubbles usually have different densities, and so they can separate as magmas change.

As magma cools, minerals typically crystallize from the melt at different temperatures (fractional crystallization). As minerals crystallize, the composition of the residual melt typically changes. If crystals separate from the melt, then the residual melt will differ in composition from the parent magma. For instance, magma of gabbroic composition can produce a residual melt of granitic composition if early formed crystals are separated from the magma. Gabbro may have a liquidus temperature near 1,200 °C, and the derivative granite-composition melt may have a liquidus temperature as low as about 700 °C. Incompatible elements are concentrated in the last residues of magma during fractional crystallization and in the first melts produced during partial melting: either process can form the magma that crystallizes to pegmatite, a rock type commonly enriched in incompatible elements. Bowen's reaction series (Fig. 3-9) is important for understanding the idealised sequence of fractional crystallisation of magma.

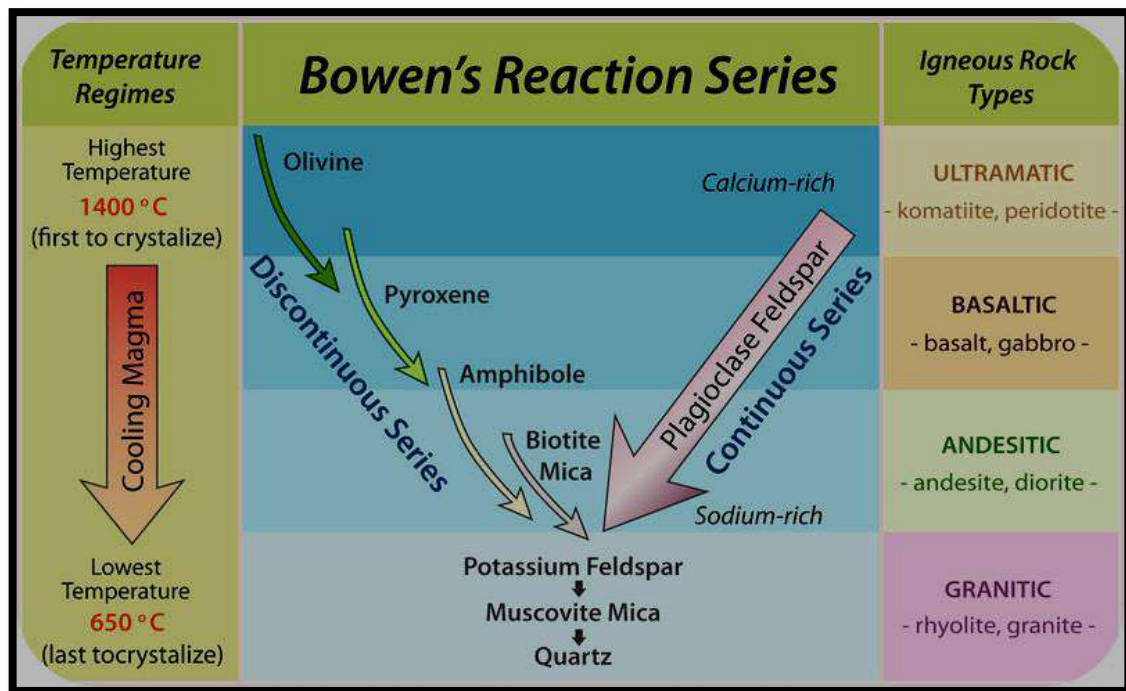


Figure 3-9 Bowen's reaction series (after [www.mrlilholt.wordpress.com](http://www.mrlilholt.wordpress.com)).

### 3.3 Classification of Igneous Rocks

The classification of the many types of different igneous rocks can provide us with important information about the conditions under which they formed. Two important variables used for the classification of igneous rocks are grain size, which largely depends on the cooling history, and the mineral composition of the rock. Feldspars, quartz or feldspathoids, olivines, pyroxenes, amphiboles, and micas are all important minerals in the formation of almost all igneous rocks, and they are basic to the classification of these rocks. All other minerals present are regarded as accessory minerals.

In a simplified classification, igneous rock types are separated on the basis of:

- The type of feldspar present
- The presence or absence of quartz
- The presence or absence of quartz
- The type of iron or magnesium minerals present

Rocks containing quartz (silica in composition) are silica-oversaturated. Rocks with *feldspathoids* are *silica-undersaturated*, because feldspathoids cannot coexist in a stable association with quartz.

Igneous rocks are classified according to:

- |                        |                         |
|------------------------|-------------------------|
| a. Mode of occurrence  | b. Texture              |
| c. Mineral composition | d. Chemical composition |

### a. Classification according to modes of occurrence

Magma can either rise all the way through the crust to erupt onto the Earth's surface, or it can solidify within the crust (Fig. 3-8). In terms of modes of occurrence, igneous rocks can be either intrusive (plutonic), extrusive (volcanic) or hypabyssal.

#### i. Intrusive

Intrusive igneous rocks also known as plutonic rocks forms when magma solidifies within the crust. Intrusive rocks are sometimes called plutonic rocks after Pluto, the Greek god of the underworld.

Intrusive rocks can also be classified according to the shape and size of the intrusive body and its relation to the other formations into which it intrudes. Typical intrusive formations are *batholiths*, *stocks*, *pluton*,... (Fig. 3-10). The central cores of major mountain ranges consist of intrusive igneous rocks, usually granite. When exposed by erosion, these cores (called batholiths) may occupy huge areas of the Earth's surface.

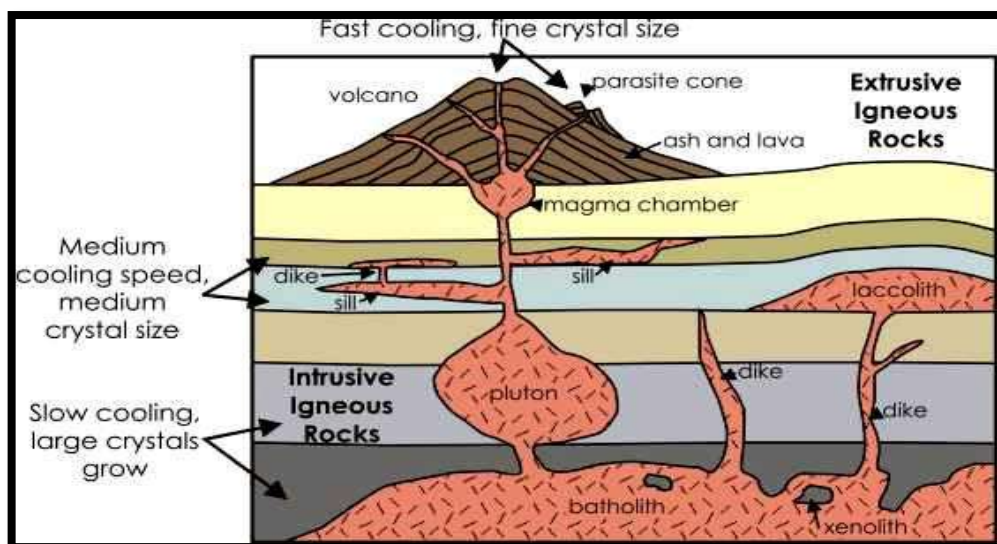


Figure 3-10 Formation of igneous rock (after [www.weebly.com](http://www.weebly.com)).

## ii. Extrusive

An extrusive igneous rock forms when magma erupts and solidifies on the Earth's surface. Because extrusive rocks are so commonly associated with volcanoes, they are also called volcanic rocks after Vulcan, the Greek god of fire.

The magma, which is brought to the surface through fissures or volcanic eruptions, solidifies at a faster rate. Hence such rocks are smooth, crystalline and fine grained. Basalt is a common extrusive igneous rock and forms *lava flows, lava sheets and lava plateaus*. Some kinds of basalt solidify to form long polygonal columns.

The melted rock, with or without suspended crystals and gas bubbles, is called magma. It rises because it is less dense than the rock from which it was created. When magma reaches the surface from beneath water or air, it is called lava. Eruptions of volcanoes into air are termed subaerial, whereas those occurring underneath the ocean are termed submarine. Black smokers and mid-ocean ridge basalt are examples of submarine volcanic activity.

The volume of extrusive rock erupted annually by volcanoes varies with plate tectonic setting. Extrusive rock is produced in the following proportions:

1. Divergent boundary: 73%
2. Convergent boundary (subduction zone): 15%
3. Hotspot: 12%.

Magma that erupts from a volcano behaves according to its viscosity, determined by temperature, composition, and crystal content.

High-temperature magma, most of which is basaltic in composition, behaves in a manner similar to thick oil and, as it cools. Long, thin basalt flows with pahoehoe surfaces are common.

Intermediate composition magma, such as andesite, tends to form cinder cones of intermingled ash, tuff and lava, and may have a viscosity similar to thick, cold molasses or even rubber when erupted.

Felsic magma, such as rhyolite, is usually erupted at low temperature and is up to 10,000 times as viscous as basalt. Volcanoes with rhyolitic magma

commonly erupt explosively, and rhyolitic lava flows are typically of limited extent and have steep margins, because the magma is so viscous.

Felsic and intermediate magmas that erupt often do so violently, with explosions driven by the release of dissolved gases-typically water vapour, but also carbon dioxide.

Explosively erupted pyroclastic material is called **tephra** and includes **tuff**, **agglomerate** and **ignimbrite**. Fine volcanic ash is also erupted and forms **ash tuff deposits**, which can often cover vast areas.

### iii. Hypabyssal

Hypabyssal igneous rocks are formed at a depth in between the plutonic and volcanic rocks. These are formed due to cooling and resultant solidification of rising magma just beneath the earth surface. Hypabyssal rocks are less common than plutonic or volcanic rocks and often form different shapes of igneous bodies:-

*Dyke* is a sheet of rock that formed in a crack in a pre-existing rock body. However, when the crack is between the layers in a layered rock, it is called a *sill*. *Laccolith* is concordant pluton with flat floor and arched roof, while *lopolith* is concordant pluton intruded into a structural basin and is generally much larger (Fig. 3.10).

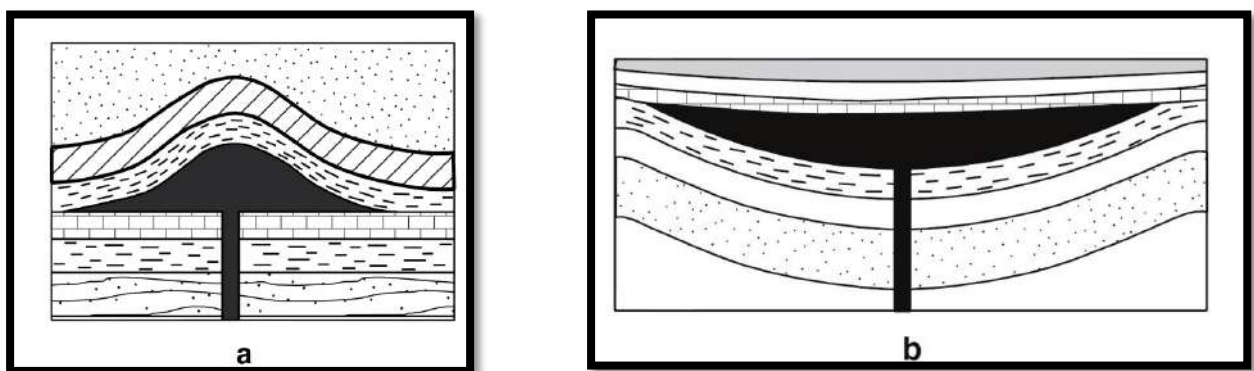


Figure 3-10 Shapes of two concordant plutons. (a) Laccolith with flat floor and arched roof. (b) Lopolith intruded into a structural basin. The scale is not the same for these two plutons; a lopolith is generally much larger than a laccolith.

### b. Classification according to textures

The texture of a rock refers to the size, shape, and arrangement of its mineral grains, or crystals (Table 3–1). Some igneous rocks consist of mineral

grains that are too small to be seen with the naked eye; others are made up of thumb-size or even larger crystals. Volcanic rocks are usually fine grained, whereas plutonic rocks are medium or coarse grained.

| Table 3-1 Igneous rock textures based on grain size |                   |
|-----------------------------------------------------|-------------------|
| GRAIN SIZE                                          | NAME OF TEXTURE   |
| No mineral grains (obsidian)                        | Glassy            |
| Too fine to see with naked eye                      | Very fine grained |
| Up to 1 millimeter                                  | Fine grained      |
| 1–5 millimeters                                     | Medium grained    |
| More than 5 millimeters                             | Coarse grained    |
| Relatively large grains in a finer-grained matrix   | Porphyritic       |

*Texture is an important criterion for the naming of **volcanic rocks**.* The texture of volcanic rocks, including the size, shape, orientation, and distribution of mineral grains and the intergrain relationships, will determine whether the rock is termed a *tuff*, a pyroclastic lava or a simple *lava*.

However, the texture is only a subordinate part of classifying volcanic rocks, as most often there needs to be chemical information gleaned from rocks with extremely fine-grained *groundmass* or from air fall tuffs, which may be formed from *volcanic ash*.

*Textural criteria are less critical in classifying **plutonic rocks*** where the majority of minerals will be visible to the naked eye or at least using a hand lens, magnifying glass or microscope. Plutonic rocks also tend to be less texturally varied and less prone to gaining structural fabrics. Textural terms can be used to differentiate different intrusive phases of large plutons.

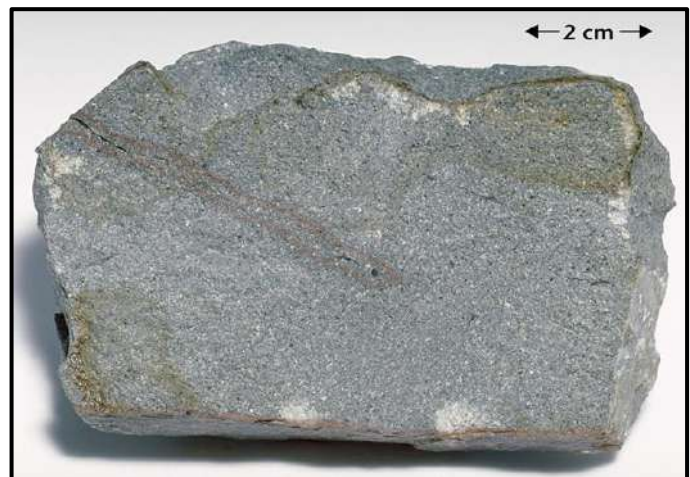
In unusual circumstances, volcanic magma may solidify within a few hours of erupting. Because the magma hardens so quickly, the atoms have no time to align themselves to form crystals. The result is the volcanic glass called obsidian (Fig. 3-11).

After magma erupts onto the relatively cool Earth surface, it solidifies rapidly—perhaps over a few days or years. Crystals form but do not have much time to grow. The result is a very fine-grained rock with crystals too small to be seen with the naked eye. Basalt is a common very fine-grained volcanic rock (Fig. 3-12).



Figure 3-11 Obsidian is natural volcanic glass. It contains no crystals. (Geoffrey Sutton)

When magma solidifies within the crust, the overlying rock insulates the magma like a thick blanket. The magma then crystallizes slowly, and the crystals may have hundreds of thousands or even millions of



years in which to grow. As a result, most plutonic rocks are medium to coarse grained. Granite, the most abundant rock in continental crust, is a medium- or coarse-grained plutonic rock (Fig. 3-13).

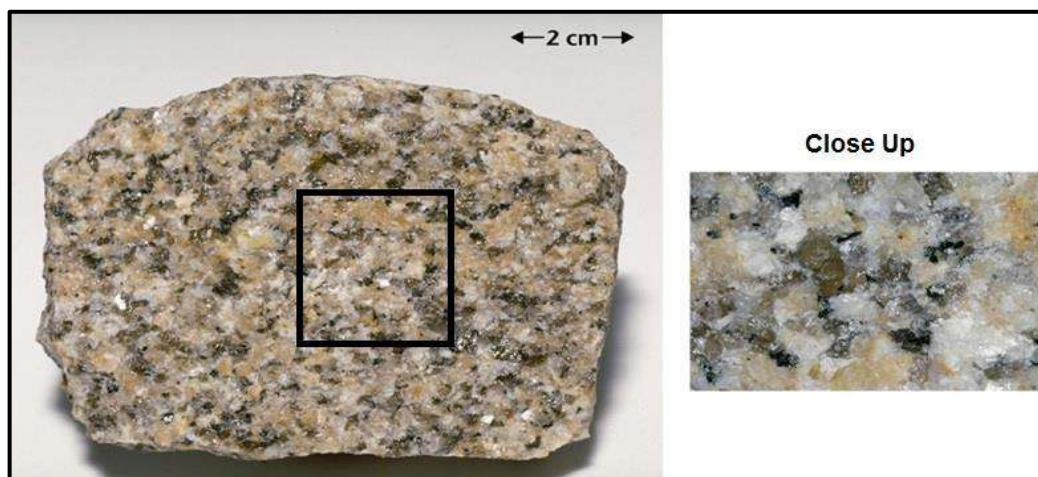


Figure 3-13 Medium to coarse grained texture of Granite.

If magma rises slowly through the crust before erupting, some crystals may grow while most of the magma remains molten. If this mixture of magma and crystals then erupts onto the surface, it solidifies quickly, forming porphyry, a rock with the large crystals, called phenocrysts, embedded in a fine-grained matrix (Fig. 3-14).



**Figure 3-13** Porphyry is an igneous rock containing large crystals embedded in a fine-grained matrix. This rock is rhyolite porphyry with large pink feldspar phenocrysts.

Igneous rocks that have *large crystals* enough to be seen by the naked eye are called *phaneritic*; those with *crystals too small* to be seen are called *aphanitic*. Generally speaking, *phaneritic* implies an *intrusive or volcanic origin*; *aphanitic* is *extrusive or plutonic one*.

According to the texture of the grains, igneous rocks may be classified as:-

**Pegmatitic:** very large crystals (Fig. 3-15)

**Phaneritic:** rocks contain minerals with crystals visible to the unaided eye, commonly intrusive (Fig. 3-15)

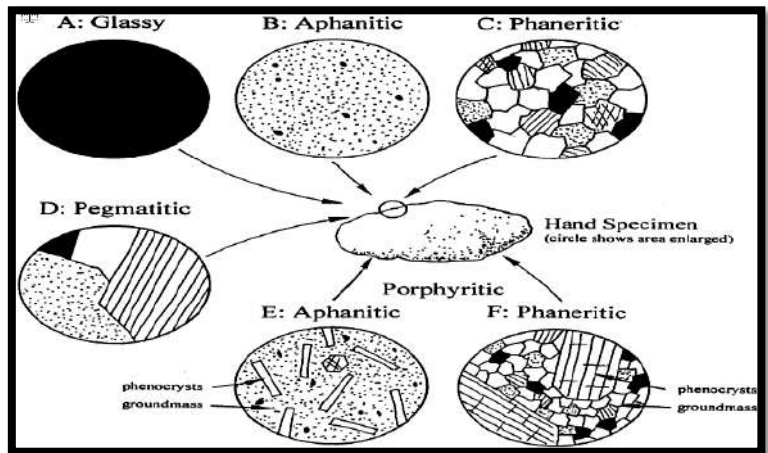


**Figure 3-15** Textures of igneous rocks.

**Aphanitic:** rapid cooling, crystal nucleation and growth is stunted, forming a uniform, fine grained rock (Fig. 3-15)

**Porphyritic:** containing phenocrysts in a fine groundmass (Fig. 3-15)

**Vesicular:** contains voids caused by trapped gas while cooling

**Glassy:** *vitreous* or *hyaline* without crystals (Fig. 3-15)

**Pyroclastic:** rock contain fragments of crystals, phenocrysts and rock fragments

**Equigranular:** rock crystals are all the same size

The textures properties of igneous rocks can be summarized in the following table

| Type of igneous textures            | Properties                                                                                                                                                                                      |
|-------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Aphanitic (fine-grained) texture    | <ol style="list-style-type: none"> <li>1. Rapid rate of cooling</li> <li>2. Microscopic crystals</li> <li>3. May contain vesicles (holes from gas bubbles)</li> </ol>                           |
| Phaneritic (coarse-grained) texture | <ol style="list-style-type: none"> <li>1. Slow cooling</li> <li>2. Large, visible crystal</li> </ol>                                                                                            |
| Porphyritic texture                 | <ol style="list-style-type: none"> <li>1. Minerals form at different temperatures</li> <li>2. Large crystals (phenocrysts) are embedded in a matrix of smaller crystals (groundmass)</li> </ol> |
| Glassy texture                      | <ol style="list-style-type: none"> <li>1. Very rapid cooling of lava</li> <li>2. Resulting rock is called obsidian</li> </ol>                                                                   |
| Pyroclastic texture                 | <ol style="list-style-type: none"> <li>1. Fragmental appearance produced by violent volcanic eruptions</li> <li>2. Often appear more similar to sedimentary rocks</li> </ol>                    |
| Pegmatitic texture                  | <ol style="list-style-type: none"> <li>1. Exceptionally coarse grained</li> <li>2. Form in late stages of crystallization of granitic magmas</li> </ol>                                         |

### c. Classification of igneous rocks by mineral composition

Mineralogical classification is most often used to classify plutonic rocks, intrusive and usually phaneritic igneous rocks (where all minerals are visible at least via microscope). Like granite and rhyolite, most common igneous rocks are classified in pairs, each member of a pair containing the same minerals but having a different texture. Figure 3–15 shows the minerals and textures of common igneous rocks.

The chemical compositions of common igneous rocks are summarized in Figures 3–16 and 3-17.

**Felsic rock**, highest content of silicon (greater than 69%), with predominance of quartz, alkali feldspar; these rocks (e.g., granite, rhyolite) are usually light coloured, and have low density.

**Mafic rock**, lesser content of silicon relative to felsic rocks, with predominance of mafic minerals pyroxenes, olivines and calcic plagioclase; these rocks (example, basalt, gabbro) are usually dark coloured, and have a higher density than felsic rocks.

**Ultramafic rock**, lowest content of silicon (less than 45%), with more than 90% of mafic minerals (example, dunite).

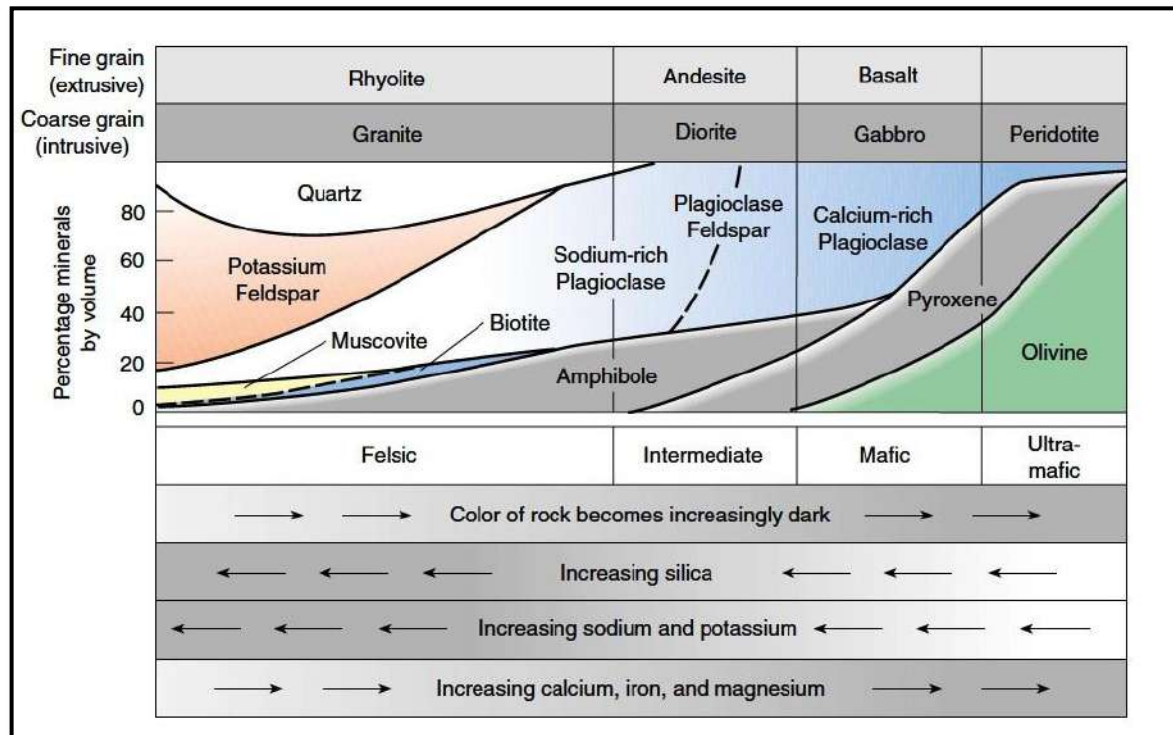


Figure 3-16 The names of common igneous rocks are based on the minerals and texture of a rock. In this figure, a mineral's abundance in a rock is proportional to the thickness of its colored band beneath the rock name. If a rock has a fine grain texture, its name is found in the top row of rock names; if it has a coarse grain texture, its name is in the second row.

| Descriptive Terms | Felsic (granitic)                                                                     | Intermediate (andesitic)                                                              | Mafic (basaltic)                                                                       | Ultramafic                                                                            |
|-------------------|---------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|
| Intrusive         | Granite                                                                               | Diorite                                                                               | Gabbro                                                                                 | Peridotite                                                                            |
| Extrusive         | Rhyolite                                                                              | Andesite                                                                              | Basalt                                                                                 |                                                                                       |
| Composition       | Aluminum oxide 14%<br>Iron oxides 3%<br>Magnesium oxide 1%<br>Other 10%<br>Silica 72% | Iron oxides 8%<br>Magnesium oxide 3%<br>Other 13%<br>Aluminum oxide 17%<br>Silica 59% | Magnesium oxide 7%<br>Other 16%<br>Silica 50%<br>Iron oxides 11%<br>Aluminum oxide 16% | Other 8%<br>Silica 45%<br>Magnesium oxide 31%<br>Iron oxides 12%<br>Aluminum oxide 4% |
| Major minerals    | Quartz<br>Potassium feldspar<br>Sodium feldspar (plagioclase)                         | Amphibole<br>Intermediate plagioclase feldspar                                        | Calcium feldspar (plagioclase)<br>Pyroxene                                             | Olivine<br>Pyroxene                                                                   |
| Minor minerals    | Muscovite<br>Biotite<br>Amphibole                                                     | Pyroxene                                                                              | Olivine<br>Amphibole                                                                   | Calcium feldspar (plagioclase)                                                        |
| Most common color | Light colored                                                                         | Medium gray or medium green                                                           | Dark gray to black                                                                     | Very dark green to black                                                              |

Figure 3-17 Chemical compositions, minerals, and typical colors of common igneous rocks.

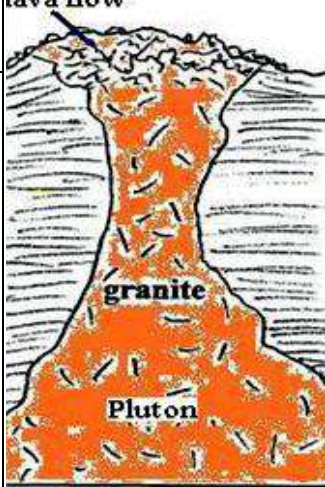
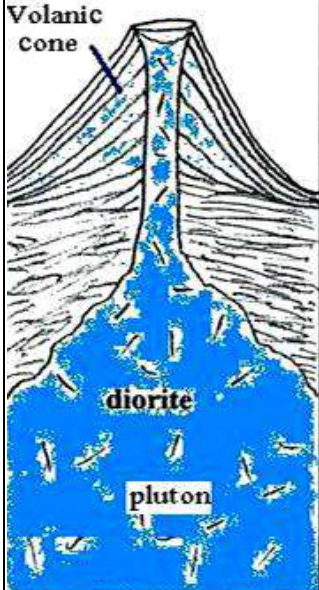
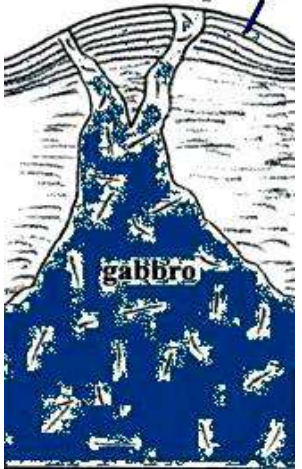
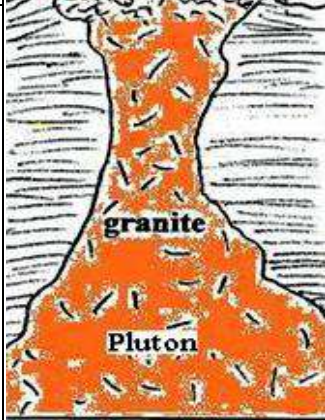
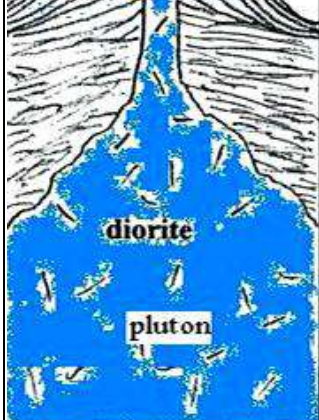
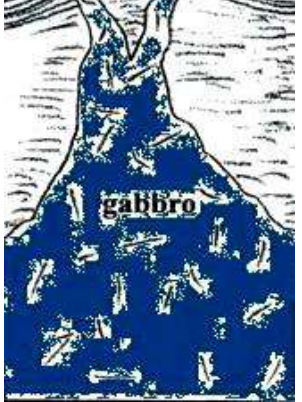
| Textures<br>Occurrence<br>Forms<br>Rate of cooling<br>Rock name                                                                                                                  | Composition                                                                        |                                                                                          |                                                                                      |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|
|                                                                                                                                                                                  | Felsic                                                                             | Intermediate                                                                             | Mafic                                                                                |
|                                                                                                                                                                                  | Potassium feldspar, quartz, mica; light colour<br>Low temperature                  | Amphibole, Na-Ca-rich plagioclase, gray to salt-and-pepper<br>Colour; medium temperature | Olivine, pyroxene, Ca-rich plagioclase feldspar, dark colour;<br>High temperature    |
| <b>Fine-grained</b><br>Volcanic (or extrusive) rocks; rapid cooling of lava at surface; obsidian is natural glass composed of unordered atoms, so it has no specific composition |  |       |  |
| <b>Coarse-grained</b><br>Intrusive (or plutonic) rocks slow cooling of magma underground                                                                                         |  |       |  |

Figure 3-18 combined classification of very common igneous rocks(modified after [www.geology.campus.ad.csulb.edu](http://www.geology.campus.ad.csulb.edu)).

#### d. Classification of igneous rocks by chemical composition

Chemical classifications are preferred to classify volcanic rocks, with phenocryst species. **Total alkali versus silica classification scheme (TAS)**( Fig. 3.19): as proposed in Le Maitre's 2002 *Igneous Rocks - A classification and glossary of terms*.

Chemical: total alkali-silica content (TAS diagram) for volcanic rock classification used when modal or mineralogic data is unavailable.

Chemical classification also extends to differentiating rocks that are chemically similar according to the TAS diagram, for instance;

- **Ultrapotassic**; rocks containing molar  $K_2O/Na_2O > 3$
- **Peralkaline**; rocks containing molar  $(K_2O + Na_2O)/Al_2O_3 > 1$
- **Peraluminous**; rocks containing molar  $(K_2O + Na_2O)/Al_2O_3 < 1$

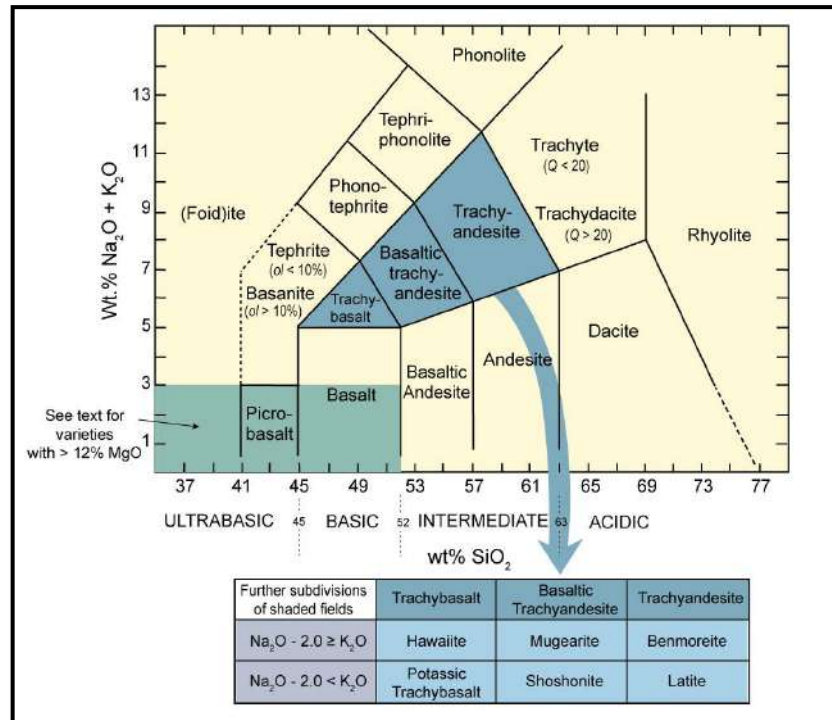


Figure 3-19 Total alkali versus silica classification (after Le Maitre's 2002).

## REVIEW QUESTIONS

1. Describe the three main classes of rocks.
2. What criteria are used to categorize rocks into the three classes that you described in question 1?
3. List two common rock types in each of the three main classes of rocks. Were these rock names familiar to you before you read this chapter?
4. What is the most important concept described by the rock cycle?
5. What is magma?
6. Describe and explain each of the three processes that melt rock to form magma.
7. Describe each of the three main geologic environments in which magma forms in large quantities.
8. Describe the processes that melt rock to generate magma in each of the three environments that you discussed in the previous question.
9. Explain how oceanic crust forms only at the mid-oceanic ridge but makes up the entire sea floor.
10. Describe the locations of some volcanically active regions associated with subduction zones.

11. What is the temperature of magma?
12. What is the general chemical composition of most magmas?
13. Why do magmas begin to rise through the Earth's outer layers as soon as they form?
14. How would you distinguish a plutonic rock from a volcanic rock in the field?
15. What factor distinguishes obsidian from all other types of igneous rocks?
16. What are the most common minerals in igneous rocks? Why?
17. What do the terms mafic, ultramafic, felsic, and intermediate mean?
18. Describe the mineralogy, texture, and common geologic occurrence of the following types of igneous rocks: granite, rhyolite, basalt, gabbro, andesite, and peridotite.
19. What type of igneous rock is the most abundant constituent of continental crust? What type makes up most oceanic crust?
20. Why is it sometimes difficult to identify a volcanic rock accurately in the field?
21. Why does magma normally have a higher silica content than the rock from which it formed?

### DISCUSSION QUESTIONS

1. The temperature of most magma is thought to be approximately equal to the initial melting temperature of the rock from which the magma formed, rarely much hotter. Why do magmas not get much hotter than their initial melting points?
2. Why is oceanic crust predominantly basalt, whereas continental crust is mainly of granitic composition?
3. Devise a scheme for naming and classifying igneous rocks that is different from the one based on mineral content presented in Figure 3–16.
4. Explain why feldspar is the most abundant mineral in the Earth's crust and yet is nearly completely absent from the peridotite of the upper mantle.
5. What could you infer about the history of another planet if you discovered extrusive igneous rocks but no intrusive igneous rocks on its surface?

6. Draw a graph with silica content on the Y-axis and felsic, intermediate, mafic, and ultramafic rocks on the X-axis. Draw similar graphs for aluminum, magnesium, iron, and potassium contents.

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# Chapter 4

## SEDIMENTARY ROCKS

### 4.1 What is sediment?

Sediment is loose, hard material lying on top of solid rock. Sediment comes in many forms and sizes, and can originate from a variety of sources. Detrital sediment is produced by the weathering and erosion of rocks exposed at Earth's surface.

### 4.2 What is a sedimentary rock?

- Sedimentary rocks form from sediment grains or crystals that are deposited in a wide variety of natural environments at Earth's surface.
- Sedimentary rocks are products of mechanical and chemical weathering
- They account for about 5 percent (by volume) of Earth's outer 10 miles, but 75% of the outcrops.
- They contain evidence of past environments.
- Clues in these rocks provide a window into the history of the earth's surface. Sedimentary rocks are important for economic considerations because they may contain Coal, Petroleum and natural gas and Sources of iron, aluminum, and manganese.

### 4.3 Importance of Sedimentary Rocks

Sedimentary rocks provide a multitude of products which modern and ancient society has come to utilize:

- 1. Marble**, although a metamorphosed limestone, is an example of the use of sedimentary rocks in the pursuit of aesthetics and art.
- 2. Architectural uses:** stone derived from sedimentary rocks is used for dimension stone and in architecture, notably slate, a meta-shale, for roofing, sandstone for load-bearing buttresses.
- 3. Ceramics and industrial materials:** clay for pottery and ceramics including bricks; cement and lime derived from limestone.

- 4. Economic geology:** sedimentary rocks host large deposits of SEDEX ore deposits of lead-zinc-silver, large deposits of copper, deposits of gold, tungsten, Uranium, and many other precious minerals, gemstones and industrial minerals including heavy mineral sands ore deposits.
- 5. Energy:** petroleum geology relies on the capacity of sedimentary rocks to generate deposits of petroleum oils. Coal and oil shale are found in sedimentary rocks. A large proportion of the world's uranium energy resources are hosted within sedimentary successions.
- 6. Groundwater:** sedimentary rocks contain a large proportion of the Earth's groundwater aquifers. Our understanding of the extent of these aquifers and how much water can be withdrawn from them depends critically on our knowledge of the rocks that hold them (the reservoir).

#### 4.4 Types of sedimentary rocks

Sedimentary rocks are formed by the lithification of inorganic and/or organic sediments, or as chemical precipitates.

- There are two types of sedimentary rocks: Clastic and Chemical
- Clastic sedimentary rocks form when existing parent rock material is weathered, fragmented, transported, and deposited in layers that compact, cement, and lithify to form sedimentary rocks. Clastic rocks make up more than 85 percent of all sedimentary rocks (Fig. 4–1). This category includes sandstone, siltstone, and shale.

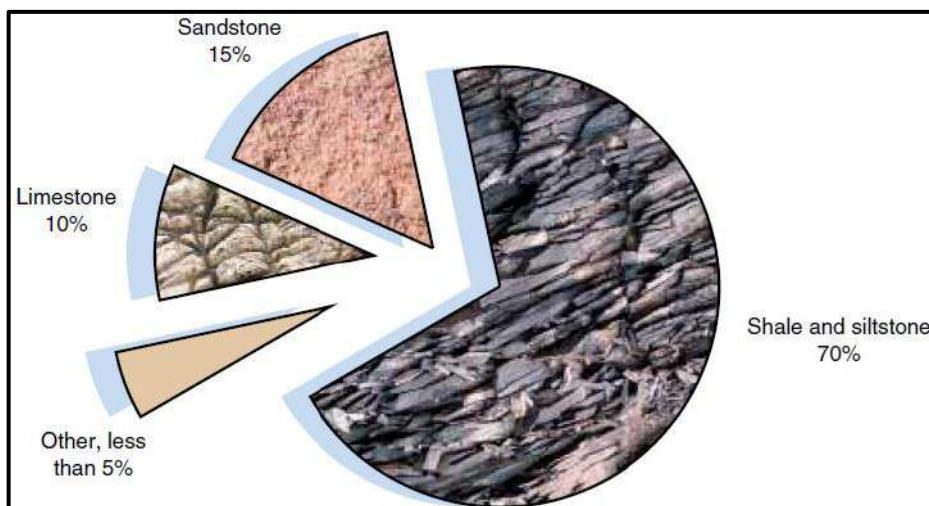


Figure 4–1 Relative abundances of sedimentary rock types.

- Chemical sedimentary rocks are formed by a variety of processes and are divided into sub-categories including inorganic, and biochemical or organic chemical sedimentary rocks.
- Inorganic chemical rocks form from chemicals that are dissolved in a solution, transported, and chemically precipitated out of solution.
- Biochemical or Organic sedimentary rocks form when plant or animal material is deposited and lithified. Those classified as biochemical chemical generally involve some form of fossilization or the accumulation of fossilized organism or organism remains, such as shell fragments. Organic rocks that are classified as clastic, involve the deposition of plant material and formation of peat and coal deposits.
- The physical, chemical, or biological changes that occur during the lithification of sedimentary rocks are described by process collectively referred to as diagenesis.

#### 4.5 Turning sediment into rock

- ❖ Many changes occur to sediment after deposition
- ❖ Diagenesis – all of the chemical, physical, and biological changes that take place after sediments are deposited
  - ❖ Occurs within the upper few kilometers of Earth's crust
- ❖ Diagenesis includes
  - Recrystallization – development of more stable minerals from less stable ones
  - Lithification – unconsolidated sediments are transformed into solid sedimentary rock by
    - *Compaction*
    - *Cementation by calcite, silica, and iron oxide*
  - Diagenesis collectively refers to the physical, chemical, and biological changes which may occur during the formation of sedimentary rocks. Recrystallization, compaction, cementation, and lithification, are all examples of diagenetic changes.
  - Recrystallization occurs when unstable minerals recrystallize to form more stable minerals. Recrystallization most often occurs during the formation of chemical sedimentary limestone rocks that previously contained aragonite a chemically unstable form of calcium carbonate ( $\text{CaCO}_3$ ).

- Compaction occurs when sediments are progressively deposited on top of one another, and over time the weight of the accumulated sediments increases and compresses the buried sediments. Continued compression of buried sediments reduces pore-spaces and removes excess water, as a result the closely packed individual grains begin to slowly compact into a solid rock.
- Cementation involves a chemical change whereby individual grains are cemented together as minerals are precipitated out of saturated solution that is percolating as a matrix between individual sediments. The accumulation of the precipitated minerals causes the grains to cement together. Cementation can occur in combination with the presence of other minerals, rock fragments, or organic constituents such as fossilized organisms.
- Lithification occurs when unconsolidated sediments are cohesively bound to form a solid sedimentary rock. Compaction and/or cementation are generally the precursor to the lithification process.

## 4.6 Naming and Classifying Sedimentary Rocks

Geologists name and classify sedimentary rocks based on their mineral composition and texture.

- Mineral composition refers to the specific minerals in the rock. For example sandstone will contain predominantly quartz, while limestone will contain mainly calcite (calcium carbonate).
- Texture includes the grain size and shape, sorting, and rounding of the sediments that form the rock.

### 4.6.1 Texture: Grain Size

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 chemical sedimentary rock (Table 4-1)

Table 4-1 Sizes and names of sedimentary particles and clastic rocks

| DIAMETER<br>(mm)                                           | SEDIMENT                       |                    | CLASTIC<br>SEDIMENTARY<br>ROCK                                           |
|------------------------------------------------------------|--------------------------------|--------------------|--------------------------------------------------------------------------|
| 256–<br>64–<br>2–<br>$\frac{1}{16}$ –<br>$\frac{1}{256}$ – | Boulders<br>Cobbles<br>Pebbles | Gravel<br>(rubble) | Conglomerate<br>(rounded particles)<br>or breccia<br>(angular particles) |
|                                                            | Sand                           |                    | Sandstone                                                                |
|                                                            | Silt<br>Clay                   | Mud                | Siltstone<br>Claystone<br>or shale } Mudstone                            |

| Grain Size Categories | Grain Size Divisions        |
|-----------------------|-----------------------------|
| very coarse-grained   | $\geq 16$ mm                |
| coarse grained        | $\geq 2$ mm < 16 mm         |
| medium grained        | $\geq 0.25$ mm < 2 mm       |
| fine grained          | $\geq 0.032$ mm < 0.25 mm   |
| very fine-grained     | $\geq 0.0004$ mm < 0.032 mm |
| Cryptocrystalline     | < 0.0004 mm (4 $\mu$ m )    |

#### 4.6.2 Texture: Sorting

Sorting is used to describe the grain size distribution or range of grain sizes in a rock.

1. Poorly sorted rocks contain a variety of different sized grains. Poorly sorted rocks contain a wide range of grain sizes including fine, medium, and coarse (Fig. 4-2b).
2. Well sorted rocks contain almost all grains of the same size (Fig. 4-2a).
3. Moderately sorted rocks contain particles of relatively similar grain sizes. Moderately sorted rocks may contain fine and medium grains, or medium and coarse grain.

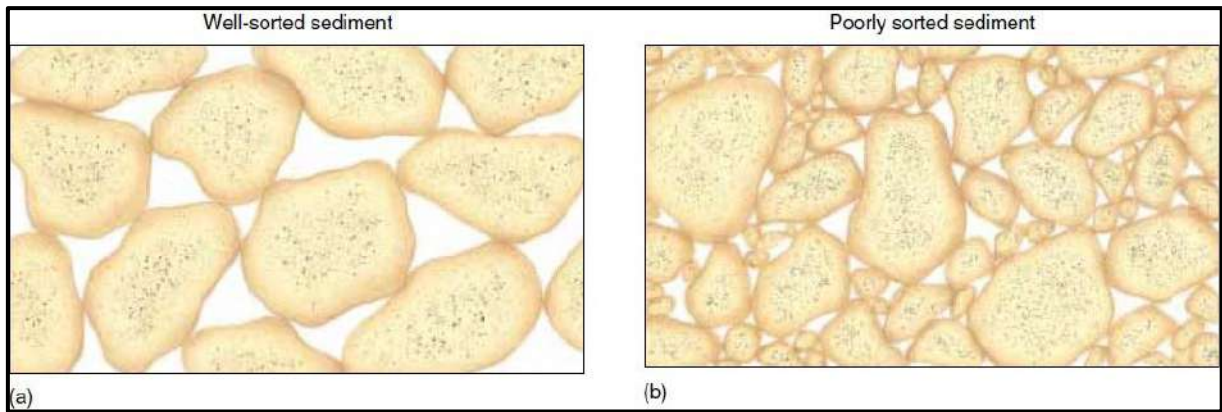


**Figure 4-2** Well-sorted sediment consists of equal-size grains and has a high porosity, about 30 percent in this case. (b) In poorly sorted sediment, small grains fill the spaces among the large ones, and porosity is lower. In this drawing it is about 15 percent.

#### 4.6.3 Texture: Rounding

Rounding is used to describe the relative shape of the grains. Classifications are described as deviations from rounded or spheroidal grain shapes.

1. Well rounded grains are smooth with rounded edges (Fig. 4-3a).
2. 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. Poorly rounded grains may be sharp or angular (Fig. 4-3b).



**Figure 4-3** Well-rounded spheroidal grains (a) poorly rounded angular grains (b).

#### 4.6.4 Texture and Weathering

- The texture of a sedimentary rock can provide a lot of information about the types of environments that the sediments were weathered in, transported by, and deposited in prior to their lithification into sedimentary rocks.

- Most sedimentary rocks consist of grains that weathered from a parent rock and were transported by water, wind, or ice before being deposited.
- Grain size is a good indicator of the energy or force required to move a grain of a given size. Large sediments such as gravel, cobbles, and boulders require more energy to move than smaller sand, silt, and clay sized sediments. Grain size is also an indicator of the distance or length of time the sediments may have traveled. Smaller grain sizes generally indicate greater transport distances and duration than larger grains.
- Sorting will generally improve with the constant or persistent moving of particles, and thus can indicate if particles were transported over a long distance or for a long time period. Sorting can also indicate selective transport of a particular grain size.
- Rounding is a good indicator for the amount of abrasion experienced by sediments. In general, sediments that have been transported longer distances will be more rounded than those which have traveled shorter distances.
- An example based on these principles, is that sediments deposited by rapid mass wasting events, such as landslides are expected to be coarse grained, poorly sorted, and poorly rounded; and sediments deposited by slower, more gradual processes, such as dune formation, are expected to be fine grained, well sorted, and well rounded.

#### **4.7 Classification of sedimentary rocks**

Sedimentary rocks are classified according to the type of material into two major groups (Table 4-2):

1. Detrital (transported as solid particles)
2. Chemical (transported as solutions, produced primarily by chemical weathering)

Two major textures are used in the classification of sedimentary rocks

1. Clastic (Discrete fragments and particles-All detrital rocks have a clastic texture).

2. Nonclastic (Pattern of interlocking crystals-May resemble an igneous rock).

Table 4-2 classifying sedimentary rocks.

| CLASTIC SEDIMENTARY ROCKS                              |                         |                                                       |                                |
|--------------------------------------------------------|-------------------------|-------------------------------------------------------|--------------------------------|
| TEXTURE                                                | SEDIMENT PARTICLE SIZE  | OTHER CHARACTERISTICS                                 | SEDIMENTARY ROCK               |
| CLASTIC                                                | Gravel (> 2 mm)         | Rounded rock fragments, Poorly-sorted                 | Conglomerate                   |
|                                                        |                         | Angular rock fragments, Poorly-sorted                 | Breccia                        |
|                                                        | Sand (0.0625 mm – 2 mm) | Quartz (>50%), Moderate – well sorted                 | Quartz sandstone               |
|                                                        |                         | Quartz with Feldspar, Moderate – Well sorted          | Arkose                         |
|                                                        |                         | Quartz, Feldspar, Clays, Rocky Fragments, Well-sorted | Graywacke                      |
|                                                        | Mud (< 0.0625 mm)       | Fine, thin layers, or cohesive clumps, Well-sorted    | Shale, Siltstone, and Mudstone |
| CHEMICAL SEDIMENTARY ROCKS (INORGANIC AND BIOCHEMICAL) |                         |                                                       |                                |
| GROUP                                                  | TEXTURE                 | CHEMICAL COMPOSITION                                  | SEDIMENTARY ROCK               |
| INORGANIC                                              | clastic or non-clastic  | Calcite, $\text{CaCO}_3$                              | Limestone                      |
|                                                        | non-clastic             | Dolomite, $\text{CaMg}(\text{CO}_3)_2$                | Dolostone                      |
|                                                        | non-clastic             | Microcrystalline quartz, $\text{SiO}_2$               | Chert                          |
|                                                        | non-clastic             | Halite, $\text{NaCl}$                                 | Rock salt                      |
|                                                        | non-clastic             | Gypsum, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$     | Rock Gypsum                    |
| BIOCHEMICAL                                            | clastic or non-clastic  | Calcite $\text{CaCO}_3$                               | Limestone                      |
|                                                        | non-clastic             | Microcrystalline quartz, $\text{SiO}_2$               | Chert                          |
|                                                        | non-clastic             | Altered plant remains                                 | Coal                           |

### 4.7.1 Clastic Sedimentary Rocks

#### a) Conglomerate and breccia

- Both are composed of particles greater than 2mm in diameter, larger pieces are called clasts which are embedded in groundmass
- The clasts provide clues to provenance
- Conglomerate consists of large rounded clasts
- Breccia consists of large angular clasts

#### **Conglomerate**

- Conglomerates are poorly-sorted composites of a wide range of rounded grain sizes ranging from sand to cobbles (< 0.062 to > 2 mm, Fig. 4-4).
- Conglomerates usually contain a framework of large grains held together

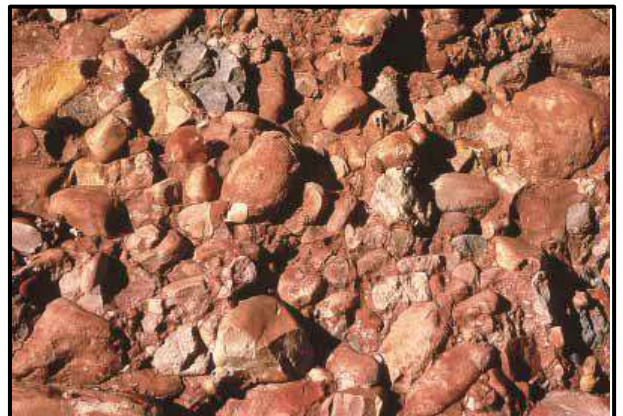


Figure 4-4 Conglomerate is lithified gravel

by a matrix of sands, silt, and clay-sized particles.

- The combination of poorly-sorted, predominantly coarse, rounded grains suggests that conglomerates form in high-energy environments such as steep-gradient streams.

### **Breccia**

- Breccia is a poorly-sorted composite of a wide range of grain sizes ranging from clays to gravel ( $< 0.062$  to  $> 2$  mm, Fig. 4-5).
- Breccias usually contain a framework of gravel-sized grains held together by a matrix of sands, silts, and clay.



Figure 4-5 Poorly sorted and angular grains of Breccia

- Breccia is similar to a conglomerate except that it consists of angular grains, as opposed to rounded grains.
- The combination of poorly-sorted, predominantly coarse, angular grains suggests that breccias form from rapid deposition in high energy environments such as steep-gradient streams, glacial flood deposits, landslides, talus, alluvial fans, or in association with faulting.

### **b) Sandstone**

- Composed of sand-sized particles
- Forms in a variety of environments
- Sorting, shape, and composition of the grains can be used to interpret the rock's history
- Quartz is the predominant mineral

Sandstone rocks are composed almost entirely of sand-sized quartz grains (0.063 – 2 mm, Fig. 4-6) cemented together through lithification. Sandstone rocks are generally classified as quartz sandstone, arkose (quartz with

feldspars), or greywacke (quartz with feldspar, clay, and other coarse-grained mineral fragments).

Sandstones comprise about 20% of all sedimentary rocks and are formed in a variety of different environments including fluvial (rivers), marine, coastal (oceans and beaches), aeolian (wind blown), and glacial (ice).

The differences in texture, sorting, and rounding help geologists decipher the environmental conditions that formed the sandstone.

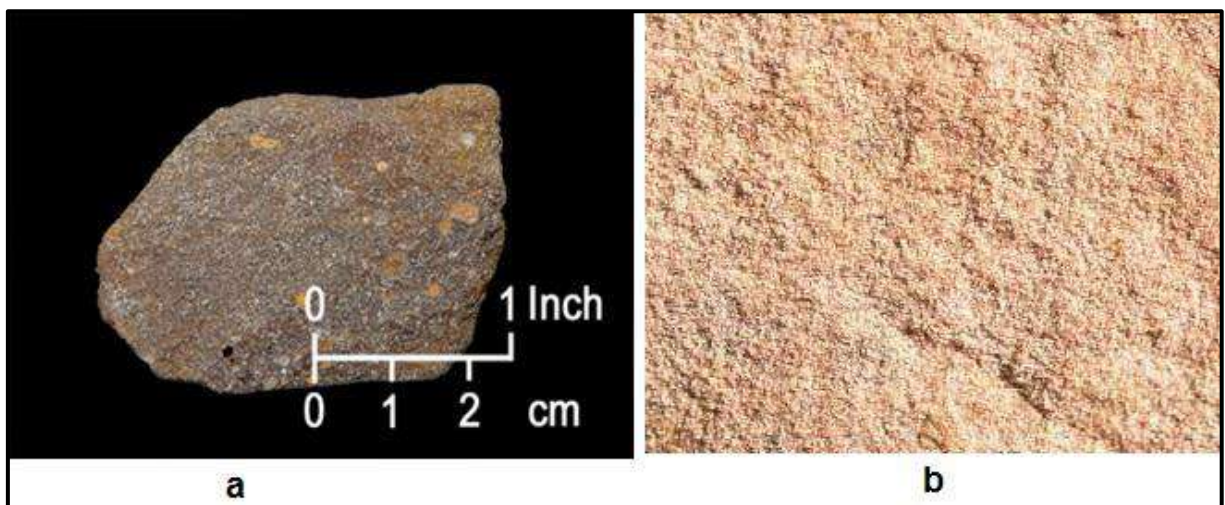


Figure 4-6 Sandstone is lithified sand. (a) A close-up of sandstone (b).

### c) Shale

Shale is a mud-sized particles in thin layers that are commonly referred to as laminae. Shale is a fine-grained, moderately to well-sorted rock formed by the compaction of well-rounded silt- and clay-sized grains (Fig. 4-7).



Figure 4-7 Shale is made up mostly of platy clays.

Shales often contain fine laminations which helps impart fissility to the rock. Fissility is a term used to describe layered laminations formed by compression forces exerted over long-time periods.

Shale usually contains about 50% silt, 35% clay, and 15% chemical materials, many shales may also contain organic plant materials and fossils.

Shale is characterized by thinly, laminated layers, representing successive deposition of sediments. Shale accounts for about 50% of all sedimentary rocks deposited on the Earth's surface.

The sediments that form shale are most likely deposited very gradually in non-turbulent, environments such as a lakes, lagoons, flood plains, and deep-ocean basins.

#### d) Mudstone

Mudstone consists of very silt-sized and clay-sized grains ( $<0.0625$  mm, Fig. 4-8) and are often well consolidated with little pore space.



Figure 4-8 mudstone

Mudstones do not contain laminations or fissility, but they may contain bedding-plane features such as mud cracks or ripples. Mud cracks are formed by subaerial drying conditions. Ripples suggest gentle wave activity or water movement during deposition.

#### 4.7.2 Chemical/Biochemical sedimentary rocks

- ❖ Consist of precipitated material that was once in solution
- ❖ Precipitation of material occurs in two ways
  - ❖ Inorganic processes
  - ❖ Organic processes (biochemical origin)
- ❖ Common chemical sedimentary rocks

#### a) Limestone

- Most abundant chemical rock
- Composed chiefly of the mineral calcite

- Marine biochemical limestones form as coral reefs, coquina (broken shells), and chalk (microscopic organisms)

### ***Coral Reefs***

- Coral Reefs are limestone formations created by marine organisms (Fig. 4-9).
- Corals are invertebrate animals which secrete a calcareous (calcite-rich) external skeleton. Over long periods of time coral colonies form massive reef formations. Some of which surround entire islands or extend along the shoreline for 100's of miles.



Figure 4-9 Coral Reefs.

### ***Coquina and Chalk***

- Coquina rock formations are poorly cemented, coarse-textured masses of shells and shell fragments (Fig. 4-10a).
- The shells and shell fragments are easily discerned, and they give the rock a rough, sharp texture.
- Chalk is formed from calcareous microscopic marine organisms (nanofossils). When the organisms die their exoskeletons fall to the ocean floor creating a sedimentary layer (Fig. 4-10b).

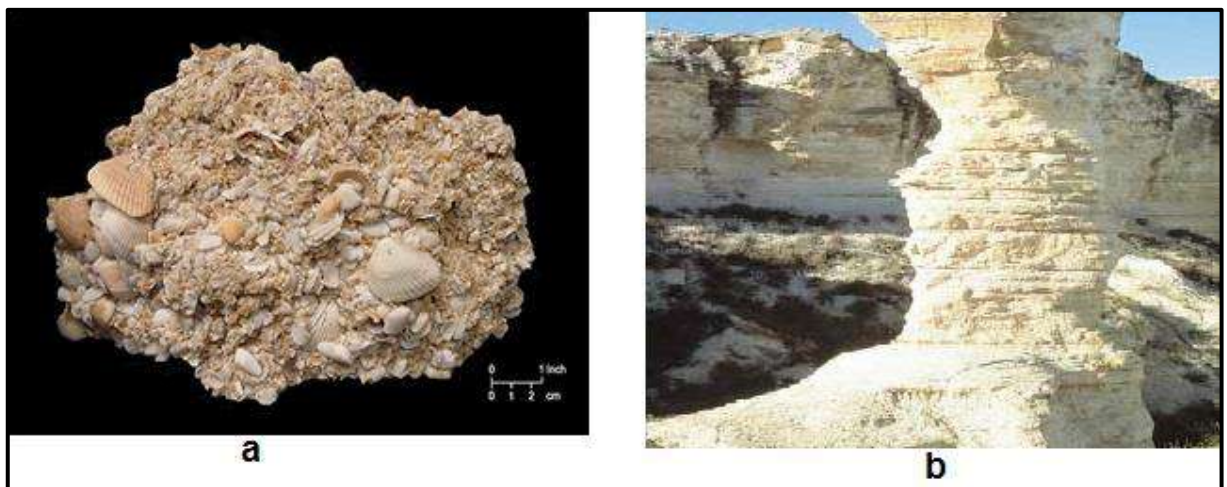


Figure 4-10 Coquina (a) and Chalk (b)

## b) Inorganic limestone

### *Travertine*

- Travertine is an inorganic limestone that forms when calcium carbonate precipitates out of ground water that discharges from seeps, caves, grottos, springs, or along faults.
- More carbon dioxide dissolved in the water escapes, causing calcium carbonate to precipitate out of the solution.
- Travertine also forms where water emerges from hot springs (Fig. 4.11).



Figure 4-11 Travertine (a hot spring in Yellowstone National Park).

### *Oolite*

- Oolitic limestone (Fig. 4-12) is formed by the cementation of tiny spherical grains called ooids.
- Ooids form in warm, shallow marine environments. When small grains of shell roll back and forth in the current, they are coated with calcium carbonate precipitating out of the supersaturated marine water.
- Ooids exhibit growth rings from the accumulation of the calcium carbonate precipitates. The presence of algae and sea-grasses accelerates and increases the formation of ooids.



Figure 4-12 Oolitic limestone

- Ooid formation and oolitic limestones cover vast areas of the Bahamas creating shoals and tidal flats.

### c) Chert

Chert is made of microcrystalline quartz, varieties include flint and jasper (banded form is called agate, Fig. 4-13)

- Chert represents a group of hard rocks made from micro- and cryptocrystalline silica ( $\text{SiO}_2$ ). Chert can develop as a nodule inside other rocks or as rock layers.
- Most cherts are hypothesized to originate from silica derived from one of three sources: solution in water, biochemical sediments, or lava flows and volcanic ash.
  - Silicate materials can be precipitated out of a solution in marine waters, or produced as a byproduct of water dwelling organisms. Diatoms and radiolarians extract it from their surroundings and use it to grow silica-rich skeletons. When these organisms die and settle to the bottom, their skeletons provide the silica source for the chert to develop.
  - Large beds of chert have been found to develop in association with lava flows and volcanic ash. It is thought that the chert is the produced by the decomposition of volcanic ash.
- Chert occurs in a variety of forms including flint, jasper, and agate.
- Chert is a very hard rock that generally breaks along conchoidal fractures, this characteristic makes it possible to carve sharp-pointed edges onto the rock. Native American's used chert to create arrowheads that were attached to primitive spears, arrows, and knives.
- Flint is the most common form of chert. It is often a dark, glassy, colored rock that forms as nodules embedded in limestone. The dark color of the chert comes from the organic matter it contains.
- Jasper is a red variety of chert that gets its color from iron oxide (Fig. 4-13a).
- Agate is a banded form of chert that may contain several different colors layered throughout the rock (Fig. 4-13b).



Figure 4-13 Jasper (a) Agate forming inside a coral (b).

#### d) Coal

Coal is different from other rocks because it is composed of organic material (Fig. 4-14). Coal is made almost entirely of plant material and other organic deposits that have been buried for millions of years under elevated conditions of heat and pressure. Although the chemical



Figure 4-14 Coal

composition of coal changes from its organic origins, it often retains fossilized imprints of plant leaves, bark, wood, and organisms that lived during the time the organic materials were deposited. It requires very specific environmental conditions for plant material to become coal. The organic material must be deposited in an anoxic (oxygen free) environment to prevent it from decomposing. Most coal beds originated in swampy, saturated, environments.

### 4.7.3 Chemical Inorganic Sedimentary Rocks

#### a) Dolostone

- Typically formed secondarily from limestone, consists of the mineral dolomite.
- Dolomite, also known as dolostone (Fig. 4-15) and “dolomite rock,” is a sedimentary rock composed primarily of the mineral dolomite,  $\text{CaMg}(\text{CO}_2)_3$ .

- Dolomite is found in sedimentary basins worldwide. It is thought to form by the post depositional alteration of lime mud and limestone by magnesium-rich groundwater.
- Dolomite and limestone are very similar rocks. They share the same color ranges of white-to-gray and white-to-light brown (although other colors such as red, green and black are possible). They are approximately the same hardness and they are both soluble in dilute hydrochloric acid. They are both crushed and cut for use as construction materials and used for their ability to neutralize acids.



Figure 4-15 Dolostone.

### b) Evaporites

Evaporation triggers deposition of chemical precipitates (Examples include rock salt and rock gypsum, Fig. 4-16).

Evaporites are chemical deposits formed when restricted bodies of saline water evaporate, precipitating out a range of



Figure 4-16 Halite and Gypsum

minerals. Evaporite deposits do not involve a single chemical precipitate, instead they consist of chlorides, sulfides, carbonates, and borates. Halite and gypsum are two common examples of mineral precipitates.

## 4.8 Sedimentary Structures

The process of deposition usually imparts variations in layering, bedforms, or other structures that give clues to environment in which deposition occurs. Such things as water depth, current velocity, and current direction can be sometimes be determined from sedimentary structures. Thus,

it is important to recognize various sedimentary structures so that we can interpret the clues that they offer to these conditions. Also, because sedimentary rocks can be deformed by folding and faulting long after the deposition process has ended, it is important to be able to determine which way was up in the rock when it was originally deposited, especially if one is going to use the rocks to determine the sequence of events that occurred or interpret the geologic history of an area. Features that tell us which way was up are often referred to as top and bottom indicators.

Sedimentary structures provide useful information in the interpretation of Earth history.

#### 4.8.1 Types of sedimentary structures

- a- Strata, or beds (most characteristic of sedimentary rocks, (Fig. 4.17a))
- b- Bedding planes that separate strata (Fig. 4.17b)
- c- Cross-bedding (Fig. 4.17c)
- d- Mud cracks (Fig. 4.17d)
- e- Graded beds and Turbidites
- f- Ripple marks (Fig. 4.17e)
- g- Mud cracks, raindrop prints
- h- Bioturbation

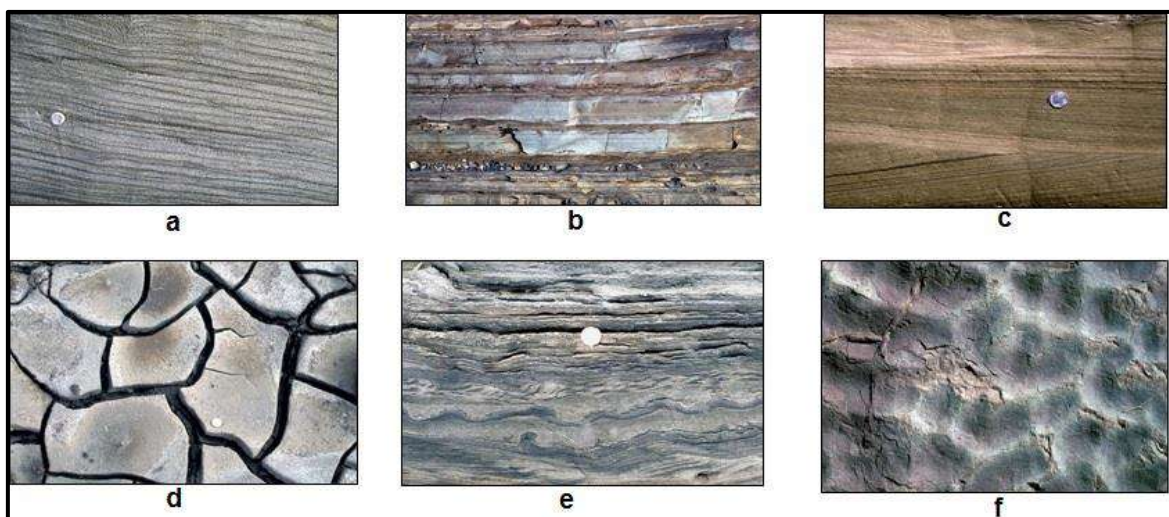


Figure 4-17 Laminations (a) Bedding Planes (b) Cross-Bedding (c) Mud Cracks (d) Ripple Marks (e) Ripples and Mudcracks (f).

## 1) Layering (bedding)

One of the most obvious features of sedimentary rocks and sediment is the layered structure which they exhibit (Fig. 4-18). The layers are evident because of differences



Figure 4-18 Stratification

in mineralogy, clast size, degree of sorting, or color of the different layers. In rocks, these differences may be made more prominent by the differences in resistance to weathering or color changes brought out by weathering. Layering is usually described on the basis of layer thickness as shown in Table (4-3).

Table (4-3) Shows layer name according to its thickness.

| Layer Thickness | Name                | Layer Thickness | Name               |
|-----------------|---------------------|-----------------|--------------------|
| > 300 cm        | Massive             | 3 - 10 cm       | Thinly bedded      |
| 100-300 cm      | Very thickly bedded | 1 - 3 cm        | Very thinly bedded |
| 30 - 100 cm     | Thickly bedded      | 0.3 - 1 cm      | Thickly laminated  |
| 10 - 30 cm      | Mediumly bedded     | <0.3 cm         | Thinly laminated   |

## 2) Graded bedding

Graded bedding means that the grain size within a bed decreases upwards (Fig. 4-19). This type of bedding is commonly associated with so called turbidity currents. Turbidity currents originate on slope between continental shelves and deep sea basins. They are initiated by slope failure (see diagram below), after sediment buildup has steepened the slope for a while, often some high energy event (earthquake) triggers downslope movement of sediment. As this submarine landslide picks up speed the moving sediment mixes with

water, and forms eventually a turbid layer of water of higher density (suspended sediment) that accelerates downslope (may pick up more sediment). When the flow reaches the deep sea basin/deep sea plain, the acceleration by gravity stops, and the flow decelerates. As it slows down the coarsest grains settle out first, then the next finer ones, etc. Finally a graded bed is formed. However, decelerating flow and graded bedding are no unique feature of deep sea sediments (fluvial sediments -- floods; storm deposits on continental shelves), but in those other instances the association of the graded beds with other sediments is markedly different (mud-cracks in fluvial sediments, wave ripples in shelf deposits).

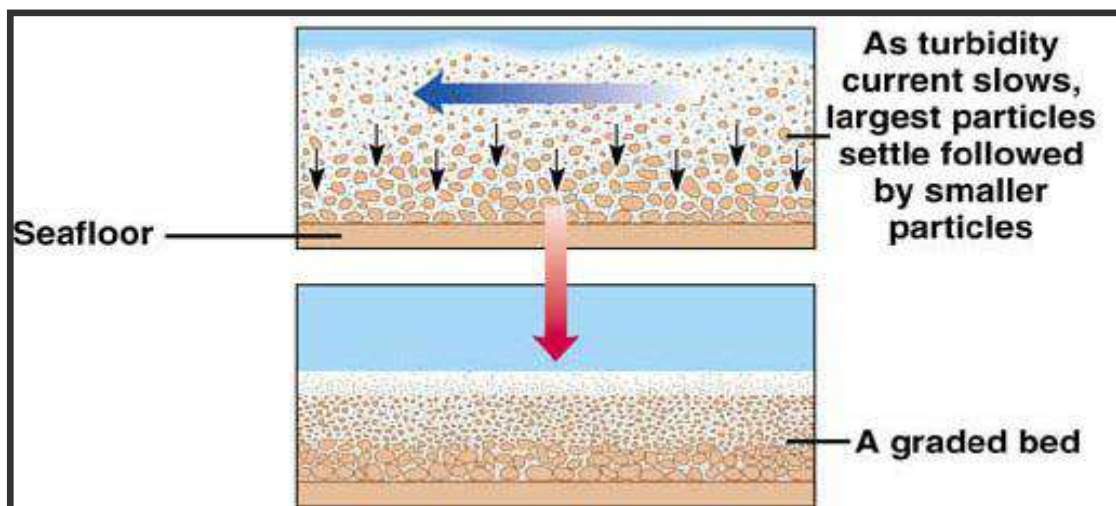


Figure 4-19 A graded bed in Tonga, southwestern Pacific. Larger grains collected near the bottom, and smaller particles settled near the top of the bed.

### 3) Cross-bedding

Cross bedding is a feature that occurs at various scales, and is observed in conglomerates and sandstones (Fig. 4-20). It reflects the transport of gravel and sand by currents that flow over the sediment surface (e.g. in a river channel). When cross-bedding forms, sand is transported as sand-dune like bodies (sandwave), in which

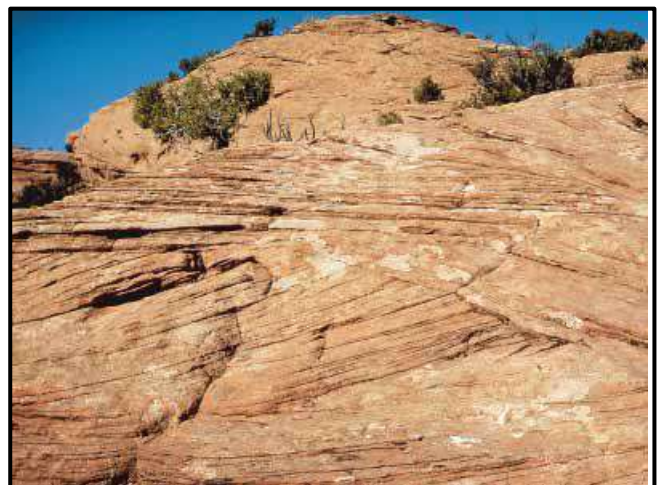


Figure 4-20 Cross-bedded sandstone

sediment is moved up and eroded along a gentle upcurrent slope, and redeposited (avalanching) on the downcurrent slope (see upper half of picture at left). After several of these bedforms have migrated over an area, and if there is more sediment deposited than eroded, there will be a buildup of cross-bedded sandstone layers. The inclination of the cross-beds indicates the transport direction and the current flow (from left to right in our diagram). The style and size of cross bedding can be used to estimate current velocity, and orientation of cross-beds allows determination direction of paleoflow.

#### 4) Ripple marks

Ripple marks (Fig. 4-21) are characteristic of shallow water deposition. They are caused by waves or winds piling up the sediment into long ridges. Asymmetrical ripple marks (Fig. 4-22a) can give an indication of current direction when formed in water, and when formed by wind, give wind direction. Symmetrical ripples (Fig. 4-22b) form when the water moves back and forth. Symmetrical ripple marks occur in environments where there is a steady back and forth movement of the water, such as tidal action.



Figure 4-21 Ripple marks in billion-year-old mud rocks

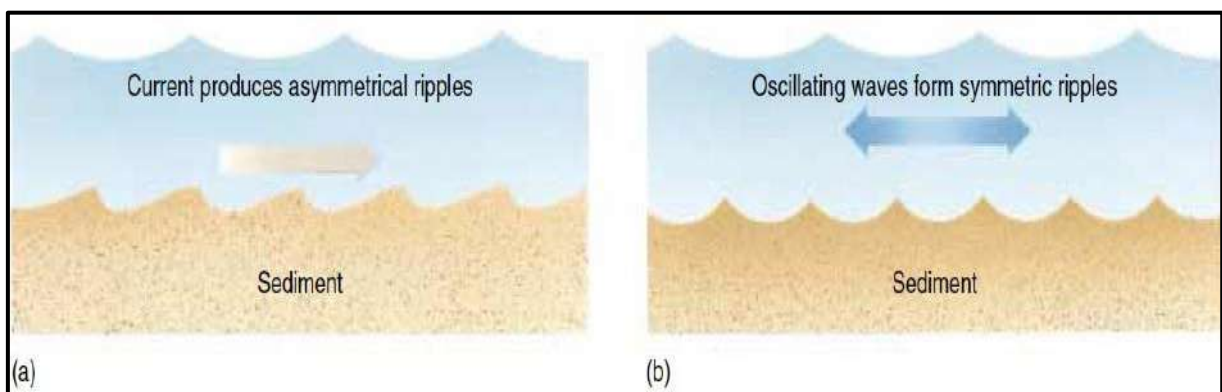


Figure 4-22 (a) Asymmetric ripple marks form when wind or currents move continuously in the same direction. (b) Symmetric ripple marks form when waves oscillate back and forth.

### 5) Mud cracks

These structures result from the drying out of wet sediment at the surface of the Earth (Fig. 4-23). The cracks form due to shrinkage of the sediment as it dries. In cross section the mud cracks tend to curl up, thus becoming a good top/bottom indicator. The presence of mud cracks indicates that the sediment was exposed at the surface shortly after deposition, since drying of the sediment would not occur beneath a body of water.



Figure 4-23 Mud cracks form when wet mud dries and shrinks

### 6) Casts and molds

Any depression formed on the bottom of a body of water may become a mold for any sediment that later gets deposited into the depression. The body of sediment that takes on the shape of the mold is referred to as a cast.

- Load Casts - These are bulbous protrusions that are formed when compaction causes sediment to be pushed downward into softer sediment.
- Flute Casts (Sole Marks) - Flutes are elongated depressions that form on the bottom of a body water as the current erodes. The flutes may form a mold into which new sediment is deposited. Preservation of the overlying sediment as a cast result in flute casts, which are sometimes referred to as sole marks. Flute casts are excellent indicators of current direction and tops/bottoms of beds.

**REVIEW QUESTIONS**

1. Why do sedimentary rocks cover more than 75 percent of the Earth's land surface when they compose only 5 percent of the volume of the continental crust?
2. List the five stages in the formation of sedimentary rocks.
3. How do clastic sediments differ from dissolved sediment and chemical sediment?
4. Define bioclastic sediment.
5. In what ways are clastic sediments modified during transport?
6. Why is the maximum size of particles transported by wind finer than the maximum size transported by streams?
7. Why is the maximum size of particles transported by glaciers coarser than the maximum size transported by streams?
8. Describe how loose clastic sediment becomes lithified to form hard rock.
9. What is pore space in a clastic sediment? How is it modified during lithification?
10. What is the difference between conglomerate and breccias?
11. Why are most sandstones made up predominantly of quartz?
12. In what geologic environment does arkose form?
13. How do shale, sandstone, and limestone differ from one another?
14. How do shales acquire fissility? Why do mudstones lack that property?
15. How do limestones form?
16. What is bioclastic limestone?
17. How do dolomites form? What is the dolomite problem?
18. How does coal form?
19. How do evaporites form?
20. What does cross-bedding in a sandstone tell you about depositional environment?
21. What do the presence of mud cracks in a mudstone tell you about the depositional environment?

**DISCUSSION QUESTIONS**

1. Field geologists sometimes come upon large sections of sedimentary rocks that have been turned upside down by tectonic activities. How would you use sedimentary structures to determine whether a sequence of sedimentary rocks is upright or overturned?
2. On a field trip you discover a sequence of sedimentary rocks composed of thin black shales containing marine fossils interbedded with layers of gypsum and halite. What can you deduce about the depositional environment of these rocks?
3. Large portions of the Canadian Rockies are composed of limestone and shale. From this information alone, what can you tell about the geologic history of the region?
4. All the large-scale depositional environments are marine, while small-scale depositional environments can be either marine or terrestrial. Explain.
5. What types of sedimentary structures would you expect to find under the following circumstances? a. A catastrophic flood washes a huge amount of mixed sediment into a lake. b. Sand accumulates in a dry, windy environment. The prevailing wind direction shifts periodically, over a few million years. c. Mud collects on the bottom of a large, shallow, inland sea.
6. Why is shale the most abundant sedimentary rock?
7. Would you expect to find large quantities of sedimentary rocks on the Moon? Why or why not? If you do expect to find them, what types would you expect?

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# Chapter 5

## METAMORPHIC ROCKS

### Goals:

1. *Identify Metamorphism*
2. *Agents of metamorphism*
3. *Types of metamorphism*
4. *Textures of metamorphic rocks*
5. *Classification of metamorphic rocks*
6. *Metamorphic grade*
7. *Economic importance of metamorphic rocks*

### 5.1 Metamorphism

The word Metamorphism comes from the Greek: meta = change, morph= form, so metamorphism means to change form. The Metamorphism is the solid-state recrystallization of pre-existing rocks due to changes in physical and chemical conditions, primarily heat, pressure, and the introduction of chemically active fluids. Mineralogical, chemical and crystallographic changes can occur during this process. Changes at or just beneath Earth's surface due to weathering and/or diagenesis are not classified as metamorphism. Simply, metamorphic rocks are rocks that have undergone a change from their original form due to changes in temperature, pressure or chemical alteration. **Metamorphism** principally formed in solid state and before melting. It can be considered to be isochemical, except perhaps for removal or addition of volatiles (H<sub>2</sub>O, CO<sub>2</sub>). The process of extensive chemical changes during transformation is known as metasomatism

### 5.2 Agents of metamorphism

The agents of metamorphism are temperature or heat, pressure and chemically active fluids. These agents can be summarized as temperature (T), pressure (P) and fluids.

### i. Temperature

Temperature (T) has many sources. The most common source is geothermal gradient which is the rate of temperature changes with depth (the temperature rises some 30 degrees per kilometer). The geothermal gradient is closely related to heat flow through the crust. Also, heat flow is mostly due to heat flow from the mantle, radioactive decay and rising bodies of magma. Increase of temperature cause the grains of metamorphosed rock to recrystallize (i.e. increase in grain-size).

The temperature lower limit of metamorphism is considered to be 100 - 200 °C to exclude diagenetic changes, due to compaction, which result in sedimentary rocks. The maximum temperature for metamorphism is typically 700 - 900 °C, depending on the pressure and on the composition of the rock. The main sources of Temperature for metamorphism include the following:

- a. Heat flowing into the base of the crust from the mantle.
- b. Heat brought into the crust by rising magma bodies.
- c. Heat generated from radioactive decay.
- d. The effect of rapid uplift and erosion.
- e. Heat related to burial effect and geothermal gradient.

### ii. Pressure

Pressure (P) is a measure of the force per unit area to which a rock is subjected. It depends on the weight of overlying rock (depth). The pressure due to the weight of the overlying rocks is known as the lithostatic pressure (Fig.5-1a). It is assumed that this pressure is uniform in all directions and it is used to approximate the total confining pressure to which a rock was subjected. However, lithostatic pressure does not itself cause deformation (Fig.5-1b and 5-2a). Deformation (i.e. textural changes (Fig.5-2b) are a result of unequal stresses acting on a rock. (i.e. deviatoric or directive stress).

The main sources of pressure applied during metamorphism are the following:

- a. burial influence of an overlying rock column
- b. Plate tectonic and movement of plate segments
- c. Geobaric gradient which mean the change of pressure with depth it has an average = 0.285 kbar/km or nearly 1kbar/3km).

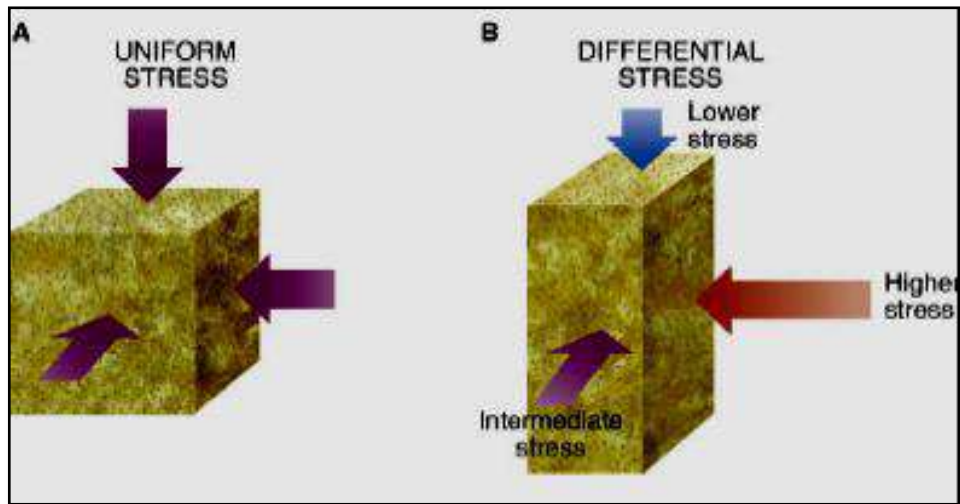


Figure 5-1 Types of pressures applied on metamorphic rocks [1].

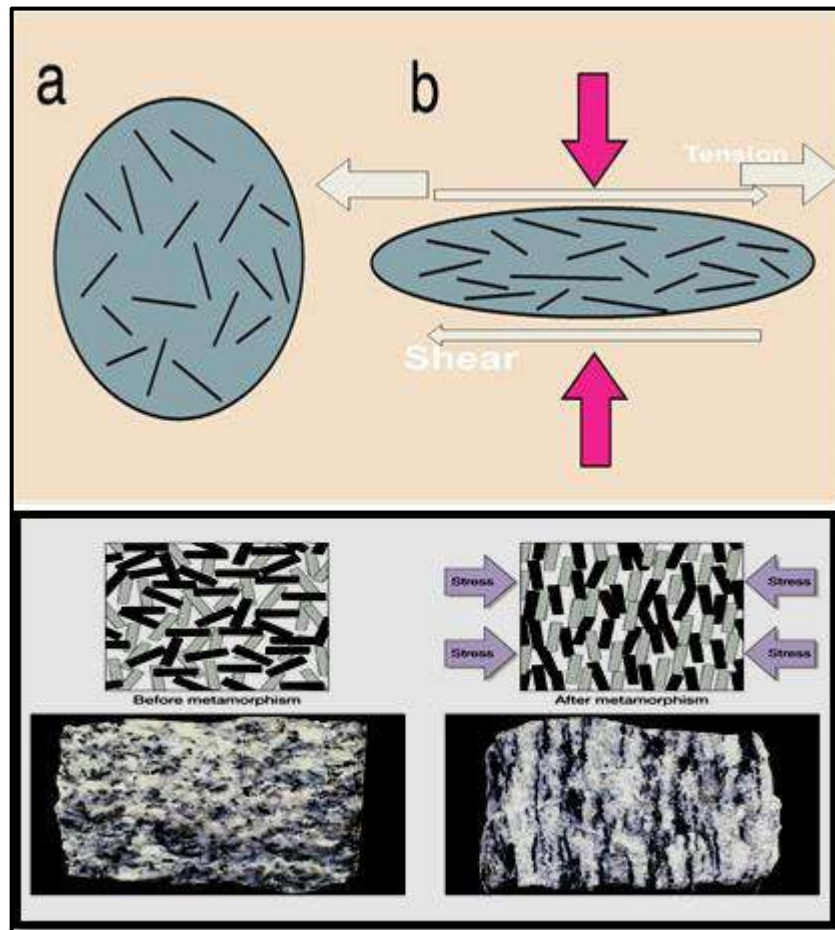


Figure 5-2 Textural change due to the pressure during metamorphism [2].

### iii. Fluids

At least a small volume of water and other fluids is present in virtually all rocks, and because water allows materials to move more easily, the presence of fluids makes metamorphism easier. The numerous open spaces between

grains in a sedimentary rock and the tiny fractures in igneous and metamorphic rocks are called pores. All pores are filled with a watery fluid. At higher temperature this fluid exists in a vapor form ( $\text{H}_2\text{O}$ ,  $\text{CO}_2$ ,  $\text{CO}$ ,  $\text{CH}_4$ ) and fluid dissolve ions from mineral grains with which it has direct contact. Some of the dissolved ions move from the fluid to the new minerals that are growing in the metamorphic rock. Other dissolved ions move out of the minerals in the rock and into the fluid. The intergranular fluid serves as a transporting medium to speed up the chemical reactions taking place. The main sources of fluid phase include ascending fluids from magma chamber or descending fluids of the meteoric water.

### 5.3 Metamorphic changes

Metamorphism commonly alters both the texture and mineral content of a rock.

#### i. Textural changes

As a rock undergoes metamorphism, some mineral grains grow larger and others shrink. The shapes of the grains may also change. For example, fossils give fossiliferous limestone its texture (Fig. 5-3). Both the fossils and the cement between them are made of small calcite crystals.



Figure 5-3 Fossils give this limestone its fossiliferous texture.

If the limestone is buried and heated, some of the calcite grains grow larger at the expense of others. In the process, the fossiliferous texture is destroyed.

Metamorphism transforms limestone into a metamorphic rock called marble (Fig. 5-4). Like the fossiliferous limestone, the marble is



Figure 5-4 Metamorphism has destroyed the fossiliferous texture of the limestone in Figure 8-1 and replaced it with the large, interlocking calcite grains of marble.

composed of calcite, but the texture is now one of large interlocking grains, and the fossils have vanished.

## ii. Mineralogical changes

As a general rule, when a parent rock (the original rock) contains only one mineral, metamorphism transforms the rock into one composed of the same mineral but with a coarser texture. The mineral content does not change because no other chemical components are available during metamorphism. Limestone converting to marble is one example of this generalization. Another is the metamorphism of quartz sandstone to quartzite, a rock composed of recrystallized quartz grains.

In contrast, metamorphism of a parent rock containing several minerals usually forms a rock with new and different minerals and a new texture. For example, a typical shale contains large amounts of clay, as well as quartz and feldspar (Fig. 5-5). When heated, some of those minerals decompose, and their atoms recombine to form new minerals such as mica, garnet, and a different kind of feldspar. Figure 5-6 shows a rock called hornfels that formed when metamorphism altered both the texture and minerals of shale.

If migrating fluids change the chemical composition of a rock, new minerals invariably form.



Figure 5-5 Shale is a very fine-grained sedimentary rock, containing clay, quartz, and feldspar.



Figure 5-6 Hornfels forms by metamorphism of shale.

### iii. Deformation and foliation

Changes in temperature, pressure, or the chemical environment alter a rock's texture during metamorphism. But another factor also causes profound textural changes. Metamorphic rocks commonly form in large regions of the Earth's crust near a subduction zone, where two tectonic plates converge. The tectonic forces crush, break, and bend rocks in this environment as the rocks are undergoing metamorphism. This combination of metamorphism and deformation creates layering in the rocks.

Micas are common metamorphic minerals; they form as many different parent rocks undergo metamorphism. Recall from Chapter 3 that micas are shaped like pie plates. When metamorphism occurs without deformation, the micas grow with random orientations, like pie plates flying through the air (Fig. 5-7). However, when metamorphism and deformation occur together, the micas develop a parallel orientation. This parallel alignment of micas (and other minerals) produces the metamorphic layering called foliation (Fig. 5-8).

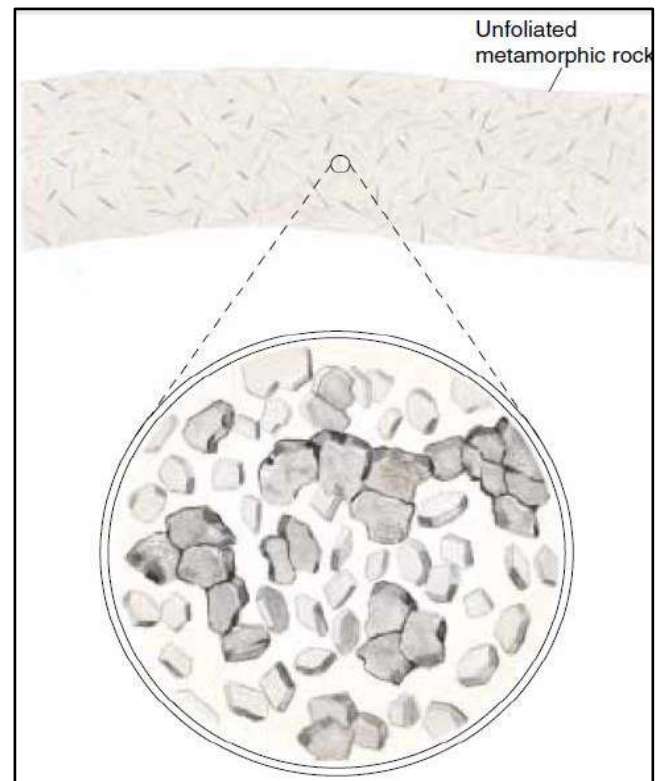


Figure 5-7 When metamorphism occurs without deformation, platy micas grow with random orientations.

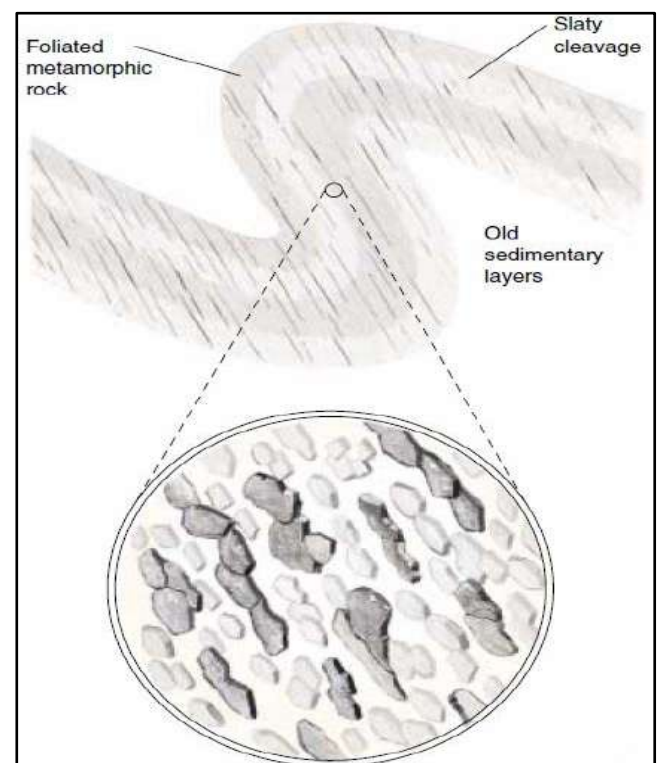


Figure 5-8 When deformation accompanies metamorphism, platy micas orient in a parallel manner to produce metamorphic layering called foliation.

The layers range from a fraction of a millimeter to a meter or more in thickness. Metamorphic foliation can resemble sedimentary bedding but is different in origin.

Micas and other platy minerals orient at right angles to the tectonic force squeezing the rocks. Pencil-shaped minerals such as amphiboles align in a similar manner. When horizontal forces deform shale into folds during metamorphism, the clays decompose and micas grow with their flat surfaces perpendicular to the direction of squeezing. As a result, the rock develops vertical foliation perpendicular to the horizontal force. Many metamorphic break easily along the foliation planes. This parallel fracture pattern is called slaty cleavage. In most cases, slaty cleavage cuts across the original sedimentary bedding.

## 5.4 Metamorphic grade

**Metamorphic grade** expresses the intensity of metamorphism that affected a rock. Because temperature is the most important factor in metamorphism, metamorphic grade closely reflects the highest temperature attained during metamorphism. Geologists can interpret the metamorphic grade of most rocks because many metamorphic minerals form only within certain temperature ranges.

The temperature in shallow parts of the Earth's crust rises by an average of 30°C for each kilometer of depth. It continues to rise in deeper parts of the crust and in the mantle, but at a lesser rate. The rate at which temperature increases with depth is called the **geothermal gradient**. Consequently, the metamorphic grade of many rocks is related to the depth to which they were buried (Fig. 5–9). Low-grade metamorphism occurs at shallow depths, less than 10 to 12 kilometers beneath the surface, where temperature is below 350°C. High-grade conditions are found deep within continental crust and in the upper mantle, 40 or more kilometers below the Earth's surface. The temperature in these regions is 600°C or hotter and is near the melting point of rock. High-grade metamorphism can occur at shallower depths, where magma rises to a shallow level of the Earth's crust.

### i. The rate of metamorphism

A rule of thumb among laboratory chemists is that the speed of a chemical reaction doubles with every 10°C rise in temperature. Thus, reactions occur slowly in a cold environment, but rapidly in a hot one. For the same reason, metamorphic changes occur slowly at low temperature, but much faster at high temperature. For example, clay minerals in 20-million-year-old shale buried to a depth of 2 to 3 kilometers in the Mississippi River delta show

mineralogical changes at 50°C, about the temperature of a cup of hot coffee. Elsewhere, similar clays at the same temperature, but only 1 million years old, show no changes. Thus, metamorphism can occur at temperatures as low as 50°C, but the reactions require millions of years.<sup>1</sup> In contrast, geologists routinely produce metamorphic reactions in the laboratory at temperatures above 500°C in a few days.

The upper limit of metamorphism is the point at which rocks melt to form magma. That temperature varies depending on rock composition, pressure, and amount of water present, but it is between 600° and 1200°C for most rocks. A rock heated to its melting point creates magma, which forms igneous rocks when it solidifies.<sup>1</sup> Metamorphism refers only to changes that occur *without* melting.

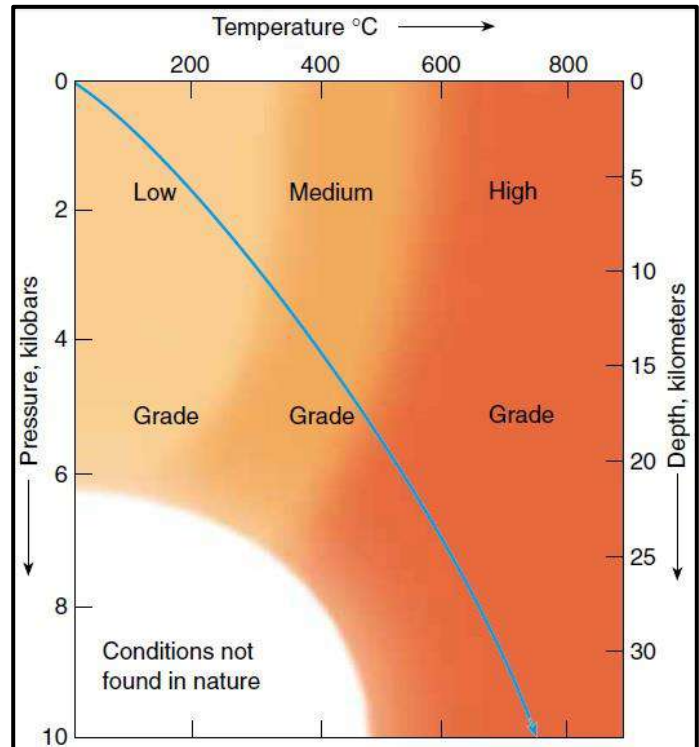


Figure 5-9 Metamorphic grade commonly increases with depth because the Earth becomes hotter with increasing depth. The blue line traces an average geothermal gradient: the path of temperature and pressure in an average part of continental crust.

<sup>1</sup> Many geologists call mineral reactions that occur between 50°C and 250°C diagenesis and reserve the term metamorphism for changes that occur at temperatures above about 250°C.

If you are studying a metamorphic rock exposed on the Earth's surface, it is impossible to measure the temperature and pressure at which it formed because the rock may have formed several kilometers beneath the surface and millions or even a few billion years ago. However, scientists estimate the temperature and pressure at which the rock formed using an experimental approach. They heat and apply pressure to chemical compounds similar to the composition of the rock until new minerals form. They then repeat the experiment at different temperatures and pressures until they duplicate the mineral content of the real rock. Thus, by comparing natural rocks with experimental results, scientists determine the temperature and pressure of metamorphism within 10° or 20°C and a fraction of a kilobar. This experimental approach is not reliable for the slow reactions that form low-grade metamorphic rocks, but it works well for determining the temperature and pressure at which higher grade rocks formed.

Relative terms such as high-temperature or low-pressure are often used to refer to the physical conditions of metamorphism but without precise designation of the temperatures and pressures involved. In order to maintain similarity of meaning it is proposed that the whole spectrum of temperature conditions encountered in metamorphism be divided into five parts, and the corresponding metamorphism may be designated as: very low-, low-, medium-, high-, very high-temperature metamorphism. Likewise the broad range of pressure conditions may be divided into five to give: very low-, low-, medium-, high-, very high-pressure metamorphism.

In the highest part of the very high pressure ultra-high-pressure metamorphism may be distinguished. In a P-T grid the above divisions are represented by five isothermal and five isobaric bands respectively.

Circumstances of temperature and pressure may be combined together, for example, medium-pressure/low temperature metamorphism. Related terms may be used to describe the ratio of pressure to temperature during metamorphism. The whole range of P/T ratios encountered may be divided into three fields (radial sectors in a PT diagram) to give: low, medium, high,

P/T metamorphism (Fig. 5-10), in addition terms such as very low and very high P/T metamorphism may also be used.

Metamorphic grades are a general term for describing the relative P-T conditions under which the metamorphic rocks form. The grades could be subdivided into:

- Very low grade
- Low grade
- Medium grade
- High grade
- Very high grade

Depending on whether metamorphism is accompanied by increasing or decreasing temperature two types can be distinguished.

- a. Prograde (= progressive) metamorphism is a metamorphism giving rise to the formation of minerals which are typical of a higher grade (i.e. higher temperature) than the former phase assemblage (Fig. 5-11).
- b. Retrograde (= retrogressive) metamorphism is a metamorphism giving rise to the formation of minerals which are typical of a lower grade (i.e. lower temperature) than the former phase assemblage.

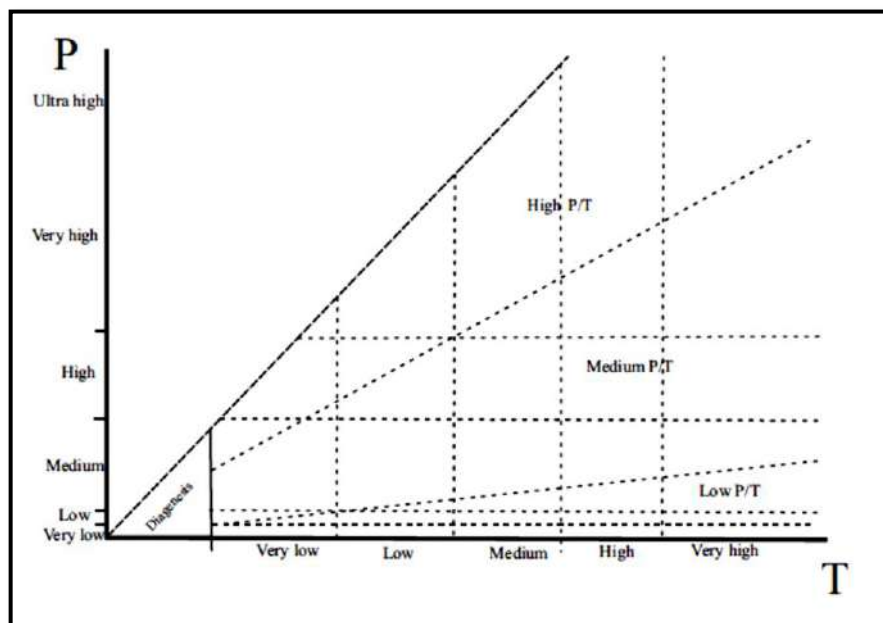


Figure 5-10 Schematic representation in P-T space of the five isothermal, five isobaric bands and three P/T radial sectors

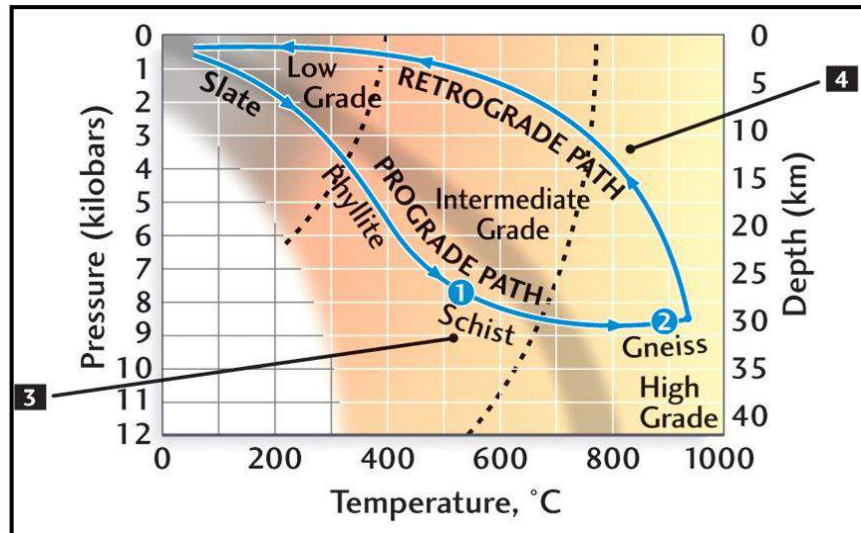


Figure 5-11 Schematic P-T-t paths of monometamorphism prograde and retrograde metamorphisms.

## ii. Metamorphic facies

Imagine that you are studying the outcrop of metamorphic rock. One striking feature of this outcrop is that it contains two very different rocks, one consisting mostly of black minerals and the other of white ones. Recall that temperature, pressure, and composition control the mineral content of a metamorphic rock. You know that the metamorphic temperature and pressure must have been identical for the two rocks because they are so close together. Therefore, the difference in mineral content must result from a compositional contrast between the two rocks.

Ideally, all metamorphic rocks that formed under identical temperature and pressure conditions are grouped together into a single category called a **metamorphic facies**. Each rock differs from others in the same facies by having a different chemical composition and therefore a different mineral assemblage. Metamorphic facies differ from one another in that they form under different conditions of temperature and pressure. Each facies is given a name derived from a mineral and/or texture commonly found in rocks of that facies (Fig. 5-12).

Think of the white and black rocks shown in Figure 8–16. Initially, the white rock layers were limestone, and the black layers were shale. Limestone has a different composition from that of shale. Both rocks were metamorphosed at the temperature and pressure of the amphibolite facies. The limestone became marble. The shale converted to schist. Each contains different minerals because of their different original compositions. Both rocks, however different they may be, belong to the amphibolite facies because they both formed under the same temperature and pressure conditions.

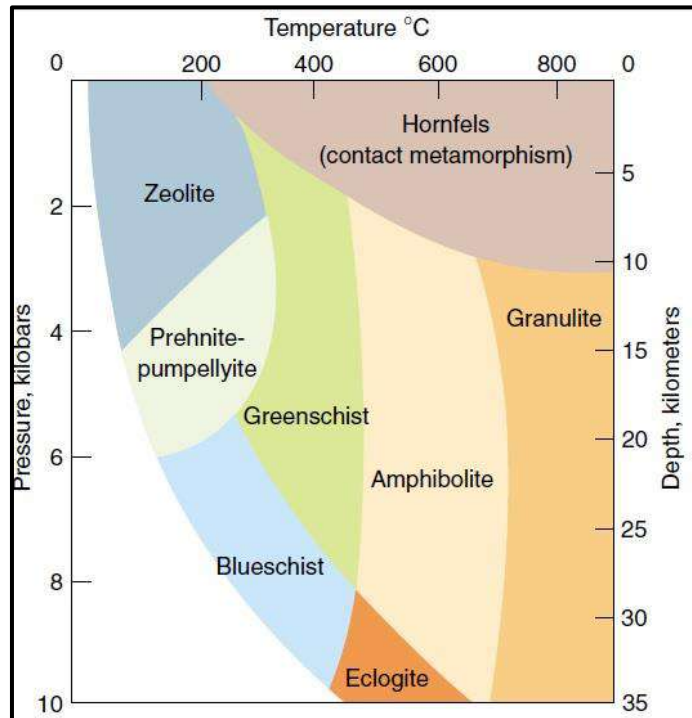


Figure 5–12 The names and metamorphic conditions of the metamorphic facies.

## 5.5 Types of metamorphism and metamorphic rocks

Recall that three conditions cause metamorphism: rising temperature, rising pressure, and changing chemical environment. In addition, tectonic deformation develops foliation and thus strongly affects the texture of a metamorphic rock. These conditions occur in four geologic environments.

### i. Contact metamorphism

**Contact metamorphism** occurs where hot magma intrudes cooler country rock. The country rock may be of any type—sedimentary, metamorphic, or igneous. The highest-grade metamorphic rocks form at the contact, closest to the magma. Lower-grade rocks develop farther out (Fig. 5–13). A metamorphic halo around a pluton can range in width from less than a meter to hundreds of meters, depending on the size and temperature of the intrusion and the effects of water or other fluids. Contact metamorphism

commonly occurs without deformation. As a result, the metamorphic minerals grow with random orientations—like the pie plates flying through the air—and the rocks develop no metamorphic layering.

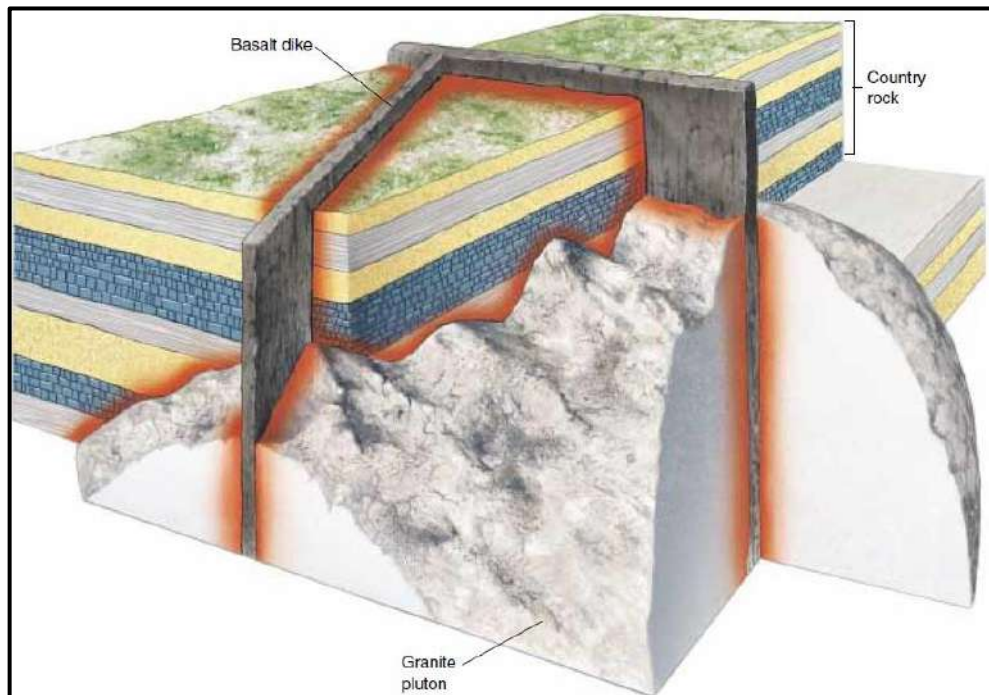


Figure 5–13 A halo of contact metamorphism in red surrounds a pluton. The later intrusion of the basalt dike metamorphosed both the pluton and the sedimentary rock.

The zone of the contact metamorphism is known as contact aureole (Fig. 5-13) which varies from meter to few kilometers in width. The width of the zone depends up on:

- 1- Volume of the magmatic bodies
- 2- Nature of the magmatic bodies (basaltic or granitic composition)
- 3- The intrusion depth of magmatic bodies
- 4- Type of country rocks (Shale, limestones or igneous rocks)
- 5- Structures of the country rocks (cracks and fissures)

### **Common Contact Metamorphic Rocks**

The hornfels shown in Figure 6–6 is a hard, dark, finegrained rock usually formed by contact metamorphism of shale. Mica and chlorite are common in the cooler, outer parts of a hornfels halo. Hornblende and other amphiboles occur in the middle of the halo, and pyroxenes can form next to the pluton, in the highest-temperature zone. Quartz and feldspar are common throughout the halo, because they are stable over a wide temperature range.

## ii. Burial metamorphism

**Burial metamorphism** results from deep burial of rocks in a sedimentary basin. A large river carries massive amounts of sediment to the ocean every year, where it accumulates on a delta. Over tens or even hundreds of millions of years, the weight of the sediment becomes so great that the entire region sinks isostatically, just as a canoe sinks when you climb into it. Younger sediment may bury the oldest layers to a depth of more than 10 kilometers in a large basin.

Pressure is commonly expressed in kilobars. One kilobar is approximately equal to 1000 times the pressure of the atmosphere at sea level.<sup>2</sup> Because rocks are heavy, pressure within the Earth increases rapidly with depth, at a rate of about 0.3 kilobar per kilometer. Over time, temperature and pressure increase within the deeper layers until burial metamorphism begins.

Geologists have studied sedimentary basins in detail because most of the world's oil and gas form in them. Thousands of wells have been drilled into the Mississippi River basin, where burial metamorphism is occurring today. Temperature measurements made in the wells (the deepest of which reaches a depth of about 8 kilometers), combined with rock samples recovered as the wells were drilled, allow geologists to identify the mineralogical changes that occur with increasing depth and temperature.<sup>2</sup>

No metamorphic changes occur in the upper 2 kilometers of the Mississippi delta sediment. In this zone, pressure compacts the clay-rich mud and squeezes most of the water from the sediment. The water rises and returns to the ocean.

At about 2 kilometers, however, where the temperature reaches 50°C,<sup>3</sup> the original clay minerals decompose, and their components recombine to form new, different clays. At greater depths and higher temperatures, the clays

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<sup>2</sup> By international agreement, geologists now express pressure in units of *gigapascals* (Gpa). One Gpa is equal to 10 kilobars. We continue to use kilobars in this text because it is a more familiar unit of pressure.

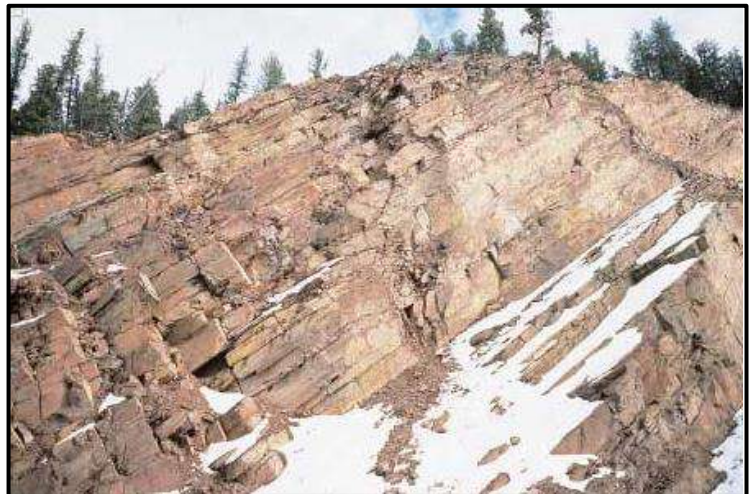
<sup>3</sup> 50°C does not correspond to a depth of 2 kilometers in a region with a normal geothermal gradient. The gradient in these sediments is abnormally low because shallow parts of the delta are filled with young, cold sediment.

continue to react and change character. At the greatest depths attained in the basin, corresponding to temperatures of about 250°C to 300°C, the clay minerals have completely transformed to mica and chlorite. Similar metamorphic reactions are occurring today in the sediments underlying many large deltas, including the Amazon Basin on the east coast of South America and the Niger River delta on the west coast of Africa.

Burial metamorphism occurs without tectonic deformation. Consequently, metamorphic minerals grow with random orientations and, like contact metamorphic rocks, burial metamorphic rocks are unfoliated.

### ***Common Burial Metamorphic Rocks***

Because of the lack of deformation, rocks formed by burial metamorphism often retain sedimentary structures. Shale and siltstone become harder and better lithified to form argillite (Fig. 5–14), which looks like the parent



rock although new minerals have replaced the original ones. Quartz sandstone becomes quartzite. When sandstone is broken, the fractures occur in the cement between the sand grains. In contrast, quartzite becomes so firmly cemented during metamorphism that the rock fractures through the grains. Burial metamorphism converts limestone and dolomite to marble.

### **iii. Regional metamorphism**

**Regional metamorphism** occurs in and near a subduction zone, where tectonic forces build mountains and deform rocks. It is the most common and widespread type of metamorphism and affects broad regions of the Earth's crust.

Figure 5–15 shows magma forming in a subduction zone, where oceanic lithosphere is sinking beneath a continent. As the magma rises, it heats large regions of the crust. The high temperatures cause new metamorphic minerals to form throughout the region. At the same time, the tectonic forces squeeze and deform rocks. The rising magma further deforms the hot, plastic country rock as it forces its way upward. As a result of all of these processes acting together, regionally metamorphosed rocks are strongly foliated and are typically associated with mountains and igneous rocks. Regional metamorphism produces zones of foliated metamorphic rock tens to hundreds of kilometers across.

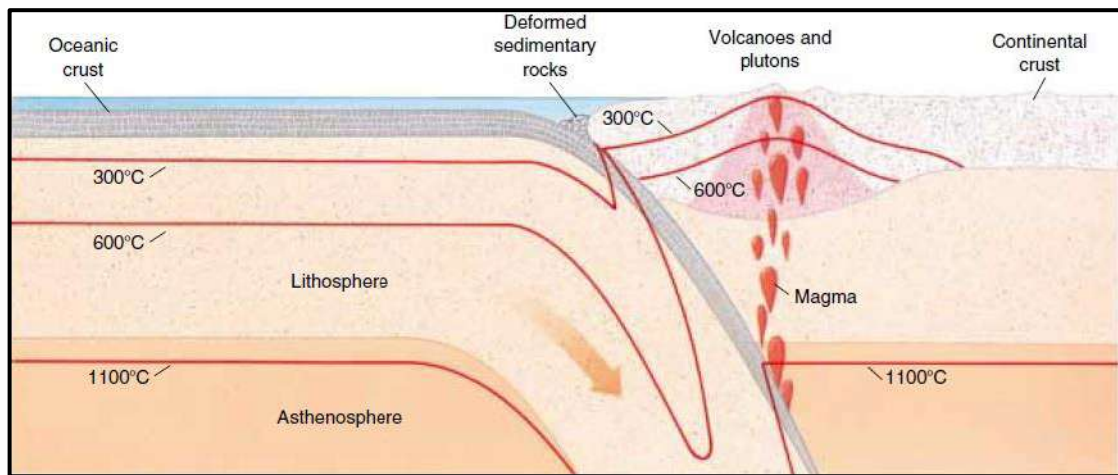


**Figure 5–15** Regional metamorphism is common near a subduction zone. The pink shaded area is a zone where rising magma and tectonic force cause abnormally high temperatures and regional metamorphism. The red lines connect points of equal temperature and are called isotherm.

### ***Common Rocks Formed by Regional Metamorphism***

Shale consists of clay minerals, quartz, and feldspar and is the most abundant sedimentary rock. The mineral grains are too small to be seen with the naked eye and can barely be seen with a microscope. Shale undergoes a sequence of changes as metamorphic grade increases.

Figure 5–16 shows the temperatures at which certain metamorphic minerals are stable. Thus, it shows the sequence in which minerals appear, and then decompose, as metamorphic grade increases. As regional metamorphism begins, the clay minerals break down and are replaced by mica and chlorite. These new, platy minerals grow perpendicular to the direction of tectonic squeezing. As a result, the rock develops slaty cleavage and is called slate. With

rising temperature and continued deformation, the micas and chlorite grow larger, and wavy or wrinkled surfaces replace the flat, slaty cleavage, giving phyllite a silky appearance.

As temperature continues to rise, the mica and chlorite grow large enough to be seen by the naked eye, and foliation becomes very well developed. Rock of this type is called schist. Schist forms approximately at the transition from low to intermediate metamorphic grades. In some schists, crystals of nonplaty minerals such as garnet, quartz, and feldspar give the rock a knotty appearance.

At high metamorphic grades, light- and dark-colored minerals often separate into bands that are thicker than the layers of schist to form a rock called gneiss (pronounced “nice”). At the highest metamorphic grade, the rock begins to melt, forming small veins of granitic magma. When metamorphism wanes and the rock cools, the magma veins solidify to form **migmatite**, a mixture of igneous and metamorphic rock.

Under conditions of regional metamorphism, quartz sandstone and limestone transform to foliated quartzite and foliated marble, respectively.

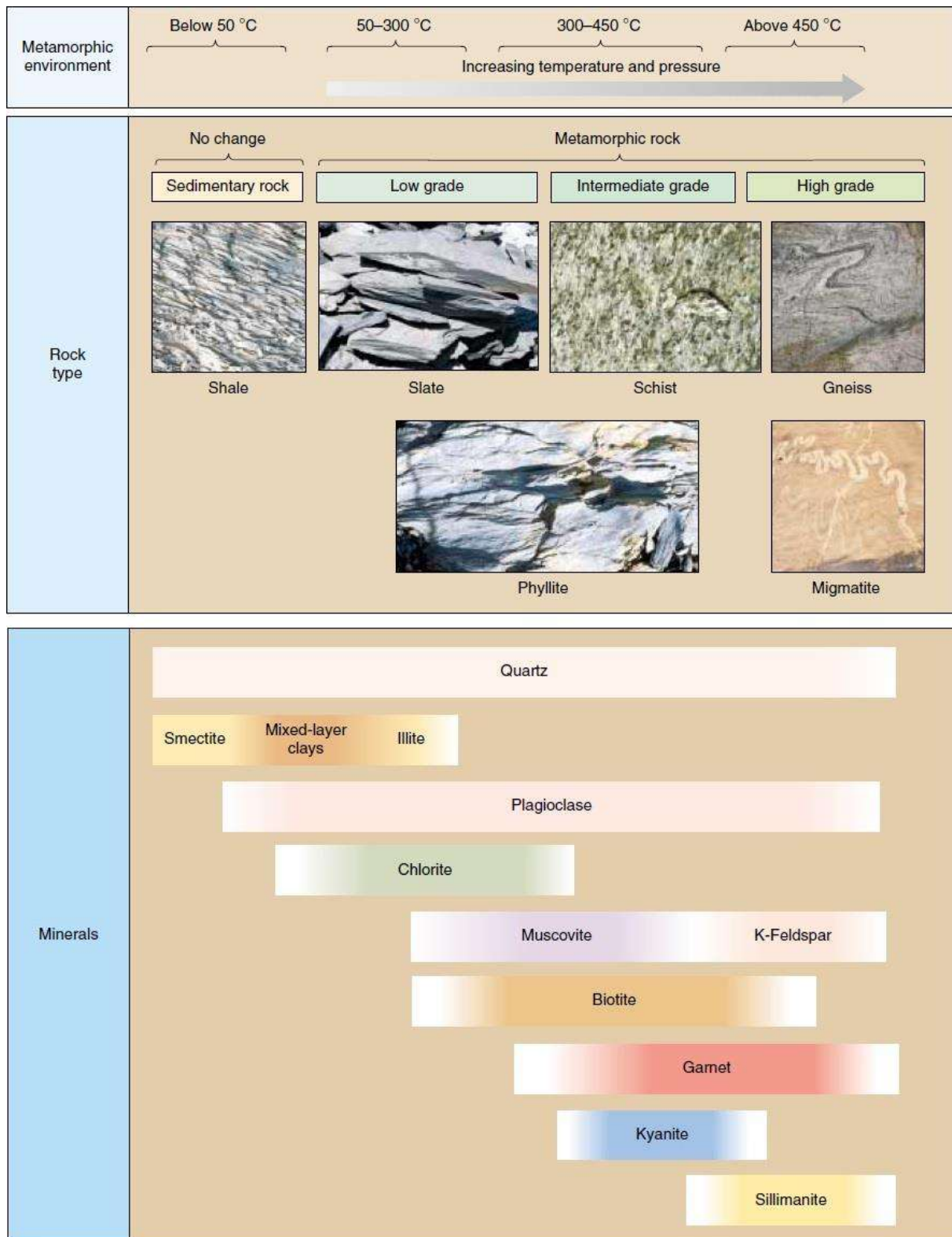


Figure 5–16 Shale changes in both texture and minerals as metamorphic grade increases. The lower part of the figure shows the stability ranges of common metamorphic minerals.

#### iv. Hydrothermal metamorphism

Water is a chemically active fluid; it attacks and dissolves many minerals. If the water is hot, it attacks minerals even more rapidly. **Hydrothermal metamorphism** (also called *hydrothermal alteration* and *metasomatism*)

occurs when hot water and ions dissolved in the hot water react with a rock to change its chemical composition and minerals. In some hydrothermal environments, water reacts with sulfur minerals to form sulfuric acid, making the solution even more corrosive.

The water responsible for hydrothermal metamorphism can originate from three sources. **Magmatic water** is given off by a cooling magma. **Metamorphic water** is released from rocks during metamorphism. Most hydrothermal alteration, however, is caused by circulating ground water—the water that saturates soil and bedrock. Cold ground water sinks through bedrock fractures to depths of a few kilometers, where it is heated by the hotter rocks at depth or, in some cases, by a hot, shallow pluton. Upon heating, the water expands and rises back toward the surface through other fractures (Fig. 5–17). As it rises, it alters the country rock through which it flows.

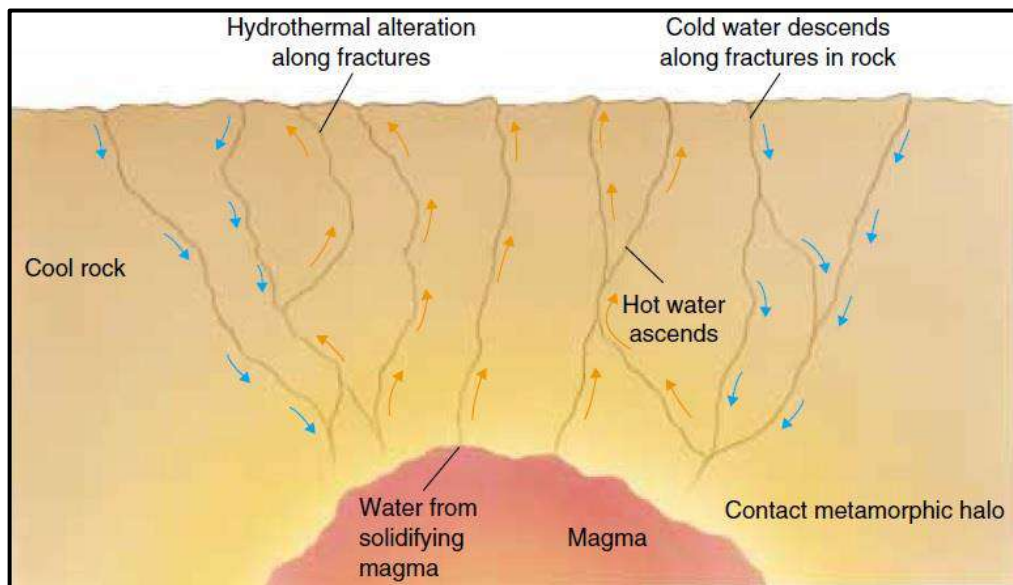


Figure 5–17 Ground water descending through fractured rock is heated by magma and rises through other cracks, causing hydrothermal metamorphism in nearby rock.

### ***Rocks Formed by Hydrothermal Metamorphism***

Hydrothermal metamorphism is like an accelerated form of weathering. As in weathering, feldspars and many other minerals of the parent rock dissolve. The hot water carries away soluble components, such as potassium, sodium, calcium, and magnesium. Aluminum and silicon remain because they have low solubilities. They combine with oxygen and water to form clay

minerals. Hydrothermally metamorphosed rocks often have a white, bleached appearance and a soft consistency because the clays are white and soft.

Most rocks and magma contain low concentrations of metals such as copper, gold, lead, zinc, and silver. For example, gold makes up 0.0000002 percent of average crustal rock, while copper makes up 0.0058 percent and lead 0.0001 percent. Although the metals are present in very low concentrations, hydrothermal solutions sweep slowly through vast volumes of country rock, dissolving and accumulating the metals as they go. The solutions then deposit the dissolved metals when they encounter changes in temperature, pressure, or chemical environment (Fig. 5–18). In this way, hydrothermal solutions scavenge and concentrate metals from average crustal rocks and then deposit them locally to form ore.

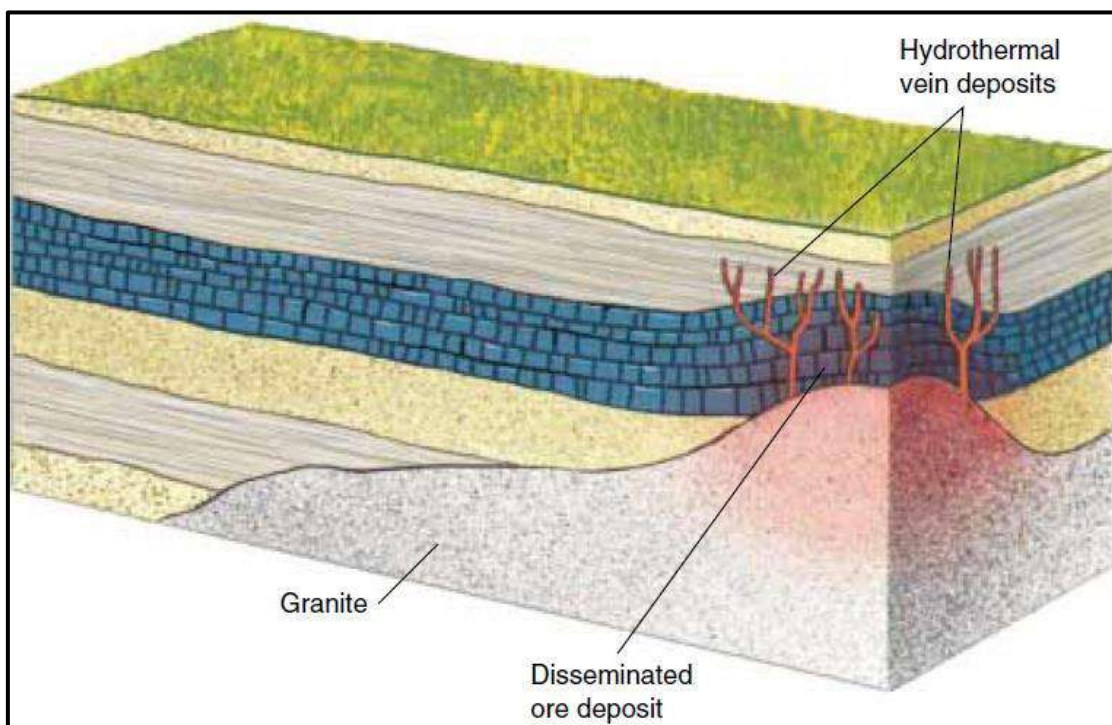


Figure 5–18 Hydrothermal ore deposits form when hot water deposits metals in fractures and surrounding country rock.

## 5.6 Textures of metamorphic rocks

In metamorphic rocks the orientation and arrangement of minerals in differ from a rock to another. In the regional metamorphic the rocks have textural similarities. At the same time, a single rock may contain several textures or textural elements. The most common metamorphic textures are slaty cleavage, schistosity and gniessosity.

**Slaty cleavage**, slates form at low metamorphic grade by the growth of fine grained chlorite and clay minerals. The preferred orientation of these sheet silicates causes the rock to easily break planes parallel to the sheet silicates, causing a slaty cleavage (Fig. 5-19a and b).

**Schistosity** is the parallel arrangement of tabular minerals (mica, amphiboles...etc.) to give a more or less planar fissility. With decrease in grain size, this grades to slaty cleavage (slate). Stretched or flattened grains, such as in quartz in deformed quartzites, may also form schistosity (Fig.5-19c).

**Gneissosity** is the alternation of lighter and darker layers, such as micaceous or amphibole-rich layers with quartz-feldspathic layers. The term is often used to include metamorphic layering regardless of its origin (Fig.5-19d).

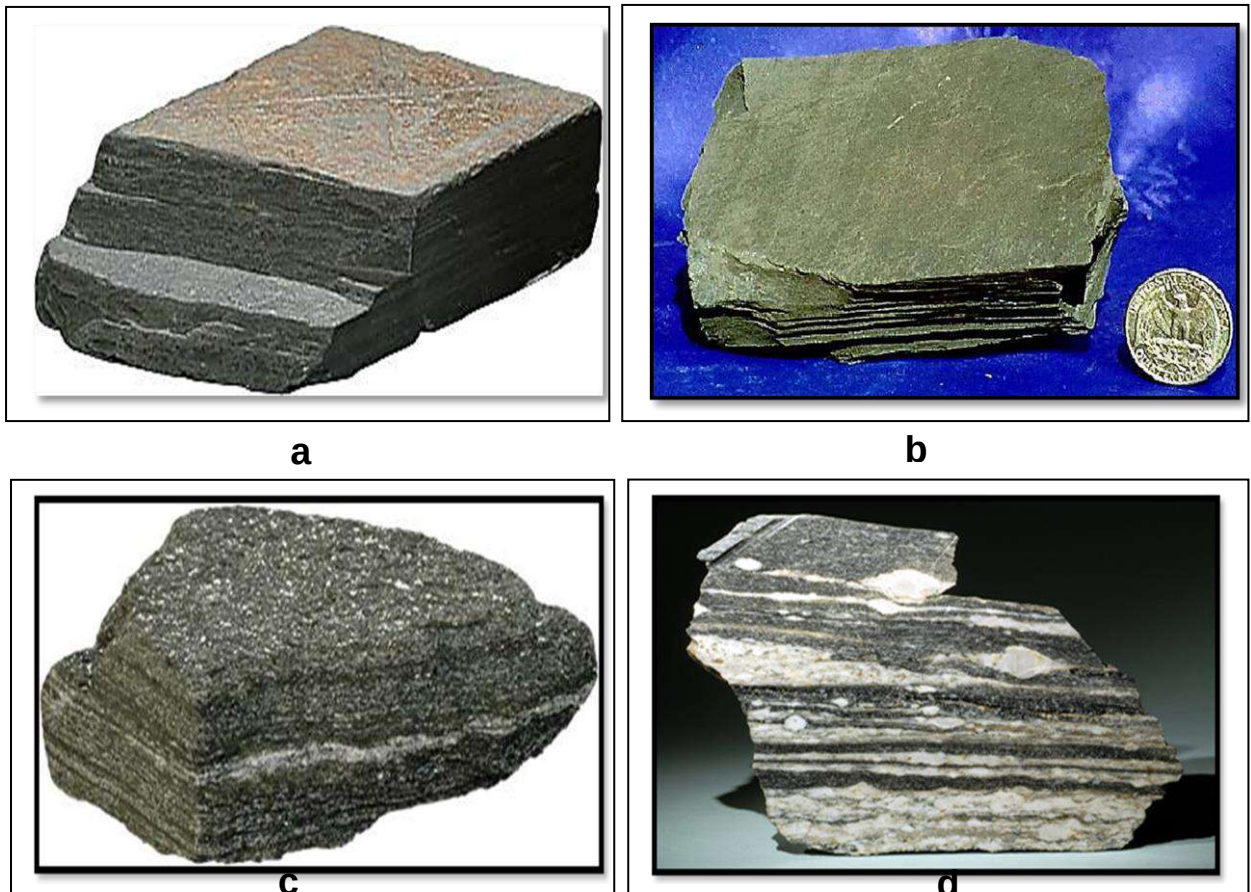


Figure 5-19 Slaty cleavage in slate (a) Well developed slaty cleavage in phyllite (b) Rhythmic layering (schistosity) in schist (c) Rhythmic layering of alternating light and dark bands (gneissosity) in Gneiss (d).

## 5.7 Classification of metamorphic rocks

Process oriented classification just as is that for the igneous rocks. The two dominant processes are regional and contact metamorphism. According to

these two types of metamorphism the metamorphic rocks could be classified to foliated and non-foliated.

### i. Foliated metamorphic rocks

They contain linear or planar features. Form in response to active pressure during regional metamorphism. Foliation is not to be confused with the original sedimentary layering. The foliated rocks include, slate, phyllite, schist and gneiss.

**Slate** is heavy, often dark colored and smooth when it breaks in sheets (Fig. 5-20). It does not contain visible minerals, but with a microscope, you would see that all its minerals are lined up. The properties of slate make it ideal to use on the top of pool tables, shingles on roofs, walking stones, and the original blackboards, which teachers write on.

**Phyllite** resembles slate but has a somewhat coarser texture. The flat surfaces have a lustrous sheen (silky appearance as it subjected to sunlight) due to mica and chlorite. However, it is not as hard or flat as slate, and not used in construction like slate (Fig. 5-20).

**Schist** is finely foliated forming thin parallel bands. The individual minerals are visible but are usually platy or rod-like. Some minerals are larger within the foliated minerals (Fig. 5-20). Schist looks like it is composed of “glitter.”

**Gneiss** is consists of coarsely foliated alternating bands. The bands can be straight, pancake-like, or wavy (Fig. 5-20). The bands differ in composition and are coarse grained making them easy to identify. Many of the light-

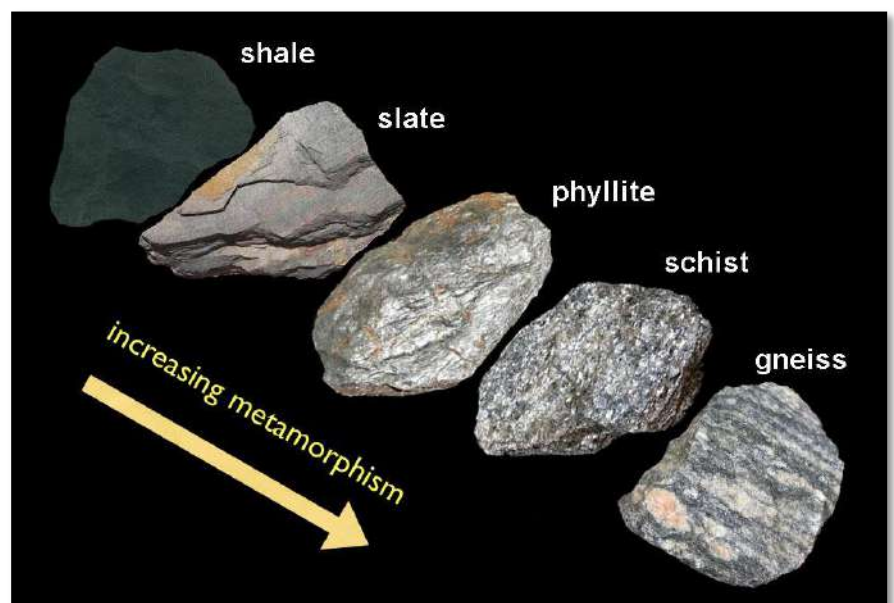


Figure 5-20 Increasing the degree of metamorphism, light color, grain-size from slate through phyllite, schist to gneiss.

colored bands are composed of either quartz or feldspar. The dark bands belong to the biotite/hornblende groups. It requires a higher degree of metamorphism. It is the most common metamorphic rocks (Fig. 5-20). It is clear that the degree of metamorphism, grain-size and light color increase from slate through phyllite, schist to gneiss.

## ii. Non-foliated metamorphic rocks

They are show no evidence of foliation and are apt to form in a contact metamorphic environment where pressure is unimportant. The non-foliated rocks include, marble and quartzite.

**Marble** a metamorphosed limestone or recrystallized limestone harder and coarser than the original limestone (Fig. 5-21). It contains calcium carbonate (calcite) it will release CO<sub>2</sub> in the presence of acid and softer than quartzite.

**Quartzite** a metamorphosed sandstone (mainly of quartz grains) it is coarser and harder than the original sandstones (Fig. 5-22).

**Serpentinite:** a foliated or non-foliated rock with >50 serpentine minerals with greenish yellow color and greasy feel. Serpentinite formed by effect of hydrothermal fluids on ultramfic igneous rocks (Fig. 5-23). It may be contains chromite and platinum.



Figure 5-21 Marble as a result of metamorphism of limestone.

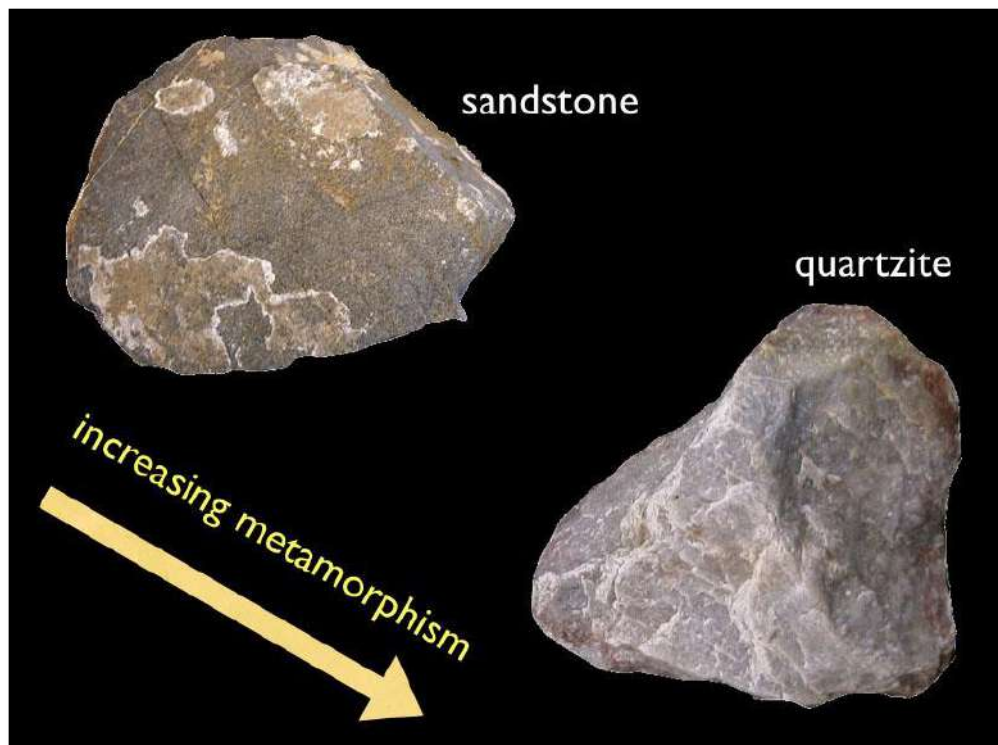


Figure 5-22. Quartzite as a result of metamorphism of sandstone [1]

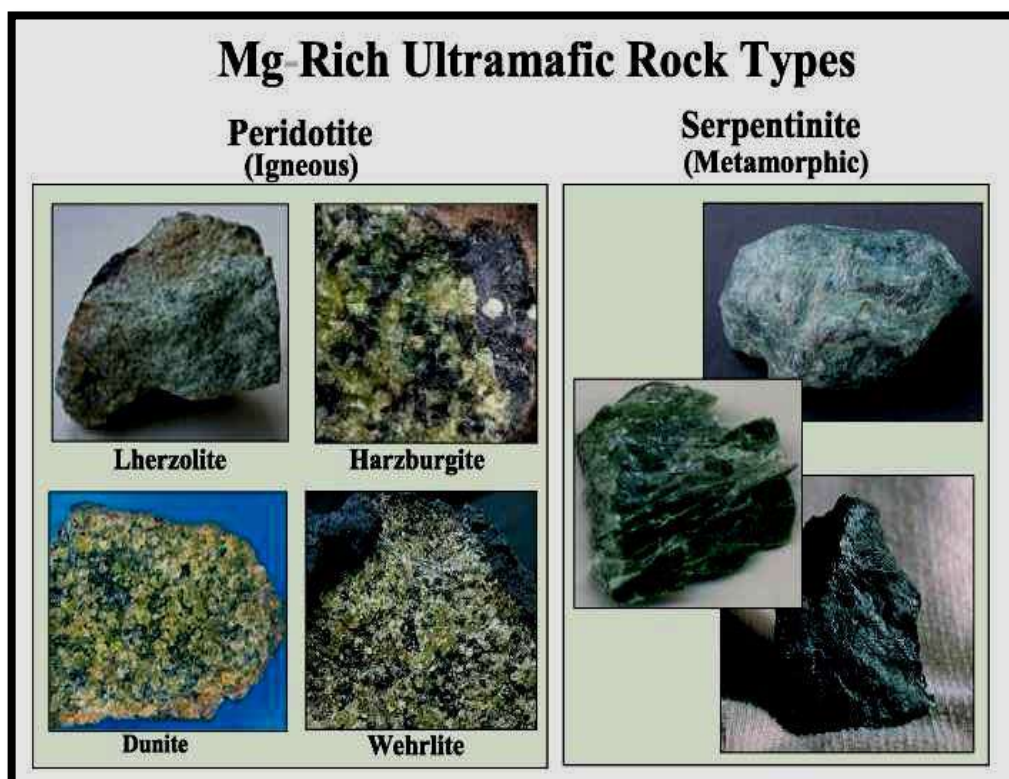


Figure 5-23 Serpentinite rock formed by the hydrothermal alteration of ultramafic igneous rock

## 5.8 Economic importance of metamorphic rocks

Metamorphic rocks are used in counter tops, building construction, paving, sculpture, and jewelry. We may use it for countertops such as marble and Slate. Slate used for roofing marble for decorative stonework. Talc is a metamorphic mineral is used as a lubricant and Serpentine mineral is used for carving. Corundum, another metamorphic mineral, is used for abrasives, while kyanite mineral and its polymorphs are used for ceramics. Graphite used in pencils. Asbestos is a metamorphic mineral which was formerly used for insulation. Many economic deposits of gold, copper, tungsten and iron occur in metamorphic rocks.

### REVIEW QUESTIONS

1. Describe the two general kinds of changes that a rock undergoes during metamorphism.
2. Describe four main factors that cause and control metamorphism.
3. How does the nature of parent rock affect the products of metamorphism?
4. What is the approximate temperature range over which metamorphism occurs? What factors define the upper and lower temperatures of metamorphism?
5. Explain how deformation produces foliated textures in metamorphic rocks.
6. Name and briefly describe each of the different types of metamorphism.
7. Describe and name a rock that might result from contact metamorphism of a shale.
8. What rock types might form by contact metamorphism of limestone?
9. Describe and name the succession of metamorphic rocks that form as shale experiences progressively higher grades of regional dynamothermal metamorphism.
10. Where does the water responsible for hydrothermal alteration originate?
11. How does contact metamorphism differ from regional metamorphism?
12. What is a metamorphic facies?

### DISCUSSION QUESTIONS

1. Discuss processes that might cause the composition of a rock to change during metamorphism. What would be the effects of a change in composition?
2. Referring to Figure 5–9, what metamorphic grades would be expected to occur in rocks exposed to the following conditions? a. 400°C and 3 kilobars; b. 400°C and a depth of 12 kilometers; c. 600°C at the Earth's surface; d. 200°C and a depth of 15 kilometers. Referring to Figure 5–12, what metamorphic facies would be expected to form under the same sets of conditions?
3. What types of metamorphic rocks would you expect to find in the following environments? a. adjacent to a hot spring in Yellowstone Park; b. in the Appalachian Mountains, which is an old region of mountain building caused by collision of two tectonic plates; c. at a depth of 6000 meters beneath southern Louisiana.
4. Referring to Figure 5–12, what metamorphic facies would you expect to find at 600°C and at a depth of 20 kilometers?

### References

- [1] Monroe, J.S., Wicander, R., Hazlett, R. (2007): Physical Geology: Exploring the Earth. 6<sup>th</sup> edition, Thomson Brooks, California, USA, 690 p, ISBN: 0-495-01148-7
- [2] Plummer, C. C., McGeary, D., Carlson, D.H. (2001): Physical geology, Updated 8<sup>th</sup> edition. WCB/McGraw-Hill, 578 p. ISBN: 0072904437.
- [3] Thompson, G.R., Turk, J. (1997): Introduction to Physical Geology. 13<sup>th</sup> edition, Brooks Cole, USA, 371p, ISBN 13: 9780030243486



Geology Department  
Faculty of Science  
Zagazig University



# Practical: Principals of Geology (G 102)



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# ***Part 1:***

# ***Crystallography***

# Crystallography

## ***Section 1: parts of crystal***

Is the science that deals with the study of crystals and crystalline materials, whether they are prepared in the laboratory (sugar crystal) or the crystals which are formed by nature (e.g. quartz, calcite, diamond).

➤ **Crystal** is a homogenous solid material with a definite chemical composition bounded by naturally formed smooth plane surfaces which having symmetry relationships.

➤ **Crystal parts:**

**1- Faces:** it is the external smooth plane surfaces of the crystal. The crystal faces reflect or show the internal atomic arrangement of the crystallized material.

**2- Edges:** it is the line resulting from meeting of two neighboring faces.

**3- Interfacial angle:** it is the angle between two neighboring faces.

➤ **Elements of symmetry**

**1. Plane of Symmetry:** is an imaginary plane which divide the crystal into 2 equal and identical halves each or which is a mirror image to the other.

**2. Axis of Symmetry:** is an imaginary axis or line passing through the center of the crystal. Around this line the crystal can be rotated and similar face come to occupy the same position more than once in a complete rotation of  $360^\circ$ .

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

- **Hexad (six-fold) axis:** When rotation repeats form every 60 degrees.
- **Tetrad (four-fold) axis:** When rotation repeats form every 90 degrees.
- **Triad (three-fold) axis:** When rotation repeats form every 120 degrees.
- **Diad (two-fold) axis:** When rotation repeats form every 180 degrees.

### 3. Center of Symmetry

- This is an imaginary point, which lies inside the crystal exactly in its center. Now it should be also added that 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 should be met with at equal distance beyond the center of the other side of this line. In this case only, the concerned crystal is said to possess a center of symmetry.

### ➤ Elements of crystallization

#### 1. Crystallographic axes

- These are three or four imaginary lines passing through the center of the crystal.

**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.

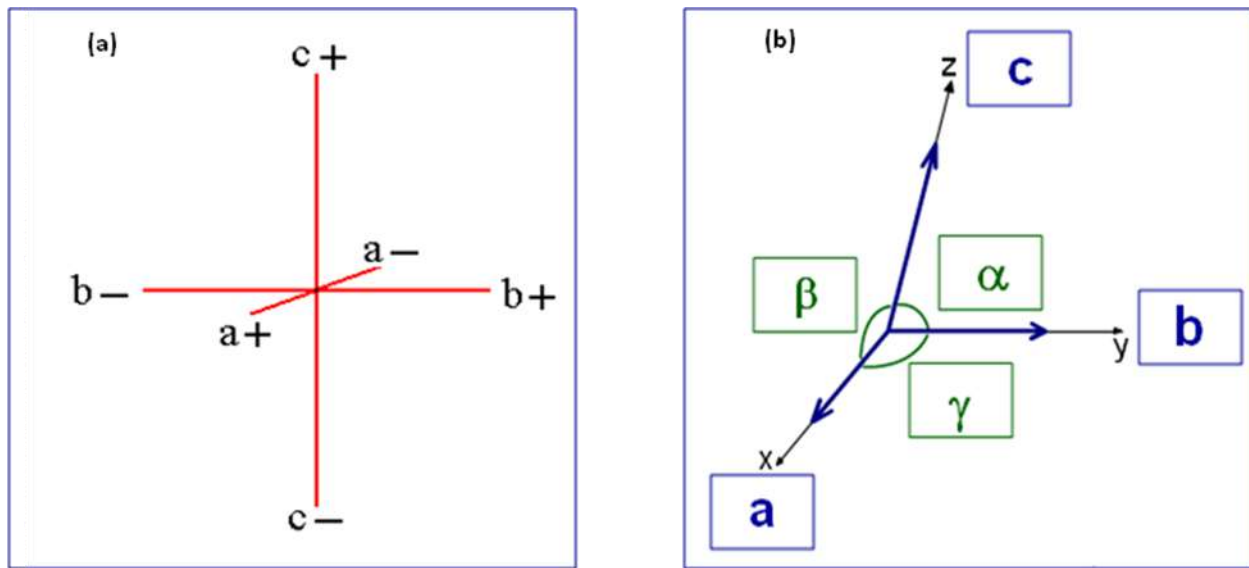


Figure 1-7 (a) crystallographic axes, (b) crystallographic angles

## 2. Crystallographic angles

- The intersections of the crystallographic axes at center of crystals give three angles called as  $\alpha$ ,  $\beta$  and  $\gamma$  (Fig. 1-7b).

**alpha ( $\alpha$ ):** lies between the b and c axes

**beta ( $\beta$ ):** lies between the a and c axes

**gamma ( $\gamma$ ):** lies between the a and b axes

- **Crystal Form:** is a set of crystal faces that are similar in size and shape and related to each other by symmetry.

**Open form** is one or more crystal faces that cannot close the crystal in all directions alone such as, pedion, 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.

**Simple crystal:** This is a crystal containing one closed form with its similar faces enclosing the crystal from all direction.

**Compound (combined) crystal:** This is a crystal containing more than one form combined together in a regular arrangement to close the crystal.

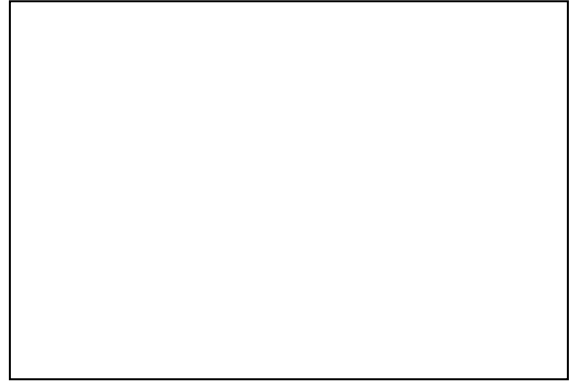
➤ **Crystallographic systems**

According to elements of crystallization (Crystallographic axes and angles), crystals can be classified into 7 systems; cubic, tetragonal, orthorhombic, monoclinic, triclinic, hexagonal and trigonal systems.

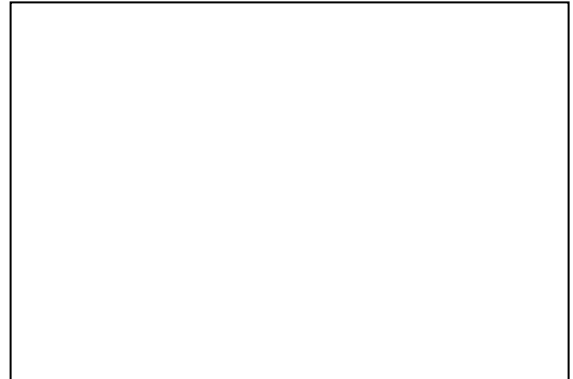
## Sheet 1

Draw the crystal and try to identify the elements of symmetry and describe the crystal forms:

- Axis of symmetry:
- Planes of symmetry:
- Description of crystal form:
- Forms Names:



- Axis of symmetry:
- Planes of symmetry:
- Description of crystal form:
- Forms Names:



- Axis of symmetry:
- Planes of symmetry:
- Description of crystal form:
- Forms Names:



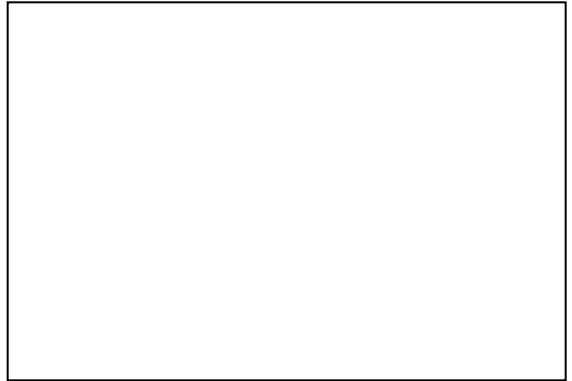
- Axis of symmetry:
- Planes of symmetry:
- Description of crystal form:
- Forms Names:



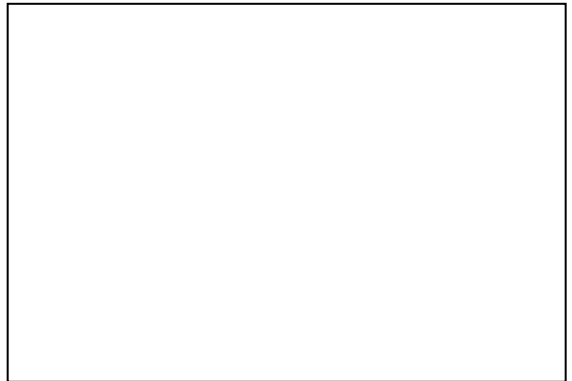
- **Axis of symmetry:**
- **Planes of symmetry:**
- **Description of crystal form:**
- **Forms Names:**



- **Axis of symmetry:**
- **Planes of symmetry:**
- **Description of crystal form:**
- **Forms Names:**



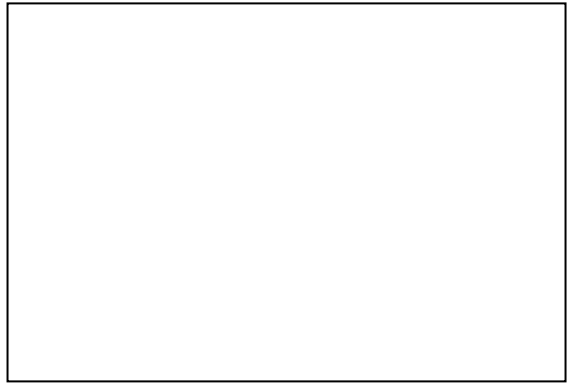
- **Axis of symmetry:**
- **Planes of symmetry:**
- **Description of crystal form:**
- **Forms Names:**



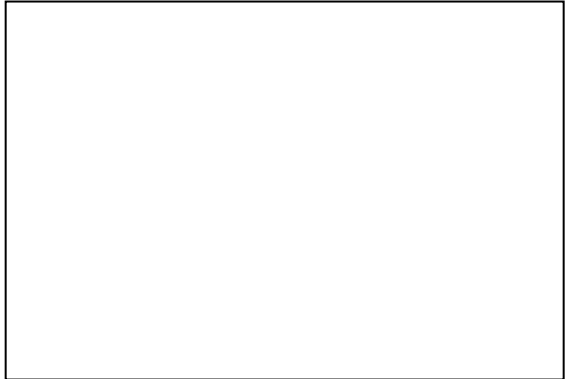
- **Axis of symmetry:**
- **Planes of symmetry:**
- **Description of crystal form:**
- **Forms Names:**



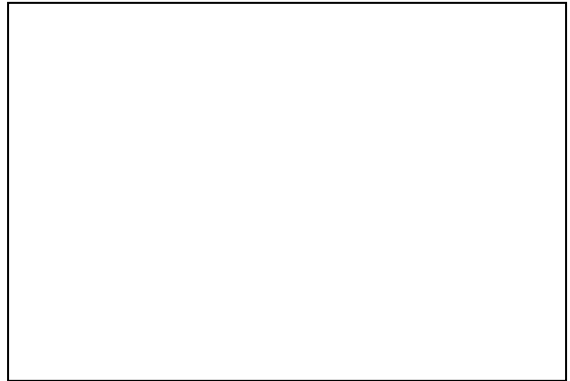
- **Axis of symmetry:**
- **Planes of symmetry:**
- **Description of crystal form:**
- **Forms Names:**



- **Axis of symmetry:**
- **Planes of symmetry:**
- **Description of crystal form:**
- **Forms Names:**



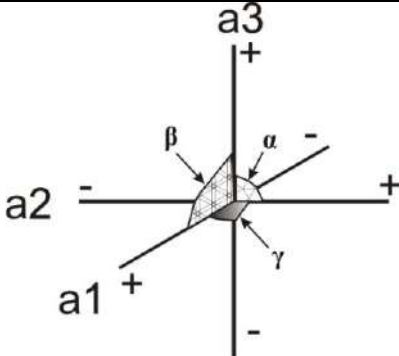
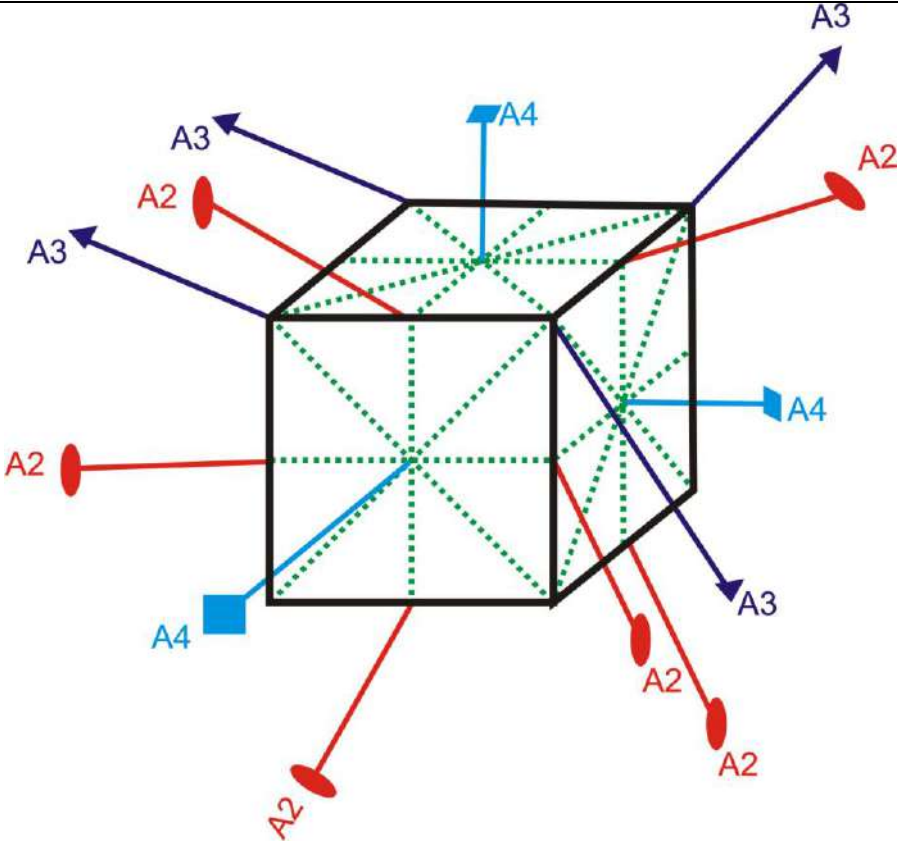
- **Axis of symmetry:**
- **Planes of symmetry:**
- **Description of crystal form:**
- **Forms Names:**

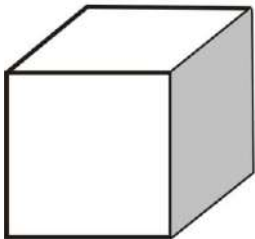
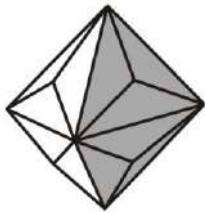
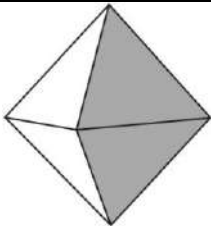
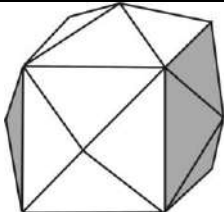
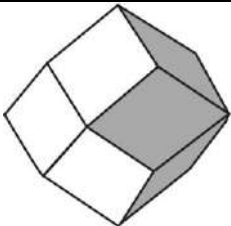
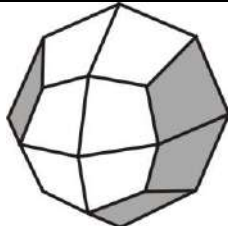
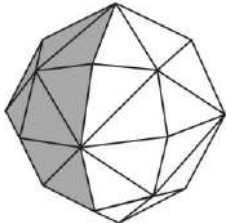


- **Axis of symmetry:**
- **Planes of symmetry:**
- **Description of crystal form:**
- **Forms Names:**



## Section 2: Cubic system

| <u>Cubic System</u>                                                                 |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|    | <p><u>Crystallographic Axes</u><br/><math>a_1 = a_2 = a_3</math></p> <p><u>Crystallographic Angles</u><br/><math>90^\circ = \gamma = \beta = \alpha</math></p>                                                                                                                                                                                                                                                                                                                                                                                                                                        |
| Elements of symmetry                                                                |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
|  | <p><u>1. Axes of symmetry</u></p> <ol style="list-style-type: none"> <li>1. Three tetrad axes perpendicular to three planes (3■).</li> <li>2. Four triad axes not perpendicular to any plane (4▲).</li> <li>3. Six diad axes perpendicular to six planes (6●).</li> </ol> <p><u>2. Planes of symmetry</u></p> <p>There are nine planes of symmetry in the holosymmetrical class, four of them are vertical, one is horizontal and the other four planes</p> <p><u>3. Center of symmetry</u></p> <p>Present</p> <p><u>4. C.S.F (complete symmetry formula):</u></p> <p><math>3■/m 4▲ 6●/m c</math></p> |

| <u>Crystal Forms</u>                                                                                                                                                           |                                                                                                                                                                             |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|  <p><b>Hexahedron or cube</b><br/>Closed form consists of 6 square faces</p>                  |  <p><b>Trisoctahedron</b><br/>Closed form consists of 24 isosceles triangular faces</p>  |
|  <p><b>Octahedron</b><br/>Closed form consists of 8 equilateral triangular faces</p>          |  <p><b>Tetrahexahedron</b><br/>Closed form consists of 24 isosceles triangular faces</p> |
|  <p><b>Rhombic dodecahedron</b><br/>Closed form consists of 12 rhombic-shaped faces</p>      |  <p><b>Trapezohedron</b><br/>Closed form consists of 24 trapezium-shaped faces</p>      |
|  <p><b>Hexaoctahedron</b><br/>Closed form consists of 48 inequilateral triangular faces</p> |                                                                                                                                                                             |

## Sheet 2

### Describe the crystal forms:

- Axis of symmetry:
- Planes of symmetry:
- Description of crystal form:
- Forms Names:

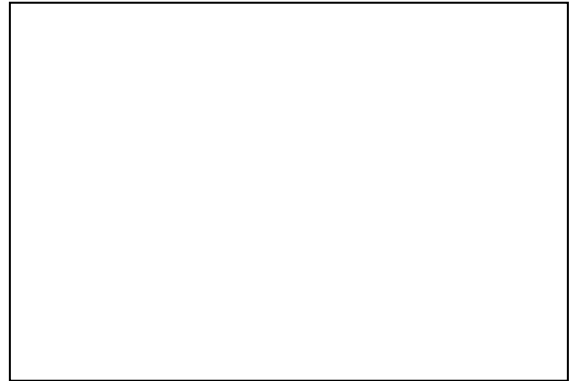
- Axis of symmetry:
- Planes of symmetry:
- Description of crystal form:
- Forms Names:

- Axis of symmetry:
- Planes of symmetry:
- Description of crystal form:
- Forms Names:

- Axis of symmetry:
- Planes of symmetry:
- Description of crystal form:
- Forms Names:

**Describe the crystal forms:**

- Axis of symmetry:
- Planes of symmetry:
- Description of crystal form:
- Forms Names:



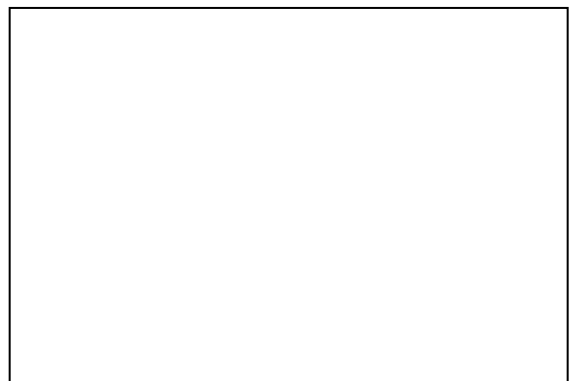
- Axis of symmetry:
- Planes of symmetry:
- Description of crystal form:
- Forms Names:



- Axis of symmetry:
- Planes of symmetry:
- Description of crystal form:
- Forms Names:

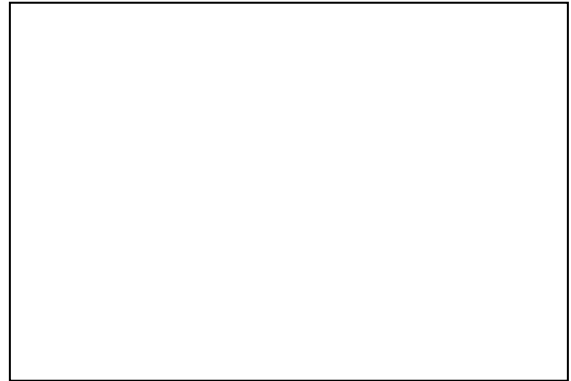


- Axis of symmetry:
- Planes of symmetry:
- Description of crystal form:
- Forms Names:



**Describe the crystal forms:**

- Axis of symmetry:
- Planes of symmetry:
- Description of crystal form:
- Forms Names:



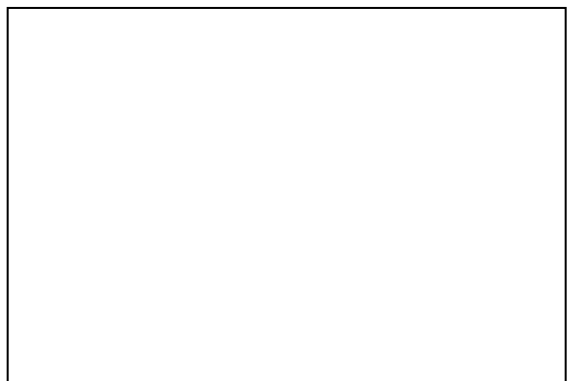
- Axis of symmetry:
- Planes of symmetry:
- Description of crystal form:
- Forms Names:



- Axis of symmetry:
- Planes of symmetry:
- Description of crystal form:
- Forms Names:

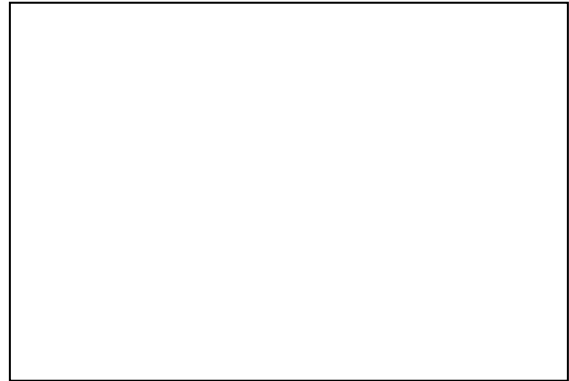


- Axis of symmetry:
- Planes of symmetry:
- Description of crystal form:
- Forms Names:



**Describe the crystal forms:**

- Axis of symmetry:
- Planes of symmetry:
- Description of crystal form:
- Forms Names:



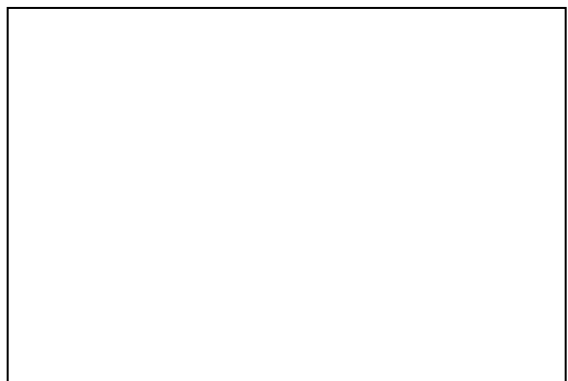
- Axis of symmetry:
- Planes of symmetry:
- Description of crystal form:
- Forms Names:



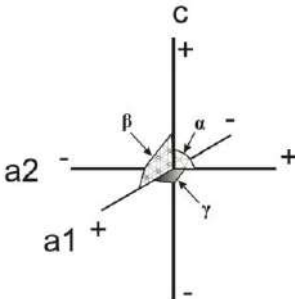
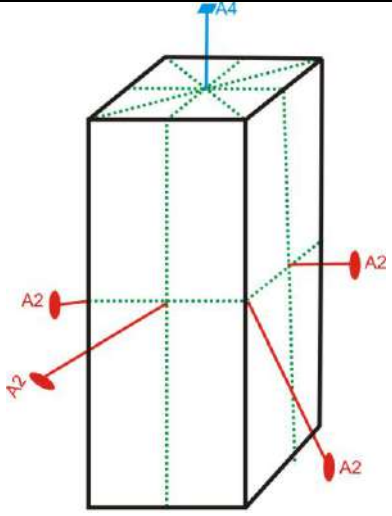
- Axis of symmetry:
- Planes of symmetry:
- Description of crystal form:
- Forms Names:

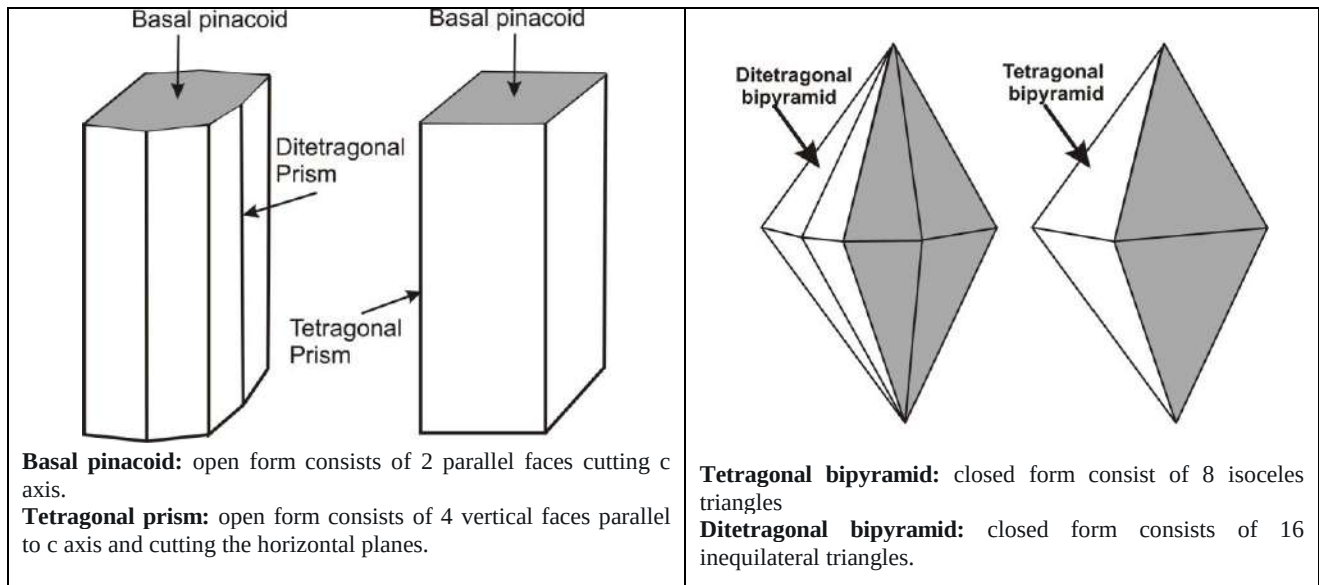


- Axis of symmetry:
- Planes of symmetry:
- Description of crystal form:
- Forms Names:



## Section 3: Tetragonal system

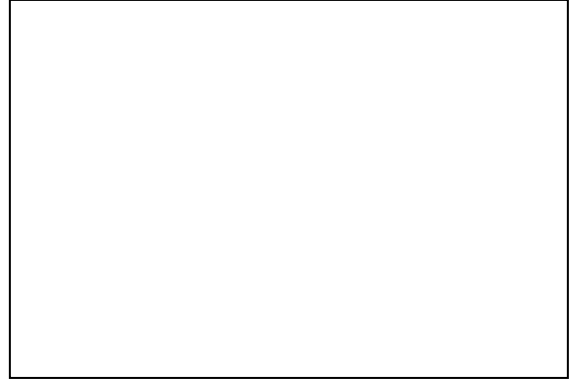
| <b><u>Tetragonal System</u></b>                                                    |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
|------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|   | <p><b><u>Crystallographic Axes</u></b><br/> <math>a_1 = a_2 \neq c</math></p> <p><b><u>Crystallographic Angles</u></b><br/> <math>90^\circ = \gamma = \beta = \alpha</math></p>                                                                                                                                                                                                                                                                                                                                                                                        |
|  | <p><b><u>Elements of symmetry</u></b></p> <p><b><u>1. Axes of symmetry</u></b></p> <ol style="list-style-type: none"> <li>1. one tetrad axis perpendicular to one planes (1■).</li> <li>2. four diad axes perpendicular to four planes (4●)</li> </ol> <p><b><u>2. Planes of symmetry</u></b></p> <p>There are five planes of symmetry in the holosymmetrical class, one of them is horizontal and the other four planes are vertical.</p> <p><b><u>3. Center of symmetry</u></b><br/> is present</p> <p><b><u>4. C.S.F:</u></b><br/> <math>1■/m \ 4●/m \ c</math></p> |



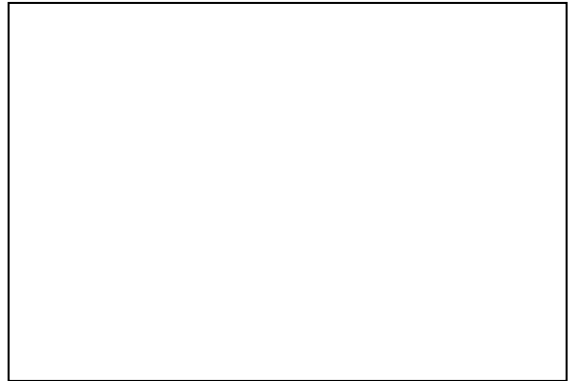
## Sheet 3

Draw the crystal and complete the following:

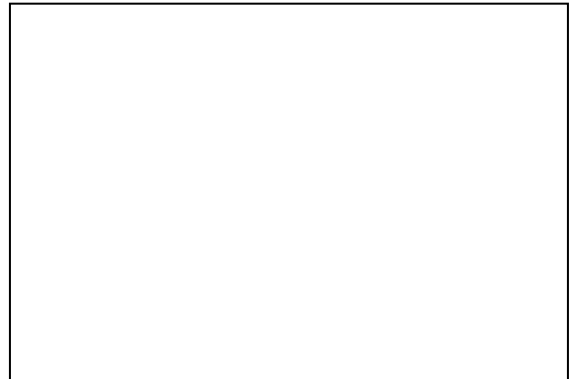
- Crystal system:
- Crystallographic axes:
- Crystal type:
- Crystal Forms:
- Forms Names:



- Crystal system:
- Crystallographic axes:
- Crystal type:
- Crystal Forms:
- Forms Names:



- Crystal system:
- Crystallographic axes:
- Crystal type:
- Crystal Forms:
- Forms Names:



- Crystal system:
- Crystallographic axes:
- Crystal type:
- Crystal Forms:
- Forms Names:

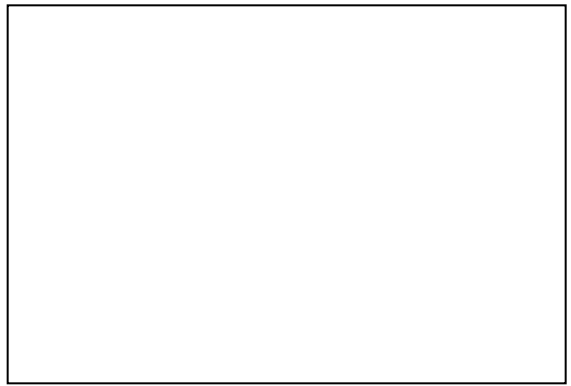


**Draw the crystal and complete the following:**

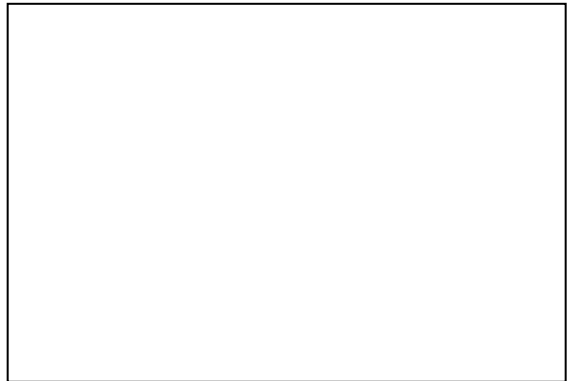
- Crystal system:
- Crystallographic axes:
- Crystal type:
- Crystal Forms:
- Forms Names:



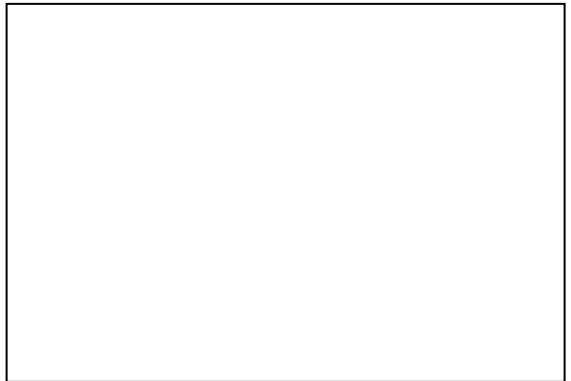
- Crystal system:
- Crystallographic axes:
- Crystal type:
- Crystal Forms:
- Forms Names:



- Crystal system:
- Crystallographic axes:
- Crystal type:
- Crystal Forms:
- Forms Names:



- Crystal system:
- Crystallographic axes:
- Crystal type:
- Crystal Forms:
- Forms Names:

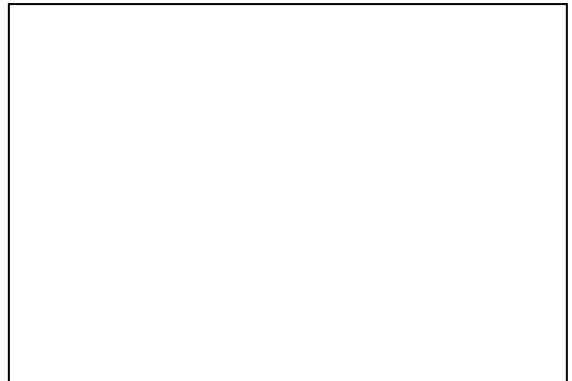


**Draw the crystal and complete the following:**

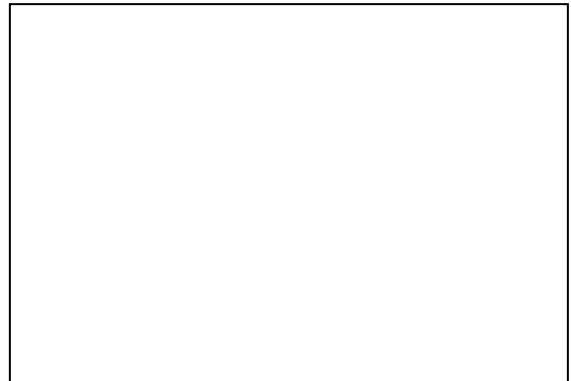
- Crystal system:
- Crystallographic axes:
- Crystal type:
- Crystal Forms:
- Forms Names:



- Crystal system:
- Crystallographic axes:
- Crystal type:
- Crystal Forms:
- Forms Names:



- Crystal system:
- Crystallographic axes:
- Crystal type:
- Crystal Forms:
- Forms Names:



- Crystal system:
- Crystallographic axes:
- Crystal type:
- Crystal Forms:
- Forms Names:

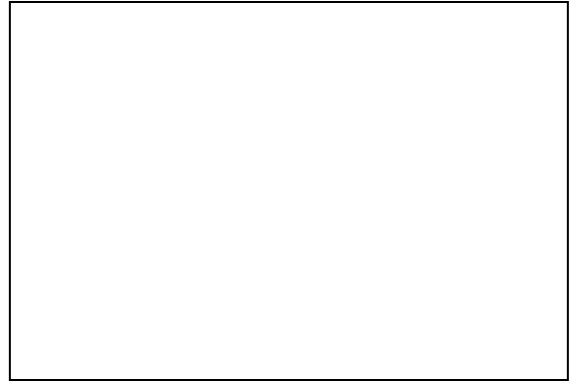


**Draw the crystal and complete the following:**

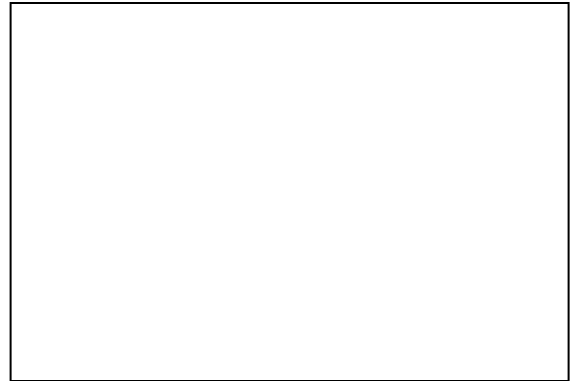
- Crystal system:
- Crystallographic axes:
- Crystal type:
- Crystal Forms:
- Forms Names:



- Crystal system:
- Crystallographic axes:
- Crystal type:
- Crystal Forms:
- Forms Names:



- Crystal system:
- Crystallographic axes:
- Crystal type:
- Crystal Forms:
- Forms Names:

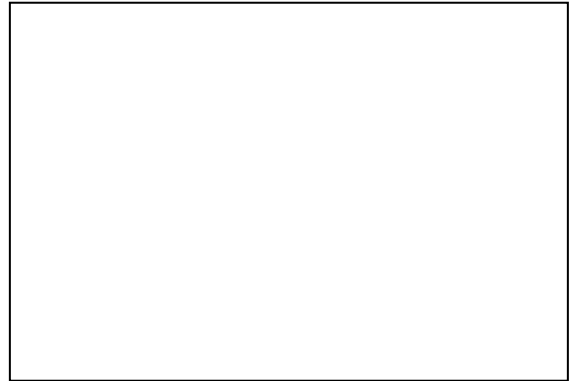


- Crystal system:
- Crystallographic axes:
- Crystal type:
- Crystal Forms:
- Forms Names:



**Draw the crystal and complete the following:**

- Crystal system:
- Crystallographic axes:
- Crystal type:
- Crystal Forms:
- Forms Names:



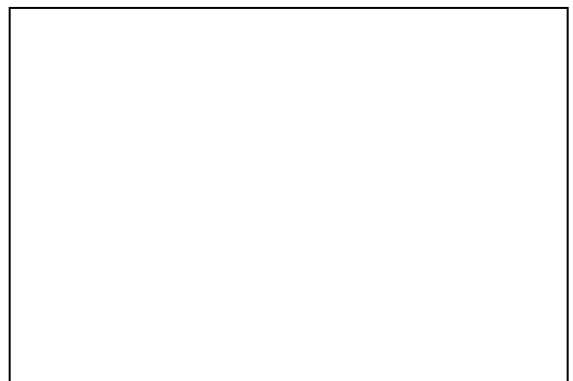
- Crystal system:
- Crystallographic axes:
- Crystal type:
- Crystal Forms:
- Forms Names:



- Crystal system:
- Crystallographic axes:
- Crystal type:
- Crystal Forms:
- Forms Names:

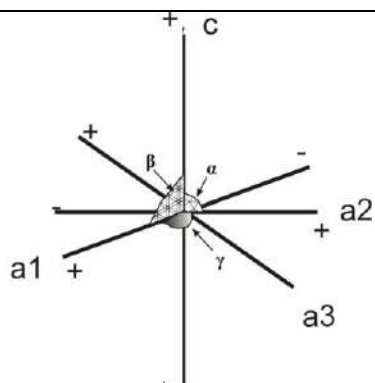


- Crystal system:
- Crystallographic axes:
- Crystal type:
- Crystal Forms:
- Forms Names:



## Section 4: Hexagonal and Orthorhombic systems

### Hexagonal System

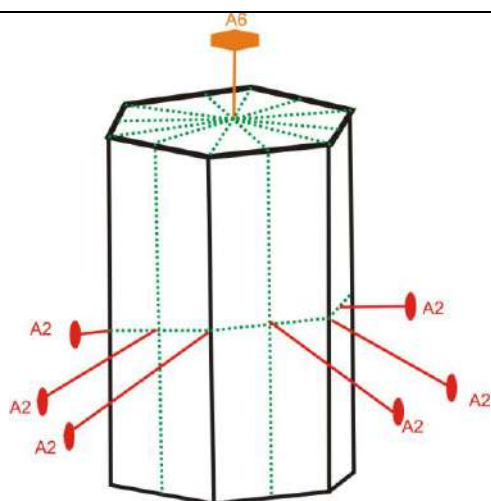


#### Crystallographic Axes

$$a_1 = a_2 = a_3 \neq c$$

#### Crystallographic Angles

$$\alpha = \beta = 90^\circ, \gamma = 120^\circ$$



#### Elements of symmetry

##### 1. Axes of symmetry

1. one hexad axis perpendicular to one planes (1)
2. six diad axes perpendicular to four planes (6)

##### 2. Planes of symmetry

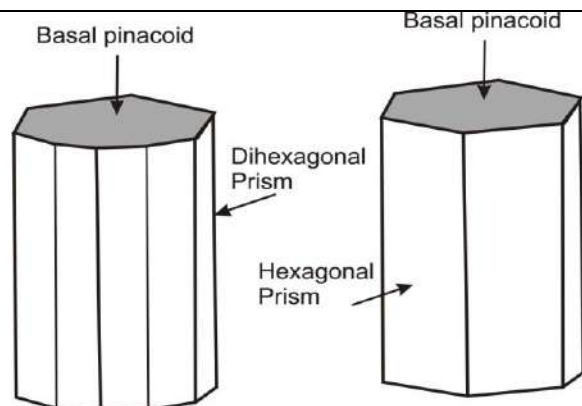
There are seven planes of symmetry in the holosymmetrical class, one of them is horizontal and the other six planes are vertical

##### 3. Center of symmetry

Present

##### 4. C.S.F:

$$12/m \bar{6} 2/m c$$

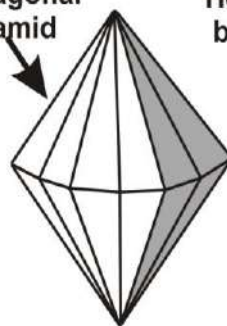


**Basal pinacoid:** open form consists of 2 parallel faces cutting c axis.

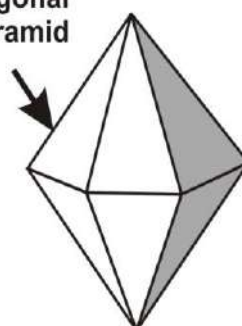
**Hexagonal prism:** open form consists of 6 vertical faces parallel to c axis and cutting the horizontal planes.

**Dihexagonal prism:** open form consists of 12 vertical faces parallel to c axis and cutting the horizontal planes.

#### Dihexagonal bipyramid



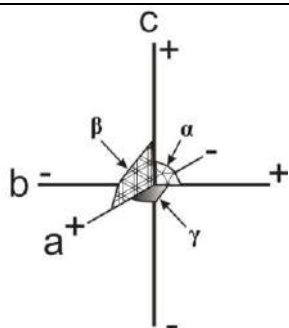
#### Hexagonal bipyramid



**Hexagonal bipyramid:** closed form consists of 6 isosceles triangles.

**Dihexagonal bipyramid:** closed form consists of 12 inequilateral triangles.

## Orthorhombic System

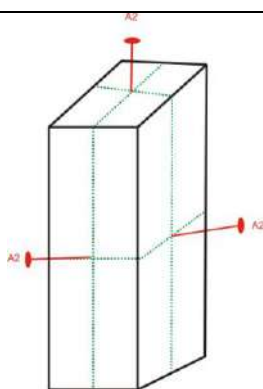


### Crystallographic Axes

$$a \neq b \neq c$$

### Crystallographic Angles

$$90 = \gamma = \beta = \alpha$$



### Elements of symmetry

#### Axes of symmetry

Three diad axes (3) in the same places of crystallographic axes.

#### Planes of symmetry

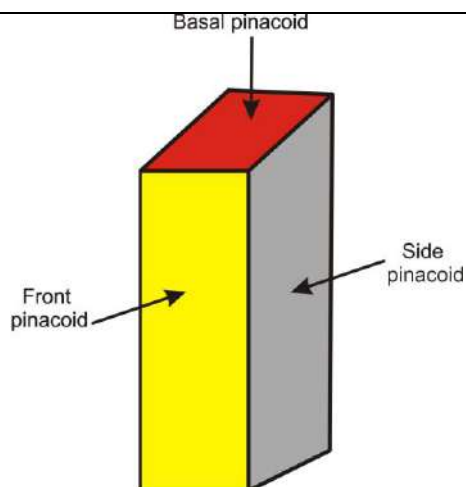
Three planes of symmetry one of them is horizontal and the other two planes are vertical.

#### Center of symmetry

Present

#### C.S.F:

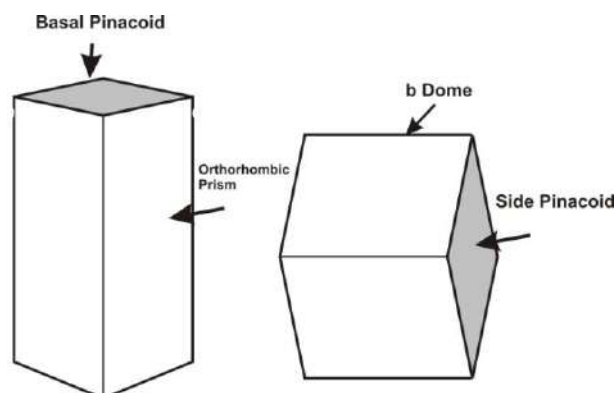
$$3 \bullet / m c$$



**Basal (c) pinacoid:** It is an open form composed of two parallel faces that intercept the c axis and are parallel to the a and b axes.

**(a) Pinacoid:** It is an open form composed of two parallel faces that intercept the a axis and are parallel to the c and b axes.

**(b) Pinacoid:** It is an open form composed of two parallel faces that intercept the b axis and are parallel to the a and c axes.



**Orthorhombic prism:** It is an open form, consists of 4 faces which are parallel to c axis and intersect the other two axes.

**Orthorhombic bipyramid:** It is a closed form, consists of 8 triangular faces, each of them intersects all 3 crystallographic axes.

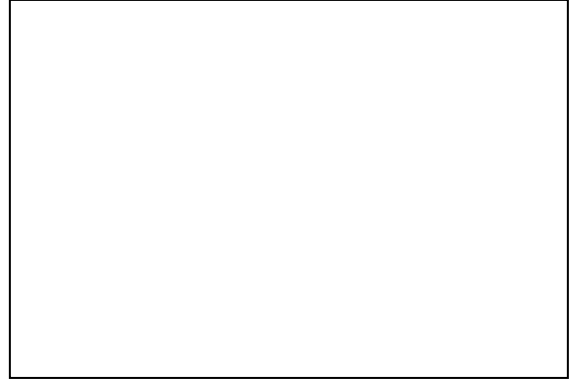
**(a) or Brachy dome:** It is an open form, consists of 4 faces, parallel to a axis and intersect the other two axes (c, b).

**(b) or Macro dome:** It is an open form, consists of 4 faces parallel to b axis and intersect the other two axes (c, a). It is apparent that the dome form either (a) or (b) is always intersects the c axis. So there is no c-dome.

## Sheet 4

Draw the crystal and complete the following:

- Crystal system:
- Crystallographic axes:
- Crystal type:
- Crystal Forms:
- Forms Names:



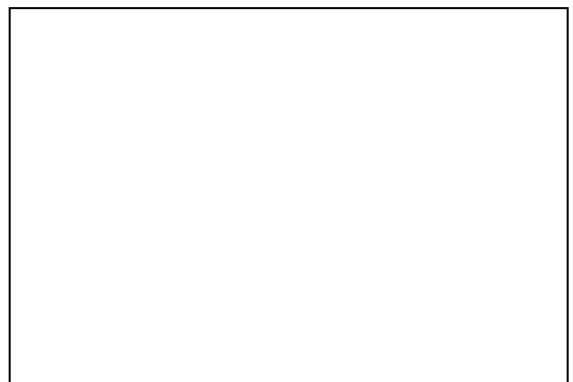
- Crystal system:
- Crystallographic axes:
- Crystal type:
- Crystal Forms:
- Forms Names:



- Crystal system:
- Crystallographic axes:
- Crystal type:
- Crystal Forms:
- Forms Names:



- Crystal system:
- Crystallographic axes:
- Crystal type:
- Crystal Forms:
- Forms Names:

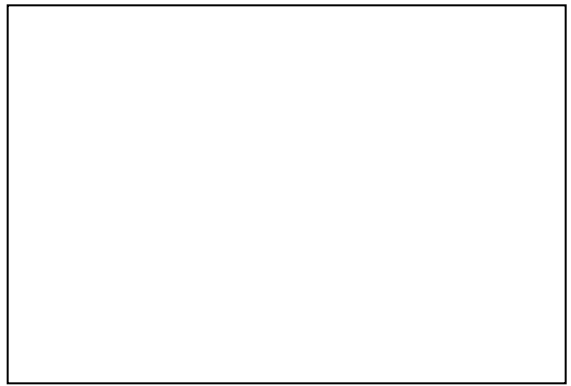


**Draw the crystal and complete the following:**

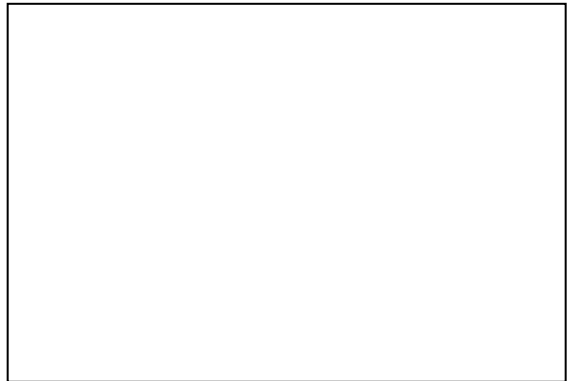
- Crystal system:
- Crystallographic axes:
- Crystal type:
- Crystal Forms:
- Forms Names:



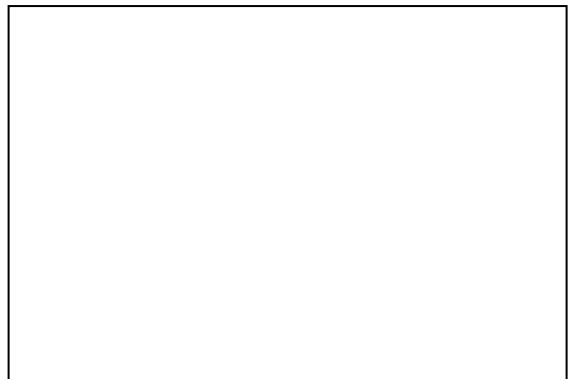
- Crystal system:
- Crystallographic axes:
- Crystal type:
- Crystal Forms:
- Forms Names:



- Crystal system:
- Crystallographic axes:
- Crystal type:
- Crystal Forms:
- Forms Names:



- Crystal system:
- Crystallographic axes:
- Crystal type:
- Crystal Forms:
- Forms Names:



**Draw the crystal and complete the following:**

- Crystal system:
- Crystallographic axes:
- Crystal type:
- Crystal Forms:
- Forms Names:



- Crystal system:
- Crystallographic axes:
- Crystal type:
- Crystal Forms:
- Forms Names:



- Crystal system:
- Crystallographic axes:
- Crystal type:
- Crystal Forms:
- Forms Names:



# ***Part 2:***

# ***Minerals***

# Minerals

## Section 5: Optical properties of minerals

### 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

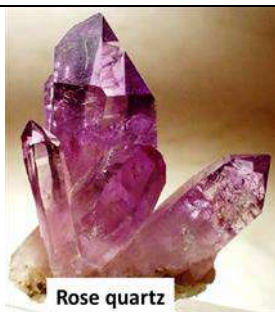
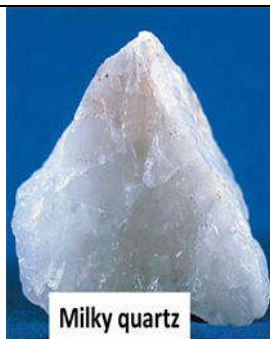
### Physical properties of minerals

#### 1. Optical properties (dependent upon light)

#### 1.1 Color many minerals have a characteristic color

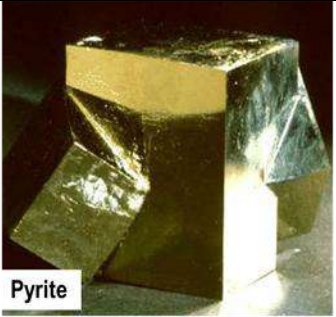
Ex: malachite is almost always green and Sulfur is almost always yellow

However, minerals such as quartz, tourmaline and garnet can be virtually any color

| a. Constant-colored minerals such as Azurite and Malachite                          |                                                                                     |                                                                                      |                                                                                       |
|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|
|   |  |                                                                                      |                                                                                       |
| sulfur ..... yellow color                                                           | Malachite..... green color                                                          |                                                                                      |                                                                                       |
| Varied-colored minerals such as Quartz                                              |                                                                                     |                                                                                      |                                                                                       |
|  |  |  |  |
| Pure quartz                                                                         | Rose quartz                                                                         | smoky quartz                                                                         | Milky quartz                                                                          |

#### 1.2 Luster

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

|                                                                           |                                                                                     |                                                                                      |
|---------------------------------------------------------------------------|-------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|
| <b>Metallic luster</b><br>= shiny like metal<br>(Galena,<br>Pyrite,.....) |  |  |
|                                                                           | Galena                                                                              | Pyrite                                                                               |

**Nonmetallic luster****Vitreous:** luster of glass (Quartz)**Resinous :** luster of resin (Sulphur)**Pearly :** iridescence pearl-like luster (Talc)**Greasy:** as if covered with a 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)

### 1.3 Streak

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



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



Different streak color of mineral than its color



Sulphur has yellow colour and white streak



Pyrite has brass-yellow colour and black streak

### 1.4. Transparency

It's the ability of a mineral to pass the light.



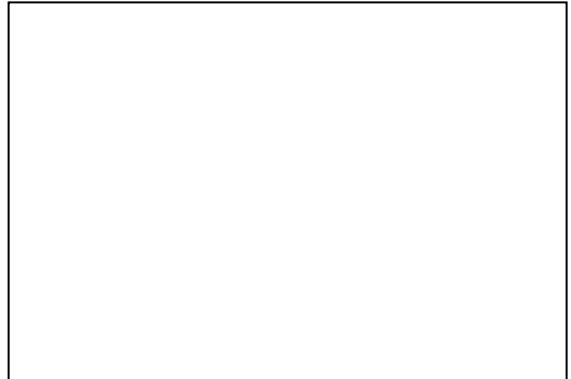
## Sheet 5

Draw the mineral and complete the following:

- Mineral name:
- Color:
- Streak
- Transparency:
- Luster:



- Mineral name:
- Color:
- Streak
- Transparency:
- Luster:

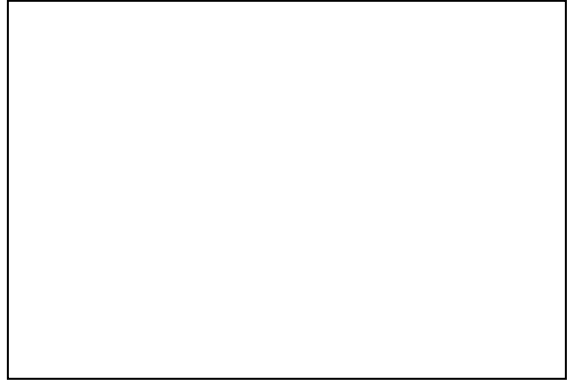


- Mineral name:
- Color:
- Streak
- Transparency:
- Luster:

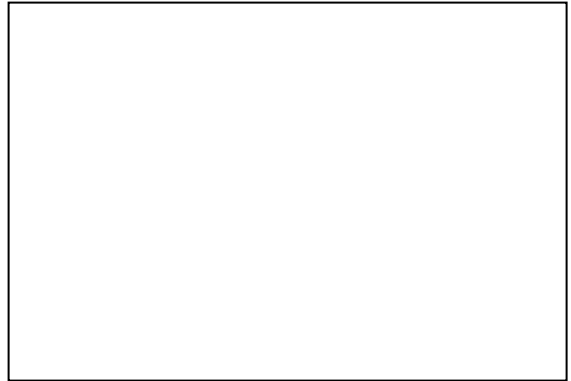


**Draw the mineral and complete the following:**

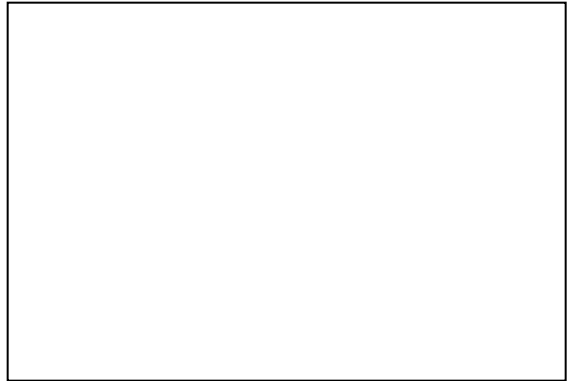
- Mineral name:
- Color:
- Streak
- Transparency:
- Luster:



- Mineral name:
- Color:
- Streak
- Transparency:
- Luster:



- Mineral name:
- Color:
- Streak
- Transparency:
- Luster:



- Mineral name:
- Color:
- Streak
- Transparency:
- Luster:

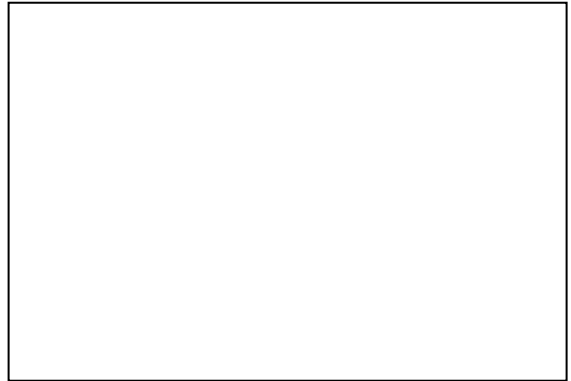


**Draw the mineral and complete the following:**

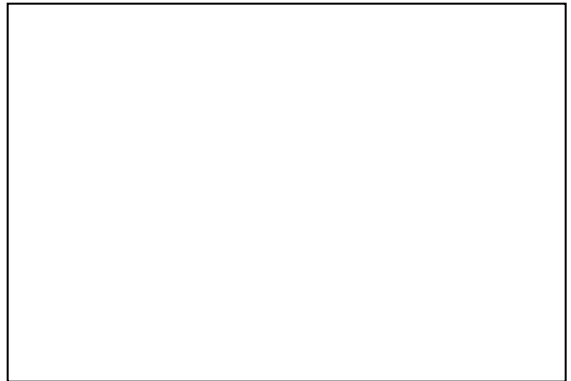
- Mineral name:
- Color:
- Streak
- Transparency:
- Luster:



- Mineral name:
- Color:
- Streak
- Transparency:
- Luster:



- Mineral name:
- Color:
- Streak
- Transparency:
- Luster:

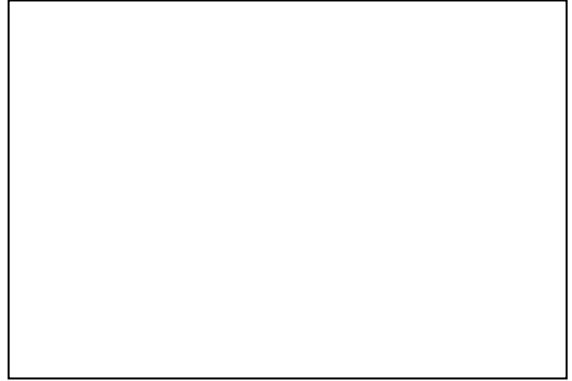


- Mineral name:
- Color:
- Streak
- Transparency:
- Luster:

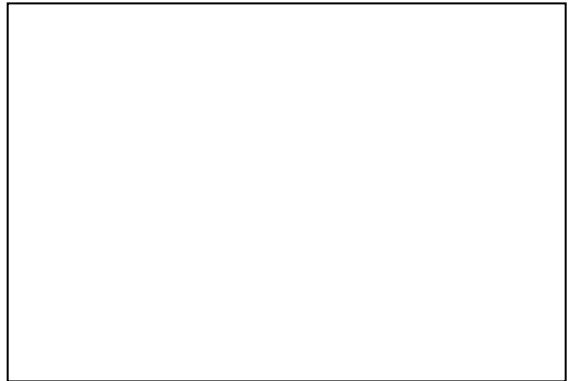


**Draw the mineral and complete the following:**

- Mineral name:
- Color:
- Streak
- Transparency:
- Luster:



- Mineral name:
- Color:
- Streak
- Transparency:
- Luster:



- Mineral name:
- Color:
- Streak
- Transparency:
- Luster:



## Section 6: Cohesive properties of minerals

### 2. Cohesive properties

**2.1 Hardness:** The hardness is a measure of mineral's resistance to abrasion process (scratching).

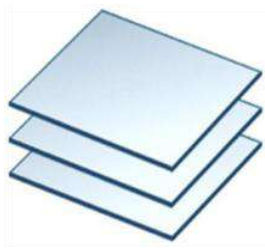
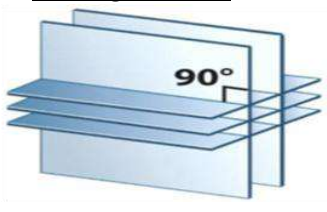
| Hardness | Mineral    | Common Objects                 |
|----------|------------|--------------------------------|
| 1        | Talc       | Fingernail<br>Fingernail (2.5) |
| 2        | Gypsum     |                                |
| 3        | Calcite    | Copper Penny (3)               |
| 4  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

### 2.2 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

|                                                                                                                                                                |                                                                                                                                                                                                        |                                                                                                                                                                                        |                                                                                                                                                 |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------|
| <p><b>One set of cleavage:</b><br/>ex: Mica</p>  <p>One set of cleavage</p> | <p>• <b>Two sets of cleavage:</b><br/><u>Pyroxene two sets of cleavages at 90°</u></p>  <p>Two sets of cleavage</p> | <p><b>Three sets of cleavage:</b><br/><u>Calcite</u></p>  <p>Three sets of cleavage not at 90°</p> | <p><b>Four sets of cleavage:</b><br/>Such as Fluorite</p>  |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------|

**Parting** is also a plane of weakness in the crystal structure, but they are weakened by some applied force.

Corundum showing parting



### 2.3 Fracture—minerals that break at **random** with rough or jagged edges

The quality of such surface is often further described as:

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



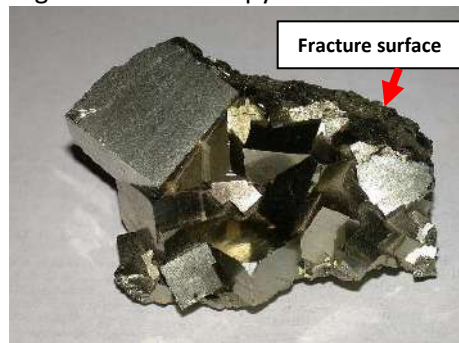
**Earthy:** like freshly broken soil such as Limonite



**Hackly:** jagged surface with sharp edges such as native metals (copper)



**Uneven:** rough surface has random regularities such as pyrite



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



### 3. Other physical properties

#### 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- $\text{H}_2\text{S}$  odor),
- Breathing up on (kaolin-mud odor)
- Rubbing (phosphate-garlic odor).

***Section 7: Mineral Identification***

# Mineral Identification Tables

| Mineral name      | Chemical composition                                                                                    | Crystal system    | Color                   | Streak | Luster            | Hardness | Cleavage | Other properties                                  |
|-------------------|---------------------------------------------------------------------------------------------------------|-------------------|-------------------------|--------|-------------------|----------|----------|---------------------------------------------------|
| <b>Talc</b>       | $\text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2$                                                      | <u>Monoclinic</u> | Pale green, White, Gray | White  | Pearly            | 1        | 1 set    | Soap touch                                        |
| <b>Gypsum</b>     | $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$                                                               | <u>Monoclinic</u> | White or colorless      | White  | Vitreous or silky | 2        | 2 sets   | Transparent to translucent                        |
| <b>Calcite</b>    | $\text{CaCO}_3$                                                                                         | Trigonal          | White or colorless      | White  | Vitreous          | 3        | 3 sets   | Effervesces with cold & dilute HCl<br>Transparent |
| <b>Fluorite</b>   | $\text{CaF}_2$                                                                                          | Cubic             | Green or violet         | White  | Vitreous          | 4        | 4 sets   | Fluorescence                                      |
| <b>Barite</b>     | $\text{BaSO}_4$                                                                                         | Orthorhombic      | Honey                   | White  | Vitreous          | 2.5-3    | 3 sets   | Transparent<br>High specific gravity              |
| <b>Orthoclase</b> | $\text{KAlSi}_3\text{O}_8$                                                                              | Monoclinic        | Buff                    | White  | Vitreous          | 6        | 2 sets   | Translucent                                       |
| <b>Quartz</b>     | $\text{SiO}_2$                                                                                          | <u>Trigonal</u>   | White                   | White  | Vitreous          | 7        | -        | Conchoidal fracture                               |
| <b>Muscovite</b>  | $\text{KAl}_3\text{Si}_3\text{O}_{10}(\text{OH})_2$                                                     | Monoclinic        | Colorless or Silver     | White  | Vitreous          | 2-2.5    | 1 set    | Platy shape (flakes)<br>Elasticity                |
| <b>Biotite</b>    | $\text{K}(\text{Mg}, \text{Fe})_2\text{Al}(\text{Si}, \text{Al})_3\text{O}_{10}(\text{OH}, \text{F})_2$ | Monoclinic        | Black, dark brown       | White  | Vitreous          | 2.5-3    | 1 set    | Platy shape (flakes)<br>Elasticity                |
| <b>Magnetite</b>  | $\text{Fe}_3\text{O}_4$                                                                                 | Cubic             | Black                   | Black  | Metallic          | 6-6.5    | -        | Ferromagnetic (attract to magnet)                 |
| <b>Halite</b>     | $\text{NaCl}$                                                                                           | Cubic             | Colorless or white      | White  | Vitreous          | 2        | 3 sets   | Saline taste                                      |

| Mineral name        | Chemical composition                            | Crystal system | Color                   | Streak         | Luster      | Hardness | Cleavage | Other properties                                                 |
|---------------------|-------------------------------------------------|----------------|-------------------------|----------------|-------------|----------|----------|------------------------------------------------------------------|
| <b>Chromite</b>     | $\text{FeCr}_2\text{O}_4$                       | Cubic          | Black or Brownish black | Reddish brown  | Submetallic | 5.5      | -        | High specific gravity<br>Opaque                                  |
| <b>Pyrolusite</b>   | $\text{MnO}_2$                                  | Tetragonal     | Black or very dark grey | Black          | Metallic    | 3-3.5    | -        | Opaque<br>Leave black impact on fingers<br>High specific gravity |
| <b>Hematite</b>     | $\text{Fe}_2\text{O}_3$                         | Trigonal       | Brick red               | Red            | Earthy      | 5-6      | -        | Opaque                                                           |
| <b>Malachite</b>    | $\text{Cu}_2(\text{CO}_3)(\text{OH})_2$         | Monoclinic     | Green                   | Green          | Dull        | 3.5- 4   | -        | Opaque                                                           |
| <b>Magnesite</b>    | $\text{MgCO}_3$                                 | Trigonal       | White                   | white          | Dull        | 3-3.5    | -        | Give Effervesces with HCl when heated                            |
| <b>Kaolinite</b>    | $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$ | Triclinic      | White, gray             | White          | Dull        | 2-2.5    | -        | Earthy fracture<br>Brittle tenacity<br>kaolin-mud odor           |
| <b>Graphite</b>     | C                                               | Hexagonal      | Grey                    | Gray           | metallic    | 1-2      | One set  | Low specific gravity<br>Leave black impact on fingers            |
| <b>Sulfur</b>       | S                                               | Orthorhombic   | Yellow                  | White          | Resinous    | 1.5-2.5  | -        | Low specific gravity<br>By heating (sulfur- match odor)          |
| <b>Galena</b>       | $\text{PbS}$                                    | Cubic          | Silver grey             | Black          | Metallic    | 2.5      | 3 sets   | High specific gravity                                            |
| <b>Chalcopyrite</b> | $\text{CuFeS}_2$                                | Tetragonal     | Brassy yellow           | Greenish black | Metallic    | 3.5-4    | -        | Opaque, brittle                                                  |

## Sheet 7

Draw the mineral and complete the following:

- Mineral name: .....
- Color: .....
- Streak: .....
- Transparency: .....
- Luster: .....
- Hardness: .....
- Cleavages: .....
- Fracture: .....
- Other properties: .....

- Mineral name: .....
- Color: .....
- Streak: .....
- Transparency: .....
- Luster: .....
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# ***Part 3:***

# ***Rocks***

# Rocks

## Section 8: Igneous rocks

**Rock** is a natural substance, a solid aggregate of one or more minerals. For example, granite, a common rock, is a combination of the minerals quartz, feldspar and biotite.

Three major groups of rocks are defined: igneous, sedimentary, and metamorphic. The scientific study of rocks is called petrology, which is an essential branch of geology.

Many rocks contain silica ( $\text{SiO}_2$ ); a compound of silicon and oxygen that forms 74.3% of the Earth's crust. This material forms crystals with other compounds in the rock. The proportion of silica in rocks and minerals is a major factor in determining their names and properties.

Rocks are classified according to characteristics such as mineral and chemical composition, permeability, texture of the constituent particles, and particle size. These physical properties are the result of the processes that formed the rocks.

### Igneous rock

Igneous rock (derived from the Latin word *igneus*, meaning *of fire*, from *ignis* meaning *fire*) is formed through the cooling and solidification of magma or lava

About 64.7% of the Earth's crust by volume consists of igneous rocks, making it the most plentiful category. Of these, 66% are basalts and gabbros, 16% are granite, and 17% granodiorites and diorites. Only 0.6% are syenites and 0.3% peridotites and dunites. The oceanic crust is 99% basalt.

According to their chemical composition (Silica  $\text{SiO}_2$  %), igneous rocks are classified into FOUR categories:

- 1- Acidic or felsic igneous rocks, which contain more than 66 % silica. They are light in color and have low specific gravity compared with other types. Examples are granite, rhyolite, dacite, granodiorite.
- 2- Intermediate igneous rocks, which contain 66-52 % silica. They have intermediate color and have medium specific gravity compared with other types. Examples are andesite, diorite, syenite and trachyte.

3- Basic or mafic igneous rocks, which contain 52-45 % silica, They are dark in color and have high specific gravity compared with other types. Examples, Basalt and gabbro.

4- Ultrabasic igneous rocks, which contain less than 45 % silica. They are very dark in color and have very high specific gravity compared with other types. Examples peridotite.

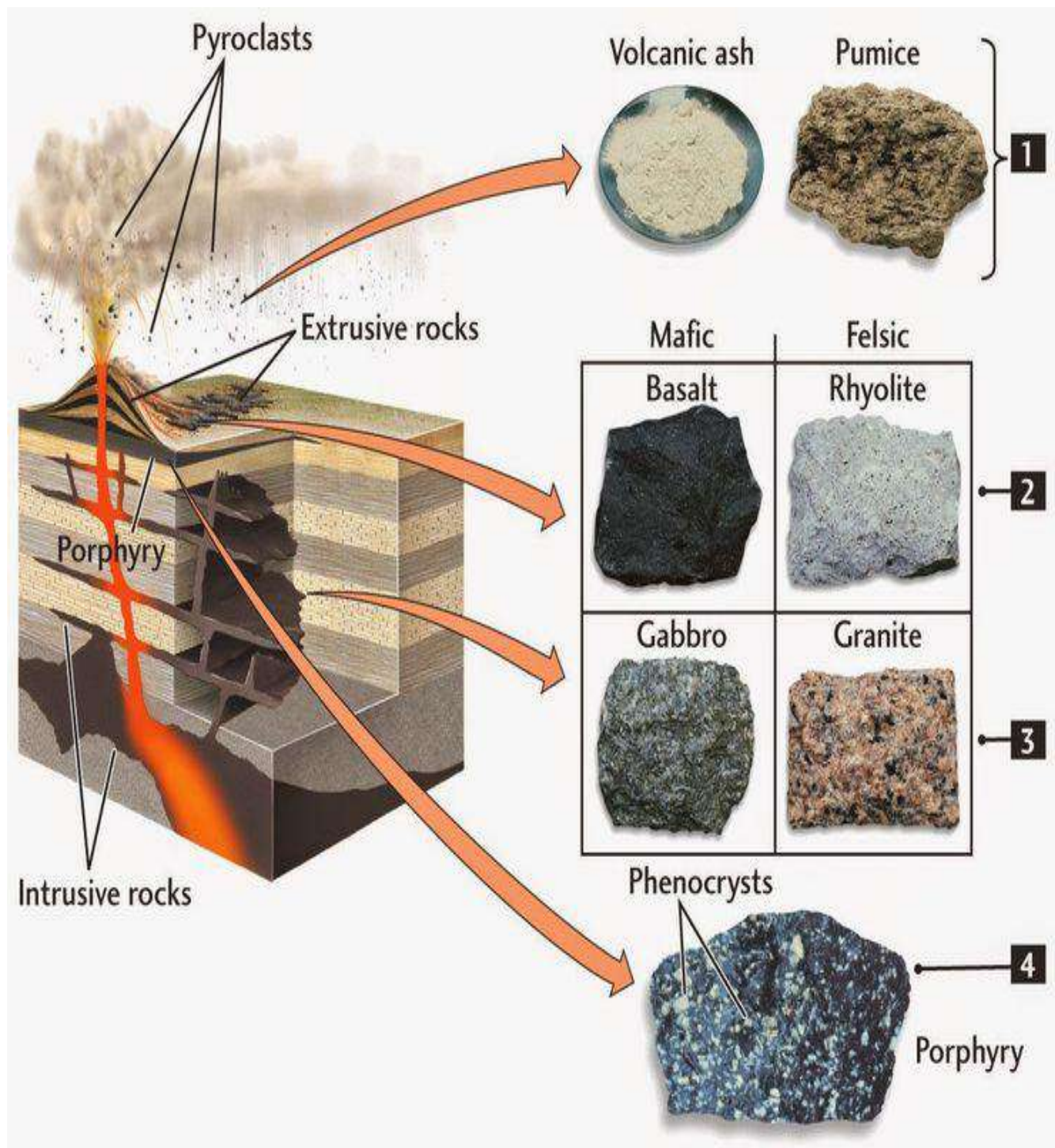
According to their occurrence, igneous rocks are classified into THREE categories:

- 1- Plutonic or intrusive igneous rocks result when magma cools and crystallizes slowly within the Earth's crust. A common examples of this type is granite, granodiorite, syenite, diorite, gabbro and peridotite.
- 2- Subvolcanic Igneous rocks which occur in between plutonic and volcanic. Examples porphyritic rhyolite, porphyritic andesite, porphyritic basalt.
- 3- Volcanic or extrusive igneous rocks result from magma reaching the surface as lava or, forming minerals such as rhyolite, dacite, trachyte, andesite, basalt,

They classified according to their textures into:

- 1- Phaneritic or coarse grain igneous rocks, which are plutonic
- 2- Porphyritic igneous rocks consist of coarse grain crystals (phenocryst) set in fine-grained groundmass. Examples porphyritic basalt, porphyritic andesite, porphyritic dacite.
- 3- Aphanitic or fine grain igneous rocks, which are volcanic.

## Plutonic, Sub-volcanic and volcanic igneous rocks



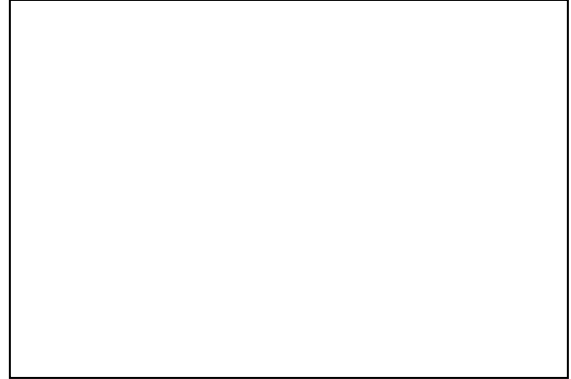
## Classification of Igneous Rocks

|                                       |                                                       |                                                              |                      |                                          |                      |                             |             |
|---------------------------------------|-------------------------------------------------------|--------------------------------------------------------------|----------------------|------------------------------------------|----------------------|-----------------------------|-------------|
| Ultrabasic (ultramafic)               | Basic (mafic)                                         | Intermediate                                                 |                      | Acidic (felsic)                          |                      | 1. Chemical composition     |             |
| Very dark                             | Dark                                                  | Medium                                                       |                      | Light                                    |                      | 2. color                    |             |
|                                       | 2.9                                                   | 2.8                                                          |                      | 2.7-2.4                                  |                      | 3. Specific gravity         |             |
| Less than 45%                         | 52-45 %                                               | 66-52 %                                                      |                      | more than 66 %                           |                      | SiO <sub>2</sub> % (Silica) |             |
| Pyroxene<br>Olivine<br>Ca-plagioclase | Ca-plagioclase<br>Pyroxene,<br>Olivine,<br>Hornblende | Na-Plagioclase, Ca-Plagioclase, Hornblende, mica, K-feldspar |                      | Quartz, K-feldspar, Na-plagioclase, Mica |                      | Minerals                    |             |
|                                       |                                                       |                                                              |                      |                                          |                      | Texture                     | Occurrence  |
|                                       | Basalt                                                | Andesite                                                     | Trachyte             | Dacite                                   | Rhyolite             | Aphanitic (fine)            | Volcanic    |
|                                       | Diabase (dolerite)                                    | Porphyritic Andesite                                         | Porphyritic Trachyte | Porphyritic Dacite                       | Porphyritic Rhyolite | Porphyritic                 | Subvolcanic |
| Peridotite                            | Gabbro                                                | Diorite                                                      | Syenite              | Granodiorite                             | Granite              | Phaneritic (coarse)         | Plutonic    |

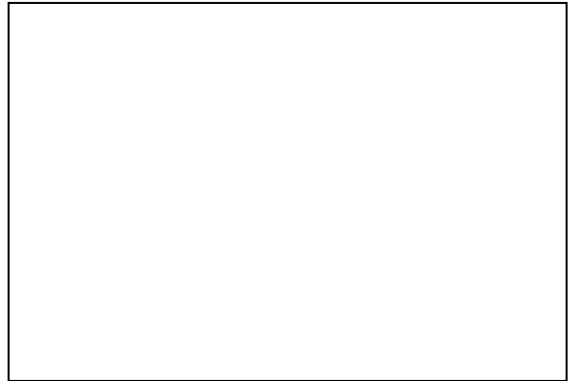
## Sheet 8

### Describe the rock sample:

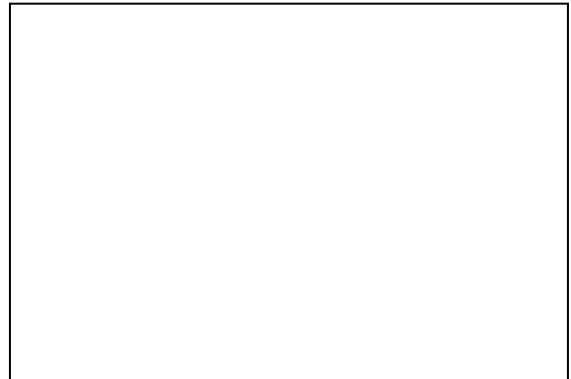
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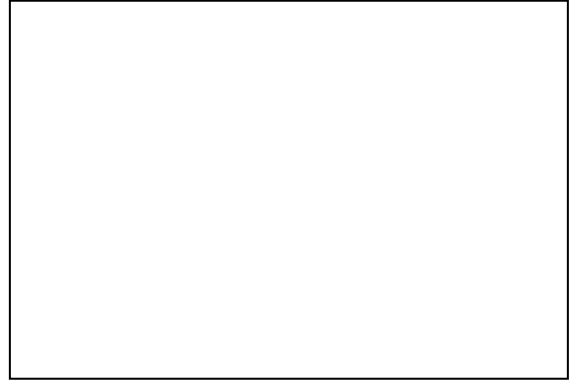


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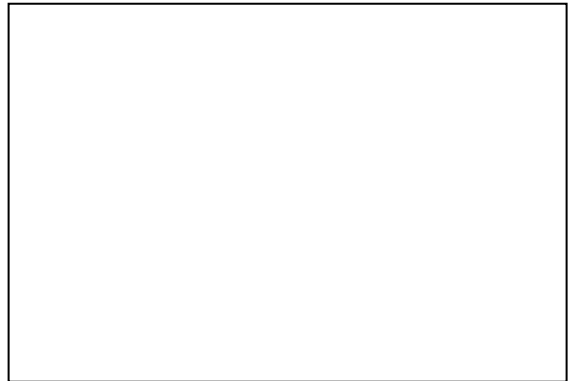


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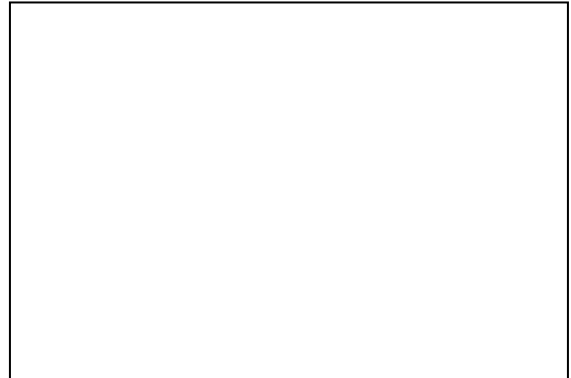
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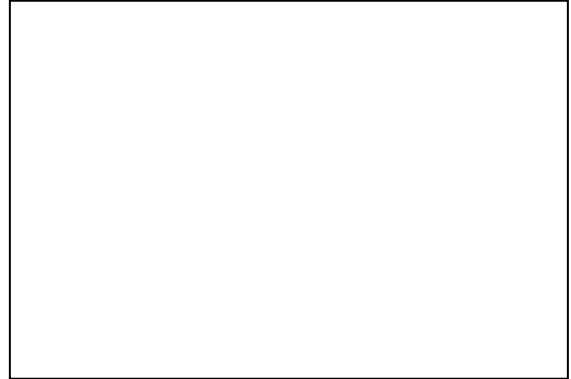


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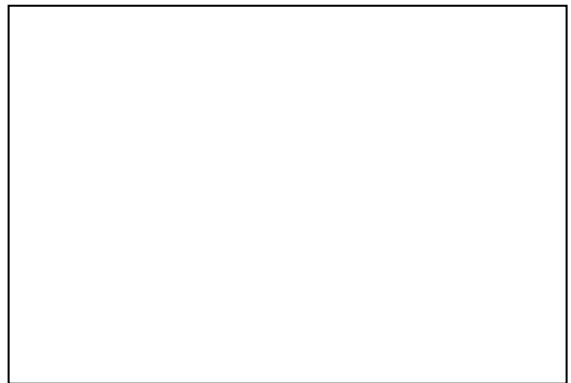


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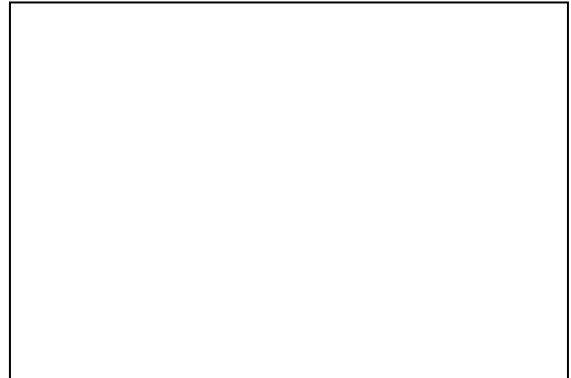
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## **Section 9: Sedimentary rocks**

### **Sedimentary rocks**

Sedimentary rocks are formed at the earth's surface by the accumulation and cementation of fragments of earlier rocks, minerals, and organisms or as chemical precipitates and organic growths in water (sedimentation). This process causes clastic sediments (pieces of rock) or organic particles (detritus) to settle and accumulate, or for minerals to chemically precipitate (evaporite) from a solution.

Before being deposited, sediments are formed by weathering of earlier rocks by erosion in a source area and then transported to the place of deposition by water, wind, ice, mass movement or glaciers. Mud rocks comprise 65% (mudstone, shale and siltstone); sandstones 20 to 25% and carbonate rocks 10 to 15% (limestone and dolostone). About 7.9% of the crust by volume is composed of sedimentary rocks, with 82% of those being shales, while the remainder consists of limestone (6%), sandstone (12%).

The sedimentary rocks are classified according to their origin into:

- 1- Mechanical or clastic sedimentary rocks, which formed from fragments of earlier rocks. Examples conglomerate, breccia, sandstones, siltstones and claystone.
- 2- Chemical sedimentary rocks, which formed chemical precipitation from water. Examples are limestone, dolostone, chert, gypsum and rock salt
- 3- Biochemical sedimentary rocks, which formed from organic particles (detritus) to settle and accumulate. Examples are chalk, and coal, oolitic limestone and fossiliferous liestone.

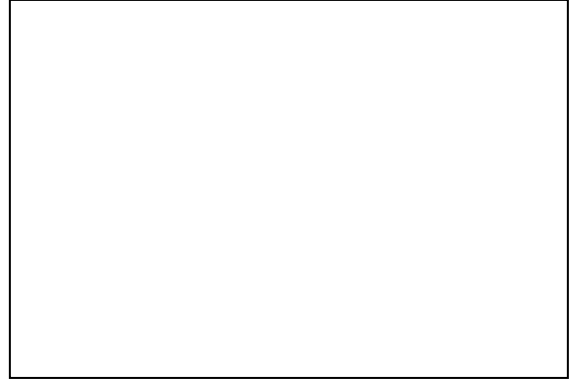
## Classification of sedimentary rocks

| SEDIMENTARY ROCK ANALYSIS AND CLASSIFICATION                                            |                                                                                             |                                                                           |                                                                          |                                                |                         |                                                    |      |
|-----------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|---------------------------------------------------------------------------|--------------------------------------------------------------------------|------------------------------------------------|-------------------------|----------------------------------------------------|------|
| STEP 1:<br>What is the rock's composition?                                              |                                                                                             | STEP 2:<br>What are the rock's textural and other distinctive properties? |                                                                          |                                                | STEP 3:<br>Rock Name(s) |                                                    |      |
| DETRITAL (CLASTIC)                                                                      | Mainly rock fragments or mineral grains (quartz, feldspar, clay) weathered from other rocks | Mainly gravel ( $\geq 2$ mm)                                              |                                                                          | Rounded grains                                 | CONGLOMERATE            |                                                    |      |
|                                                                                         |                                                                                             |                                                                           |                                                                          | Angular grains                                 | BRECCIA                 |                                                    |      |
|                                                                                         |                                                                                             | Mainly sand ( $1/16 - 2$ mm)                                              |                                                                          | Mostly quartz grains                           | QUARTZ SANDSTONE        |                                                    |      |
|                                                                                         |                                                                                             |                                                                           |                                                                          | Mainly feldspar and quartz                     | ARKOSE                  |                                                    |      |
|                                                                                         |                                                                                             |                                                                           |                                                                          | Sand is mixed with much silt and/or clay (mud) | GRAYWACKE               |                                                    |      |
|                                                                                         |                                                                                             | Mainly Mud ( $< 1/16$ mm)                                                 | Mostly silt ( $1/256 - 1/16$ mm)                                         | Breaks into blocks or layers                   | SILTSTONE               |                                                    |      |
|                                                                                         |                                                                                             |                                                                           | Mostly clay ( $< 1/256$ mm)                                              | Crumbles or breaks into blocks                 | CLAYSTONE               |                                                    |      |
|                                                                                         |                                                                                             |                                                                           |                                                                          | Fissile (splits easily)                        | SHALE                   |                                                    |      |
|                                                                                         |                                                                                             | BIOCHEMICAL: Mainly fossil shells or plant fragments                      | Mainly plant fragments or charcoal                                       | Dull brown with visible plant fragments        |                         | Porous and easy to break apart the plant fragments | PEAT |
| Black                                                                                   |                                                                                             |                                                                           |                                                                          | Dense and brittle or porous and sooty          | BITUMINOUS COAL         |                                                    |      |
| Mainly fossil shells, shell fragments, or microfossils<br><br>Effervesces in dilute HCl | Mostly visible shells and shell fragments cemented into a dense mass                        |                                                                           |                                                                          | CALCIRUDITE                                    |                         |                                                    |      |
|                                                                                         | Mostly sand-sized fragments. May have a few larger shells.                                  |                                                                           |                                                                          | CALCARENITE                                    |                         |                                                    |      |
|                                                                                         | Mostly very fine grained to microcrystalline mass of calcite and microfossils               |                                                                           |                                                                          | MICRITE                                        |                         |                                                    |      |
|                                                                                         | Porous, poorly cemented mass of shells and shell fragments                                  |                                                                           |                                                                          | COQUINA                                        |                         |                                                    |      |
|                                                                                         | Mostly very fine grained, earthy, chalky, light-colored mass of microfossils                |                                                                           |                                                                          | CHALK                                          |                         |                                                    |      |
| CHEMICAL (INORGANIC):<br>Chemically precipitated crystals                               | Mainly crystals of calcite or aragonite, $\text{CaCO}_3$<br><br>Effervesces in dilute HCl   |                                                                           | Crystalline to microcrystalline bands of calcite crystals                |                                                |                         | TRAVERTINE                                         |      |
|                                                                                         |                                                                                             |                                                                           | Spherical grains like tiny beads ( $< 2$ mm) with concentric laminations |                                                |                         | OOLITIC LIMESTONE                                  |      |
|                                                                                         | Mainly dolomite $\text{CaMg}(\text{CO}_3)_2$                                                |                                                                           | Microcrystalline                                                         | Effervesces in dilute HCl only if powdered     |                         | DOLOSTONE                                          |      |
|                                                                                         | Mainly varieties of quartz, $\text{SiO}_2$ (chalcedony, flint, chert, opal, jasper, etc.)   | Microcrystalline, conchoidal fracture                                     | Scratches glass                                                          |                                                | CHERT                   |                                                    |      |
|                                                                                         | Mainly halite, NaCl                                                                         | Crystals formed as inorganic chemical precipitates                        | Salty taste                                                              |                                                | ROCK SALT               |                                                    |      |
|                                                                                         | Mainly gypsum, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$                                    | Crystals formed as inorganic chemical precipitates                        | Can be scratched with your fingernail                                    |                                                | ROCK GYPSUM             |                                                    |      |
|                                                                                         | Mostly iron-bearing minerals, like limonite and hematite                                    | Amorphous or microcrystalline                                             | Dark-colored, usually brown or red-gray                                  |                                                | IRONSTONE               |                                                    |      |

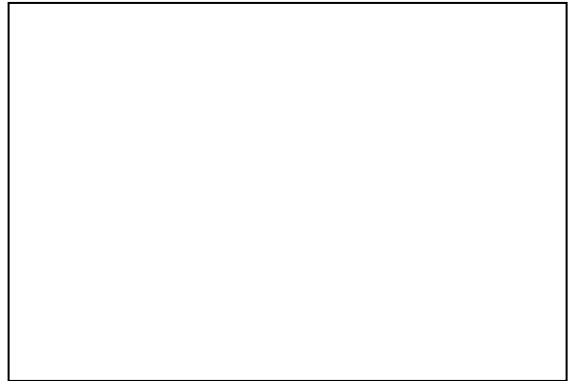
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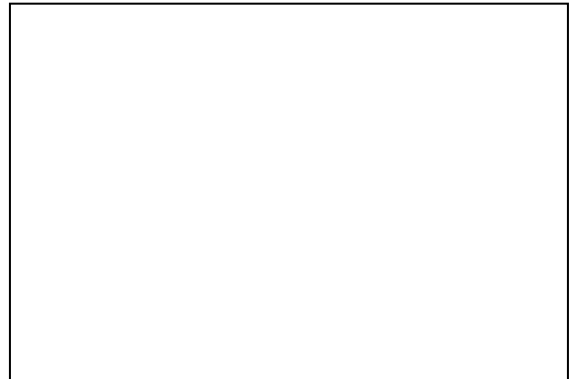
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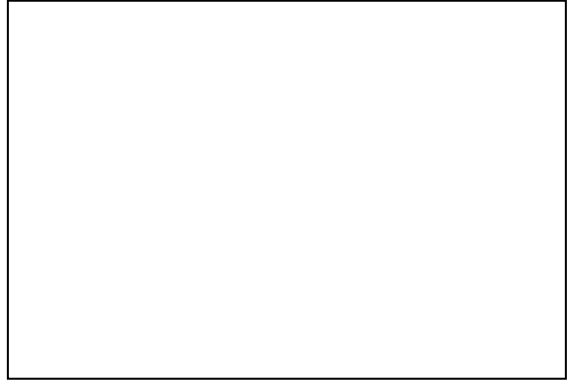


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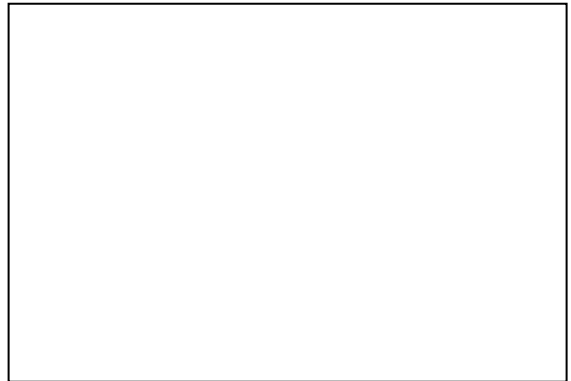


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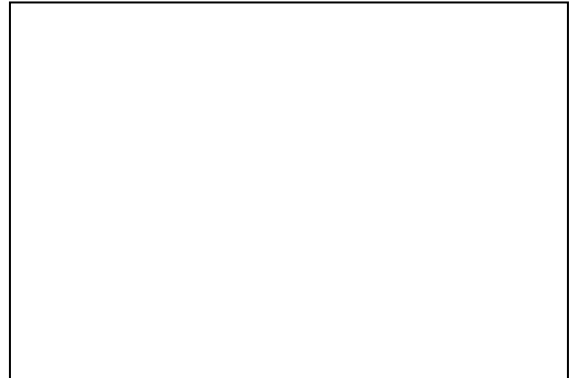
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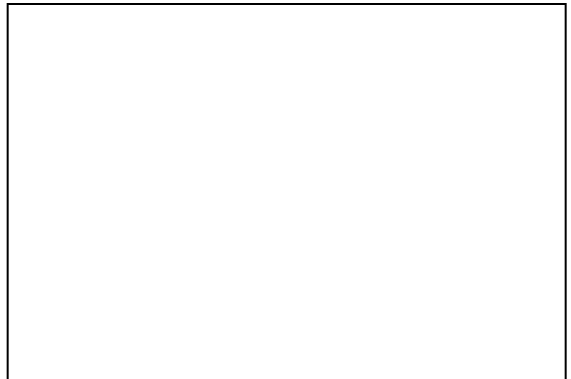
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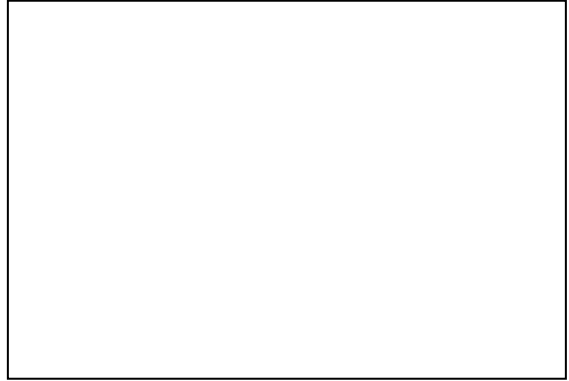


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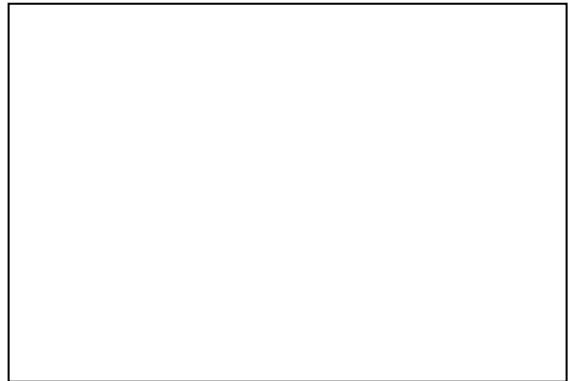


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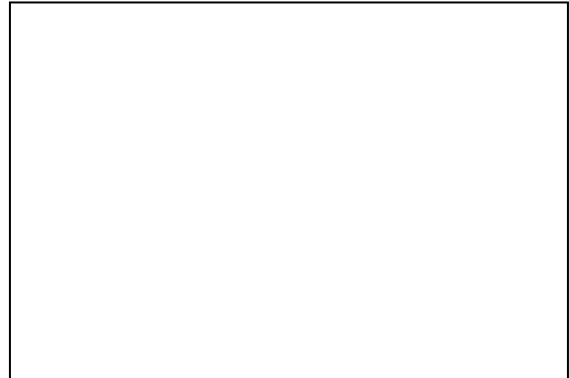
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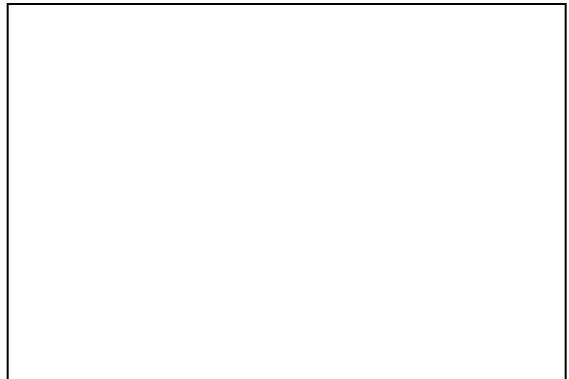
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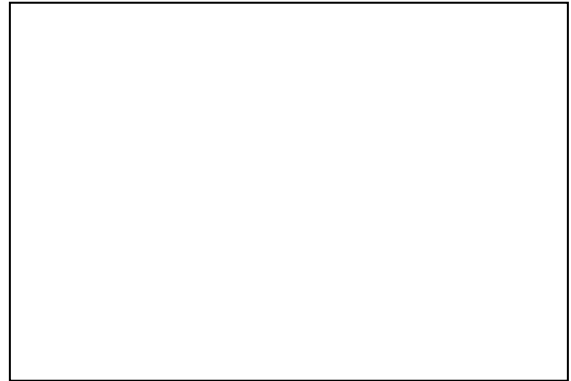


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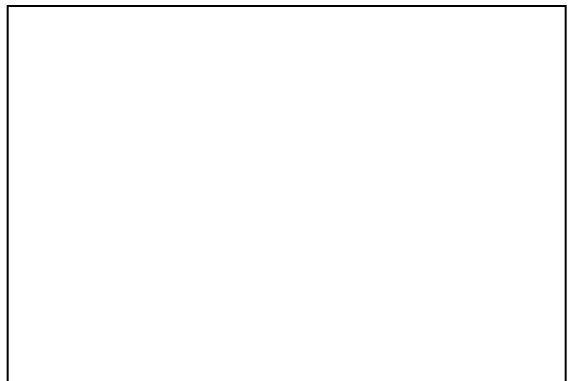
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## **Section 10: Metamorphic rocks**

### **Metamorphic rock**

Metamorphic rocks are formed by subjecting any rock type-sedimentary rock, igneous rock or another older metamorphic rock- to different temperature and pressure conditions than those in which the original rock was formed. This process is called metamorphism, meaning to "change in form. The original rock, known as the protolith. The temperatures and pressures required for this process are always higher than those found at the Earth's surface: temperatures greater than 150 to 200 °C and pressures of 1500 bars. Metamorphic rocks compose 27.4% of the crust by volume.

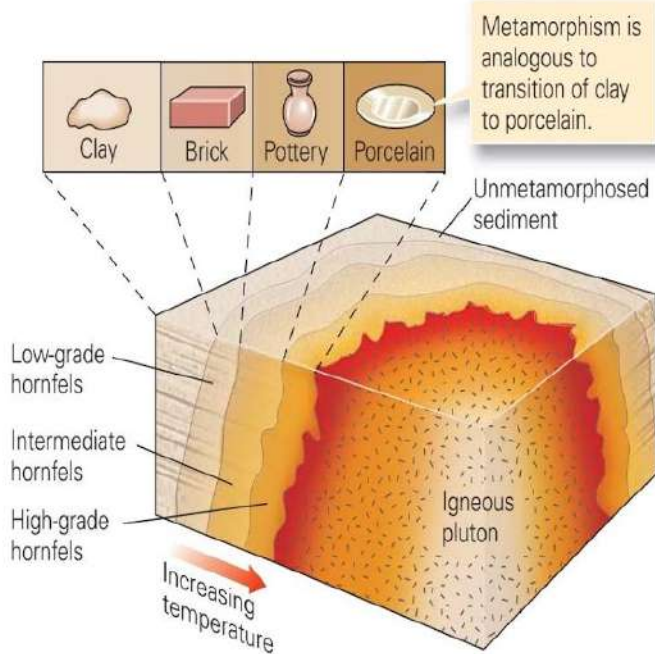
The three major classes of metamorphic rock are based upon the mode of formation and agent of metamorphism.

- 1- Thermal or contact metamorphic rocks n intrusion of magma that heats the surrounding rock causes thermal or contact metamorphism a temperature-dominated transformation. Examples are marble, quartzite and hornfelse.
- 2- Dynamic metamorphic rocks, or pressure-dominant metamorphism occurs when sediments are buried deep under the ground; pressure is dominant, and temperature plays a secondary role. Examples are mylonite and fault breccia.
- 3- Regional metamorphic rocks, where both heat and pressure play a role, the mechanism is termed regional metamorphism. Examples of this category are slate, phyllite, schist, gneiss and migmatite.

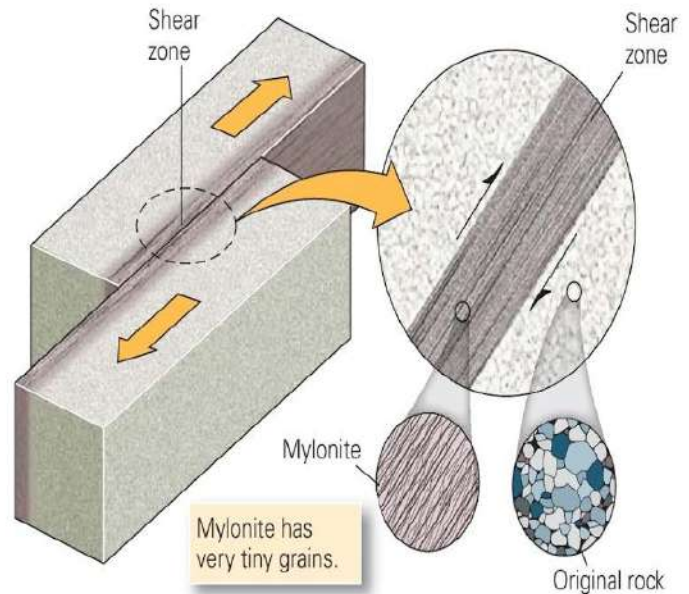
Depending on the structure, metamorphic rocks are divided into two general categories:

- 1- foliated metamorphic rocks, which include schists, gneiss, slate, phyllite, and mylonite are foliated rocks
- 2- Non-foliated metamorphic rocks, which include marble, quartzite, and serpentine.

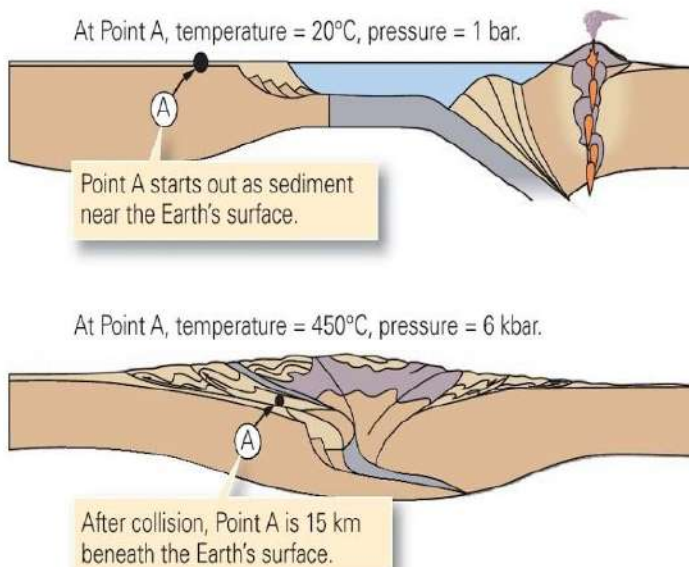
## Thermal (Contact), Dynamic and Regional metamorphic rocks



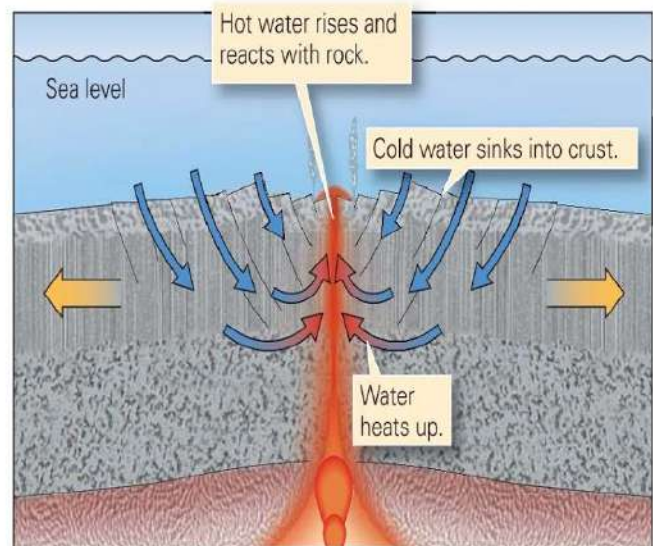
(a) Heat radiated from a large pluton can produce a metamorphic aureole, in which hornfels develops. Grade decreases progressively away from the pluton contact.



(b) Shearing of a rock under plastic conditions causes original crystals to divide into tiny crystals without breaking to form a mylonite. Mylonite has strong foliation.



(c) Dynamothermal metamorphism happens when one part of the crust shoves over another part, so that rocks once near the surface end up at great depth.



(d) The heat of rising magma at a ridge axis heats water, which then convects. The hot water reacts with the crust and forms metamorphic minerals.

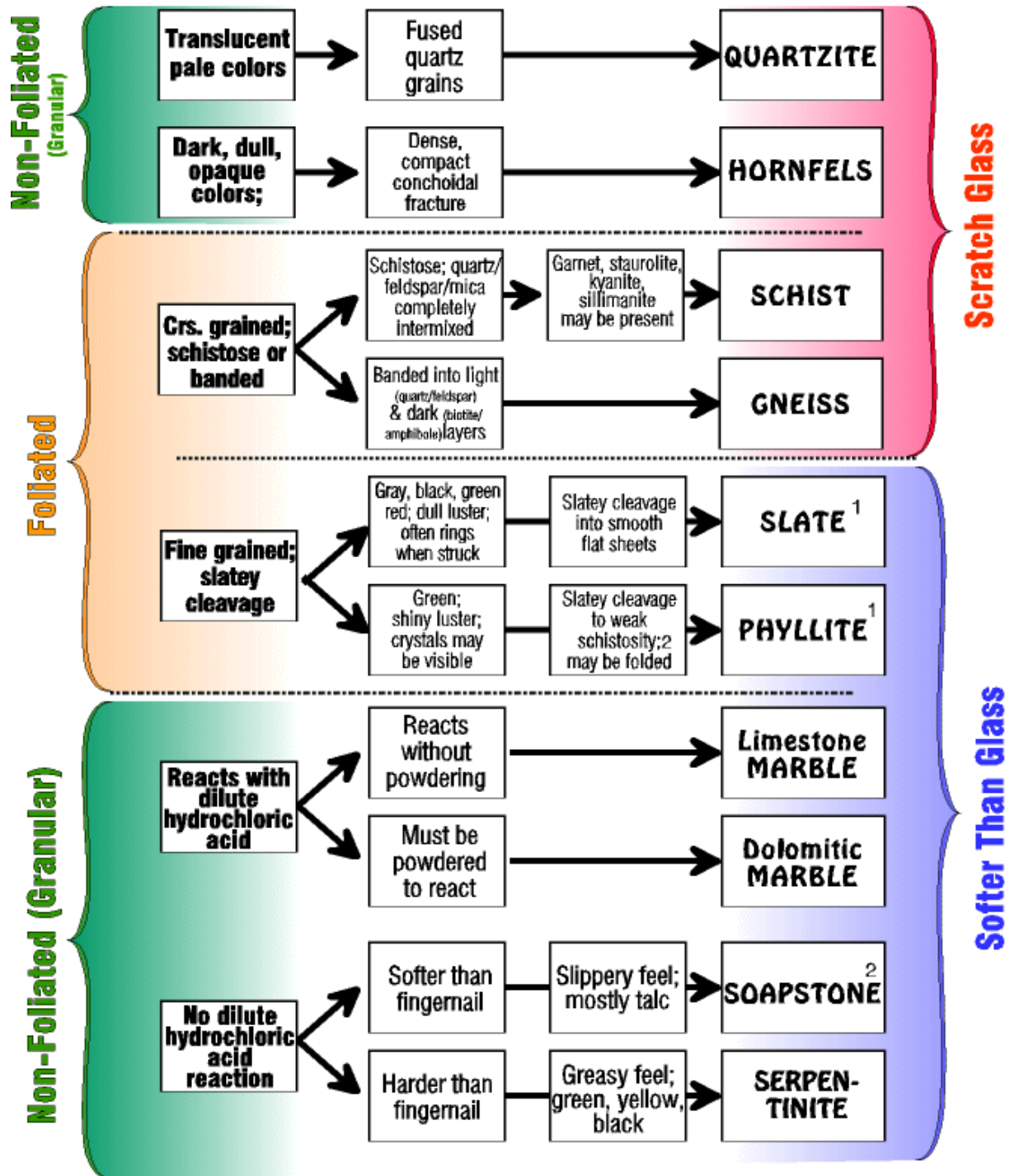
### Foliated and Non-foliated metamorphic rocks

| Rock Name  |                              | Texture      | Grain Size       | Comments                                                      | Parent Rock                        |
|------------|------------------------------|--------------|------------------|---------------------------------------------------------------|------------------------------------|
| Slate      | Increasing Metamorphism<br>↓ | Foliated     | Very fine        | Excellent rock cleavage, smooth dull surfaces                 | Shale, mudstone, or siltstone      |
| Phyllite   |                              |              | Fine             | Breaks along wavy surfaces, glossy sheen                      | Slate                              |
| Schist     |                              |              | Medium to Coarse | Micas dominate, scaly foliation                               | Phyllite                           |
| Gneiss     |                              |              | Medium to Coarse | Compositional banding due to segregation of minerals          | Schist, granite, or volcanic rocks |
| Marble     |                              | Non foliated | Medium to coarse | Interlocking calcite or dolomite grains                       | Limestone, dolostone               |
| Quartzite  |                              |              | Medium to coarse | Fused quartz grains, massive, very hard                       | Quartz sandstone                   |
| Anthracite |                              |              | Fine             | Shiny black organic rock that may exhibit conchoidal fracture | Bituminous coal                    |

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## Foliated and Non-foliated metamorphic rocks

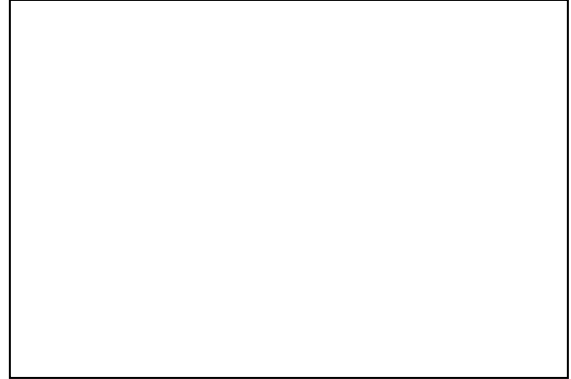
## Key to Common Metamorphic Rocks



## Sheet 10

### Describe the rock sample:

- Rock name:
- Texture:
- Type of metamor.:
- Agent of metamor.:
- Protolith:



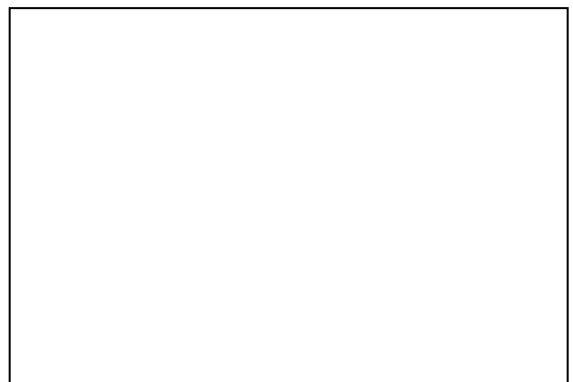
- Rock name:
- Texture:
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- Protolith:



- Rock name:
- Texture:
- Type of metamor.:
- Agent of metamor.:
- Protolith:

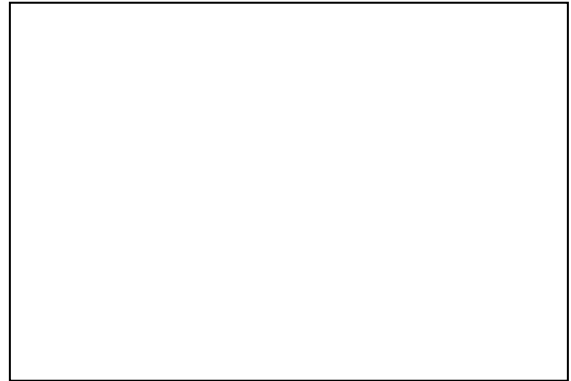


- Rock name:
- Texture:
- Type of metamor.:
- Agent of metamor.:
- Protolith:



**Describe the rock sample:**

- Rock name:
- Texture:
- Type of metamor.:
- Agent of metamor.:
- Protolith:
- 



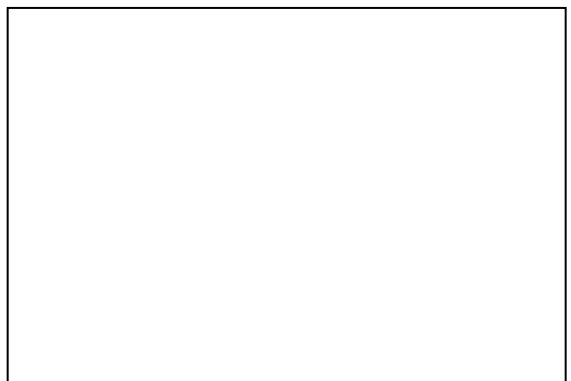
- Rock name:
- Texture:
- Type of metamor.:
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- Protolith:
- 



- Rock name:
- Texture:
- Type of metamor.:
- Agent of metamor.:
- Protolith:

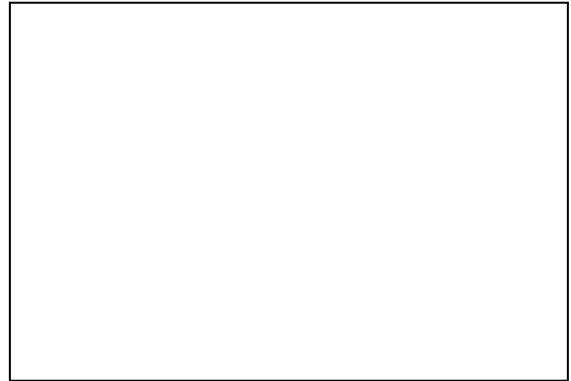


- Rock name:
- Texture:
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- Agent of metamor.:
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**Describe the rock sample:**

- Rock name:
- Texture:
- Type of metamor.:
- Agent of metamor.:
- Protolith:



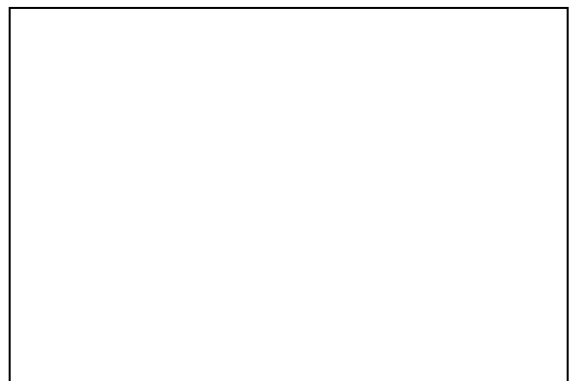
- Rock name:
- Texture:
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- Rock name:
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