Lecture Series: SGL 201 – Principles of Mineralogy

LECTURE 1
MINERALOGY AND CRYSTALLOGRAPHY

1.1 LECTURE OUTLINE
Welcome to lecture 1 of this unit. Congratulations for having covered successfully the first year prerequisite unit in Geology, namely: “SGL 101: Materials of the Earth”. In order for you to grasp fully the contents of the present lecture, you are particularly encouraged to make a review of the SGL 101 topic “Principles of Elementary Mineralogy and Crystallography”. At this level, you are now ready to be introduced to more advanced knowledge in the subject matter through this unit entitled ”Principles of Mineralogy”. As the unit title suggests, we shall begin the lecture by asking ourselves the all-important question – What is mineralogy? Mineralogy is basically the science of minerals, which includes their crystallography, chemical composition, physical properties, genesis, their identification and their classification. You will be interested to know that mineralogy is closely allied to mathematics (especially geometry), chemistry and physics. Mineralogy is a fundamental part of the science of geology and other closely related subjects such as agronomy, ceramic engineering, medical science, and metallurgy.
In this lecture we shall review the definition of a mineral, the historical perspective of mineralogy, its importance in science and application in society, and a more in-depth study of a mineral’s crystallographic symmetry elements.

**OBJECTIVES**

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

- Give the definition of a mineral from the historical, legalistic to scientific perspective.
- Review the historical perspective of the science of mineralogy.
- Describe the importance of mineralogy and its application to other related fields of scientific and technological endeavor.
- Describe various elements of crystallography in terms of crystal structure, classification, and symmetry in crystals.
- State the Law of Constancy of interfacial angles in crystals and how to measure those angles using a goniometer.
- Describe twinning in crystals.
1.2 WHAT IS A MINERAL?

The definition of the term “mineral” range from the historical perspective (any material that is neither animal nor vegetable) through the legalistic perspective (something valuable that may be extracted from the earth and is subject to depletion) to the scientific perspective (a naturally occurring solid, generally formed by inorganic processes with an ordered internal arrangement of atoms and a chemical composition and physical properties that are either fixed or that vary within some definite range).

1.3 HISTORICAL PERSPECTIVE OF MINERALOGY

Prehistoric uses of rocks and minerals predate the written language. The evidence of such prehistoric uses include the following: the red and black mineral pigments (hematite and pyrolusite) that were used in cave paintings and the diverse hard or tough minerals and rocks (e.g., jade, flint, and obsidian) that were shaped into tools and weapons. In Kenya, such prehistoric tools dating 500,000 years have been located at an archaeological site within the Rift valley, at Olorgesaille, in Narok district. In addition, mining and smelting of metallic minerals to produce gold, silver, iron, copper, lead, and bronze are also known to have predated written records.

The written records are considered to have began with the philosopher Aristotle (384-322 BC) who in his book (*Meteorologica*) included a section about stones (minerals, metals and fossils). Theophrastus (ca. 372-287 BC), who was a pupil of Aristotle, prepared a book dealing with the substances of the mineral kingdom.

A major milestone in the development of mineralogy was provided by the Danish scientist Niels Stensen, better known by the Latinized version of his name, Nicolaus Steno. In 1669, Steno showed that the interfacial angles of quartz crystals are constant, no matter what the shape and size of the crystals. This discovery drew attention to the significance of crystal form and ultimately led to the development of the science of crystallography. Robert Boyle, an English philosopher (1627 – 1691), was the first to refer to the word “mineralogy” whose origin was centered on Celtic civilization. Warner A.G., a German
professor (1750-1817), made a noteworthy contribution in standardizing the nomenclature and description of minerals.

James D. Dana (1813 –1895) articulated a feasible classification of minerals based on the chemistry that had previously been proposed by Bezzelius (1779-1848). Although the microscope was used to study minerals early in the 19th century, it was not until after 1828, when the British physicist William Nicole (1768-1828) invented the polarizer that optical mineralogy took its place as a major investigative procedure in mineralogy. The first great development in the 20th century came as a result of experiments made to determine how crystals can affect X-rays. Presently, X-rays and electron microscopes are in use as a result of experiments advanced by Bragg (1890 – 1971). In the recent past, the advances made in the introduction and widespread use of electron microscopes, X-ray diffractometers, and other sophisticated instruments and procedures (e.g., Mossbauer and infrared spectrometry), aid in the determination of certain characteristics of minerals and other crystalline materials.

1.4 IMPORTANCE OF MINERALOGY

Minerals and consequently mineralogy are extremely important to economics, aesthetics and science. Economically, the utilization of minerals is necessary if we have to maintain the current standard of living. Aesthetically, minerals shine as gems, enriching our lives with their inherent beauty, especially as we view them in museum displays. Gems in jewelry, crown-jewel collections, and other displays attract the attention of millions of people annually. As you may be aware, museums do more, however, than just displaying outstanding gems and mineral specimens. They also have assumed the function of collecting and preserving mineral specimens for posterity. Although a few minerals are common, many occur at only a few localities, and some occur within only a single

(a) Give three examples of some of the prehistoric uses of minerals and rocks.
(b) Review the historical perspective of the science of mineralogy up to the 21st Century.
deposit. Therefore, whenever possible, originally described specimens and other noteworthy specimens need to be preserved.

Scientifically, minerals comprise the data bank from which we can learn about our physical earth and its constituent materials. This knowledge enables us to understand how those materials have been formed, where they are likely to be found, and how they can be synthesized in the laboratory. As far as the scientific importance of minerals is concerned, attention is geared to the fact that each individual mineral documents the chemical and physical conditions, and consequently the geological processes that existed in the specific place at the particular time the mineral was formed.

For example, as you will later learn, the mineral referred to as sanidine feldspar, crystallizes at high temperatures associated with volcanic activity; that the polymorph of silica called coesite is formed under high-pressure conditions such as those associated with meteorite impact; and that many clay minerals are formed as the result of surface or near-surface weathering.

Thus, the science of mineralogy plays a fundamental role in geological interpretations and, in many cases, both its data and its methods are also applied in several other related fields of scientific and technological endeavor.

In addition, mineralogy is fundamental to the geological sciences, and its principles are basic to the understanding of a number of diverse aspects of several other disciplines, such as the agricultural sciences, the material sciences (ceramic engineering and metallurgy), as well as medical science.

List some of the practical applications of the science of mineralogy.
1.5 ELEMENTS OF CRYSTALLOGRAPHY AND MINERALOGY

A short review in definition of some important crystallographic terminologies that will be used in this section is presented here below:

1.5.1 Definition of Crystallographic Terms

In descriptive mineralogy, a **crystal** is defined as a solid body bounded by plane natural surfaces, which are the external expression of a regular arrangement of its constituent atoms or ions (Berry, Mason and Dietrich 1983).

**Crystal structure**: This is the orderly arrangement of atoms or group of atoms (within a crystalline substance) that constitute a crystal (Figure 1.1).

![Figure 1.1. Crystal structure of Halite. Left: Ions drawn proportional to their sizes. Right: Expanded view to show the interior of the unit cell.](image)

**Morphological crystals** are finite crystallographic bodies with finite faces that are parallel to lattice planes.

**Lattice** – This is an imaginary three-dimensional framework that can be referenced to a network of regularly spaced points, each of which represents the position of a motif (Figure 1.2).

**Unit Cell** – This is a pattern that yields the entire pattern when translated repeatedly without rotation in space. The repetition yields infinite number of identical unit cells and the pattern is regular. In order to fill space without gaps, the unit cell must at least be a parallelogram in 2D (2-dimensional) space.
Motif – This is the smallest representative unit of a structure. It is an atom or group of atoms that, when repeated by translation, give rise to an infinite number of identical regularly organized units.

1.5.2 CRYSTAL STRUCTURE

Lattices and Unit Cell

A crystal is a three-dimensional repetition of some unit of atoms or molecules. It would be convenient for the atomic scale structure to consider a set of imaginary points which has a fixed relation in space to the atoms of the crystal. In other words, we choose points in the crystal so that they have “identical surroundings”. These points are called lattice points. Because of the three dimensional periodicity in the crystal, the points constitute a three dimensional lattice which is called a point lattice (For example, see Figure 1.3).
Now let us define a parallelepiped by connecting any neighboring lattice point in the point lattice. This parallelepiped is called a **unit cell**. For example, heavily outlined ones in Figure 1.3. The size and shape of the unit cell can be described by the three vectors \( \mathbf{a}, \mathbf{b}, \mathbf{c} \) and the three angles between them \( \alpha, \beta, \gamma \) as shown in Figure 1.4. The magnitudes of these three vectors \( a_o, b_o, c_o \) are called **lattice constants** or **lattice parameters** of the unit cell.
1.5.3 CRYSTAL SHAPE

The key features of crystal boundaries are such that (a) the angles between them are determined only by the internal crystal structure, and (b) the relative sizes of the crystal boundaries depend on the rate of growth of the crystal boundaries. The crystal shape of some common minerals is presented in Figure 1.3.

Figure 1.3. Crystal shapes of some common minerals.
Although crystals of a particular chemical and structural species tend to grow with a particular shape (e.g., cube for Halite (NaCl) and octahedron for Spinel (MgAl$_2$O$_4$)), the shape may vary (but not the angles) for some species (e.g. orthoclase feldspar in Fig 1.4). The causes of variations are not well understood and several factors are probably involved, namely: (a) absorption of impurity atoms that may hinder growth on some boundary faces, and (b) atomic bonding that may change with temperature etc.

![Figure 1.4 Two crystal shapes of orthoclase feldspar.](image)

However from mathematical crystallography, such variations are unimportant, the key feature is the “constancy of angles between crystal boundaries with the same indices for all crystals of a particular chemical and structural type”. Different structural materials will have different angles between the crystal boundaries, and the angles can be related to the symmetry and shape of the unit cell – (hence the Law of Constancy of Angles proposed by Steno 1669 which states that “the angles between corresponding faces on different crystals of a substance are constant”).

### 1.5.4 CLASSIFICATION OF CRYSTALS

A crystal structure is like a 3-dimensional design with infinite repetition of some motif (a group of atoms). It is a periodic space pattern (studies have shown that there are 230 different kinds of space patterns). Each crystal belongs to one of these 230 types; hence elementary crystallography is vitally concerned with the characteristics of the patterns. Since, therefore, repetition is a fundamental property of the patterns, it has reasonably based the classification of crystals on the repetition (symmetry) operations that yield them. In developing the classification of crystals, the elements of symmetry are subdivided into three categories:
translation (parallel periodic displacement)
- point group symmetry (rotations, rotation inversion axes, reflection planes)
- space-group symmetry (screw axes, glide planes).

1.5.3.1 The Translation Lattices

Lattice – This is an array of points with the same vectorial environment (i.e. a collection of equipoints that portray the translational periodicity of the structure – hence the term translation lattice) as exemplified in Figure 1.5. A lattice must be infinite and the lattice points must be spaced regularly. A **primitive unit cell** for a single lattice is a unit cell containing only one lattice point.

![Figure 1.5. Regular arrangement of circles (e.g. atoms) in one dimension with a repeat translational period c.](image)

For simplicity, the unit cell joins four lattice points at the corners of a parallelogram: of course each lattice point being shared between four unit cells.

The names of some of the systems reflect the nature of the metrical properties: triclinic – three inclined axes; monoclinic – one inclined axis; orthorhombic – axes mutually perpendicular;
isometric (cubic) – three mutually perpendicular equal axes (Figure 1.6). The remaining names, tetragonal and hexagonal, reflect the dominant symmetry of crystals belonging to these systems. Hence a repeat unit of a lattice is known as the unit cell.

Figure 1.6. The crystallographic axes (A) for the cubic, tetragonal, and orthorhombic systems, (B) for hexagonal system, (C) for the monoclinic system, and (D) for the triclinic system.

1.5.3.2 Notation of Lattice Points, Rows and Planes

The diagram presented in Figure 1.7 illustrates the characteristic notations on the basis of the coordinate systems described. With reference to Figure 1.7 it can be noted that:

- Lattice points are specified without brackets – 100, 101, 102; etc
- Lattice rows are identified by brackets [100] – the a axis, [010] – the b axis, [001] – the c axis.
• Lattice planes are defined in terms of the Miller indices. Miller indices are prime integers proportional to the reciprocals of the intercepts of the planes on the crystallographic coordinate axes (e.g. in Figure 1.7), the plane illustrated has intercepts 1a, 1b, 2c. The Miller indices are obtained by taking the reciprocals of the intercepts and clearing the fractions such that the indices are co-prime integers. Therefore this results to: 1/1a, 1/1b, 1/2c = 2a 2b 1c. The letters are usually omitted and the indices are enclosed in parentheses; thus (221).

Figure 1.7. Notation of lattice points, rows and planes.

If the calculations result in indices that have a common factor, e.g. (442), the factor is removed to give the simplest set of integers: (221). The symbol (221) therefore applies equally to all individuals of a stack of identical, parallel planes related by a simple translation operation. Braces {} are used to designate a family of planes related by the symmetry of the lattice. The notation of hexagonal planes requires special attention. Hexagonal crystals are usually referred to the Bravais-miller axes – a₁, a₂, a₃ and c.

Given the intercepts of the crystallographic axes for respective crystallographic planes described in Table 1.1, fill in the blanks for their respectful reciprocals and Miller indices.
Table 1.1. An exercise on derivation of Miller indices.

<table>
<thead>
<tr>
<th>Face</th>
<th>Intercepts</th>
<th>Reciprocals</th>
<th>Miller Indices</th>
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<tbody>
<tr>
<td>RDE</td>
<td>2, 3, 6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FGH</td>
<td>6, 4, ∞</td>
<td></td>
<td></td>
</tr>
<tr>
<td>KLQ</td>
<td>∞, 4, ∞</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CD</td>
<td>5/2, 3/5, ∞</td>
<td></td>
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</table>

1.5.5 ZONES IN CRYSTALS

A zone in a crystal consists of a collection of a set crystal faces that are parallel to a particular line (or direction) termed as the zone axis (see Figure 1.8 (a)). On the other hand, a zone plane occurs at right angles to the zone axis (Figure 1.8 (b)).

![Zone Diagram](image)

Figure 1.8. (a) Faces a, b, c, and d belong to one zone. (b) The zone plane is perpendicular to the zone axis.

1.5.6 SYMMETRY ELEMENTS

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 centre of symmetry as discussed here below.
• **Plane of Symmetry** – This is defined as a plane along which the crystal may be cut into exactly similar halves each of which is a mirror image of the other. A crystal can have one or more planes of symmetry. A sphere for example has infinite planes of symmetry. The different planes of symmetry for a cube are illustrated in Figure 1.9

How many planes of symmetry does a cube have?

![Figure 1.9. The nine symmetry planes of the cube indicated by the dashed lines.](image)

• **Axis of Symmetry** – This is a line about which the crystal may be rotated so as to show the same view of the crystal more than once per revolution, e.g. a cube. Alternatively it can be defined as a line along which the crystal may be rotated such that the crystal assumes a position of congruence i.e. the crystal presents the same appearance to a fixed observer. If a position of congruence occurs after every 180
degrees of rotation, the axis is said to be a **diad** or two-fold symmetry axis. Other axes may be called **triad, tetrad or hexad** (three-fold, four-fold, or six-fold) axes depending on whether congruence is attained every 120, 90, or 60 degrees respectively. Symmetry axes for a cube are shown in Figure 1.10. Note also the symbols used to denote axes in diagrams.

![Figure 1.10 The thirteen symmetry axes of the cube.](image)

- **Center of Symmetry** – Center of symmetry is the point from which all similar faces are equidistant. It is a point inside the crystal such that when a line passes through it, you’ll have similar parts of the crystal on either side at same distances. A cube possesses a centre of symmetry, but a tetrahedron (e.g., Figure 1.11) does not.

![Figure 1.11 The tetrahedron, a crystal showing no centre of symmetry.](image)

Examples of the main crystal systems and symmetry classes are shown in Figures 1.12 (a) & (b).

How many axes of symmetry does a tetrahedron have?
Figure 1.12. (a) The crystal systems and symmetry classes.
Figure 1.12. (b) The crystal systems and symmetry classes.
1.5.7 THE LAW OF CONSTANCY OF INTERFACIAL ANGLES

The plane surfaces that bound natural crystals (i.e., the crystal faces) develop parallel to certain sets of net-planes (Figure 1.13) in the crystal lattice of any specific substance or mineral. Each edge between any pair of nonparallel faces is parallel to a lattice row. If the lattice for a substance has certain linear and angular dimensions, the angles between corresponding planes in each lattice domain for the given substance will be identical as long as they are measured under conditions of constant temperature and pressure. This condition is in agreement with the Law of Constancy of Angles, which states that:

*The angles between corresponding faces on different crystals of a substance are constant.*

![Figure 1.13. A planer net of a crystal lattice with shortest rows a, b, and a third axis c emerging perpendicularly from the plane of the drawing. The lines RDE, EF, etc. are the traces of lattice planes which are taken as parallel to c in the text.](image)

1.5.8 MEASUREMENT OF INTERFACIAL ANGLES

The measurement of the interfacial angles in crystal is done using an instrument termed as a goniometer. There are two types of goniometer:
1.5.8.1 Contact Goniometer

Contact goniometer consists of a printed protractor to which is attached an arm swiveling plastic that is pivoted at the center and with a hairline mark that can be read against the scale (Figure 1.14). The goniometer is held with the straight edge of the protractor in contact with one face, the straight edge of the plastic strip in contact with the other face and with the plane surface of the protractor and the strip perpendicular to both crystal faces.

Two values of the interfacial angle, which total 180°, can be read from the protractor (see Figure 1.14). One is the internal angle DBC; the other is the external angle ABC between one face and the other face extended. This latter angle, which is equal to the angle COD between the perpendiculars to the two faces (since ODA = OCB = 90°), is generally called the polar angle.

Figure 1.14. A contact goniometer on which the interfacial angle CBD = 148.5° (or the polar angle COD = ABC = 32.5°) can be read directly for the example shown in (b).
1.5.8.2 Reflecting Goniometer

Interfacial angles for small crystals are more conveniently measured with a reflecting goniometer. This instrument has a wider application than the contact goniometer because, for most minerals, small crystals occur more commonly than large ones.

In its simplest form, a reflecting goniometer consists of a rotating spindle, a collimator, and a telescope. The spindle is located at the center of a divided circular scale; the collimator and telescope are in a plane perpendicular to the spindle and have their axes intersecting the axis of the spindle. The crystal is mounted at the point of intersection. The collimator and telescope are separate, and the angle between them is usually set at about 60°. The crystal is mounted so that a prominent zone axis is parallel to the spindle axis. The angular position at which each face of the zone axis reflects the collimated beam into the receiving telescope is easily read on the divided circle. The difference between any pair of readings from adjacent faces is the interfacial (polar) angle.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Define/ Describe/ List/Distinguish</th>
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<tbody>
<tr>
<td>Define the terms: lattice, unit cell and a motif as used in crystallography</td>
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<tr>
<td>List the six crystallographic systems</td>
<td></td>
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<tr>
<td>Describe the symmetry elements of the orthorhombic and isometric systems</td>
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<tr>
<td>Distinguish a crystal and a mineral</td>
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<tr>
<td>Illustrate the notation of lattice points, planes and rows using the three crystallographic axes.</td>
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</table>
1.5.9 TWINNING IN CRYSTALS

Minerals generally occur in certain amounts of symmetry referred to us twinning. Composite crystals of a single substance in which the individual parts are related to one another in a definite crystallographic manner, are known as twinned crystals. The nature of the relationship between the parts of the twinned crystal is expressed in a twin law. Twin laws are often given specific names that are related to:

- The characteristic shape of the twin,
- A specific locality where such twin crystals were first found,
- A mineral that commonly displays the particular twin law etc.

Many important rock-forming minerals, such as orthoclase, microcline, plagioclase, and calcite, commonly occur as twinned crystals. Most twinned crystals appear to consist of two or more crystals that are united with a symmetric interrelationship. In some crystals, the orientation of two individuals of a twinned crystal may be related by reflection across a lattice plane that is common to both individuals. The lattice plane, referred to as twin plane, is a plane of symmetry that divides twinned crystals into two symmetric parts. If the two individuals of a twin meet along a plane, the plane is referred to as the composition plane.

Twinned crystals (e.g., see Figure 1.15) may be described as follows:

Simple twins – composed of only two parts
Multiple twins – composed of more than two orientations
Contact twins – this occur if a definite composition plane is present
Penetration twins – occur if two or more parts of a crystal appear to interpenetrate each other with the surface between the parts being indefinable and irregular (Figure 1.16).
Polysynthetic twinning – occurs when three or more individuals are repeated alternately on the same twinned plane. If the individuals of polysynthetic twins are thin plates, the twinning is called lamellar e.g. plagioclase feldspars.
Figure 1.15. Twinned crystals. (a) Simple contact twin (spinel), (b) Multiple (cyclic) twins (chrysoberyl), (c) Penetration twin (orthoclase Carlsbad twin), (d) Polysynthetic twinning (albite twinning in plagioclase).

Figure 1.16. Interpenetration twins of (a) staurolite (orthorhombic); and (b) fluorite (cubic).
1.5.9.1 Effects of twinning

Many substances tend to break readily along twin planes. Twinning is one of the causes of parting, which resembles cleavage, in minerals. Twinning and twinning tendencies may either promote or preclude the use of a mineral or other material in industry. For example, twins are desired in some metals because they enhance plastic deformation capabilities. On the other hand, twinning according to certain laws - e.g., the Brazil twins and Dauphine twins (electrical twins) - preclude the use of quartz as either lenses or oscillators.

The Brazil twins in particular combine a right- and left-handed crystal in a complex penetration twin typically with plane composition surfaces, which render the crystals useless for optical, and electrical purposes.

The Dauphine twin reverses the direction of the \( a \)-axes in the two parts of the twin. The Dauphine twins cannot be recognized in polarized light because it combines two crystal orientations with identical optical properties.

1.6 SUMMARY

In this lecture, we have learnt the definition of the term “mineral”, ranging from the historical perspective through the legalistic perspective to the scientific perspective. We have reviewed the historical perspective of the science of mineralogy, cited some of the evidences for the prehistoric uses of minerals and rocks, and described some of the principle applications of the science of mineralogy. In the subject of crystallography, we have learnt the definition of some of the important crystallographic terms and studied the crystal structure in terms of its lattice points, rows and planes, unit cell, crystal shape, Miller and Bravais indices, and zones in crystals. In classification of crystals we have
learned the seven crystal systems and their various symmetry elements, and understood that symmetry is the most important of all properties in the identification of crystalline substances. We have learnt about the Law of constancy of interfacial angles in crystals and how to measure those angles using a goniometer. Finally we did learn about the phenomenon of twinning in crystals and showed how twinning may promote or preclude the use of a mineral or other material in industry. For example we learnt how the presence of Brazil twins or Dauphine twins (electrical twins) in quartz crystals may precludes its use either as lenses or oscillators.

REFERENCES

BRAVAIS LATTICES

The concept of space lattices was a fundamental step in the understanding of the crystal structure of minerals. A space lattice was thought of as the smallest cell, which represented a particular crystal structure. By stacking cells of the same shape together the structural pattern of the whole crystal could thus be obtained. It was Auguste Bravais who in 1848 first demonstrated that there can be only 14 different space lattices and these are now named after him.

Bravais lattices forms can be defined by reference to three axes, a, b, and c, and their enclosing angles \( \alpha \), \( \beta \), and \( \gamma \). The cells are in some cases simple, but in other cases they have additional lattice-points either in the centre of the lattice or in the centres of some or all of the faces of the lattice.