

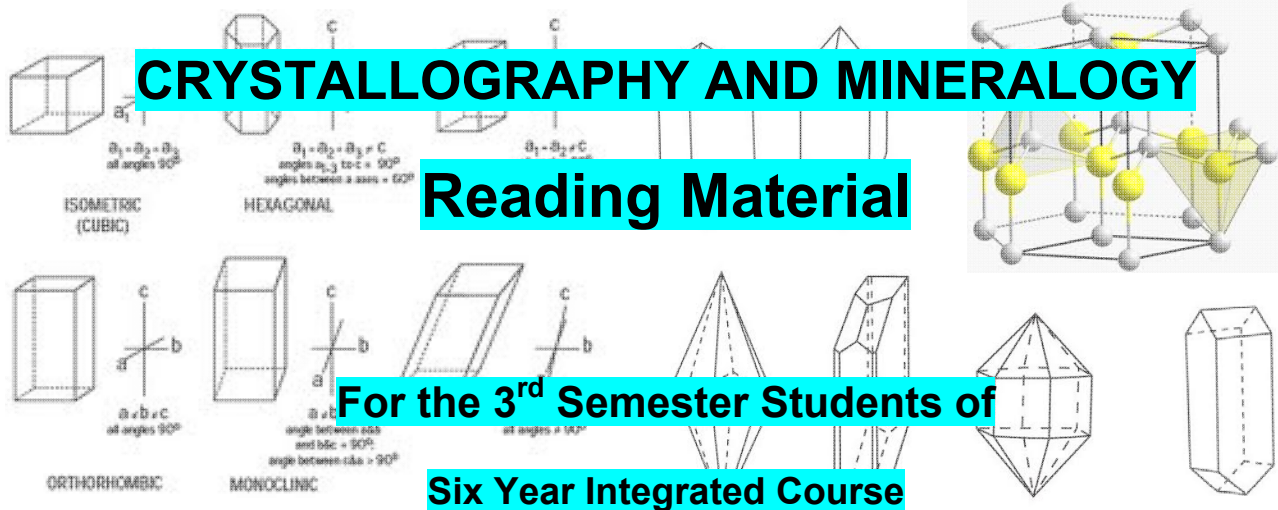
CENTRE OF EXCELLENCE IN REMOTE SENSING

Bharathidasan University, Tiruchirappalli

Paper Code MTIGT0306

CRYSTALLOGRAPHY AND MINERALOGY

Reading Material



For the 3rd Semester Students of

Six Year Integrated Course

M.Tech. Geotechnology and Geoinformatics

Prepared by

Dr.K.Palanivel

Assistant Professor

Centre of Excellence in Remote Sensing

Bharathidasan University, Tiruchirappalli-23.

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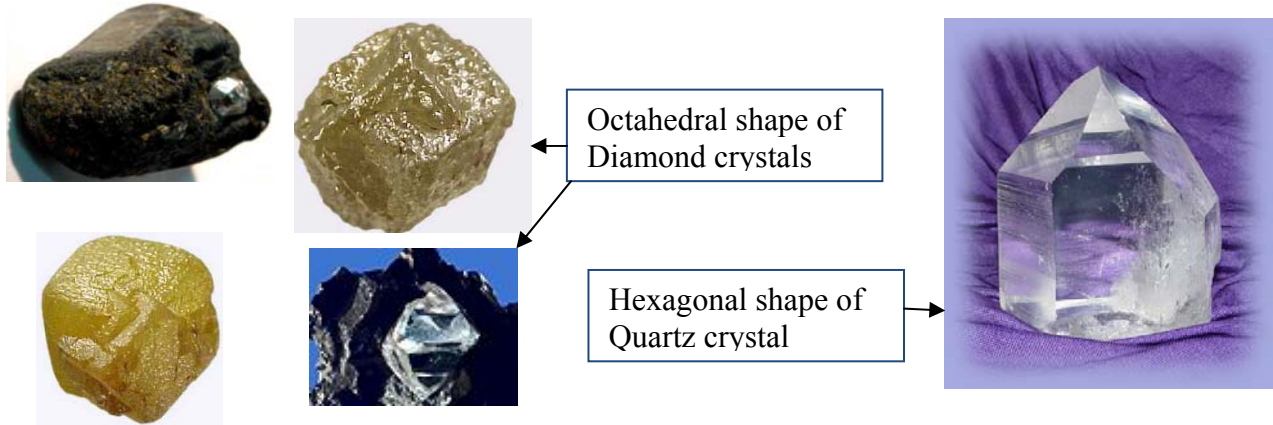
6 Year Integrated M.Tech. Geotechnology and Geoinformatics

Paper Code MTIGT0306 - CRYSTALLOGRAPHY AND MINERALOGY

Syllabus

- 1. Elements of Crystallography:** Crystalline and Amorphous forms - Symmetry and Classification of Crystals - System of Crystal Notation - (Weiss and Millerian) - Forms and Habits. Crystal Systems (Isometric, Tetragonal, Hexagonal, Orthorhombic, Monoclinic, Triclinic, Twinning-crystalline Aggregates – Columnar, Fibrous, Lamellar, Granular - Imitative shapes and Pseudomorphism. **12 Hrs.**
- 2. Crystal Properties:** Space Symmetry Elements- Translation – Rotation- Reflection - Inversion Screw and Glide-point groups and Crystal classes - Derivation of 32 Crystal classes based on Schoenflies notation - Bravais lattices and their Derivation - An outline of Space Groups. X-ray Crystallography. **12 Hrs.**
- 3. Physical Mineralogy:** Physical Properties: (Colour – Structure – Form – Luster - Transparency – Streak – Hardness – Specific Gravity – Tenacity – Feel – Taste – Odour) - Electrical, Magnetic and Thermal properties-Determination of Specific Gravity (Jolly's spring balance, Walker's steel yard, Pycnometer methods) - Empirical and Structural formula of minerals – Isomorphism, Polymorphism and Pseudomorphism - Atomic substitution and Solid solution in minerals - Non Crystalline minerals - Fluorescence in minerals - Metamict state. **16 Hrs.**
- 4. Optical Mineralogy:** Optical Properties (Colour – Form – Cleavage - Refractive Index - Relief – Alteration – Inclusions – Zoning – Pleochroism – Extinction - Polarization colours – Birefringence) – Twinning - Optic sign (Uniaxial and biaxial)- Interference figures - Primary and Secondary Optic axes - Optic axial angle measurements – Optic Orientation – Dispersion in Crystals - Optic anomalies. **12 Hrs.**
- 5. Mineral Groups:** Ortho and Ring Silicates (Olivine group - Garnet group). Alumino silicates (Epidote group - Zircon – Staurolite – Beryl - Cordierite and Tourmaline). Sheet Silicates (Mica group - Chlorite group and Clay minerals) - Chain Silicates (Pyroxene group - Amphibole group and Wollastonite). Framework Silicates (Quartz -Feldspar - Feldspathoid - Zeolite and Scapolite groups) - Non-silicate (Spinel group, Carbonates and Phosphates). **12 Hrs.**

CRYSTALLOGRAPHY AND MINERALOGY



A '**Crystal**' (or **Crystalline** or **Morphous solid**) is a chemical compound of solid material whose constituent atoms, ions, or molecules are arranged in an orderly repeating pattern extending in all three spatial dimensions.

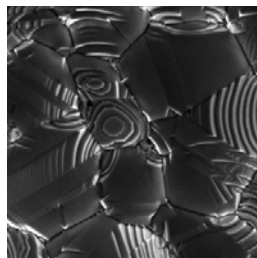
The definite repeating internal structure of crystal is expressed externally by its smooth surfaces / facets and symmetrical form (shapes - e.g. Square, Hexagonal prism, Rhomb / diamond shaped, etc.).

Process of crystal formation

Crystals are formed from a magma, solution of vapour saturated with a chemical compound at slow decreasing of temperature and pressure conditions.

Crystalline rock masses have consolidated from aqueous solution or from molten magma.

The vast majority of igneous rocks belong to this group and the degree of crystallization depends primarily on the conditions under which they solidified. Such rocks as granite, which have cooled very slowly and under great pressures, have completely crystallized, but many lavas were poured out at the surface and cooled very rapidly; in this latter group a small amount of amorphous or glassy matter is frequent.



Silver crystal growing on a ceramic substrate.

Other crystalline rocks, the evaporites such as rock salt, gypsum and some limestones have been deposited from aqueous solution, mostly owing to evaporation in arid climates.

Volatilised substances like sulphur will get deposited around the vents of volcanoes when the vapour cools are called “**Fumeroles**”. The process of crystallization from shallow intrusions without passing through liquid state is known as “**sublimation**”.

Still another group, the metamorphic rocks which includes the marbles, mica-schists and quartzites; are recrystallized, that is to say, they were at first fragmental rocks, like limestone, shale and sandstone and have never been in a molten condition nor entirely in solution. The high temperature and pressure conditions of metamorphism have acted on them erasing their original structures, and inducing recrystallization in the solid state.

Crystallinity of a crystal: The 3 different states in which a crystalline substance may appear are:



-  Euhedral – crystal developed with all its proper plane surfaces (or crystal faces)
-  Subhedral - crystal formed with a portion of faces only, and
- Anhedral - no crystal faces appear.

Subhedral and anhedral forms are due to certain circumstances like congestion / insufficient space for growth, abrupt termination / unavailability of chemical compound or sudden change / disturbances in the crystal growing environment, etc.

The scientific study of crystals and crystal formation is crystallography. The process of crystal formation via mechanisms of crystal growth is called **crystallization** or **solidification**.

The word ‘**crystal**’ is derived from the ancient Greek word “**κρύσταλλος**” (*krustallos*), which had the same meaning, but according to the ancient understanding of crystal.

At root it means anything congealed by freezing, such as *ice*. The word once referred particularly to quartz, or "rock crystal".

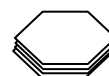
Most metals encountered in everyday life are **Polycrystals**. Crystals are often symmetrically intergrown to form **Crystal twins**.



An "**Amorphous solid**" is a solid in which there is no long-range order of the positions of the atoms. Hence, due to the absence of orderly arrangement of atoms, the minerals show no external crystalline form.

Most classes of solid materials can be found or prepared in an amorphous form. For instance, common window glass is an amorphous solid, many polymers (such as polystyrene) are amorphous, and even foods such as cotton candy are amorphous solids.

Typically, other than the physical properties such as flat faces and sharp edges of crystals, is its cleavage. The **Cleavage** of crystals can be defined as the tendency to break in certain definite directions, yielding more or less smooth surfaces.



On the contrary, **fracture** of a crystal is defined as the nature of breakage other than or normal to cleavage planes. Some types of fractures are : Even, Uneven, Hackly, etc.

The **lustre** of a crystal can be defined as the nature and the effect of reflectance of light by crystal surfaces. Some of the types of lustres are: Metallic, Vitreous, resinous, pearly, greasy, etc.

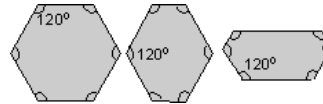
Relation between Cleavage and Lustre: If the face of a crystal is parallel to perfect cleavage, then due to the partial separation of the crystal into parallel plates, often such crystal shows pearly lustre. E.g. Apophyllite, Muscovite, Stilbite, Heulandite, etc.

An **iridescent play of colours** is also often seen with Calcite, when the separation has been sufficient to produce the prismatic colours by interference

(two light waves reflected from two layers interfere together resulting a bright light).

Samples with a naturally round shape, or samples that have a concoidal fracture pattern are nearly always described as a "glass" having no significant, long-range, 3-D order.

Although the crystals may have different sizes, all crystals have the same shape or *habit*. In particular, the angles between certain pairs of faces of the different crystals will be the same. This crystal habit was first observed by Nicholas Steno in 1669. This observation became known as the **law of constancy of interfacial angles**.



Habit denote the characteristic shapes of crystals arising from variations in the number, size and shape of the faces, like pyramidal, tabular, etc., due to speed and condition of crystal growth and the presence of impurities in the solution. Therefore crystals from one locality may be characterized by a particular habit.

Symmetry, means a structure that allows an object to be divided into parts of an equal shape and size.

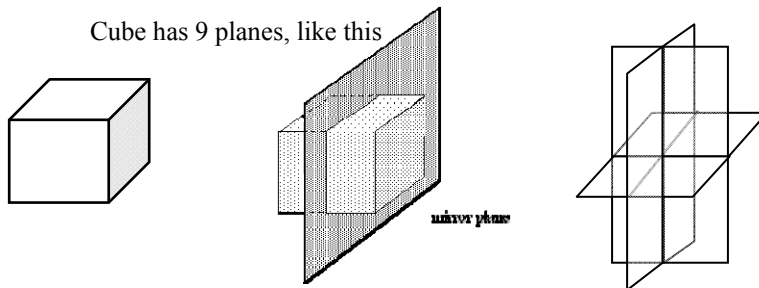
In crystallography, **symmetry** is the property of regularity of position of like faces, edges, corners, etc.

Thus, the symmetry is defined with reference to three criteria: `

1. Plane of symmetry

2. Axis of symmetry

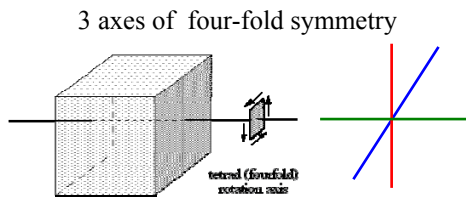
3. Centre of symmetry



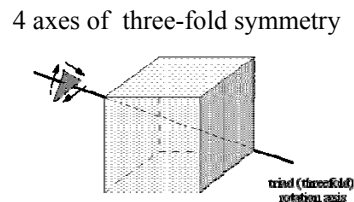
Planes divides a crystal into equal / similar halves,

On 1 complete rotation along axes, a crystal may come to occupy the same position, once, twice, thrice, four or six times.

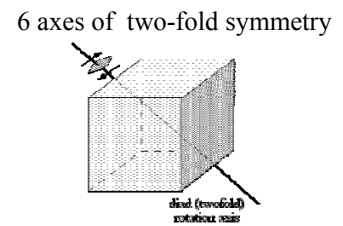
Axes connecting
opposite **faces**



Axes connecting
opposite **corners**



Axes connecting
opposite **edges**



Thus, a cubic crystal has a total of 13 axes of symmetry as shown in the illustrations above.

Like faces, edges, etc., are arranged in pairs in corresponding positions on opposite sides of a central point – Centre of symmetry. It is noted as 'Present or Absent'.

A **crystal's structure** and **symmetry** play a role in determining many of its properties, such as cleavage, electronic bond structure, and optical properties.

To be classified as a true mineral, a substance must be a solid and have a crystalline structure. It must also be a naturally occurring, homogeneous substance with a defined chemical composition.

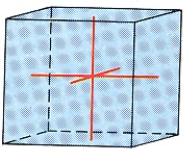
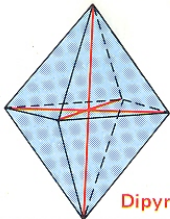
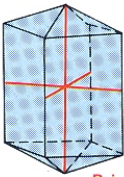
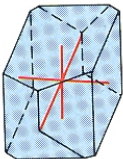
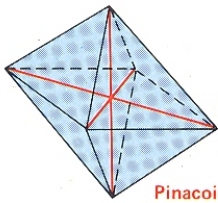
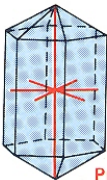
Crystal System	Common Crystal Form and Description	Mineral Examples
Isometric	 Equidimensional crystals with three axes of equal length and at 90° to one another Cube cubic prism octahedron cube-octahedron combination	halite diamond garnet
Tetragonal	 Crystals with three axes at right angles to one another, two of which are of equal length, and the third longer or shorter Dipyramid	zircon (zirconium silicate) cassiterite (tin oxide) rutile (titanium oxide)
Orthorhombic	 Crystals with three axes at right angles, each of a different length Prism-dipyramid combination	olivine anhydrite gypsum topaz
Monoclinic	 Crystals with three unequal axes, two of which are inclined to one another and the third at right angles to these Pinacoid-prism combination	hornblende augite orthoclase
Triclinic	 Crystals with three unequal axes all of which are inclined to one another Pinacoid	turquoise plagioclase
Hexagonal	 Crystals with three equal axes in the same plane intersecting at 60°, and a fourth axis perpendicular to the plane of the other three Prism-dipyramid combination	quartz calcite dolomite

Figure 2-14 Crystal systems and crystal forms.

A **mineral** is a naturally occurring solid formed through geological processes that has a characteristic chemical composition, a highly ordered atomic structure, and specific physical properties.

An assortment of minerals

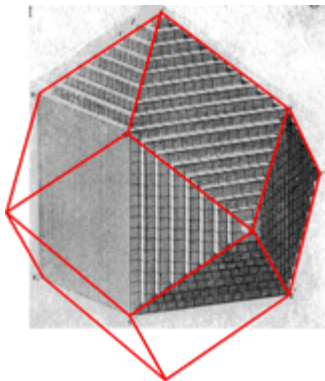


A **rock**, by comparison, is an aggregate of minerals and/or mineraloids, and need not have a specific chemical composition.

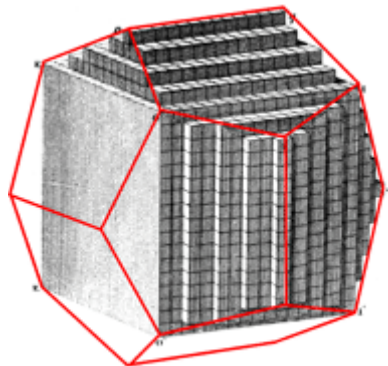
Minerals range in composition from pure elements and simple salts to very complex silicates with thousands of known forms. The study of minerals is called **mineralogy**.

The reciprocals of the parameters which form the basis of crystallographic notation are called '**indices**'.

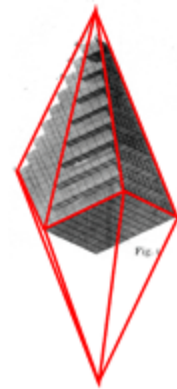
Through the early studies of Steno and others (17th century), René-Just Haüy was able to postulate that if crystals of calcite and cubic garnets were built from many small regularly-repeating blocks, then these blocks could easily be used to describe the faces of these crystals in terms of **rational indices**. This **law of rational indices** forms the basis of optical crystallography.



Rhomb-dodecahedron



Pentagon-dodecahedron



Scalenohedron

Figures: Models from Haüy's *Traité de minéralogie* (1801) - the crystal form have been redrawn in red.

These regularly-repeating tiny components are now known as "unit cells". The dimensions of a unit cell are described by the lengths of the three axes, a , b , and c , and the three interaxial angles, α , β , and γ .

In mineralogy and crystallography, a **crystal structure** is a unique arrangement of atoms in a crystal. A crystal structure is composed of a **motif**, a set of atoms arranged in a particular way (a pattern or decorative design), and a **lattice**.

Motifs are located upon the points of a **lattice**, which is an array of points repeating periodically in three dimensions. The points can be thought of as forming unit cells, that fill the space of the lattice. The lengths of the edges of a unit cell and the angles between them are called the **lattice parameters**. The ratios of the distances from the origin at which the face cuts the crystallographic axes are the “**ratios of the Intercepts**”. The **symmetry** properties of the crystal are embodied in its space group.

The expression of length & angle measurement and calculation as multiples of one of their number is known as “**axis ratio**”.

There are many choices of repeating blocks in any given lattice. The main principles defining the lattice is that each lattice point must be in an identical environment as any other lattice point, and that the individual blocks in the lattice must have the smallest volume possible. Often there are many ways to select the vectors between lattice points and even the locations of the lattice points themselves. These unique lattice vectors are called *basis vectors* or *basis set*. Some 2-dimensional examples of these lattice choices are shown below.

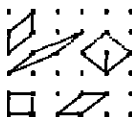
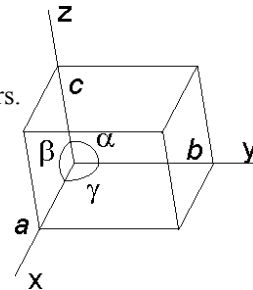


Figure: Different choices of lattice vectors and lattice points.

Figure: Unit cell showing cell parameters.



Crystallographic notation is a concise method of writing the relation of any crystal face to the crystallographic axes. The most widely used systems depend upon either parameters or indices. Of these systems of notation, the chief are two:

1. The Parameter System of Weiss and
2. The Index System of Miller (modified by Bravais).

Parameter System of Weiss:

Axes are taken in this way:

a, a, a – for three equal axes,
 a, a, c – for two axes equal and
 a, b, c – for unequal axes.

The intercept that the crystal face under discussion makes on the a -axis is then written before a , the intercept on the b -axis before b , and the intercept on the c -axis before c .

These intercepts are ofcourse measured in terms of the intercepts made by the unit form on the corresponding crystallographic axes. The most general expression for a crystal face in the Weiss notation is: na, mb, pc , where, n, m, p are the lengths cutoff by the face on the a, b, c axes as compared with the corresponding lengths cutoff by the unit form. It is usual to reduce either n or m to unity.

If a crystal face is parallel to an axis, it can be imagined as cutting that axis at infinite distance (∞). Thus a face cutting the a -axis at a distance 1unit and cutting the b -axis at a distance 2units or twice the distance cutoff by the unit form along the b -axis and running parallel to the c -axis has the Weiss symbol,

$$a, 2b, \infty c.$$

A face cutting the a -axis, parallel to the b -axis and c -axis obviously has the symbol,

$$a, \infty b, \infty c.$$

Index System of Miller:

In this system of notation, the indices or reciprocals of the parameters are used. They are written in the axial order a, b, c and are always given in their most simple form by clearing fractions. For e.g., consider the crystal face dealt with in the previous paragraph which has the Weiss symbol

$$a, 2b, \infty c.$$

The reciprocals of the parameters are

$$1, \frac{1}{2}, 0$$

Clearing of fractions and omitting the axial letters the Miller symbol is obtained 210, which is read as *two, one, nought*.

Crystalline materials are separated into 7 crystal different systems. These crystal systems are most easily identified by the constraints on the cell parameters. Note, however, that the cell parameter constraints are only necessary conditions.

Table 1. Crystal Systems		
Crystal System	#	Cell Parameters
Triclinic	6	$a \neq b \neq c; \alpha \neq \beta \neq \gamma$
Monoclinic	4	$a \neq b \neq c; \alpha = \gamma = 90^\circ, \beta \neq 90^\circ$
Orthorhombic	3	$a \neq b \neq c; \alpha = \beta = \gamma = 90^\circ$
Tetragonal	2	$a = b \neq c; \alpha = \beta = \gamma = 90^\circ$
Trigonal		
Hexagonal	2	$a = b \neq c; \alpha = \beta = 90^\circ, \gamma = 120^\circ$
Rhombohedral	2	$a = b = c; \alpha = \beta = \gamma \neq 90^\circ$
Cubic	1	$a = b = c; \alpha = \beta = \gamma = 90^\circ$

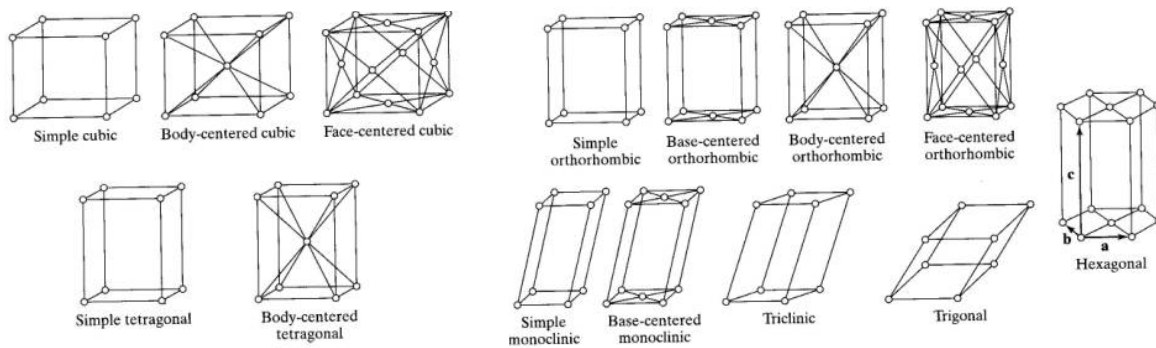
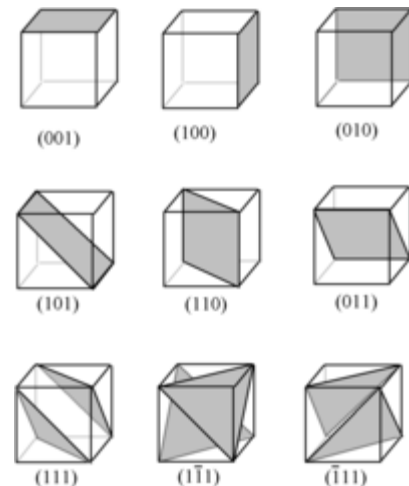
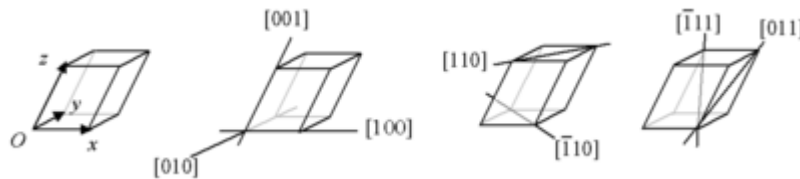


Figure Bravais Lattices



Planes with different Miller indices in cubic crystals

Miller indices are a notation system in crystallography for planes and directions in crystal (Bravais) lattices

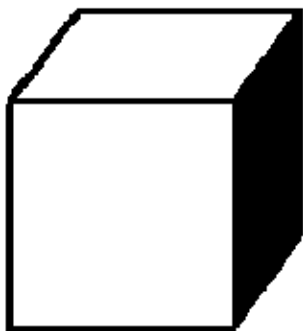


Six Major Crystal Systems and their forms

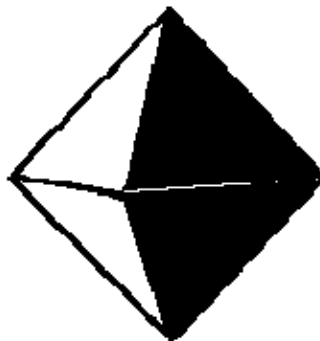
1. CUBIC OR ISOMETRIC SYSTEM

Axes: Cubic crystal forms are referred to 3 axes of equal lengths which intersect at right angles. These axes are interchangeable and of equal value. They are called a_1 , a_2 and a_3 as in figure. There are 5 classes here included. They are (1) Normal, (2) Pyritohedral (3) Tetrahedral (4) Plagiohedral and (5) Tetartohedral.

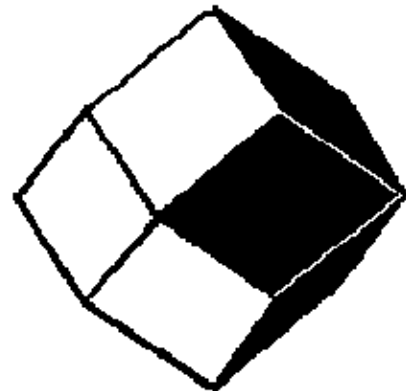
Isometric System



Cube



Octahedron

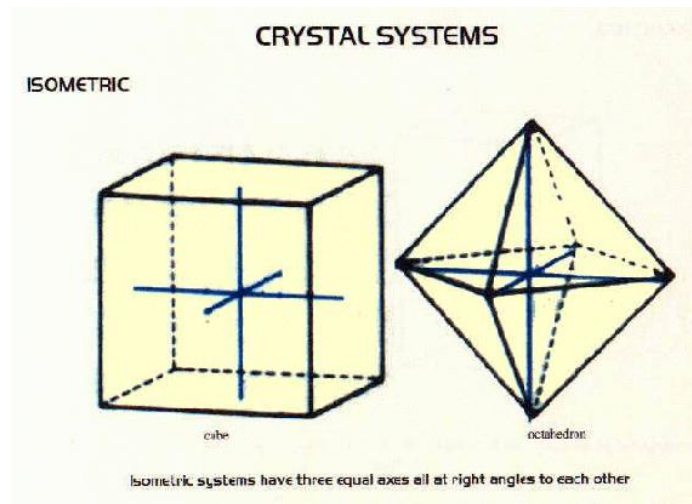


Dodecahedron

I. Normal class : Galena type

Normal class possesses the highest degree of symmetry for the cubic system. This type takes its name from the class from its general form, the Hexoctahedron.

Symmetry: The centre of the forms of this class is always symmetrical. There are 3 principal planes of symmetry and six diagonal planes. There are 3 principal axes of 4 fold symmetry. They coincide with the 3 crystallographic axes. They are known as cubic axes as they are perpendicular to the faces of the cube. There are 4 diagonal axes of three fold symmetry. They are known as Octahedral axes as they are perpendicular to the faces of the Octahedron. There are 6 diagonal axes of 2 fold symmetry. They are known as Dodecahedral axes as they are perpendicular to the faces of the Dodecahedron.



Forms: The possible forms of this class are grouped under seven types of solids:

1. Cube (100)
2. Octahedron (111)
3. Dodecahedron (110)
4. Tetrahexadron (hko) as, (310); (210); (320) etc.
5. Trisoctahedron (hhl) as, (331); (221); (332) etc.
6. Trapezohedron (hll) as, (311); (211); (322) etc.
7. Hexoctahedron (hkl) as (421); (321) etc.

1. **Cube:** It's general symbol is (100). It is bounded by similar faces. Each face is parallel to two of the axes. Each face is square prism. Interfacial angles are all 90° .

2. **Octahedron:** Octahedron has general symbol (111). It is bounded by 8 similar faces. Each face meets the three axes at equal distances. Each face is an equilateral triangle. The normal interfacial angle, (111), (1T1), is $70^{\circ} 31' 44''$.

3. **Dodecahedron:** The rhombic dodecahedron has the general symbol (110). It is bounded by twelve faces. Each face meets two of the axes at equal distances and is parallel to the third axis. Each face is a rhomb. The normal interfacial angle is 60° . The faces are parallel to the 6 diagonal axes of symmetry.

4. **Tetrahexadron:** It has 24 faces. Each face is an isosceles triangle. There are 4 faces in the place of the face of a cube and hence the name. There are 2 kinds of edges. The general symbol is (hko). Each face is parallel to one axis and cuts the other two axes at unequal lengths. There can be many tetrahexahedrons such as (320), (310), (210) etc. On this account this form is said to be a variable form. When either h (or) k becomes zero, the form becomes a cube. When h is made equal to k the form becomes a dodecahedron. Therefore the forms cube and dodecahedron are the limiting forms of the tetrahexahedrons.

5. **Trisoctahedron:** It has 24 faces. Each face is an isosceles triangle. There are 3 faces in the place of the face of an Octahedron and hence the name. The general symbol is (hhl). Each face meets two of the axes at unit length and the third at a distance greater than unity. There are two kinds of edges. The smaller edges in each octant form a 'y' upside down. Octahedron and dodecahedron are the limiting forms.

6. **Trapezohedron:** It has 24 like faces. Each face is a Trapezium or quadrilateral. Each face cuts two axes at equal length and the third at a smaller length. The general symbol is (hll). The cube and the octahedron are the limiting forms. There are two kinds of edges. The smaller edges in each octant meet in a

'y' which is right way up. Analcite, Garnet, Spinel, Magnetite, etc., are the minerals in which this form can be seen.

7. **Hexoctahedron:** it has 48 like faces. Each face is a scalene triangle. Each face cuts the three axes at unequal lengths. The general symbol is (khl) . This is the general form of this system. By varying the number of the symbol, symbols of all the other forms can be obtained. The six other forms of the class are special forms. There are 3 kinds of edges in the Hexoctahedron. The Hexoctahedron alone is a very rare form. It is seen in combination with Cube (Fluorite) and Dodecahedron (Garnet).

Some common Galena type minerals:

1. Galena: Commonly in crystals showing combinations of the Cube and Octahedron or as simple Cubes.
2. Fluorspar, Rock-salt, as simple Cubes.
3. Leucite, Analcite; as a simple Trapezohedron.
4. Spinel, Magnetite; occur as simple Octahedron, sometimes combined with Dodecahedron or Trapezohedron.
5. Garnet: Dodecahedron or Trapezohedron or the combination of the two.
6. Diamond: occurs as Octahedral crystals.

II. Pyritohedral or Diploidal class (Pyrite type)

This class takes its name from the common mineral Pyrite. It is also called the Diploidal class from its general form Diploid.

Symmetry: There is a centre of symmetry. There are 3 axial planes of symmetry. There are 3 crystallographic axes of 2 fold symmetry and 4 diagonal axes of 3 fold symmetry.

Typical forms: The typical forms of this class are Pyritohedron and Diploid. The faces of both forms are arranged in parallel pairs. On this account, they are called 'Parallel Hemihedrons'. These are the cases of parallel faced hemihedrism or pentagonal hemihedrism (as the faces are pentagonal).

Pyritohedron: This is common with pyrite. It is bounded by 12 faces. Each face is a pentagon. One edge of each pentagon is longer than the other 4 similar edges. It is often called pentagonal dodecahedron. The longer edges run in pairs parallel with the crystallographic axes. Each face cuts two axes at different length and is parallel to the third. The general symbol is (hko) . Pyritohedron is produced by the development of alternate faces of a Tetrahexahedron. There are two complementary forms called 'Positive and Negative Pyritohedrons'. The complementary forms may be superposed by being rotated 90° about one of the crystallographic axes.

Diploid: It is the general form of this class. It is bounded by 24 faces. Each face meets the axes at unequal distances. The general symbol is (hkl) . Each face is a trapezium. Faces are grouped in pairs. Hence the name Diploid is assigned. There are two complementary forms called 'Positive and Negative Diploids' for every corresponding holohedral form, Hexoctahedron. The extension of the alternate faces of the Hexoctahedron results in diploid.

Other forms: The forms (100) , (111) , (110) , (hhl) , (hll) have the same geometrical form, respectively as Cube, Octahedron, Dodecahedron, Trisoctahedron and Trapezohedron of the normal class. However, in molecular structure they are distinct, showing the pyritohedral symmetry. The molecular symmetry of the pyrite in cube is exhibited in the form of striations. Fine striations are found parallel to the alternate edges. These striations result from what is known as an 'oscillatory combination'.

Cobaltite and Smaltite are the other minerals that crystallize in this type.

III. Tetrahedral Class (Tetrahedrite type)

Symmetry: The forms of this class have 3 axes of binary symmetry. These axes coincide with the 3 crystallographic axes. There are also 4 diagonal axes of trigonal symmetry. There are 6 diagonal planes of symmetry.

Typical forms: The typical form of this class is the Tetrahedron this class derives its name from it. There are also three other distinct forms. The faces of the tetrahedral forms are inclined to each other and hence they are sometimes spoken as inclined hemihedrons. The type of this hemihedron is called Inclined or tetrahedral hemihedrism. The tetrahedron is a four faced solid. The faces are meeting the axes at equal distances. Its general symbol is (111). Each face is an equilateral triangle. These crystallographic axes join two middle points of opposite edges. There are 2 possible tetrahedrons; 1) Positive Tetrahedron (111) and 2) Negative Tetrahedron (111). These two forms are complementary to each other and occupy the same position as the faces of the Octahedron of the normal class. These forms occur in Sphalerite and Boracite.

The Tetragonal Tristetrahedron is composed of 12 faces. Each face is a quadrilateral. The faces correspond to twelve of the faces of the Trisoctahedron, falling in alternate octants. The symbol is (221) (hhl). This type of solid is sometimes called 'Deltoid Dodecahedron'. It does not occur alone among crystals.

There is also a complementary form, called 'Negative Deltoid'. Its faces belong to the other set of alternate octants of Trisoctahedron.

The Trigonal Tristetrahedron has the general symbol (hll) e.g., (211) . It is bounded by 12 like triangular faces. These faces correspond to the faces of the alternate octants of the form Trapezohedron of the normal class. There is a complementary negative form. Its faces belong to the other set of alternate octants. It occurs both alone and in combination, especially with tetrahedron as in the species Tetrahedrite.

The form Hextetrahedron has the general symbol (hkl) e.g., (321) . It is bounded by 24 faces. The faces belong to all the faces of the alternate octants of the 48 faced hexoctahedron. The complementary negative form (hkl) embraces the remaining faces of the Hexoctahedron.

In this class also there are 7 types of forms but only 4 (describing above) of them are geometrically distinct from the corresponding forms of the normal class. Each has the same figure pyroelectricity may prove the tetrahedral symmetry of the forms. The complementary forms of this class may be superposed by being rotated 90° about one of the crystallographic axes.

IV. Plagiohedral Class (Cuprite Type)

Typical Forms: This class is also called Gyroidal class, because the faces of the general form (hkl) are arranged in spiral order.

The single typical form of this class is call pentagonal icositetrahedron. There are two complementary forms theses forms are alike geometrically but not superposable. They are related to one another as in a right to left hand glove.

They are hence said to be 'enantiomorphous'. The crystals belonging here may be expected to show circular polarization of light.

The other forms of the class are geometrically like those of the normal class.

Symmetry: There are three principal axes of tetragonal symmetry 4 diagonal axes of trigonal symmetry and 6 diagonal axes of diagonal symmetry. In other words, it has all the axes of symmetry of the normal class. Plane and centre symmetry are absent.

2. TETRAGONAL SYSTEM

The tetragonal system includes all the forms which are referred to two equal horizontal crystallographic axes and a longer or shorter vertical axis. All three axes are at right angles. Of the two horizontal axes the front to back axis is a_1 and the right to the left axis is a_2 . The vertical axis is C .

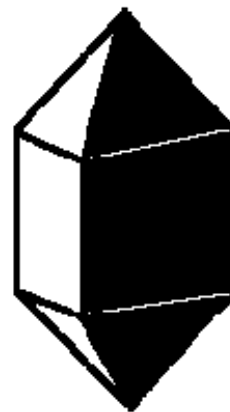
Tetragonal System



**Tetragonal
Prism**



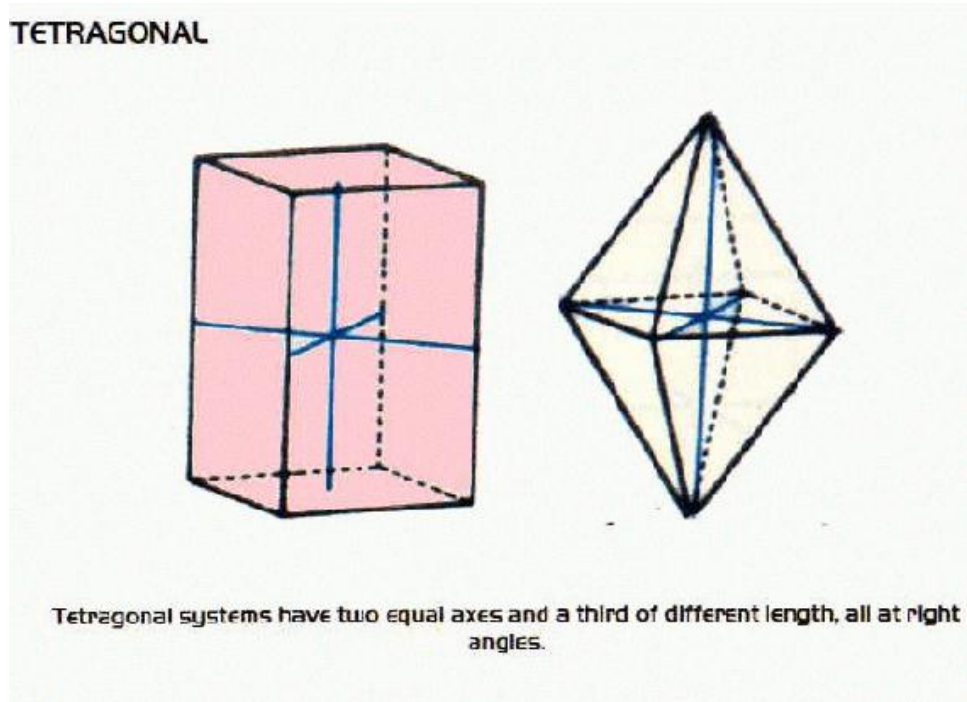
Dipyramid



**Pyramid
with Prism**

I. Normal class: Zircon type:

Symmetry: The forms of this class have one principal axis of 4 fold symmetry (hence the name of the system). This symmetry axis is C. there are 4 horizontal axes of 3 fold symmetry, two of them coincide with the horizontal crystallographic axes. The other two are diagonal axes which intersect the angles between the first two.



They have horizontal axial plane of symmetry, and 4 vertical planes. Two of the vertical planes are axial planes, and the other two are diagonal. The centre of these forms is symmetrical.

Forms: The various forms under this class are:

1. Base or basal pinacoid (001)
2. Prism of the first order (110)
3. Prism of the second order (100)
4. Ditetragonal prism (hko) as, (310); (320), etc.,
5. Pyramid of the first order (hhl) as, (223); (111), (221) etc.,
6. Pyramid of the second order (hol) as, (203); (101), (201) etc.,
7. Ditetragonal pyramid (hkl) as, (421); (321), (121) etc.

1. **Base or Basal Pinacoid:** The base include two similar faces which are parallel to the horizontal axial plane. The indices those faces are 001 and 00T. It is an open form.
2. **Prisms:** The faces of the prisms are parallel to the vertical axis (c). The prism of the first order includes 4 faces. Those faces meet the horizontal axes at equal distances and are parallel to the vertical axis. Its general symbol is (110). It is a square prism with an interfacial angle of 90° . it is an open form.
3. **Prism of the II order:** This includes four faces. The faces are parallel to the vertical axis and one of the horizontal axes. Therefore it has the general symbol (100). It is a square prism with an interfacial angle of 90° . It is an open form.
4. **Ditetragonal prism:** It is bounded by 8 similar faces. Each face is parallel to the vertical axis and meets the two horizontal axes at unequal distances. It is the general symbol (hko). It is an open form.
5. **Pyramid of the first order:** The pyramids are strictly bipyramids. Pyramids are closed form. The pyramid of the first order is bounded by eight similar faces. The faces meet the horizontal axes at equal distances and also intersect the vertical axis. If the general symbol (hhl). It is a square pyramid.
6. **Pyramid of the second order:** The faces of the pyramids of the second order are parallel to one of the horizontal axes while meeting the other two axes. The general symbol (hol). It is a square pyramid. There may be a number of second order pyramids, varying at the ratio of the intercepts on the axes a A and C.

7. **Ditetragonal pyramid:** The Ditetragonal pyramid is double eight sided pyramid. It is composed of 8 pairs of faces. Each meets the three axes at unequal distance. The general symbol is (hkl).

Minerals: The commonest minerals crystallizing in the Zircon type are: Zircon, Rutile, Cassiterite, Anatase, Idiocrase and Apophyllite.

II. Tripyramidal Class

Symmetry: The forms of this class have one plane of symmetry, only (horizontal axial plane) and vertical axis of tetragonal symmetry. The centre is symmetrical.

Forms: The distinctive forms are the tetragonal prism (hko) and pyramid of the third order. They are square prism and pyramid. They may be considered as derived from the Ditetragonal forms of the normal class by taking only one half the faces and omission of the remaining faces. Therefore, there are two complementary third order pyramids and third order prisms. The complementary forms are designated left and right.

The other forms of this class are the base (001), the other square prisms and pyramids. There are geometrically like the corresponding forms of the normal class. As this class shows three types of square pyramids this class is called 'Tripyramidal class'.

Minerals: The important minerals Scheelite and Meionite belong to this class.

The forms of this class are sometimes described as showing pyramidal hemihedrism.

III. Pyramidal Hemimorphic Class (Wulfenite Type)

The forms of this class are closely related to the Tripyramidal class, but they are hemimorphic in distribution. The faces present are only those belonging to one extremity of an axis of symmetry. Therefore there would be distinct complementary forms.

The vertical axis is an axis of tetragonal symmetry in the forms of this class. The mineral Wulfenite of the Scheelite group probably belongs here.

IV. Sphenoidal Class (Chalcopyrite Type)

The typical forms and the combination of this class have three crystallographic axes of binary symmetry and two vertical diagonal planes of symmetry. Centre of symmetry is absent.

The Sphenoid and the Tetragonal Scalenohedron are the typical forms of this class. The faces are recent in the alternate octants only.

The sphenoid is a 4- faced solid. Each face is an isosceles triangle. This form may be considered as derived from the first order pyramid of the normal class by the development of only the alternate faces of the pyramid. Therefore there are two complementary forms known as 'positive and negative sphenoid'. The general symbol of the positive unit sphenoid is (111) and that of the negative unit sphenoid units is (1-11). These forms occur in chalcopyrite.

The Tetragonal Scalenohedron is bounded by eight similar scalene triangles. The general symbol is (hkl). It may be considered as derived from the Ditetragonal pyramid of the normal class by taking the alternate pairs of faces of the latter form. Therefore the faces of the complementary positive and negative forms embrace all the faces of the Ditetragonal pyramid. This form appears in combination in chalcopyrite.

The other forms are geometrically like those of the normal class. The lower symmetry is revealed by etching.

V. Trapezohedral Class (Nickel Sulphate Type)

The vertical axis of the forms of the forms of this class is an axis of tetragonal symmetry. There are four horizontal axes of binary symmetry. Plane of symmetry and centre of symmetry are absent.

The typical form tetragonal Trapezohedron may be derived from the Ditetragonal pyramid of the normal class by the extension of the alternate faces. There are two complementary forms called right – and left – handed. These two forms embrace all the faces of the Ditetragonal pyramid of the normal class.

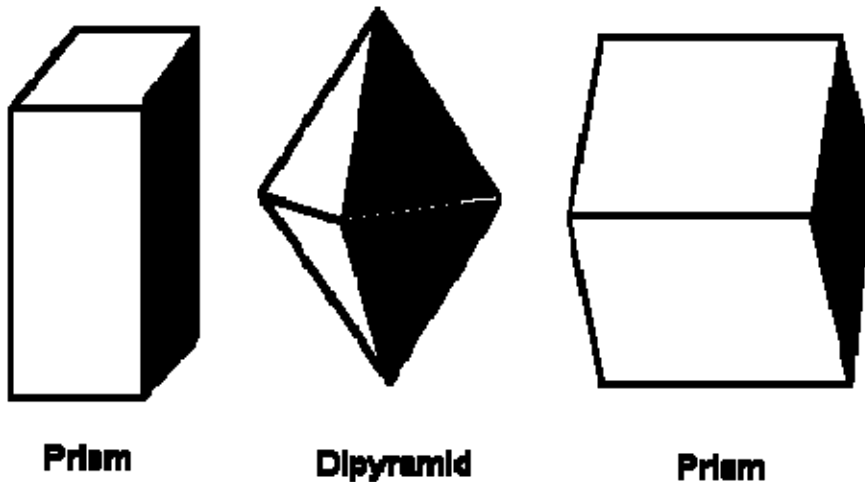
There two forms are enantiomorphous, and the mineral belonging to this class show circular polarization of light. Nickel sulphate and a few other artificial salts belong in this class.

3. ORTHORHOMBIC SYSTEM

The forms of the orthorhombic system are referred to 3 axes at right angles to each other, all of different lengths.

Any one of the three axes may be taken as the vertical axis; the longer horizontal axis is always taken as the b or macro axis. It is parallel to the observer. The 'a' or brachy-axis is the shorter axis. It is perpendicular to the observer. The length of the b axis is taken as unity and the lengths of the other axes are expressed in terms of it.

Orthorhombic System

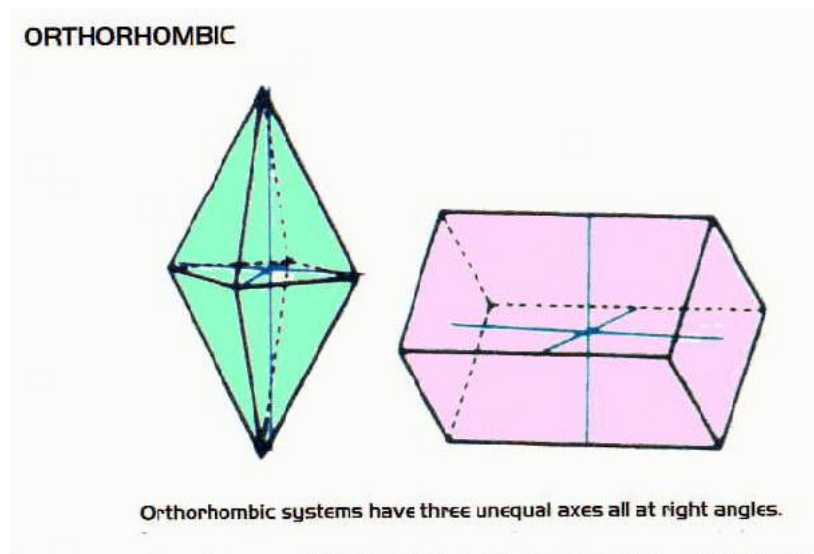


I. Normal Class: Barite Type

Symmetry: The forms of this class are characterized by three axes of binary symmetry. These axes coincide with the crystallographic axes. There are three unlike principal planes of symmetry. Symmetry is present.

Forms: the various forms possible in this class are as follows:

- | | | |
|----|------------------------------|-------|
| 1. | Macropinacoid or a-Pinacoid | (100) |
| 2. | Brachypinacoid or b-Pinacoid | (010) |
| 3. | Base or c-Pinacoid | (001) |
| 4. | Prisms | (hko) |
| 5. | Macrodomes | (hol) |
| 6. | Brachydomes | (okl) |
| 7. | Pyramids | (hkl) |



Pinacoids: A pinacoid is a form whose faces are parallel to two of the axes that is, to an axial plane. The macropinacoid includes 2 faces. Each face is parallel to the macro-axis b and to the vertical axis c . the symbol of this form (100). It is briefly and conveniently called the a -face or the a -pinacoid.

The brachypinacoid includes 2 faces. Each face is parallel to brachy axis ' a ' and to the vertical axis ' c '. The symbol is (010). It is called the b -face or b -pinacoid.

The base or basal pinacoid includes the two faces parallel to the plane of the horizontal axes. The symbol is (001). It is called the c -face or c -pinacoid.

Each one of these pinacoids is an open form. These three pinacoids together make the so-called diametral prism. The diametral prism has three pairs of unlike faces, three kinds of edges and eight similar solid angles.

Prisms: A prism is one whose faces are parallel to vertical axis, but intersect the two horizontal axes. Their general symbol is (hko) . The faces of the unit prism (110) intersect the horizontal axes at their unit lengths.

There are a larger number of other possible prisms. The faces of the macroprisms lie between the faces of the macropinacoid and the unit prism. 'hko' is the symbol of the brachy prism.

Domes: A dome (or horizontal prism) is one whose faces are parallel to one of the horizontal axes, but intersect the vertical axis.

The faces of the macrodomes are parallel to the macro-axis b and intersect the vertical axis c and the horizontal axis a . hence the general symbol is (hol) . The unit macrodome is (101) . It fixes the axial ratio $a:c$. there may be a large number of macrodomes between the base and the macro-pinacoid. (100)

The faces of the brachydomes are parallel to the brachy axis 'a' and they intersect the other axes 'c' and 'b'; their general symbol is (okl) . The angle of the unit brachy dome fixes the ratio $b:c$. there may be a large number of brachy domes between the base and the brachy pinacoid.

Pyramids: A pyramid is a form whose faces meet all the three axes. The pyramids of this system belong to the type called double rhombic pyramid. The pyramid is bounded by eight faces. Each face of it is a scalene triangle. This form has 3 kinds of edges, each set with a different interfacial angle. This is the general form of this system. The symbol is (hkl) .

The unit pyramid is corresponding to the unit prism (hkl) /and the general symbol becomes with different intercepts on the vertical axis. There may be several unit pyramids lying between the base and the unit prisms. In the symbol of these forms $h=k$.

The macro pyramids and brachypyramids are corresponding to the macroprisms and brachyprisms. Further there is large number of macropyramids and

brachypyramids in the horizontal zone and again corresponding to each one of them in the vertical zones.

Minerals: Many common minerals crystallize in the Barites type. Examples are Barite, Celestite, Olivine, Enstatite, and Andalusite, Topaz, Anhydrite, Aragonite, Sulphur, and Staurolite.

II. Hemimorphic class (Calamine type)

Symmetry: Orthorhombic hemimorphic class are characterized by two unlike principal and vertical planes of symmetry. The vertical axis is an axis of binary symmetry. There is no center of symmetry.

Forms: The forms are hemimorphic. The prisms and vertical pinacoids are like those of the normal class. There is one face for basal pinacoid either at the positive or negative end of the vertical axis. There are two macropinacoids and two brachy pinacoidal faces.

There are also two macrodomes, (hol) & (hol), two brachy domes and two pyramids. Each pyramid will have two faces.

Minerals: Calamine and Struvite represent typical crystals of this class.

III. Sphenoidal class (Epsomite type)

Symmetry and typical forms: The forms of this class are characterized by three unlike principal axes of binary symmetry. The general form (hkl) has four faces only. It is called rhombic sphenoid. The complementary positive and negative sphenoids are enantiomorphous. The forms occur in Epsomite.

4. MONOCLINIC SYSTEM

Axes: The forms of the monoclinic system are referred to three unequal axes. a, b, and c.

'a' axis inclined towards the observe and it is called 'Clino-axis', 'b' axis is called 'Ortho-axis'. It is horizontal and parallel to the observer and the 'c' is vertical. The acute angle between the 'a' and 'c' axes is β . The angles between a, b and c are right angles.

Monoclinic System



Prism



Prism

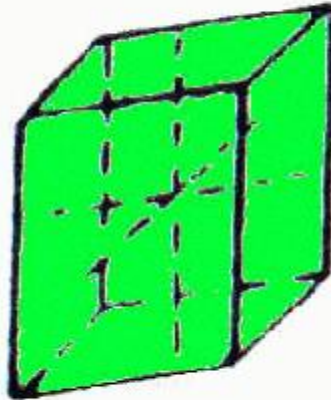


Clinopinacoid

I. Normal class: Gypsum types

Symmetry: there is one principal plane of symmetry. It is a-c plane. 'b' axis is normal to this plane and it is an axis of two fold symmetry. There is a centre of symmetry.

MONOCLINIC



Monoclinic systems have two axes at right angles and a third axis at a right angle to one of these, but inclined to the other.

Forms: The various forms, belonging to this class are:

- | | |
|-----------------------------------|-------|
| 1. Orthopinacoid or a – Pinacoid | (100) |
| 2. Clinopinacoid or b - Pinacoid | (010) |
| 3. Basal pinacoid or c – Pinacoid | (001) |
| 4. Prisms | (hko) |
| 5. Orthodomes | (hol) |
| 6. Clinodomes | (okl) |
| 7. Pyramids | (hkl) |

Pinacoids: The orthopinacoid (100) includes the two faces which are parallel to the plane of the ortho-axis and the vertical axis c. the faces are situated at the extremities of the a axis. Therefore it is called a-face or a-pinacoid.

The clinopinacoid (010) includes the two faces which are parallel to the plane of symmetry (clino axis and c). the faces are situated at the extremities of the 'b' axis and hence the form is called b-face or b-pinacoid.

The basal pinacoid (001) includes the two faces which are parallel to the horizontal axes. The faces are situated at the extremities of the c-axis and therefore the form is called the c-face of c-pinocoid. It is inclined to the orthopinacoid. The angle between the orthopinacoid and the base is the acute axial angle β .

These three pinacoids form the diametral prism this prism is bounded by three sets of unlike faces. It has 4 similar vertical edges and 4 similar edges parallel to the axis a. the 4 edges parallel to b axis are of 2 sets. The two solid angles above in front are similar to these below behind. The remaining 4 solid angles are similar.

Prisms: These prisms are the oblique rhombic prisms. The unit prism is (110). The orthoprisms have the symbol. (hko) where $h > k$. The orthoprisms are lying between ortho pinacoid (100) and unit prism (110). The clino prisms have the symbol (hko) where $h < k$. They are lying between clinopinacoid (010) and unit prism (110). The orthoprisms and clinoprisms meet the ortho axis and clino axis at unequal distance and are parallel to 'a' axis.

Orthodomes: the 4 faces which are parallel to the ortho axis and meeting the other two axes fall into two sets. Therefore they are called hemiorthodomes. Their symbols are $(h0l)$ and $(0h0)$. The faces of the unit hemiorthodomes (101) replace the two obtuse edges between (100) and (001) . The faces of the other unit orthodome (010) replace the acute edges between (100) and (001) . There are several sets of hemiorthodomes where h may be greater or less than 1. Each form has only 2 faces.

Clinodomes: The faces of the clinodomes are parallel to the inclined axis a and intersect the other two axes. Their general symbol is (okl) . They lie between the base (001) and the clinopinacoid (010) . Each form has four faces. The symbol of the unit clinodome is (011) . There are several clinodomes where k may be greater or less than 1.

Pyramids: the pyramids of this system hemipyramids. Each form has four faces only. The general symbol is (hkl) . The solid angles of the diametral prism are replaced by these pyramidal faces. These solid angles are of 2 kinds and therefore the pyramids are composed of 4 faces only and hence the name hemipyramid.

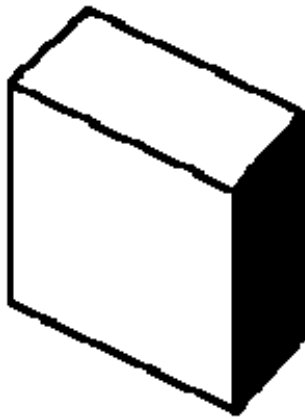
The pyramids may also be divided into three classes as unit pyramids, (111) orthopyramid (hkl) when $h > k$; or clinopyramids (hkl) when $h < k$.

Minerals: Gypsum is the type mineral and other common minerals are Pyroxene, Orthoclase, Epidote, Mica, Sphene etc.

5. TRICLINIC SYSTEM

Axes: The forms of the triclinic system are referred to three unequal axes with all their intersections oblique. The vertical axis is c . The front to back axis is sloping toward the observer and is called 'a' or brachy axis. The 'b' axis is longer than the 'a' axis and is known as 'macro axis'. But this is not invariably true when $a > b$, the 'a' is called macro and 'b' brachy axes. The angle between the axes 'b' and 'c' is the angle between 'a' and 'b' is β and the angle between 'a' and 'c' is γ .

Triclinic System



Prism



Prism

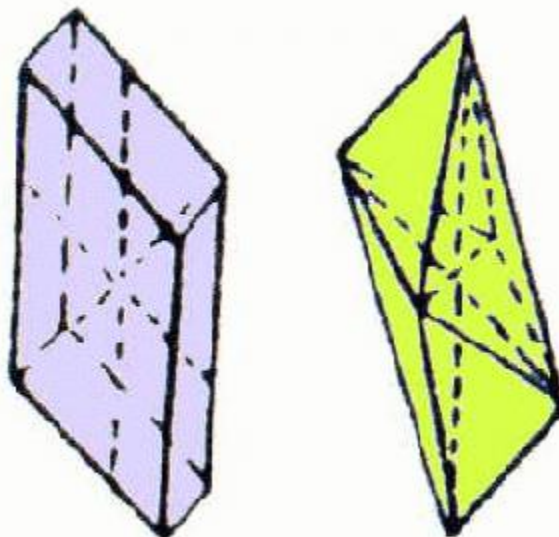


Dipyramid

I. Normal class or Axinite type

Symmetry: This class is characterized by a centre of symmetry alone.

TRICLINIC



Triclinic systems have three axes all inclined toward each other.

Forms: each form of this class includes two face only. The various types of forms are:

- | | |
|----------------------------------|----------------|
| 1. Macropinacoid or a- Pinacoid | (100) |
| 2. Brachy pinacoid or b-pinacoid | (010) |
| 3. Base or c-pinacoid | (001) |
| 4. Prisms | (hko), (h k o) |
| 5. Macrodomes | (hol), (hol) |
| 6. Brachy domes | (okl), (okl) |
| 7. Pyramid | (hkl) |
| | (hkl) |
| | (hkl) |
| | (hkl) |

a-Pinacoid: This form has two parallel faces. Each faces cuts the a-axis and is parallel to the vertical axis and the b-axis. Its symbol is (100).

b-Pinacoid: The two faces of this form cut the b axis and are parallel to the vertical axis and the a-axis. The symbol is (010).

Basal Pinacoid: The form consists of two parallel faces. Each face cuts the c axis and is parallel to the a-axis and the b-axis. The symbol is (001).

The diametral prism is constituted by these three pinacoids this prism is composed of 3 sets of unlike faces, 6 sets of like edges and 4 sets of solid angles.

Prisms: the four vertical edges of the diametral prism are of 2 kinds. Therefore, the prism faces replacing those edges are also of two kinds. There are two types of prisms with symbols (hko) and (h-ko). Each prism is of 2 faces only and therefore the prisms are called Hemiprisms. The two unit Hemiprisms have the symbols (110) and (110) correspondingly. The prisms are parallel to 'c' axis and

intersect the 'a' and 'b' axes. In between unit prism and the a axis and unit prism and the b axis there may be a large number of macro and brachy prisms in which h may be greater or less than k.

Domes: Dome faces cut the vertical axis and meet either the 'a' axis or 'b' axis and parallel to either one of them. The edges of the diametral prism, parallel to 'b' axis are of two kinds, and again those parallel to a-axis are also of two kinds. Therefore the domes are called 'hemibrachydomes' and 'hemimacrodomes'. Each hemidome is of two faces only. There may be a large number of hemibrachydomes and hemimacrodomes.

(hol) $h = 1 = \text{unit}$; $h > \text{or} < 1 = \text{hemimacro}$
 (-hol) = $-h = 1 = \text{unit}$; $-h > \text{or} < 1 = \text{and hemi-}$
 (okl) = $k = 1 = \text{unit}$; $k > \text{or} < 1 = \text{brachydomes}$
 (o-kl) = $-k = 1 = \text{unit}$; $k > \text{or} < 1 =$

Pyramids: The eight solid angles of the diametral prism fall into four sets of 2 like faces. Therefore the faces replacing those solid angles are also of 4 sets of 2 like faces. Each set of faces is a pyramid and therefore the pyramids of this class are called 'quarter pyramids'.

(hkl) there may be 4 unit quarter

(hkl)

(hkl) Pyramids. In between unit

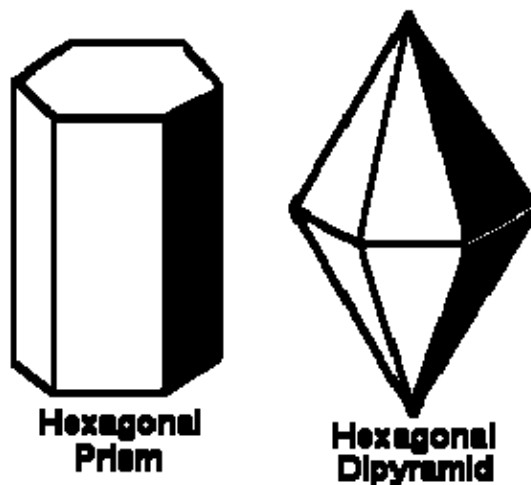
(hkl) Pyramids and the a-axis and the unit pyramids and b-axis there may be a larger number of macro and brachy quarter pyramids. Corresponding to the each macro and brachy quarter pyramid there may be a large number of quarter pyramids. Their symbol depends upon the axial ratio between the c- and a- and the c and b.

Common minerals: Axinite is the type mineral of this class. Other important minerals are: Plagioclase Feldspars, Microcline.

6. HEXAGONAL SYSTEM

Axes: The forms of the Hexagonal system are referred to 4 axes three axes are equal and horizontal intersecting at angles of 60° (a_1 , a_2 , a_3). One is vertical at right angles to them c . The c axis may be longer or shorter than the horizontal axes. ' a_2 ' axis is horizontal and parallel to the observer. a_1 and a_3 make an angle of 30° either side of the line perpendicular to the observer. The axis to the left is taken as a_1 , and the axis to the right is taken as a_3 .

Hexagonal System



Symbols: The general position of any plane may be expressed with indices.

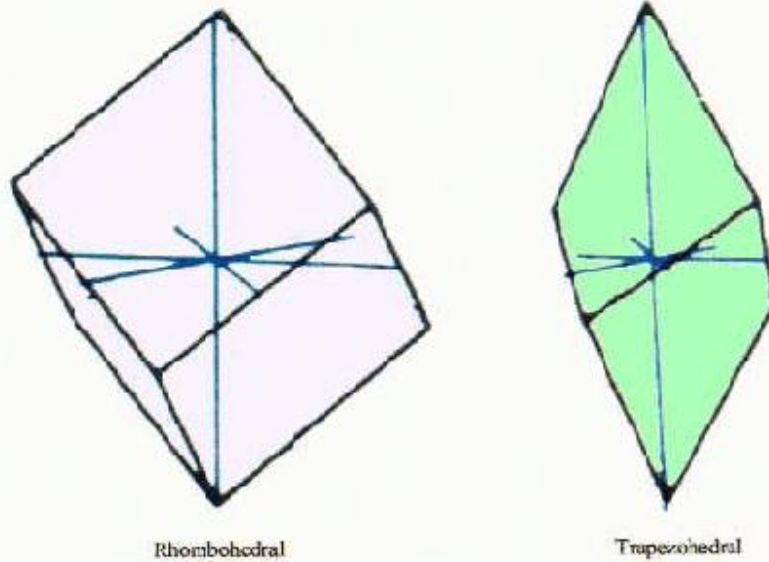
Parameters: $1/ha_1$, $1/ka_2$, $1/ia_3$, $1/lc$

The corresponding indices for this plane are h, k, i, l .

It is found convenient to consider the axis a_3 as negative in front. Therefore the general symbol becomes ' hki '. The angular relation of the horizontal axes renders this true that the algebraic sum of the indexed hki , is equal to zero.

$$h+k+i=0$$

HEXAGONAL



Hexagonal systems have three equal axes in the same plane, intersecting at angles of 60 degrees, and a fourth axis at right angles to all of these.

There are two divisions of the Hexagonal system: Hexagonal Division and Rhombohedral Division.

Hexagonal Division

I. Normal class: Beryl type

Symmetry: The crystals of this class have one principal axis of hexagonal or six fold symmetry. This axis coincides with the vertical crystallographic axis. There are also six horizontal axes of 2 fold symmetry. Three of these axes are coinciding with the horizontal crystallographic axes. The remaining three axes fall at 30 angles between the first set there is one horizontal principal plane of symmetry. There are 6 vertical planes of symmetry. Three of these planes are principal planes. The remaining three bisect the angles between the first set.

Forms: The possible forms in this class are

- | | |
|------------------------------|--------|
| 1. Base | (0001) |
| 2. Prism of the first order | (1010) |
| 3. Prism of the second order | (1120) |

4. Dihexagonal prism (hkio) as (2130)
5. Pyramid of the first order (hohl) as (1011) (2021), etc.,
6. Pyramid of the second order (h.h.2h.1) as (1122)
7. Dihexagonal pyramid (hkil) as (2131).

In the above h, h, and $h+k = -i$.

Base: The least or basal pinacoid includes the two faces which are parallel to the horizontal axes (0001 & 000 $\bar{1}$).

Prism of the first order: It includes 6 faces. Each face is parallel to the vertical axis and meets two adjacent horizontal axes at equal distances and is parallel to the third horizontal axis. The general symbol is (1010).

Prism of the second order: it has 6 faces. Each face is parallel to the vertical axis and meets two alternate axes at the unit distance and the intermediate axis at one half this distance. The general symbol is (1120).

Both, the first and second order prism are geometrically alike. They are regular hexagonal prisms with normal interfacial angles of 60° .

Dihexagonal prism: It is twelve sided prism bounded by 12 faces. Each face is parallel to the vertical axis and meets two adjacent horizontal axes at equal distances. This prism has two unlike edges. The general symbol is (hkil).

Pyramid of the First order: It is bounded by 12 similar triangular faces. Each face meets two adjacent horizontal axes at equal distances and is parallel to the third horizontal axis. The pyramidal faces also intersect the vertical axes above and below. The general symbol is (hohl).

The unit pyramid of the first order is (1011). There may be a number of pyramids of the first order in between the base (001) and the faces of the unit prism (1010). These pyramids differ in the ratio of the intercepts on the horizontal to the vertical axis (1014), (1013), (3032), (2021) etc. the faces of the first order pyramids replace the edges of the first order prism. On the other hand, they replace the solid angles of the second order prism.

Pyramids of the second order: It includes 12 similar faces. Each face meets two alternate horizontal axes at the unit distance and the intermediate axis at one

half of this unit distance. It also intersects the vertical axis. They have the general symbol $(h.h.2h.1)$.

(1122) is considered to be the unit second order pyramid. These indices are to be obtained by adding those of the faces of the first order init pyramid, as $(1111) + (011) = 1122$.

The faces of the second order pyramid replace the edges between the faces of the second order prism and the base. Further, they replace the solid angles of the first order prism. There may be number of second order pyramids forming a zone between the base (0001) and the faces of the second order prism. (1120) . Eg. 1124 , 2243 , 1121 , etc.

Dihexagonal pyramid: It has 24 similar faces with the general symbol $(hkil)$. Each face meets the vertical axis and also meets two adjacent horizontal axes at unequal distances. There may be a large number of dihexagonal pyramids between the base and the dihexagonal prism. The dihexagonal pyramid is often called a Berylloid, because it is a common form with the species Beryl.

II. Hemimorphic Class – Zincite Type

Symmetry: This class has six vertical planes of symmetry. They meet at angles of 30° in the vertical crystallographic axis. The vertical crystallographic axis is an axis of hexagonal symmetry. There is no centre of symmetry.

Forms: The two basal planes are here two distinct forms (pedians), (0001) ; $(00\bar{0}1)$. There are upper and lower pyramids of first order, second order and dihexagonal prisms. The prisms do not differ geometrically from the prisms of the normal class.

Minerals: Zincite, Grecochite, Wurtzite are the minerals of this class.

III. Tripyramidal Class: Apatite Type

Typical forms and symmetry: This class is important because it includes the common minerals of the Apatite group-Apatite. Pyromorphite, Mimetite, Vanadinite: The typical form is the third order hexagonal prism. $(hkio)$ and the Third order hexagonal pyramid $(hkil)$. They and the order forms of this class have

only one plane of symmetry (plane of the horizontal axes) and also the vertical axis of hexagonal symmetry. There is also a centre of symmetry.

Prism and pyramid of the third order: the prism of the third order has six like faces. The general symbol is $(hkio)$. It is a regular hexagonal prism with angles of 60° . It is not different geometrically from the other hexagonal prisms. The third order prism is considered as derived from the dihexagonal prism of the normal class by the omission of the half of the faces. Therefore there are two complementary forms known as right handed and left handed. These two forms together embrace all the faces of the dihexagonal prism.

The third order pyramid is regular 12 faced pyramid it is not geometrically distinct from the normal hexagonal pyramid. It is considered as derived from the dihexagonal pyramid of the normal class by the omission of the one half of the faces. The general symbol is $(hkil)$. There are two complementary forms known as right handed and left handed.

These third order prism and pyramids do not often appear on crystals as predominating forms. Commonly these faces are present modifying other fundamental forms.

Other forms: The remaining forms of this class are geometrically like those of the normal class: The base (0001) , the first order prism (1010) , the second order prism (1120) , the first and second order pyramids $(hohl)$, $(h.h.2h.1.)$. Their molecular structure corresponds to the symmetry of this class and it is readily proved by etching.

This class is given its forms include three distinct types of pyramids.

IV. Pyramidal-Hemimorphic Class: Nephelite Type

The vertical axis is an axis of hexagonal symmetry. The forms are like those of the tripyramidal class, except that the forms are hemimorphic. Etching-figures show the hemimorphic character distinctly.

V. Trapezohedral Class: B-Quartz Type

The vertical axis of this class is an axis of hexagonal symmetry and there are six horizontal axes of binary symmetry. Planes of symmetry and Centre of symmetry are absent.

The typical forms may be derived from the dihexagonal pyramid by the omission of the alternate faces. There are two possible types known as the right and left hexagonal trapezohedrons. These forms are enatiomorphous. The few crystallized salts falling in this class show circular polarization.

HEXAGONAL SYSTEM - RHOMBOHEDRAL DIVISION

I. Rhombohedral Class: Calcite Type

Symmetry: In the forms of this class there are three diagonal planes of symmetry. They intersect at angles of 60° in the vertical crystallographic axes. The vertical axis is a crystallographic axis of binary symmetry. The centre is symmetrical.

Typical forms:

Rhombohedral: The rhombohedron is a solid bounded by six like faces. Each face is a rhomb. It has six like lateral edges forming a zigzag line about the crystal. There are six terminal edges, three above and three below. The vertical axis joins the two trihedral solid angles and the horizontal axes join the middle point of the opposite sides. The general symbol is (hohl). As the vertical axis diminishes, the rhombohedrons become more and more obtuse or flattened. As the vertical axis increases they become more and more acute.

There are two complementary forms of rhombohedron known as positive and negative. They together embrace all the like faces of the pyramid of the first order. An Etching or pyroelectrical phenomenon distinguishes the two forms when they are in combination.

Of the two series or zones of rhombohedrons, the faces of the positive Rhombohedrons replace the edges between the base (0001) and the first order prism (1010). All the faces of the negative rhombohedrons replace the alternate edges of the same forms, that is, the edges between (0001) and (0110).

The form of the series which truncates the terminal edges of a given form of the other will have one half the intercept on the vertical crystallographic axis of the latter.

Scalenohedron: It is the general form of this class. The general symbol is (hkl). It is a solid bounded by twelve faces. An each face is a scalene triangle. There

are two sets of terminal edges. One edge is more obtuse than the other. The lateral edges form a zigzag edge around the form. This form may be considered as derived from the dihexagonal pyramid by taking the alternating pairs of faces. The pyramid by taking the alternating pairs of faces, the faces of the upper half. The scalenohedrons may be either positive or negative Eg: (2131) and (1231) respectively.

Other forms: The remaining forms are geometrically like those of the corresponding class of the hexagonal division viz. base (001), the prisms (1010), (1020), (hklo); the second order pyramids, as (1121). Etching figures often serve to reveal the difference from the similar forms. A normal class

II. Rhombohedral-Hemimorphic Class: Tourmaline Type

Minerals and symmetry: A member of prominent rhombohedral mineral, such as Tourmaline, Pyrargyrite, Pyrolusite, belong to this class. The grouping of the faces differs at the two extremities of the vertical axis. The forms have three diagonal planes of symmetry. They meet at angles of 60° in the vertical axis. The vertical axis is an axis of trigonal symmetry. Centre of symmetry is absent.

Typical forms: The basal planes (or pedians) (0001) and (000-1) are distinct forms. The other characteristic forms are the two trigonal prisms (1010) of the first order series four trigonal first order pyramids (three upper and three lower), second order hexagonal pyramid and four ditrigonal pyramids (upper and lower positive and negative forms).

III. Tri-Rhombohedral Class: Phenacite Type

Symmetry: Vertical axis is an axis of trigonal symmetry and there is a centre of symmetry. Plane of symmetry is absent.

Typical forms: the distinct forms of the class are the rhombohedron of second order and the hexagonal prism and rhombohedron of the third order. Thus this class is characterized by three rhombohedrons of distinct types (each + and -), hence the name.

The second order rhombohedron may be derived by taking one half the faces of the normal hexagonal pyramid of the second order. There will be two complementary forms known as positive and negative Eg: (1122) (1212).

The rhombohedron of the third order has the general symbol ($h\bar{k}il$). It may be derived from the normal dihexagonal pyramid, by taking one quarter of the faces of the latter.

There are 4 complementary third order rhombohedrons positive right-handed ($21\bar{3}1$), positive left handed ($31\bar{2}1$), negative right handed ($1\bar{3}21$) and negative left handed ($1\bar{2}31$).

The hexagonal prism of the third order may be derived from the normal dihexagonal prism, by taking one half the faces of the latter. There are two complementary forms known as right and left handed.

The remaining faces are geometrically like those of the rhombohedral class. Base (0001), first order prism ($10\bar{1}0$), second order prisms ($11\bar{2}0$), rhombohedrons of the first order ($10\bar{1}1$) and ($01\bar{1}1$), etc.

Minerals: This class is an important one. It is illustrated by the mineral Diopside, Phenacite, Willemite, Dolomite, Limonite, etc.

IV. Trapezohedral Class: R-Quartz Type

Symmetry: in the forms of this class vertical axis is an axis of 3 folds symmetry. There are three crystallographic horizontal axes of 2 fold symmetry. Plane of symmetry and centre of symmetry are absent.

Typical forms: The characteristic forms of the class are the trigonal Trapezohedron. The general symbol is ($h\bar{k}il$). The faces of the form correspond to the quarter of the faces of the normal dihexagonal pyramid. Therefore, there are 4 such trapezohedrons, two positive (right handed and left handed) and two similar right handed and left handed negative forms. The two forms are enantiomorphous. Circular polarization is a striking character of the minerals of this class.

The complementary positive form includes the 12 faces of positive Scalenohedron. The faces of all four include the 24 faces of the dihexagonal pyramid.

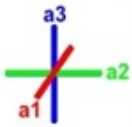
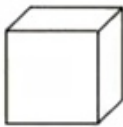
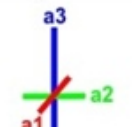
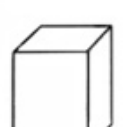
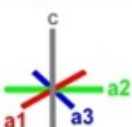
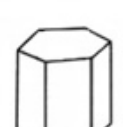
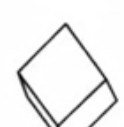
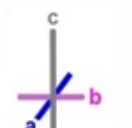
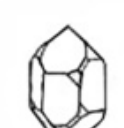
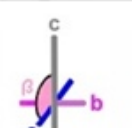
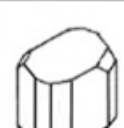
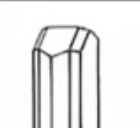
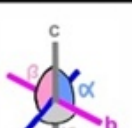
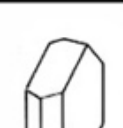
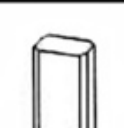
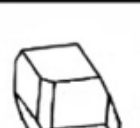
Corresponding to these trapezohedrons there are two ditrigonal prisms respectively right and left handed.

The remaining characteristics forms are the right and left handed trigonal prism ($11\bar{2}0$) and ($21\bar{1}0$) also the right and left handed trigonal pyramid ($11\bar{2}2$) and ($21\bar{1}2$). They may derived by taking respectively one half the faces of the hexagonal prism of the second order ($11\bar{2}0$) or of the corresponding pyramid ($11\bar{2}2$).

Other forms: The other forms of the class are geometrically like those of the normal rhombohedral class. They are the base (0001), the hexagonal first order prism ($10\bar{1}0$) and positive and negative rhombohedrons, (1000) and ($01\bar{1}1$).

Minerals: This class includes the mineral quartz and Cinnabar.

Crystal Systems and Examples / Kristallsysteme und Beispiele

cubic kubisch						
tetragonal						
hexagonal trigonal						
rhombic rhombsch						
monoclinic monoklin						
triclinic triklin						

MP

Symmetry elements of 6 crystal systems

<u>Crystal family</u>	Crystal system	Required symmetries of point group	<u>Point groups</u>	<u>Space groups</u>	<u>Bravais lattices</u>	<u>Lattice system</u>
<u>Triclinic</u>		None	2	2	1	<u>Triclinic</u>
<u>Monoclinic</u>		1 twofold <u>axis of rotation</u> or 1 <u>mirror plane</u>	3	13	2	<u>Monoclinic</u>
<u>Orthorhombic</u>		3 twofold axes of rotation or 1 twofold axis of rotation and two mirror planes.	3	59	4	<u>Orthorhombic</u>
<u>Tetragonal</u>		1 fourfold axis of rotation	7	68	2	<u>Tetragonal</u>
<u>Hexagonal</u> !	<u>Trigonal</u>	1 threefold axis of rotation	5	7	1	<u>Rhombohedral</u> !
	<u>Hexagonal</u> !			18	1	<u>Hexagonal</u>
		1 sixfold axis of rotation	7	27		

Cubic		3 fourfold axes of rotation	5	36	3	Cubic
Total: 6	7		32	230	14	7

Six crystal systems consist of 32 crystal classes

crystal family	crystal system	point group / crystal class	Schönflies	Hermann-Mauguin	Orbifold	Coxeter	Point symmetry	Order	Group structure
triclinic		triclinic-pedial	C ₁	1	11	[] ⁺	enantiomorphically polar	1	trivial
		triclinic-pinacoidal	C _i	1	1x	[2,1 ⁺]	centrosymmetric	2	cyclic
monoclinic		monoclinic-sphenoidal	C ₂	2	22	[2,2] ₊	enantiomorphically polar	2	cyclic
		monoclinic-domatic	C _s	m	*11	[]	polar	2	cyclic
		monoclinic-prismatic	C _{2h}	2/m	2*	[2,2 ⁺]	centrosymmetric	4	2×cyclic
orthorhombic		orthorhombic-sphenoidal	D ₂	222	222	[2,2] ₊	enantiomorphically polar	4	dihedral
		orthorhombic-pyramidal	C _{2v}	mm2	*22	[2]	polar	4	dihedral

		orthorhombic-bipyramidal	D_{2h}	mmm	*222	[2,2]	centrosymmetric	8	2×dihedral
tetragonal		tetragonal-pyramidal	C_4	4	44	$[4]^+$	enantiomorphic polar	4	cyclic
		tetragonal-disphenoidal	S_4	4	2x	$[2^+, 2]$	non-centrosymmetric	4	cyclic
		tetragonal-dipyramidal	C_{4h}	4/m	4*	$[2, 4^+]$	centrosymmetric	8	2×cyclic
		tetragonal-trapezoidal	D_4	422	422	$[2, 4]^+$	enantiomorphic	8	dihedral
		ditetragonal-pyramidal	C_{4v}	4mm	*44	[4]	polar	8	dihedral
		tetragonal-scalenoidal	D_{2d}	42m or 4m2	2*2	$[2^+, 4]$	non-centrosymmetric	8	dihedral
		ditetragonal-dipyramidal	D_{4h}	4/mmm	*422	[2,4]	centrosymmetric	16	2×dihedral
hexagonal	trigonal	trigonal-pyramidal	C_3	3	33	$[3]^+$	enantiomorphic polar	3	cyclic
		rhombohedral	S_6 (C_{3i})	3	3x	$[2^+, 3]^+$	centrosymmetric	6	cyclic
		trigonal-trapezoidal	D_3	32 or 321 or 312	322	$[3, 2]^+$	enantiomorphic	6	dihedral

		ditrigonal-pyramidal	C_{3v}	3m or 3m1 or 31m	*33	[3]	polar	6	dihedral
		ditrigonal-scalahedral	D_{3d}	3m or 3m1 or 31m	2*3	$[2^+, 6]$	centrosymmetric	12	dihedral
	hexagonal	hexagonal-pyramidal	C_6	6	66	$[6]^+$	enantiomorphic polar	6	cyclic
		trigonal-dipyramidal	C_{3h}	6	3*	$[2, 3^+]$	non-centrosymmetric	6	cyclic
		hexagonal-dipyramidal	C_{6h}	6/m	6*	$[2, 6^+]$	centrosymmetric	12	2×cyclic
		hexagonal-trapezoidal	D_6	622	622	$[2, 6]^+$	enantiomorphic	12	dihedral
		dihexagonal-pyramidal	C_{6v}	6mm	*66	[6]	polar	12	dihedral
		ditrigonal-dipyramidal	D_{3h}	6m2 or 62m	*322	[2, 3]	non-centrosymmetric	12	dihedral
		dihexagonal-dipyramidal	D_{6h}	6/mmm	*622	[2, 6]	centrosymmetric	24	2×dihedral
	cubic	tetrahedral	T	23	332	$[3, 3]^+$	enantiomorphic	12	alternating
		hextetrahedral	T_d	43m	*332	[3, 3]	non-centrosymmetric	24	symmetric

	diploidal	T_h	m3	3^*2	$[3^+,4]$	centrosymmetric	24	2×alternating
	gyroidal	O	432	432	$[4,3]^+$	enantiomorphic	24	symmetric
	hexoctahedral	O_h	m3m	*432	$[4,3]$	centrosymmetric	48	2×symmetric

IMPERFECTIONS OF CRYSTALS

Imperfection of crystals may fall into 4 categories

1. Distortions
2. Surface imperfections
3. Variation in the angles and
4. Internal imperfections and inclusions.

1. **Distortion:** Distortion means variations in the forms of crystals. Distortion may be symmetrical or irregular. In irregular distortion certain faces may become larger and others smaller than those in the ideal geometrical solid. This irregular or accidental distortion may not be accompanied by change in the interfacial angle.

Symmetrical distortion gives rise to the distorted forms which will resemble the form of a different system. E.g: an elongation in the cubic axis may give the appearance of tetragonal symmetry - Native gold, silver, copper.

2. **Surface imperfections** include striations and curved surfaces. The horizontal striations on prismatic crystals of Quartz are due to the oscillation between prismatic and rhombohedral faces. Such parallel lines or furrows on the surfaces of crystals such as Tourmaline, Pyrite and Magnetite are called 'striate' due to oscillatory combination.

The striations of the basal plane of Albite and other triclinic feldspars, rhombohedral surfaces of some Calcite are due to polysynthetic twinning.

Erosion may cause uneven surfaces. Etching by some chemical agents may cause crystalline structure. Depressions and elevations may show the successive stages in the developmental history of the crystal. The minute elevations are a part of the original molecular growth of the crystal. Minute elevations upon the faces having the form of low pyramids are called vicinal prominences. These may be imperfections arising from the interrupted or disturbed development of the form. (E.g.: on the rhombohedral faces of Quartz).

Angular elevations on crystal faces may be due to oscillatory combination. Octahedral faces of fluorite have minute cubes, proceeding from an oscillation between the cube and octahedron.

Whatever their cause, these minute markings are molecular symmetry of the crystal.

Curved Surfaces may result from (1) oscillatory combination (2) some independent molecular condition producing curvatures in the laminae of the crystal (Diamond) (or) 3) from a mechanical cause (common in Tourmaline and Beryl – crystals appear as if they had been broken into many pieces, a slight displacement of which has given a curved form to the prism.

3. Variation in the angles of crystals: Those imperfections that produce convex curved or striated faces necessarily cause change or variation in the interfacial angle. Circumstances of heat and pressure have resulted not only in distortion of form but also some variation in angle. The presence of impurities at the time of crystallization may also have a like effect.

Changes in the angles of crystals may also be caused by subsequent pressure on the matrix or by the metamorphism of the enclosing rock.

However, variations in angles are rare.

4. International imperfections and inclusions: The general name inclusion is given to any foreign enclosed within the crystal. These inclusions may be gaseous, liquid or solid. Rapid crystallization is a common explanation of inclusions E.g: Quartz crystal contains large cavities full or nearly full of water or they may contain sand or iron oxide in large amount of water, salt solution, liquid carbon and such inclusions are marked by the presence in the cavity of a movable bubble of gas.

In some cases the cavities in crystals appear to be empty. If these cavities have a regular form determined by the crystallization of the minerals, they are often called negative crystals. Such cavities are commonly of secondary origin.

Magnetite is a very common impurity in the form of solid inclusion in many minerals. Quartz crystals very commonly enclose foreign material such as Chlorite, Tourmaline, Rutile, Hematite asbestos and many other minerals. The solid inclusions may consist of a heterogeneous mass of material.

Minute forms or microscopic crystals, crystallites and microlites are common as inclusions in Obsidian and other glassy rocks of volcanic origin.

These solid inclusions may be arranged with some evident reference to the symmetry of the form, or external faces of the crystals. Eg. Augite shows inclosing Magnetite, Feldspar and Nepheline microlites. Garnet may contain Quartz. In Andalusite enclosed carbonaceous impurities are of symmetrical figures of various forms. Staurolite may also show such symmetrically arranged impurities. The Magnetite in Muscovite is always symmetrically disposed. Leucite crystals very commonly enclose symmetrically arranged foreign matter. The Magnetite in Muscovite is found as inclusion usually parallel to the directions of the percussion figure. The asterism of Phlogopite is explained by the presence of symmetrically arranged inclusions.

MINERALOGY

PHYSICAL PROPERTIES OF MINERALS

1) LIGHT BASED CHARACTERS:

- a. Colour
 - i. Streak
 - ii. Play of colours
 - iii. Change of colour
 - iv. Opalescence – pearly / milky
 - v. Tarnish – oxidation, chemical action of sulphur
 - vi. Iridescence – display of prismatic colours-interference of rays of light in minute fissures
- b. Lustre – appearance of min. in reflected light- Metallic, Sub metallic, Non-metallic, i.e., Glassy or Vitreous, Subvitreous, Greasy, Waxy, Resinous, Pearly, Silky, Adamantine or Brilliant and dull or earthy.
- c. Transparency
- d. Translucency
- e. Phosphorescence & Fluorescence – Emitting light after having been subjected to heating, rubbing, electric radiation or to ultra-violet light. E.g. Fluorspar, Quartz-on rubbing together in dark room, Diamond, ruby-after exposed to X-rays.

2) SENSE BASED CHARACTERS:

- a. Taste – Water Soluble minerals - e.g. Saline- NaCl, Alkaline-Potash and Soda, Cooling – Nitre or Pottassium chlorate, Astringent – Green vitriol, Sweetish astringent-Alum, Bitter-Epsom, Sour-Sulphuric acid.
- b. Odour – When struck, rubbed, breathed upon or heated – e.g. Alliacious-Garlic - Arsenic minls, Horse radish – Selenium minls. Sulphurous-rotten eggs-Pyrites, sulphides, Foetid-rotten eggs-qtz, l.st, Argillaceous-clayey.
- c. Feel – Smooth, Greasy, Unctuous, harsh / Meagre / rough. Certain minls. Adhere to the tongue.

3) STATE OF AGGREGATION:

Crystal habits and forms

In mineralogy, shape and size give rise to descriptive terms applied to the typical appearance, or **habit** of crystals.



Pyrite sun (or dollar) in laminated shale matrix. Between tightly spaced layers of shale, the aggregate was forced to grow in a laterally compressed, radiating manner. Under normal conditions, pyrite would form cubes or pyritohedrons.

The many terms used by mineralogists to describe crystal habits are useful in communicating what specimens of a particular mineral often look like. Recognizing numerous habits helps a mineralogist to identify a large number of minerals.

Some habits are distinctive of certain minerals, although most minerals exhibit many differing habits (the development of a particular habit is determined by the details of the conditions during the mineral formation/crystal growth).

Crystal habit may mislead the inexperienced as a mineral's internal crystal system can be hidden or disguised.

Factors influencing a crystal's habit include:

1. A combination of two or more crystal forms; trace impurities present during growth;
2. crystal twinning and
3. growth conditions (i.e., heat, pressure, space).

Minerals belonging to the same crystal system do not necessarily exhibit the same habit. Some habits of a mineral are unique to its variety and locality: For example, while most sapphires form elongate barrel-shaped crystals, those found in Montana form stout *tabular* crystals. Ordinarily, the latter habit is seen only in ruby. Sapphire and ruby are both varieties of the same mineral; corundum.

Some minerals may replace other existing minerals while preserving the original's habit: this process is called **pseudomorphous replacement**. A classic example is tiger's eye quartz, crocidolite asbestos replaced by silica. While quartz typically forms *euhedral* (well-formed), *prismatic* (elongate, prism-like) crystals, in tiger's eye the original *fibrous* habit of crocidolite is preserved.

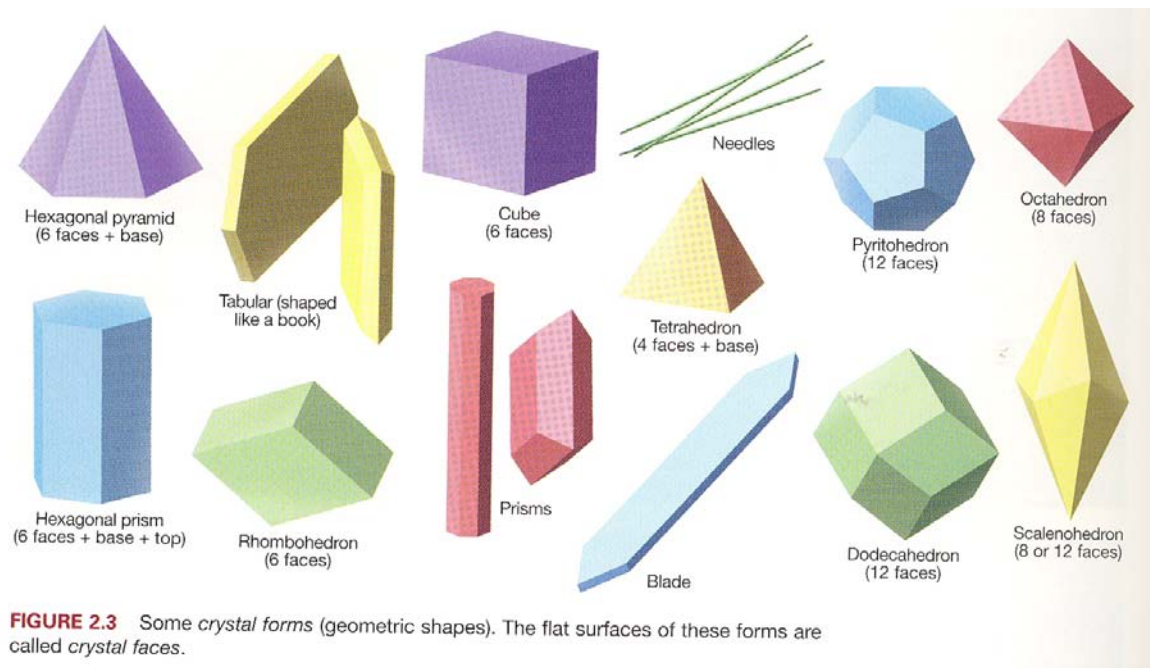
List of crystal Habits, Forms and Crystalline Aggregates

Habit:	Description:	Example:
Crystallized	Crystal having fully developed faces	Quartz, Calcite, etc.
Crystalline	aggregate of imperfectly formed crystals that are interfered with one another during their growth	NaCl crystals
Cryptocrystalline	only very little traces of crystalline structures	Obsidian
Amorphous	complete absence of crystalline structure	Opal
Acicular	Needle-like, slender and/or tapered	Rutile in quartz
Amygdaloidal	Almond-shaped	Heulandite
Anhedral	Poorly formed, external crystal faces not developed	Olivine
Bladed	Blade-like, slender and flattened	Kyanite
Botryoidal or globular	Bunch of Grapes-like, hemispherical masses	Chalcedony, Smithsonite, Hemimorphite, Adamite and Variscite.
Capillary	Fine hair like	Millerite, Nickel sulphide, Hair Pyrites
Columnar	Similar to fibrous: Long, slender prisms often with parallel growth	Calcite
Coxcomb	Aggregated flaky or tabular crystals closely spaced.	Barite
Dendritic or arborescent	Tree-like, moss-like branching in one or more direction from central point	Magnesite in opal, Mn Oxides

Dodecahedral	Dodecahedron, 12-sided	Garnet
Drusy or encrustation	Aggregate of minute crystals coating a surface	Uvarovite
Enantiomorphic	Mirror-image habit and optical characteristics; right- and left-handed crystals	Quartz
Equant, stout, stubby or blocky	Length, width, and breadth roughly equal	Zircon
Euhedral	Well-formed, external crystal faces developed	Spinel
Fibrous	Extremely slender prisms	Tremolite, Satinspar, Asbestos
Filiform or wiry	Thin wires, extremely fine twisted like the strands of a rope	Natrolite, Native silver and copper
Foliated or micaceous	Layered structure, parting into thin sheets	Mica
Granular	Aggregates of anhedral crystals in matrix	Scheelite
Hemimorphic	Doubly terminated crystal with two differently shaped ends.	Hemimorphite
Lamellar		Wollastonite
Lenticular	Flattened balls or pellets as in nodular/concretionary mnls.	
Mamilliated	Breast-like: surface formed by intersecting partial spherical shapes	Malachite
Massive or compact	Shapeless, no distinctive external crystal shape	Serpentine
Nodular, Concretionary or tuberos	Deposit of roughly spherical form with irregular protuberances	Geodes, Nodules of Flint, Chalk and Phosphates
Octahedral	Octahedron, eight-sided (two pyramids base to base)	Diamond
Plumose	Fine, feather-like scales	Mottramite
Prismatic	Elongate, prism-like: crystal faces parallel to c-axis well-developed	Tourmaline
Pseudo-hexagonal	hexagonal appearance due to cyclic twinning	Aragonite
Pseudomorphous	Occurring in the shape of another mineral through pseudomorphous replacement	Tiger's eye
Radiating or	Fibres radiating outward from a	Stibnite, Pyrite suns

divergent	central point	
Reniform or colloform	Similar to mamillary: intersecting kidney-shaped masses	Hematite
Reticulated	Cross-meshes like (net-like) acicular crystals forming intergrowths	Cerussite, Rutile needles in Mica
Rosette	Platy, radiating rose-like aggregate	Gypsum
Scaly	Small plates	Tridymite
Sphenoid	Wedge-shaped	Sphene
Stalactitic	Forming as stalactites or stalagmites; cylindrical or cone-shaped	Rhodochrosite
Stellate	Star-like, radiating	Pyrophyllite
Striated/striations	Surface growth lines parallel or perpendicular to a crystallographic axis	Chrysoberyl
Subhedral	External crystal faces only partially developed	
Tabular or lamellar	Flat, tablet-shaped, prominent pinnacoid	Ruby
Tuberoze	Very irregular rounded surfaces-gnarled, root like shapes	Aragonite variety Flos-ferri
Wheat sheaf	Aggregates resembling hand-reaped wheat sheaves	Zeolites

- a. Pseudomorphism – the assumption by a mineral of a form other than that which really belongs to it. – by incrustation, infiltration, replacement or by alteration.
- b. Polymorphism – Two minerals of markedly different physical properties, but may have identical chemical compositions. Dimorphism-Calcite – Aragonite, Graphite – Diamond; Trimorphous – Titanium Dioxide-Anatase-Brookite-Rutile.



c. **Hardness** – Mohs' Scale of Hardness.

1. Talc $\text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2$
2. Gypsum $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$
3. Calcite CaCO_3
4. Fluorite CaF_2
5. Apatite $\text{Ca}_5(\text{PO}_4)_3(\text{OH}, \text{Cl}, \text{F})$
6. Orthoclase KAlSi_3O_8
7. Quartz SiO_2
8. Topaz $\text{Al}_2\text{SiO}_4(\text{OH}, \text{F})_2$
9. Corundum Al_2O_3
10. Diamond C (pure carbon)

d. **Tenacity** –

- i. Sectility – can be cut with a knife and breaks up under a hammer – Graphite, Steatite, Gypsum.
 - ii. Malleability – can be flattened under a hammer – Native gold, silver and copper
 - iii. Flexibility – Remains bent after the removal of pressure – talc, Selenite.
 - iv. Elasticity – bent portions will spring back to its former position - Mica, Chlorite.
 - v. Brittleness – Crumbling or flying to powder – iron pyrites, Apatite and Fluorspar.
- e. **Fracture** – Character display on the broken or chipped surfaces of minerals.
- i. Conchoidal – Curved concave or convex fractures on breaking – Quartz, Flint or natural glasses.
 - ii. Even – Flat to nearly flat Fracture surface – Chert
 - iii. Uneven – Rough fracture surfaces
 - iv. Hackly – studded with sharp and jagged elevations – as in broken cast iron
 - v. Earthy – fracture of chalk, Meerschaum.
- f. **Cleavage or Parting:** Perfect- Parallel to base - Basal, Similarly Prism, Pinacoidal, Imperfect, Absence.

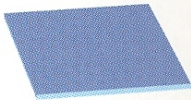
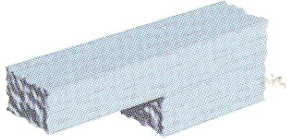
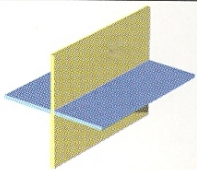
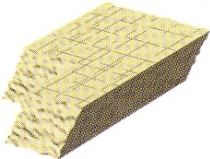
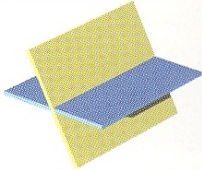
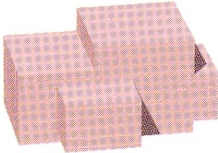
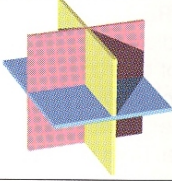
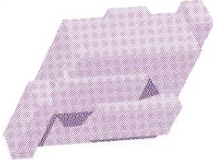
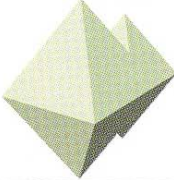
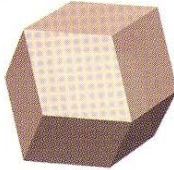
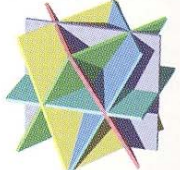
Number of Cleavage Directions	Shapes that Crystal Breaks Into	Sketch	Illustration of Cleavage Directions
0 No cleavage, only fracture	Irregular masses with no flat surfaces		None
1	Basal cleavage "Books" that split apart along flat sheets		
2 at 90°	Elongated form with rectangular cross sections (prisms) and parts of such forms		
2 not at 90°	Elongated form with parallelogram cross sections (prisms) and parts of such forms		
3 at 90°	Cubic cleavage Shapes made of cubes and parts of cubes		
3 not at 90°	Rhombohedral cleavage Shapes made of rhombohedrons and parts of rhombohedrons		
4	Octahedral cleavage Shapes made of octahedrons and parts of octahedrons		
6	Shapes made of dodecahedrons and parts of dodecahedrons		

FIGURE 2.10 Common shapes that minerals break into relative to the number and orientations of their cleavage directions.

- g. **Surface Tension Effects:** The difference in adhesive power of various liquids to different mnls-useful for economic ore separation and concentration from its gangue.

4) SPECIFIC GRAVITY

The ratio of the weight of the body to that of an equal volume of water.

Basic idea: The loss in weight of a mineral immersed in water is the weight of volume of water equal to that of the mineral.

$$\frac{W_a}{W_a - W_w}$$

5) HEAT BASED CHARACTERS:

The relative fusibility of certain minerals is a useful character using blowpipe.

Von Kobell's scale of Mineral Fusibility: The following 6 minerals have the character of increase in temperature of fusion constantly.

Stibnite → Natrolite → Almandine Garnet → Actinolite → Orthoclase → Bronzite.

6) MAGNETISM, ELECTRICITY & RADIOACTIVITY

a. Magnetism

- i. Highly Magnetic – Magnetite, Pyrrhotite
- ii. Moderately Magnetic – Siderite, Chromite, Ilmenite, Haematite, Wolframite
- iii. Non-magnetic – Quartz, Calcite, Feldspar, Corundum, Cassiterite.

b. Electricity

- i. Good conductors – Native metals, Sulphides.
- ii. Bad Conductors –
- iii. Pyroelectric mnls – On heating - Tourmaline
- iv. Piezoelectric mnls – Under Pressure - Quartz

c. Radioactivity

- i. Radioactive – Uraninite, Thorianite
- ii. Non-radioactive

SPECIFIC GRAVITY

The specific gravity of a body is the ratio of the weight of the body to that of an equal volume of water.

Wa

Wa-Ww

Methods of Determining Specific Gravity. The following are the chief methods of determining specific gravities in mineralogy, the particular method chosen depending usually upon the size and character of the specimen under examination.

- (1) With the ordinary chemical balance, for fragments of a solid mineral about as big as a walnut.
- (2) With Walker's steelyard, for large specimens.
- (3) With Jolly's spring balance, for very small specimens.
- (4) By measuring the displaced water, for the rapid determination of the approximate specific gravity of a number of specimens of a mineral.
- (5) With the pycnometer or specific gravity bottle, for friable minerals, small fragments or liquids.
- (6) With heavy liquids, used mainly for the separation of mineral mixtures into their pure components according to their specific gravities, but also for approximate determinations of specific gravity of mineral grains. For this latter determination, the diffusion column and Westphal Balance may be employed.

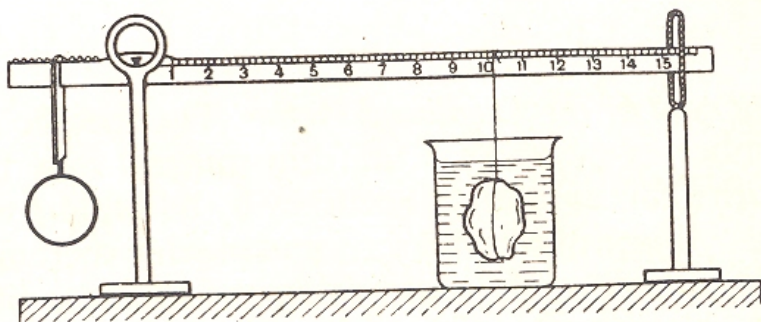


FIG. 15. Walker's Steelyard

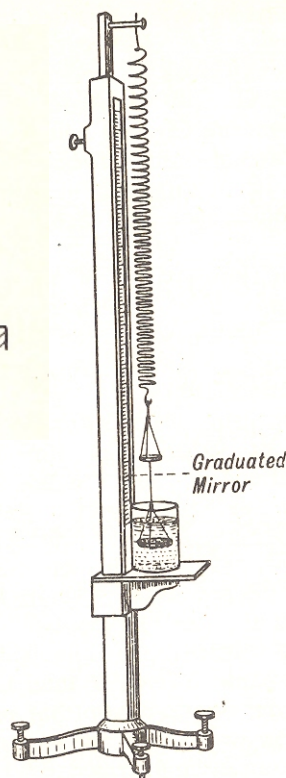


FIG. 16. Jolly's Spring Balance.

TWINNING OF CRYSTALS

When two individual crystals grow together with a part of their similar faces edges etc., in parallel positions they are said to form a twin crystal. They often appear externally consisting of two or more crystals symmetrically united, and sometimes they have the form of a cross or star.

Twinning – Intergrowth of two or more individual crystals in such a way as to yield parallelism in the case of certain parts of different individuals and at the same time other parts of the different individuals are in reverse positions in respects to each other.

They often appear externally to consist of two or more crystals symmetrically united and sometimes have the form of a cross or star.

Some crystallographic direction or plane is common to the parts of the twin. In twin crystals one part is in reverse position to the other part, or the second half of the twin may be conceived as produced by rotation about some line, one half of the crystal through an angle of 180° .

The plane dividing the twin so that one half is a reflection of the other half is called the “Twin-plane”. The axis about which rotation is necessary to restore the twin to its untwinned state is called the twin-axis.

The twin-axis is usually perpendicular to the twin-plane. The conception of the twin-axis is merely a convenient way of describing twinning-such a revolution has of course not occurred in the formation of twins.

Twinning may be the result of growth on the two sides of a sheet of atoms, the growth keeping to the proper structural pattern but proceeding with different but appropriate orientations.

The plane along which the two halves of a twin are joined is called the composition-plane. It is usually but not necessarily coincident with the twin-plane.

Types of twinning

Simple twin: The twin of calcite consisting of two halves symmetrical with respect to the twin-plane is simple twin is also known as contact-twin.

Penetration twin: The two halves of the twin have grown so mixed together that the twin cannot be divided in to two separate halves is known as penetration twin. Eg.: Iron cross twins of Pyrite, interpenetrated twins of Fluorite and cross-shaped twins of Staurolite.

Repeated twin: The repetition of twinning along the twin-plane. If it is composed of three parts it is called as 'trilling', if 4 parts – 'fourling'. If the twin-plane is parallel in all parts and there so many repetitions, is described as 'polysynthetic'. Eg.: Plagioclase feldspars. If the twin-plane does not remain parallel, the resulting twin approaches a curved form called 'cyclic'. Eg.: Aragonite.

Compound or complex twin: Twinning has taken place on two or more laws is called as compound or complex twin.

Laws of twinning: The two (or more) individual comprising a twin crystal have different orientations of their atomic structures. One orientation may be derived from another by some simple operations over certain planes of axes. If one part is derived from the other by reflection over a plane common to both the parts, the plane involved is twinning plane. If one part is derived from the other by a revolution of 180° about some crystal line common to both, the axis involved is twinning axis. These two operations may occur simultaneously. Certain fundamental laws of twinning are:

1. No symmetry plane of an individual crystal can become a twinning plane in its compound crystal.
2. No axis of even symmetry (binary, tetragonal or hexagonal in the individual crystal can become a twinning – axis in the compound crystal.
3. A symmetry plane or axis of a class of higher symmetry may become a twinning plane or axis of a crystal belonging to a class of lower symmetry of the same system.
4. Twin crystals of all crystal classes possessing a centre of symmetry will have both a plane of twinning and an axis of twinning normal to the plane.
5. Where centre of symmetry is lacking a twinning plane or axis may occur independently.

The plane by which the reversed crystals are united is the composition plane. This and the twinning plane very commonly coincide. When not coinciding, the twin planes are generally at right angles to each other-the composition are plane is a parallel to the axis of revolution.

When the crystals are not regularly developed and where they interpenetrate, the contact surface may be exceedingly irregular. In such cases the twinning planes and axis have a definite position by the composition plane loses its significance.

The twinning may be contact or penetration ones. In contact twins the two halves are united to each other by the composition plan. In penetration twins two or more complete crystals interpenetrate, as it were crossing through each other.

A parallel repetition or parallel grouping in reversed position of successive crystalline lamellae is often called 'polysynthetic twinning' (Plagioclase feldspars). The lamellae give rise to a series of parallel lines (Striations), on a crystal face or a surface of cleavage in many cases. In another case of 'repeated twinning', the individual are not parallel but the repetition of the twinning tends to produce circular forms. Trillings (6 rayed), fivelings and eightlings (eight fold) twins are the other forms of repeated twinning (Aragonite, Staurolite, Chrysoberyl, Spinel, etc.).

Twinning produced subsequently to the formation of the crystal or crystalline mass, by pressure or any such force is said to be the secondary. E.g: Calcite grains of Crystalline Limestone.

Examples of important methods of twinning:

Isometric System: the twins of the normal class are generally of one kind namely **Spinel law-twin**. The twinning axis is an octahedral axis the twin plane is parallel to an octahedral face. The twin plane coincides with composition plane in most cases Eg: Galena, copper. The spinal law twin may be contact penetration or repeated.

In the iron-cross twin of the pyritohedral class a dodecahedral plane serves as the twinning plane and normal to it is the twinning axis. It is supplementary twin as the twinned Pyritohedron has all the planes of the normal tetrahexahedron.

The Tetrahedral Sphalerite shows a twin of the ordinary spinel type of twinning with complex forms of repeated or polysynthetic nature.

Interpenetrated twins of Fluorspar in the octahedral face, Iron-cross of pyrite in the rhombododecahedral face of pyritohedrons, normal Galena type are some of the other forms.

Tetragonal System: The most common system is that, where, the twinning plane is parallel to a face of the pyramid. Rutile, Cassiterite, Zircon, etc., show this type. Rutile shows repeated twin also, in Chalcopyrite of the sphenoidal class twinning with unit sphenoid face as the twinning plane is common. In Tetragonal system: **Rutile law** is the commonest type of twinning in which the pyramidal face of second order(101) or (301) is the twin-plane and composition-plane. It produced a knee-shaped or geniculate twin with 101 face or a sharper knee twins with 301 face.

Hexagonal System: Twins are rare in the hexagonal division. In Pyrrhotite, the twinning plane is pyramid (1011). In the species of rhombohedral division twins are common. The twinning axis may be vertical axis in contact and penetration twins or the twinning plane may be the obtuse rhombohedron. In the trapezohedral class, the species quartz shows several methods of twinning. In **Brazil law** twin the twin plane is (1120) and the individuals are right handed and left handed. In Hexagonal system, **Calcite twins** (0001-base or the gliding planes such as 011-2, 10-11 & 02-21 rhombohedraons are the twin-planes), **Quartz twins** – interpenetration twin, vertical xallographic axis is the twin axis, with right and left handed crystals along 11-20 prism plane as twin-plane.

Orthorhombic system: In the commonest method the twinning plane is a prism face e.g: Aragonite. The twin is repeated and forms with pseudo-hexagonal symmetry results. Such twins, which simulate the symmetry of another and more symmetrical crystal system, are often called **mimetic twins**. The same type of twin with dome face as the twinning plane is shown by Arsenopyrite. In Orthorhombic system: **Cyclic twins** of Aragonite (110 prism is the twin-plane). The prism angle is nearly 60° so that twinning repeated five times to produce a pseudo-hexagonal crystal. **Maltese cross** (032-dome) and **skew twin** (232-bipyramid) in staurolite. The mineral Staurolite illustrates three kinds of twinning, with (032), prism (230) and pyramid as the twin planes.

Monoclinic system: Twins with vertical as the twin axis are common in Augite, Orthoclase, Gypsum. These twins in orthoclase are called **Carlsbad twins**. They may be contact or irregular penetration twins. Twins with the clinodome (021) as the twin plane are called **Baveno twin**. In **Maneback twin** the twinning plane is (001).

In Monoclinic system: **Swallow-tails twins** in Gypsum, Hornblende and Augite twins, **Carlsbad twin** and interpenetration Carlsbad twin (vertical crystallographic axis is twin axis and the clinopinacoid (010) is the composition-plane), **Baveno**

twinn (clinodome-021 is the twin-plane and composition-plane), and **Manebach twinn** (basal pinacoid-001).

Triclinic System: Twinning with (010) as the twinning plane is very common. Such polysynthetic twinning yielding their parallel lamellae are shown by plagioclase feldspars, as striations of the face c (base). This is known as Albite law. The method is **Pericline Law** twin in which the twin axis 'b'. In Triclinic system: **Albite law** (010 the side pinacoid is the twin-plane), which is also repeated and polysynthetic twin. This repeated twin produces striations on the basal planes of the crystal and is also excellently seen in thin section of plagioclase.

OPTICAL PROPERTIES OF MINERALS

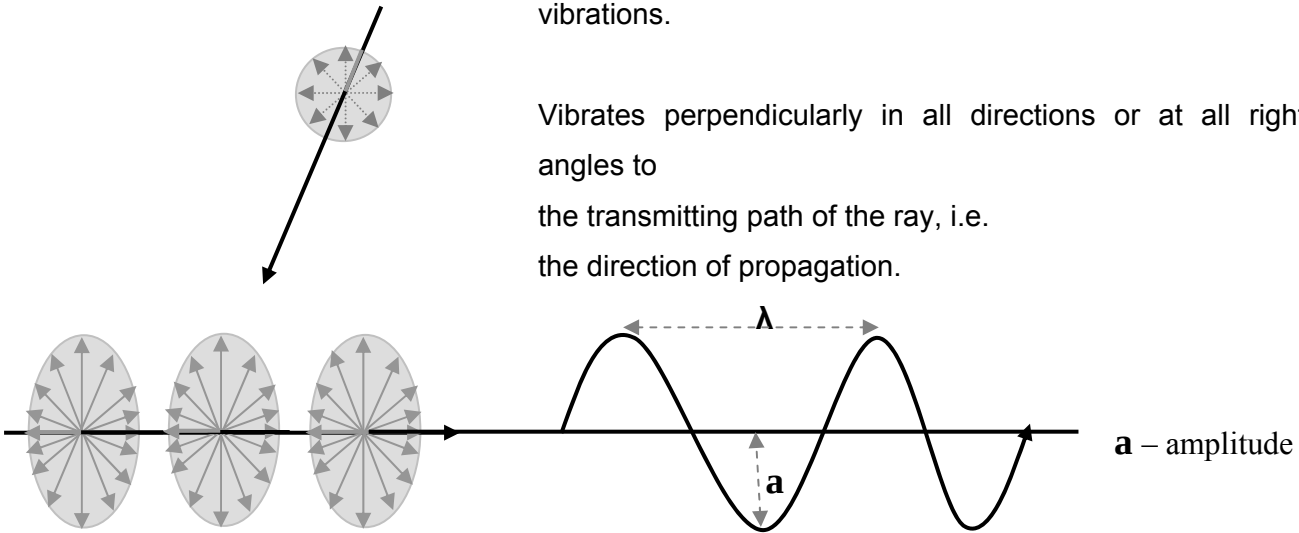
STUDY OF MINERAL THIN SECTIONS USING POLARISING MICROSCOPE:

1. UNDER ORDINARY LIGHT

Nature of light:

Light consists of electro-magnetic radiatn./ vibrations.

Vibrates perpendicularly in all directions or at all right angles to the transmitting path of the ray, i.e. the direction of propagation.



Wave-length: The distance between two subsequent crests or trough (λ).

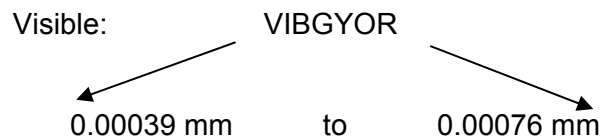
Periodic Time: The time required to travel one wave-length (t), then

Velocity of light,

$$v = \lambda / t$$

i.e. 3.86 lakhs miles/sec.

Colour: Depends upon the wave-length.



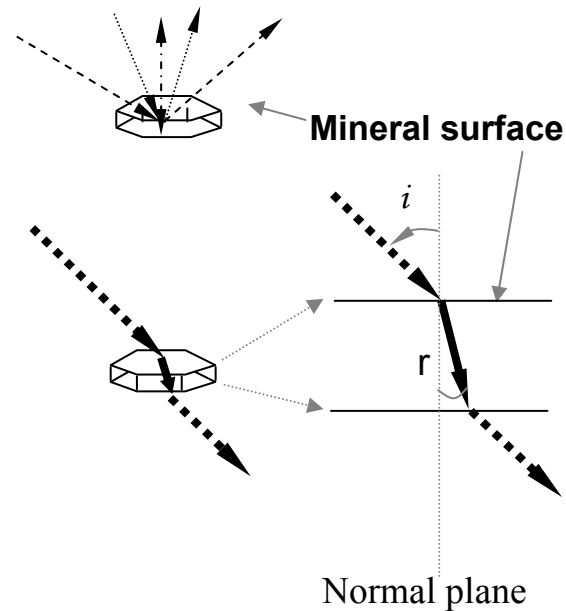
White light: Consisting of all visible rays.

Monochromatic light: one wave-length only.

Two types of Minerals / media / substances:

- Isotropic (same velocity in all directions) /
- Anisotropic (different velocity in different directions)

Reflection & Refraction:



Refractive Index: A constant value - ratio between $\sin i$ and $\sin r$

For air = 1, Water = 1.33, Flourspar = 1.4, Canada balsam = 1.54, Crown glass = 1.53, Garnet = 1.77, Diamond = 2.42.

R.I.s of two media is inversely proportional to the ' v '- velocities of light in them.

Breaking up of white light into an array of VIBGYOR is known as dispersion.

i.e., When the white light enters in to the second medium it is refracted and dispersed in it producing an array of colours.

Since the blue has the less R.I., it occurs nearest the normal and the red has the greatest R.I., it occurs farthest away from the normal.

Becke effect: Becke line – using high power objective and diaphragm (to cut off some of the light) in microscope, if the
Objective is raised, light band travels into the mineral section –Higher R.I.

Isotropic substances have the same R.I. for all directions.

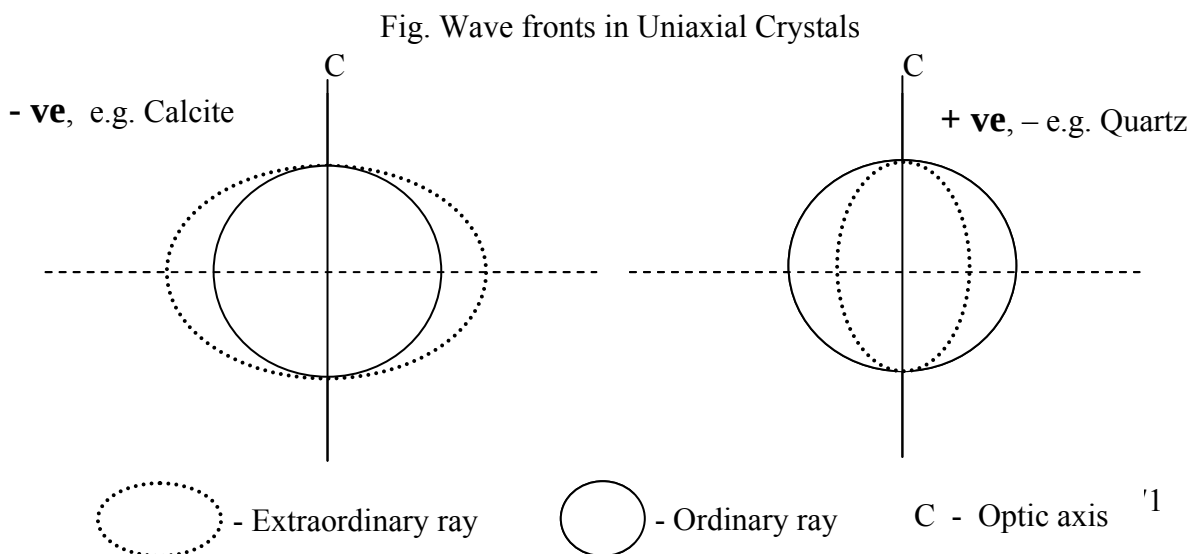
Double Refraction: The phenomenon of light ray forming two refracted rays, i.e., Ordinary and extraordinary rays while passing from an isotropic to an anisotropic medium is known as double refraction.

Ordinary image, i.e., Stationary image has been formed by ordinary ray and the extraordinary image moving around the stationary image formed by the extraordinary ray.

Ordinary ray consists of light vibrating parallel to the long diagonal of the rhomb face and

The extraordinary ray consists of light vibrating parallel to the short diagonal.

Optically uniaxial minerals: A direction in which the ordinary and extraordinary rays have the same velocities and no double refraction occurs is known as “optic axis” and such crystals showing this phenomenon of only one optic axis in such direction, they are said to be “Uniaxial crystals”.



Wave front of ordinary ray is spherical and a section of this is a circle.

The velocity of extraordinary ray varies with its direction. Along the optic axis (C), it has the same velocity as the ordinary ray, but at right angles to the optic axis, it has a maximum velocity. The minerals having the velocity of extraordinary ray greater than that of the ordinary ray are said to be “negative” and the opposite condition, i.e. lesser are “positive”.

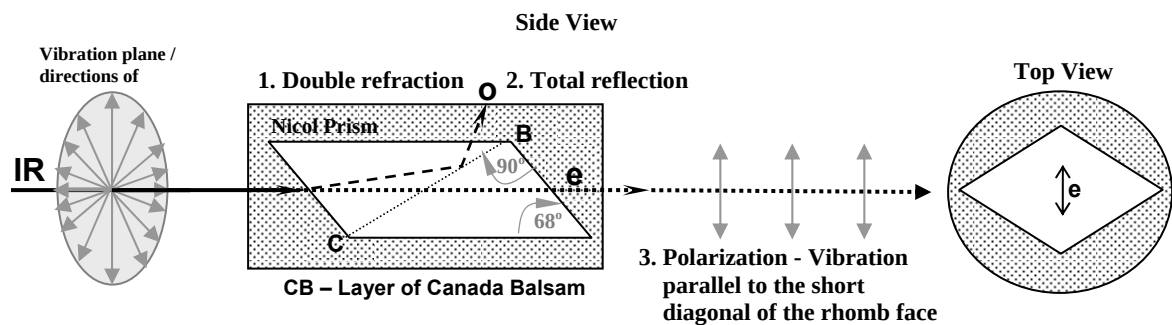
1) Isotropic Minerals: Minerals of Cubic system.

2) Anisotropic Mnls.: (a) Uniaxial Mnls: Tetragonal & Hexagonal

(b) Biaxial Mnls. : Other mnls.

2. UNDER POLARIZED LIGHT

Plane polarized / Polarized – If the light ray vibrates in one direction in this perpendicular plane.



Now a day, instead of nicol prism, the polars, having special filters are being used to produce polarized light.

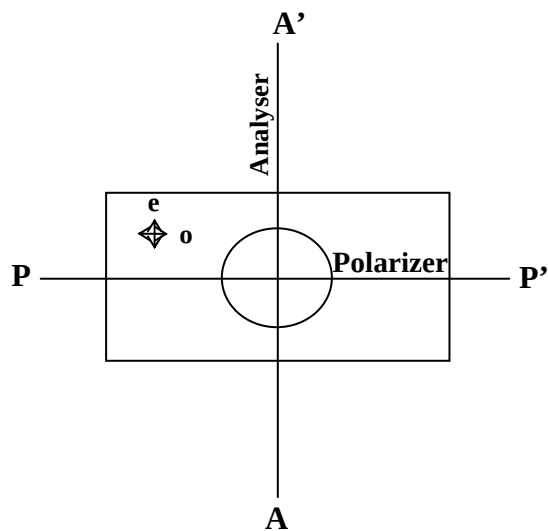
3. UNDER CROSSED NICOLS (or) CROSSED POLARIZERS

The two nicols of the microscope are said to be crossed when the shorter diagonal of the one is at right angles to the shorter diagonal of the other.

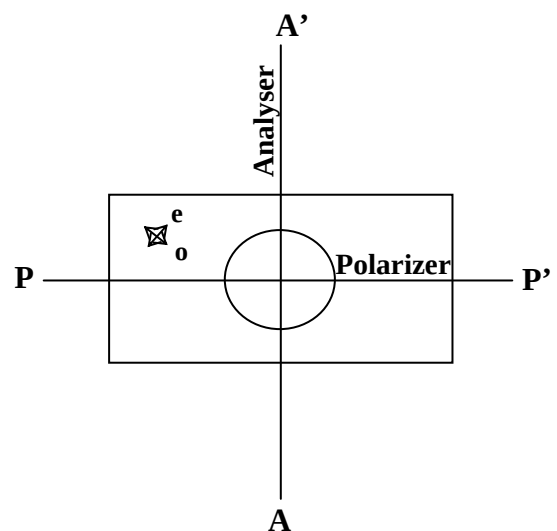
Isotropic minerals between crossed Nicols: The isotropic minerals are single refracting. It gives blackness between crossed nicols at all positions of rotation of the microscopic stage.

Anisotropic minerals between crossed Nicols:

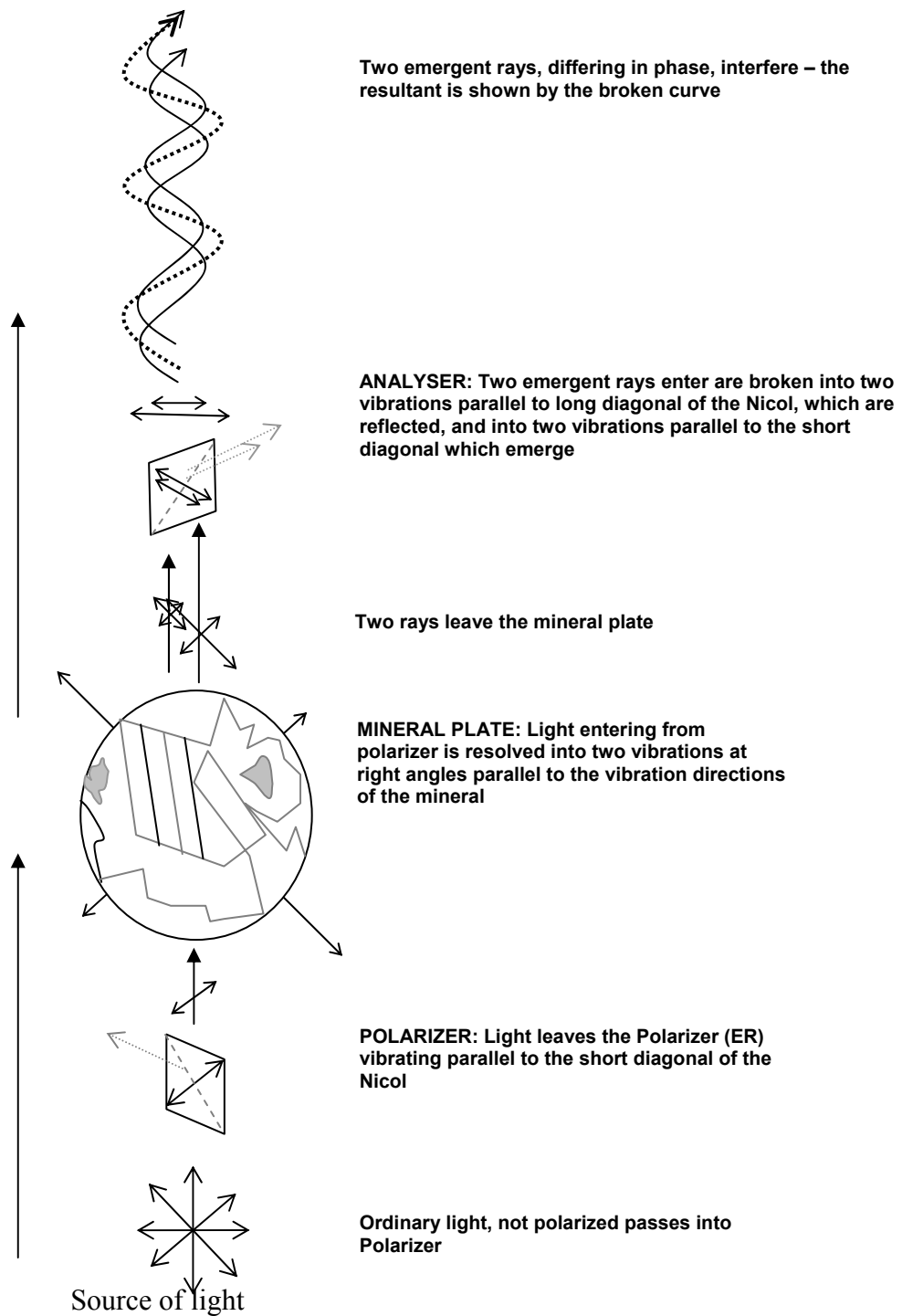
The anisotropic mnls. are doubly refracting, so that a ray of light entering a plate is broken up into two rays, vibrating at right angles and traveling with different velocities. The directions of vibration of the two rays are called the Vibration direction and one ray is the fast ray and the one slow.



Position of Extinction



Position of Illumination



Accessory Plates:

Quartz-wedge: It provides Newton's scale of Interference colours to estimate the birefringence and to determine the optic sign of uniaxial minerals.

Gypsum or Selenite plate: It gives the sensitive tint, the purple at the end of the First order, between crossed nicols. When placed over a mineral, it gives blue when the phase-difference is increased and red or yellow when it is decreased, so that phase-differences are easily told.

Mica Plate: For yellow light it gives a retardation of a quarter of a wave-length.

The gypsum and mica plates have the character fast or slow of the vibration parallel to their lengths marked on them.

Determination of Optical sign: Uniaxial and Biaxial.

INTERFERENCE COLOURS:

The microscopic property of minerals producing darkness and maximum colour at different positions on inserting Quartz Wedge in between crossed Nicols in white light, due to various components of different wave-lengths for each light in series along the wedge, is known as Newton's scale of interference colours.

INTERFERENCE FIGURES

When certain sections of uniaxial minerals are observed in convergent polarized light they show what are known as interference figures. A symmetrical interference figure is obtained in uniaxial minerals by allowing converging polarized light to pass through a basal section of the crystal. Parallel polarized light entering such a section would suffer no double refraction and consequently give no interference.

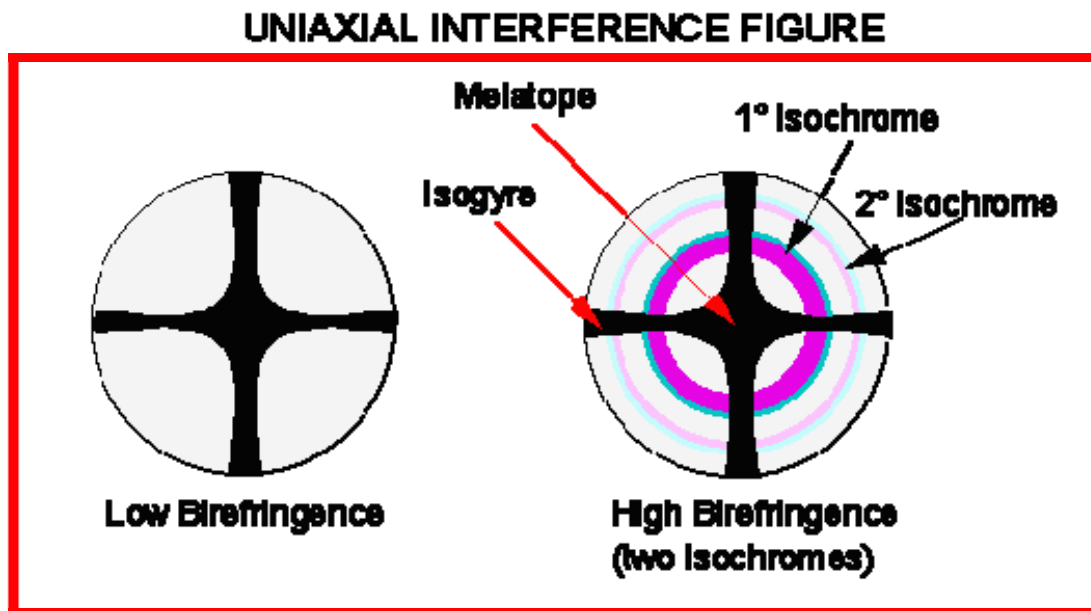
To convert the parallel polarized light that comes from the polarizer into convergent light a lens is placed above the thin section to change these oblique rays back again into a parallel position. Such an instrument is known as a **conoscope** and may be obtained by placing a pair of lenses between the polarizer and analyzer of a polariscope, or in case the polarizing microscope is used, the small converging lens that lies above the polarizer is swung into

position by a lever and at the same time a small lens known as the Bertrend lens is introduced into the microscope tube.

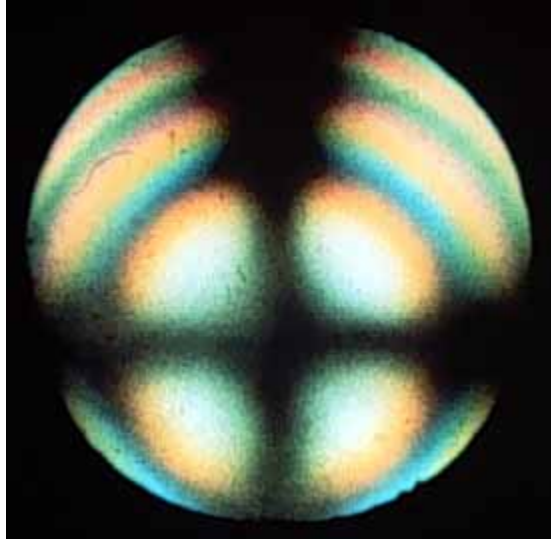
Uniaxial and Biaxial interference figures

Parts of An Interference Figure

Below is a sketch of the uniaxial optic axis figures of two minerals, one which is a low birefringence (like quartz), and one which has a higher birefringence (like calcite). As you can see, the higher birefringence mineral has two isochromes visible, reflecting the difference between the high (slow) and low (fast) refractive indices of the mineral. Be sure you can identify the isogyres, the melatope and the isochromes.



Below is a photomicrograph of an interference figure of a highly birefringent uniaxial mineral.



Use of Accessory Plates to Determine Optic Sign

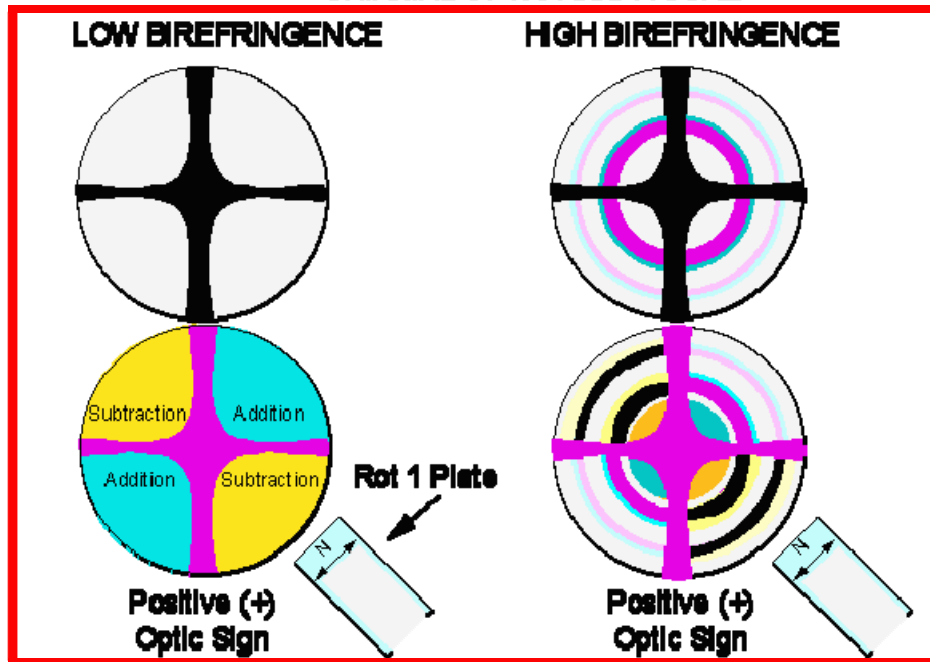
We often use accessory plates to help identify a mineral. The most commonly used accessory plate is the gypsum or Rot 1 plate. There is one with each microscope.

Accessory plates are plates of anisotropic minerals ground to a thickness that gives a particular retardation of light. When inserted into the light path, they change the retardation of light coming through the thin section by a specific amount and the resultant interference color helps to identify the mineral.

Positive Sign

Below are figures which show the shift in colours which result when the Rot 1 plate is inserted. In quartz, which is uniaxial positive, the colours in the upper left and lower right quadrant decrease in colour from 1st order grey to first order yellow, whereas the colours in the upper right and lower left quadrants increase from 1st order grey to a second order blue. The figure on the right illustrates a more highly birefringent uniaxial positive mineral. Zircon is an example of this type of mineral.

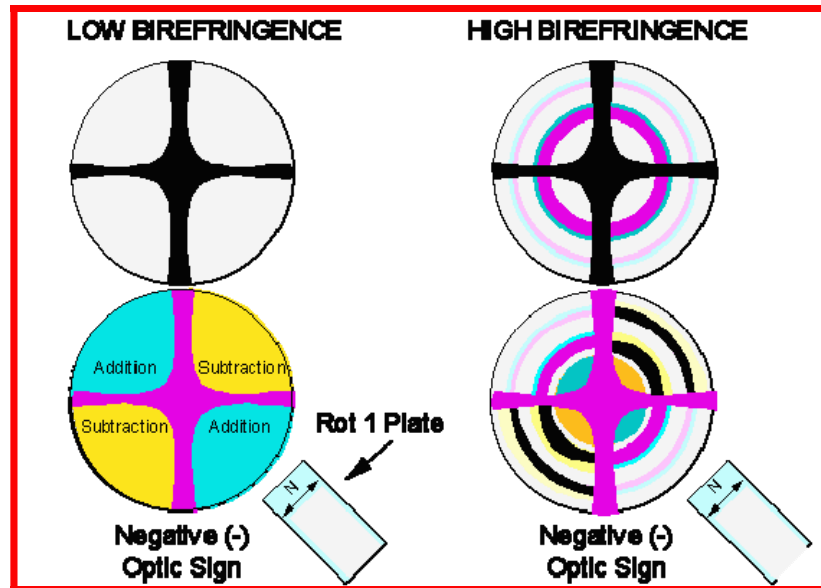
**DETERMINATION OF OPTIC SIGN USING Rot 1 PLATE
UNIAXIAL OPTIC AXIS FIGURE**



Negative Sign

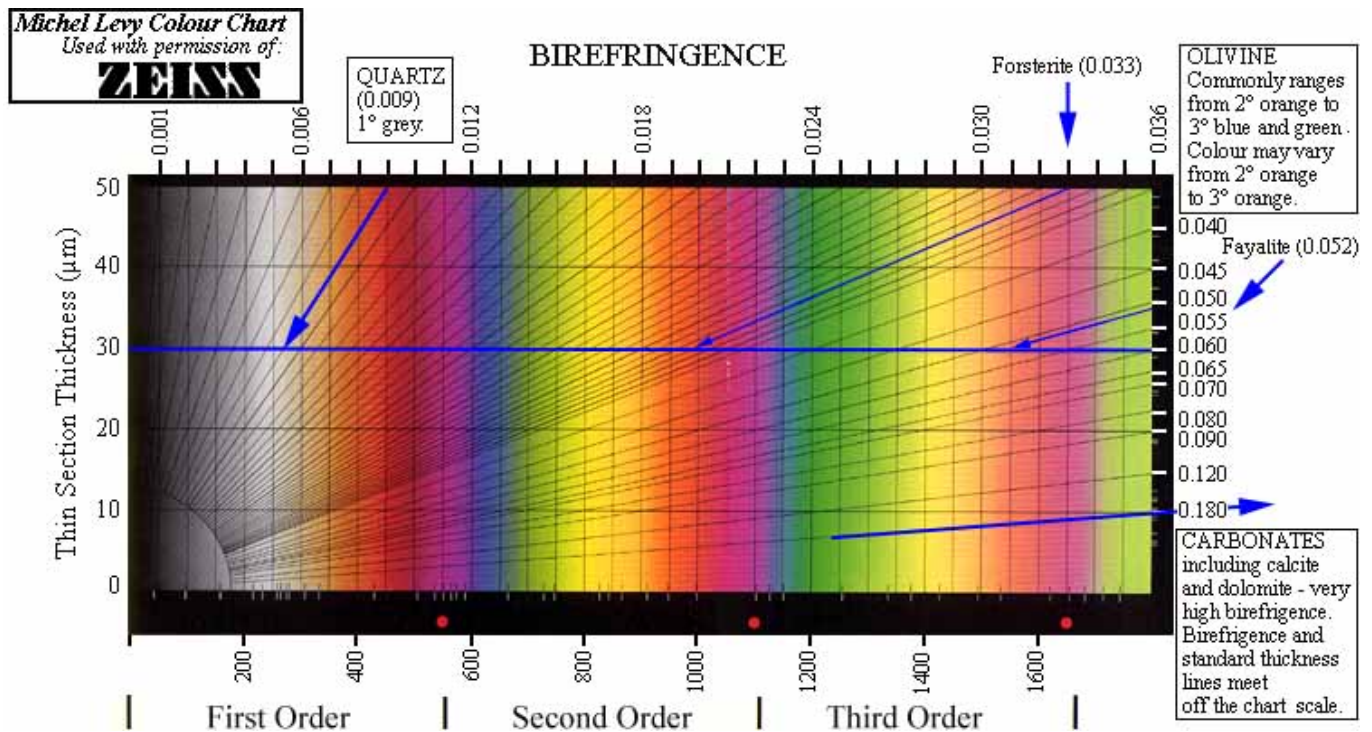
The figure below shows the opposite type of uniaxial figures, the uniaxial negative (-) interference figures. Once again, the figure on the left is of low birefringence (e.g., apatite), whereas the figure in the right shows a more highly birefringent uniaxial negative mineral (e.g., calcite).

**DETERMINATION OF OPTIC SIGN USING Rot 1 PLATE
UNIAXIAL OPTIC AXIS FIGURE**



Remember that a standard thin section is 0.03 mm thick. You can check this by examining quartz which should have a maximum interference color of 1st order white (grey) or barely 1st order yellow.

From the 0.03 mm horizontal line, and for a known interference color, read up along the appropriate diagonal line to get (birefringence). This property is useful to identify minerals. Alternatively, for a known birefringence, look down along a diagonal line to its intersection with the 0.03 mm line to see what the interference color should be in a standard thin section.



Interference Figures

To obtain an interference figure:

- o THE MICROSCOPE MUST BE IN **CONOSCOPIC** MODE!!! (*Flip the auxilliary condenser into place.*)
- o Make sure the cover slip is facing up!
- o It is vital that the high power objective be centered properly.

PROCEDURE

1. Find grains on low power (crossed nicols),
2. Make sure you are not focused on a crack or impurity in the grain.
3. Move up to medium power and double check focus
4. Then move up to high power and double check focus
5. Insert the Bertrand lens and the condensing lens and voilà! An interference figure should appear.

It doesn't??

1. Check that the microscope is in the correct configuration,
2. Check that the grain on high power is not focused on a crack or impurity.
3. Also check that the high power objective is properly centered.

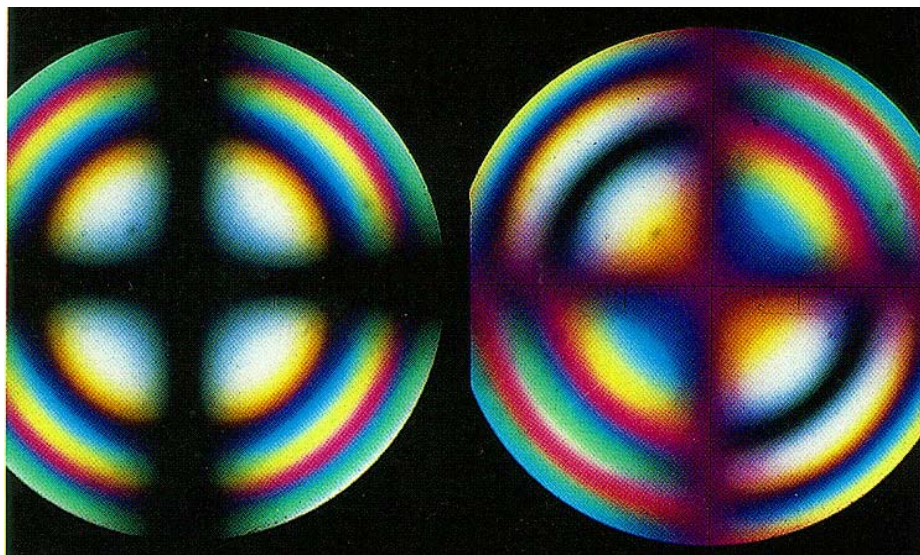
OBTAINING AN INTERFERENCE FIGURE

Now come to the major means of distinguishing whether an anisotropic mineral is uniaxial or biaxial and for determining the optic sign for an anisotropic minerals - **THE INTERFERENCE FIGURE.**

To obtain and observe an interference figure using the microscope.

1. With high power, focus on a mineral grain free of cracks and inclusions
2. Flip in the auxiliary condensor and refocus open aperture diaphragm up to its maximum.
3. Cross the polars
4. Insert the Bertrand lens or remove the ocular and look down the microscope tube.

Will not see the grain, but the interference figure, which appears on the top surface of the objective lense.



The interference figure consists of a pattern of interference colours and a black band which may form a cross. Nature and pattern for the figure is dependent on the orientation of the grain.

For Uniaxial Minerals three types of interference figures will be considered.

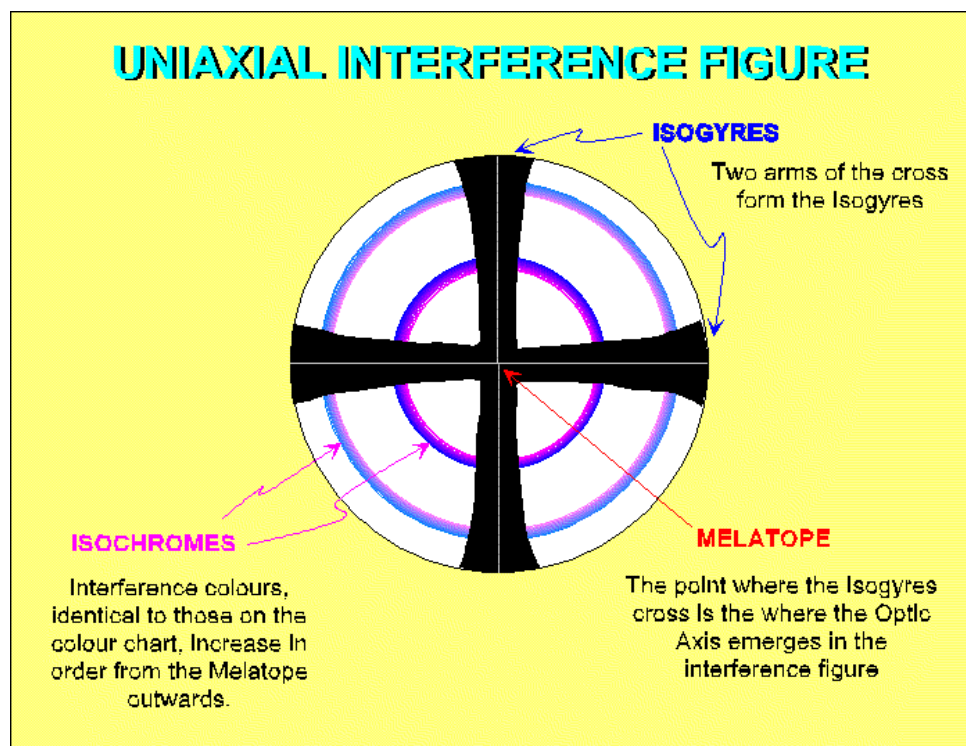
1. Optic Axis Figure - OA vertical
2. Off Centred Optic Axis Figure - OA inclined.
3. Flash Figure - OA horizontal

Each figure type is a direct reflection of the different cuts through the indicatrix.

OPTIC AXIS INTERFERENCE FIGURE

If the optic axis of the mineral is vertical, the grain will exhibit 0 birefringence and remain black or nearly black upon rotating the stage.

The interference figure produced by such a grain is a centred optic axis figure which consists of a centred black cross superimposed on circular bands of interference colours.



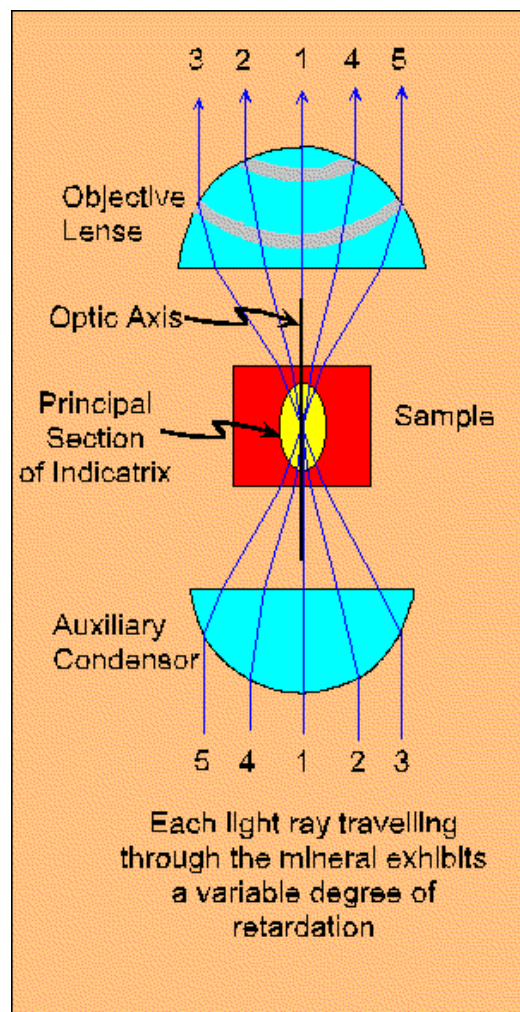
The cross is formed of black bars - isogyres, point where the two isogyres cross is the melatope and marks the point where the optic axis emerges.

Interference colours increase in order outward from the melatope, near melatope colours are low first order Each colour band is called an isochrome.

If the optic axis is vertical the interference figure for the mineral does not move as the stage is rotated.

Isochromes form and are exhibited by the interference figure due to varying retardation of convergent light rays on the sample.

FORMATION OF ISOCHROMES



Light is convergent because auxiliary condensor produces a cone of light which is focused on the sample, it passes through the sample and is collected by the objective lens.

1. Light which travels along the optic axis is not split into two rays, $n_{\text{epsilon}}' = n_{\text{omega}}$, and exits the mineral to form the melatope. No retardation "between" rays.
2. Light following paths 2 & 4 experience moderate retardation $n_{\text{epsilon}}' < n_{\text{omega}} \sim 550 \text{ nm}$
3. Light following paths 3 & 5 experience moderate retardation $n_{\text{epsilon}}' \ll n_{\text{omega}} \sim 1100 \text{ nm}$ because light makes a larger angle with optic axis and must take a longer path through the sample.

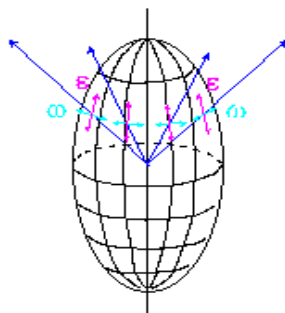
Optic axis is vertical and optical properties vary symmetrically about the optic axis, rings of equal retardation are produced around the melatope = isochromes.

Number of isochromes depends on retardation and the thickness of the sample.

Simplified, ignored the splitting of light into its two component rays, each of which refract differently.

FORMATION OF ISOGYRES

Optic Axis = c-axis

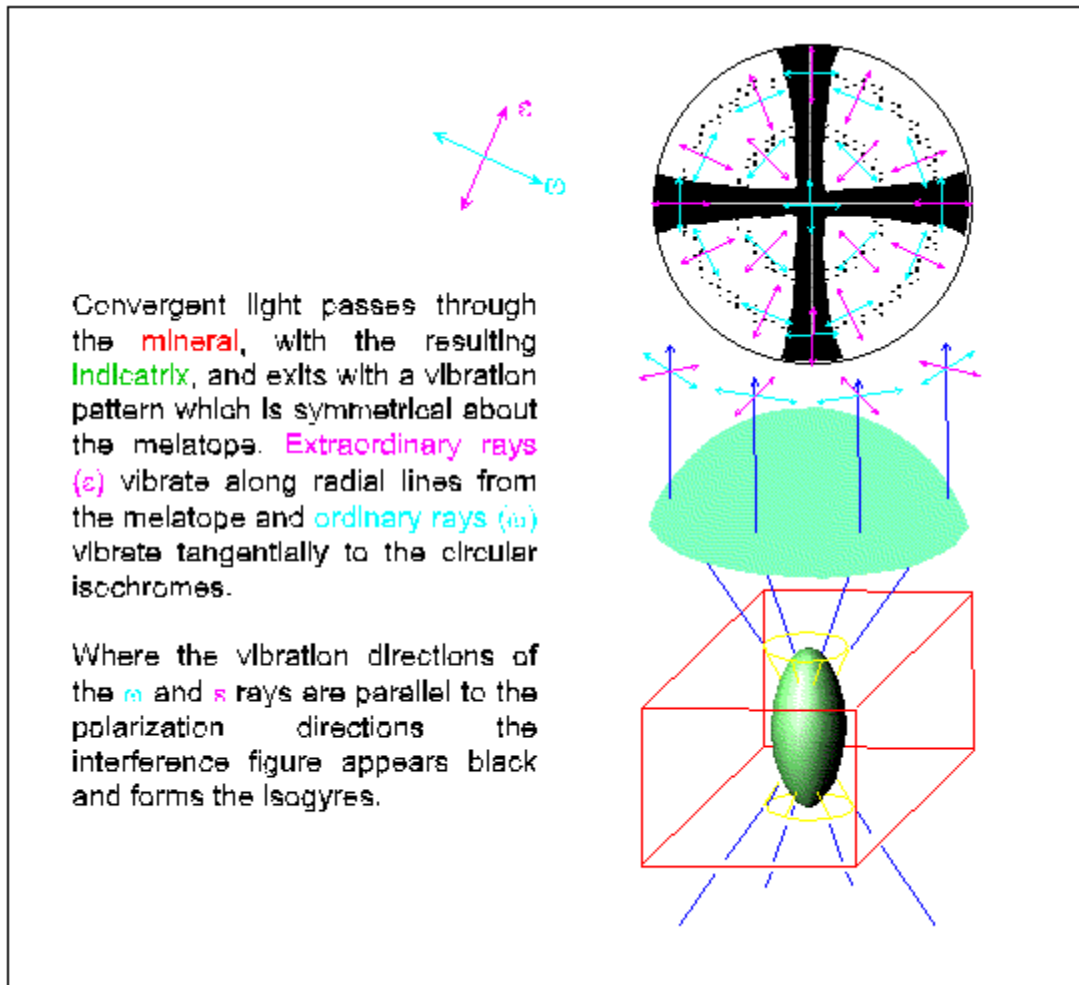


Light rays travelling out from the centre of a uniaxial positive indicatrix.

The **ordinary ray (ω)** vibrates perpendicular to the c-axis and are analogous to lines of latitude.

The **extraordinary ray (e)** vibrates parallel to the c-axis and are analogous to lines of longitude.

Isogyres form when the vibration directions in the interference figure parallel the vibration directions of the polars. These are areas of extinction.



In the uniaxial indicatrix the ordinary rays vibrate perpendicular to the optic axis and are analogous to lines of latitude on the surface of the indicatrix. They vibrate as tangents to the circular isochromes.

Extraordinary rays vibrate parallel to the optic axis and are analogous to lines of longitude on the indicatrix surface and vibrate along radial lines from melatope outwards.

Once the interference figure has been obtained and identified as to whether it is uniaxial or biaxial, the optic sign of the mineral can be determined using an accessory plate, either gypsum, quartz or mica.

OPTIC SIGN DETERMINATION

Once the interference figure has been obtained and identified as to whether it is uniaxial or biaxial, the optic sign of the mineral can be determined using an accessory plate, either gypsum, quartz or mica.

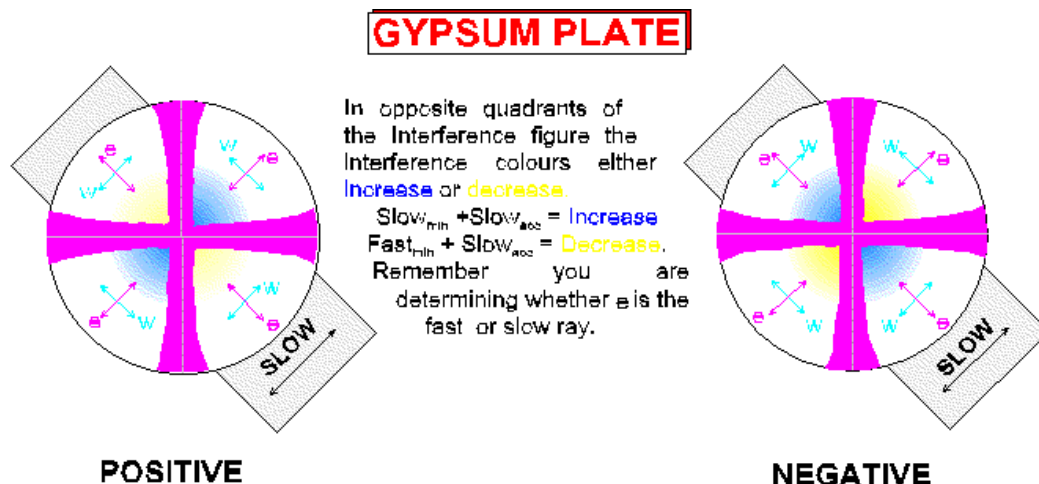
The optic sign tells us whether the ordinary ray corresponds to the fast or slow ray.

omega = Fast	Optically Positive	epsilon = Slow
omega = Slow	Optically Negative	epsilon = Fast

To determine optic sign of a uniaxial mineral:

1. Obtain an optic axis interference figure.
one that is centred in field of view
2. Insert accessory plate into the light path.
3. Observe the interference colours:
 - o in two quadrants the colours increase, move to the right,
 - o in other two quadrants the colours decrease, move to the left.
4. Look at the NE quadrant of the interference figure.

INTERPRETATION



In the centred uniaxial optic axis interference figure, remember;

- omega vibrates parallel to isochromes
- epsilon vibrates radially from centre

The accessory plate vibration direction is NE - SW, and corresponds to slow direction of plate. **It is parallel to extraordinary ray vibration direction in NE Quadrant of the interference figure.**

Examining the NE quadrant of the interference figure, two possibilities may occur:

1. The interference colours will increase, move to the right on the colour chart, when the accessory plate is inserted. This tells us that the extraordinary ray, of the mineral, must be the slow ray and therefore the mineral is optically positive.
2. The interference colours will decrease, move to the left on the colour chart, when the accessory plate is inserted. This tells us that the extraordinary ray, of the mineral, must be the fast ray and therefore the mineral is optically negative.

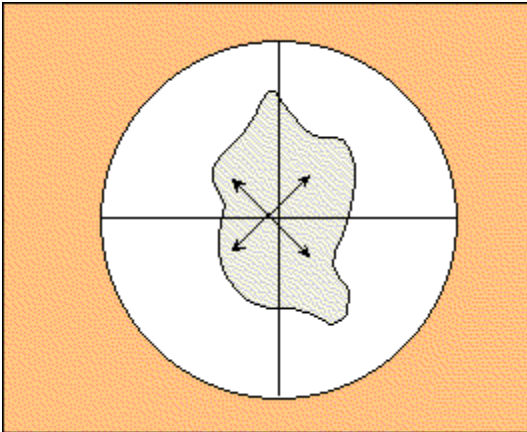
The SW quadrant of the interference figure will exhibit the same colour changes, observed in the NE quadrant because omega and epsilon vibration directions are the same.

The NW & SE quadrants exhibit the reverse colour changes.

Gypsum Plate is used to determine the optic sign, provided not too many isochromes are present.

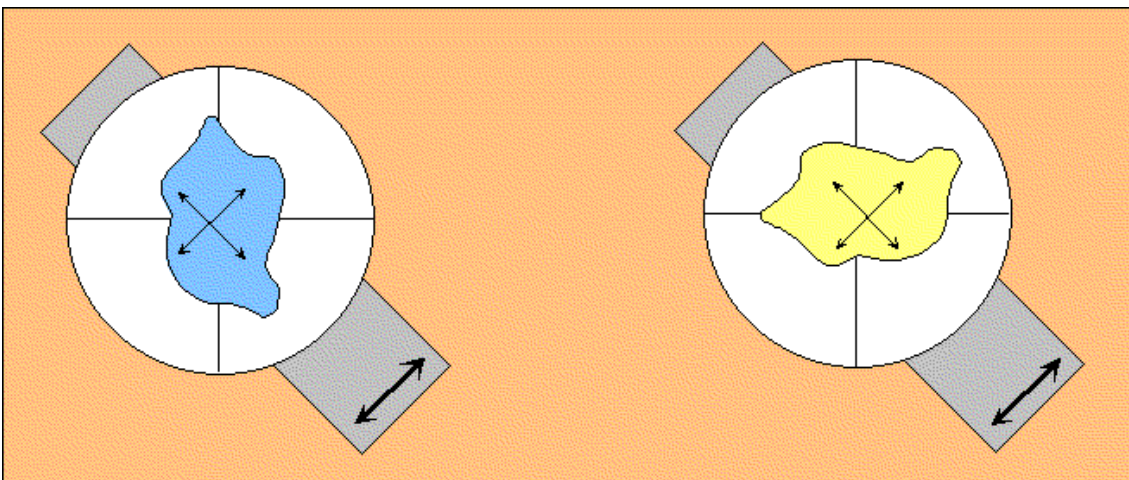
OPTIC SIGN USING THE GYPSUM PLATE

Under crossed polars, without the gypsum plate, a first order grey interference colour has a retardation of approximately 200 nm.



This first order grey colour, on inserting the gypsum plate, will either;

1. Increase to second order blue-green, the colour shown on the left below,
($200 + 550 = 750$ nm)
giving a total retardation = 750 nm
or
2. Decrease to first order yellow, the colour shown on the right below,
($200 - 550 = -350$ nm)
giving a total retardation = 350 nm.

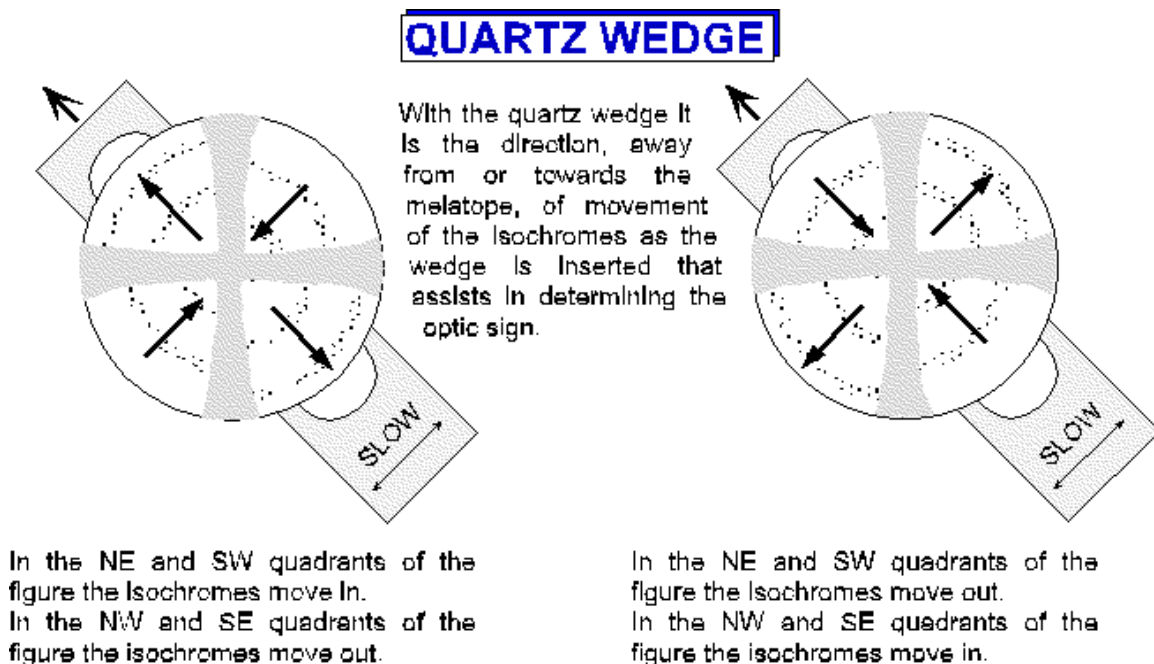


The blue or green colour results from the addition of the slow vibration direction of plate to the slow vibration direction of mineral.

The yellow colour results from the subtraction of the slow vibration direction of plate from the fast vibration direction of mineral.

OPTIC SIGN USING THE QUARTZ WEDGE

If the interference figure displays numerous isochromes colour changes produced with the gypsum plate become difficult to detect. In this case the quartz wedge is used.



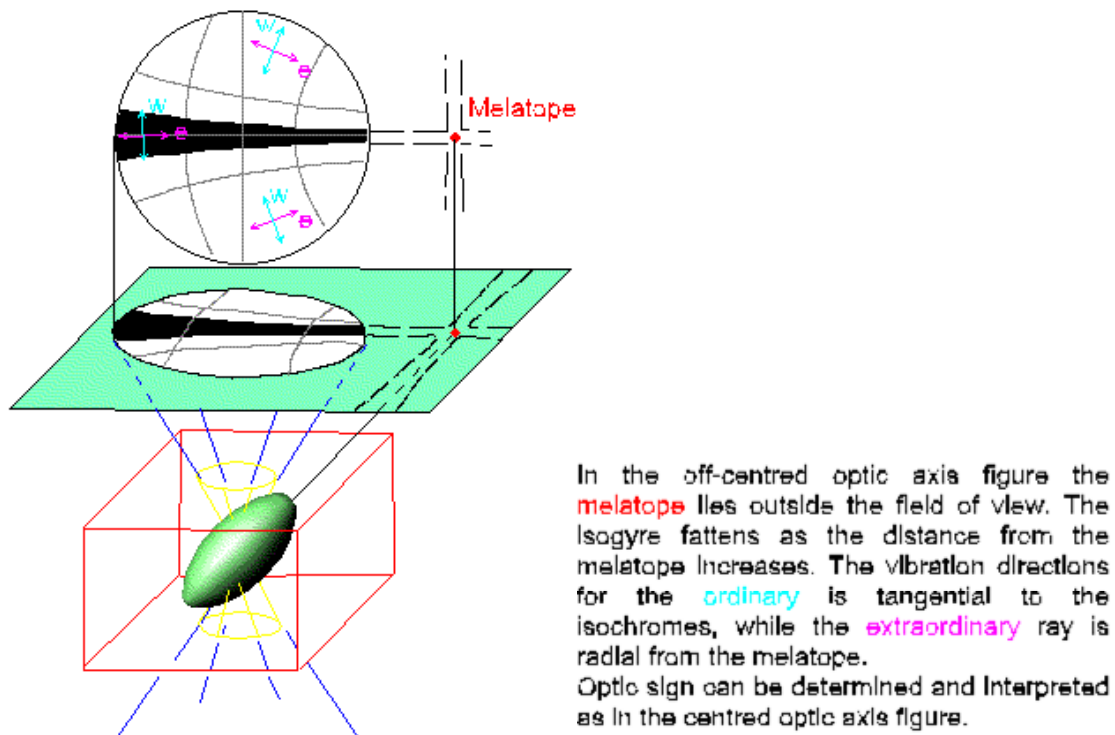
Inserting the Qtz wedge results in the movement of the isochromes about the isogyres.

In quadrants where the colours subtract, i.e. where the fast ray of the mineral is parallel to slow ray direction of the quartz wedge, the isochromes move outward as lower order colours form near the melatope and displace higher order colours.

In quadrants where the colours add, where the slow ray of the mineral is parallel to the slow ray of the quartz wedge, the isochromes move inwards, towards the melatope.

The isogyre, on insertion of the accessory adopts the interference colour corresponding to the retardation of the accessory.

OFF CENTRED OPTIC AXIS FIGURE



The interference figure is produced when the optic axis is not vertical, resulting in the interference figure, i.e. the melatope, no longer being centred in the field of view.

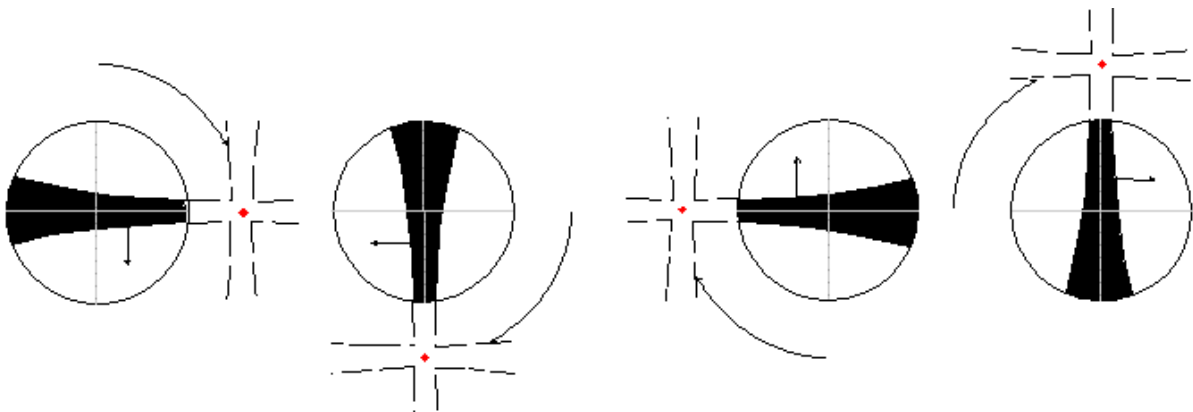
The isogyres still form a cross, with the melatope at the centre.

Because the figure is off centred, the melatope (optic axis) does not appear in the field of view, on rotation the melatope swings in a circle around the center of the field of view.

Isogyres will retain their basic NS & EW orientations and sweep across the field of view centred on the melatope, always moving parallel to the crosshairs.

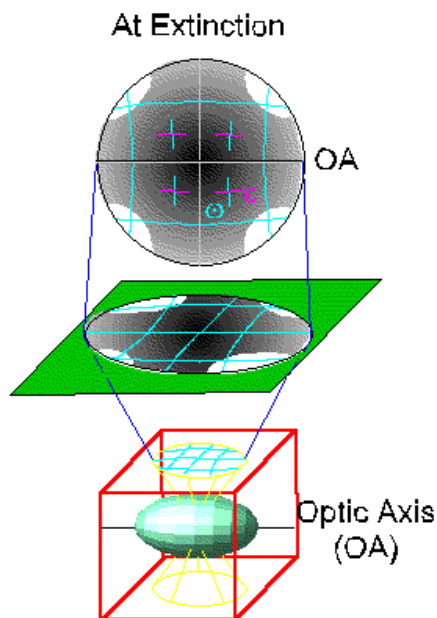
If the melatope is just in the field of view the optic sign can easily be determined, using the technique outlined above.

If the melatope is well outside the field of view the isogyres sweep across the field of view in sequence as the stage is rotated - with the isogyres always remaining parallel to the crosshairs.



By noting the direction and sequence of how the isogyres pass through the field of view, as the stage is rotated, it is possible to identify which quadrant is being viewed and therefore the optic sign may be determined, knowing the vibration directions of omega & epsilon, in the NE quadrant of the interference figure.

A grain which produces an off centred optic axis figure will exhibit a birefringence intermediate to the maximum and minimum birefringence for that mineral in the thin section.



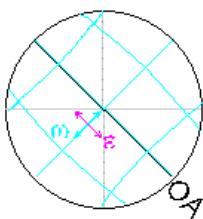
The mineral is oriented with the Optic Axis horizontal, in this case E-W. In this orientation the mineral exhibits its maximum birefringence and highest Interference colour. The resulting isogyre is a broad fuzzy

cross which nearly fills the field of view because the vibration directions in all but the outer parts of the four quadrants are essentially parallel to the vibration directions of the polars.

FLASH FIGURE :A mineral grain is oriented with its optic axis horizontal. This orientation exhibits the maximum birefringence, for this mineral in the thin section, and produces a flash figure.

The flash figure results because the vibration directions, of the indicatrix, within the field of view are nearly parallel to polarisation directions of the microscope.

45° Rotation



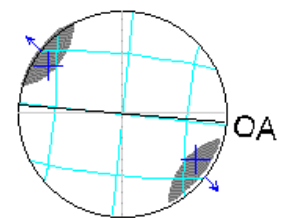
With a rotation of 45° the isogyres lie well outside the field of view and the OA is oriented NW-SE. If you rotate in the opposite direction the OA will lie NE-SW.

- extraordinary rays vibrate parallel to optic axis
- ordinary rays vibrate perpendicular to optic axis

With the grain at extinction the optic axis is oriented either EW or NS in the resulting interference figure. The interference figure produced occupies most if not all of the field of view and consists of a very broad, fuzzy isogyres cross.

Upon rotating the stage, < 5° rotation, the

< 5° Rotation



With a minor clockwise rotation, the isogyre cross splits and rapidly leaves the field of view in the quadrants into which the Optic Axis (OA) is being

isogyres will split and move out of the field of view in opposite quadrants.

The quadrants into which the isogyres move correspond to the quadrants into which the optic axis is moving, as the stage is being rotated.

With the optic axis in the 45° position, no isogyres will be present, and the field of view may exhibit some interference colours. Isochromes, if present, will be concave outward.

The colour in the centre of the field of view is the normal interference colour for that mineral under crossed polars.

In quadrants which contain the optic axis, the interference colours decrease away from the centre. In remaining two quadrants the interference colours increase away from centre.

The number of isochromes observed is dependant on the thickness of the thin section and the birefringence of the specific mineral.

If the central portion of the figure in the 45° position is white, the optic axis quadrants will be first order grey, other quadrants will be pale first order yellow.

Optic sign can be determined using flash figure, but it is not definitive.

Biaxial minerals will also produce a flash figure. It is better to look for a centred or off centred figure, either uniaxial or biaxial to determine the optic sign of the unknown mineral.

SUMMARY OF UNIAXIAL INTERFERENCE FIGURES

1. Optic axis Figure

The thin section is perpendicular to the c axis = optic axis.
The mineral appears isotropic, or nearly isotropic under crossed polars, exhibiting a very low first order grey to black interference colour.

2. Off centred Optic Axis Figure

The c axis (optic axis) is not vertical, but inclined from the vertical axis of the microscope. We will only see isogyre in the field of view at a time, which will sweep out of the field of view parallel to one crosshairs to be replaced by a new isogyre which sweeps into the field of view parallel to the other crosshair. This orientation will exhibit an intermediate colour, between the lowest and highest colour exhibited by this mineral in the thin section being examined.

3. Flash Figure

The c axis is parallel to stage.

The isogyres split and leave field of view rapidly with only a slight rotation, $<10^\circ$.

The maximum interference colour will be observed under crossed polars.

Sign determination

- + ve $n_{\omega} < n_{\epsilon}$
slow ray = epsilon, fast ray = omega
- - ve $n_{\omega} > n_{\epsilon}$
slow ray = omega, fast ray = epsilon.

Interpretation of Interference Figures

Type of Figure	Orientation	Interference Colour	Orientation of figure for sign determination	Accessory effect for a positive mineral	Vibration direction observed
Quartz	Quartz	Quartz	Quartz	Gypsum	Quartz
				Plate	Wedge
					+ve
					-ve

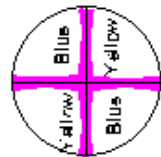
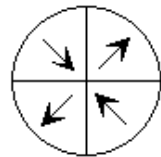
UNIAXIAL MINERALS

These are distinguished from biaxial minerals by the failure of the centre of the isogyre cross to break as the stage is rotated, or if the centre of the cross is not visible, by the isogyres remaining parallel to the crosshairs. This distinction does not apply to the flash figure.

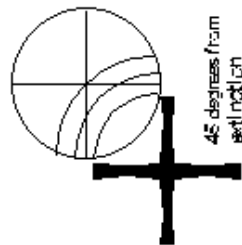
Centred Optic Axis
lenses form a
black cross which
does not split during
rotation of the stage



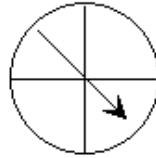
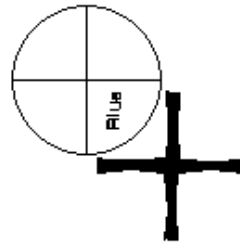
Black, very
low, 1st order

Only no vibration
direction observed in
area.

Off-Centred Optic Axis
Centres of cross displayed from centre of field. Vertical and horizontal isogyres alternately sweep across field, parallel to crosshairs.



Low to Moderate



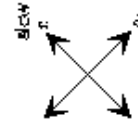
B.M.N.G. USE IN

Large diffuse black cross which breaks into hyperbolae that disappear from the field after 5-10 degrees rotation of stage into quadrants of field occupied by the optic axis.



Maximum colour for that drain

Optic axils
parallel to
microscope
stage



Not definitive to determine sign, however
Interference figure and accessory plate may
be used to determine whether a ray is fast
or slow.

4E degrees from
extinction

2020

:File - file nter.d94)

ACCESSORY PLATES

The accessory plates allow for the determination of the **FAST (low n)** and **SLOW (high n)** rays which exit from the mineral being examined.

The plates consist of pieces of quartz, gypsum or muscovite mounted in a holder so that the vibration directions of the mineral piece are parallel to the long and short axis of the holder.

Consider a mineral grain lying on the stage such that its vibration directions are in the 45° position.

The light passing through the mineral is split into two rays, with

the slow ray retarded behind the fast ray upon exiting the grain, retardation = Δ_1 .

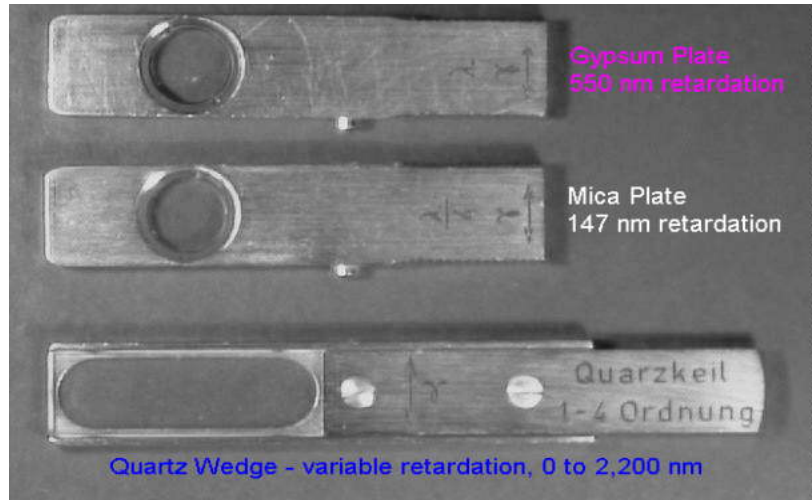
The accessory plate, gypsum plate, has a constant thickness and therefore a constant retardation, Δ_A .

If the accessory plate is superimposed over the mineral so that the slow ray vibration directions are parallel, then the ray that is the slow ray exiting the mineral is the slow ray in the accessory plate and it is further retarded.

The result is a higher total retardation

$$\Delta_1 + \Delta_A = \Delta_2$$

The two rays when they reach the upper polar result in a higher order of interference colour, the total retardation is higher and lies to the right of the original colour on the interference colour chart.



Rotating the mineral 90° results in the fast ray vibration direction of the mineral being parallel to the slow ray vibration direction of the accessory plate.

The ray which was the slow ray in the mineral becomes the fast ray in the accessory plate.

The result is that the accessory plate cancels some of the retardation produced by the mineral, the total retardation:

$$\square_1 - \square_A = \square_3$$

The interference colour produced at the upper polar is a lower order colour.

All accessory plates used are constructed such that the slow vibration direction is across the width of the plate, the fast vibrations direction is parallel to the length.

Accessory Plates are inserted into the microscope between the objective lens and the upper polar, in the 45° position.

1. *Gypsum Plate* (First Order Red Plate)

- o Become familiar with this plate, it produces ~550 nm of retardation. The interference colour in white light is a distinct magenta colour. This colour is found at the boundary between first and second order colours on Plate 1.



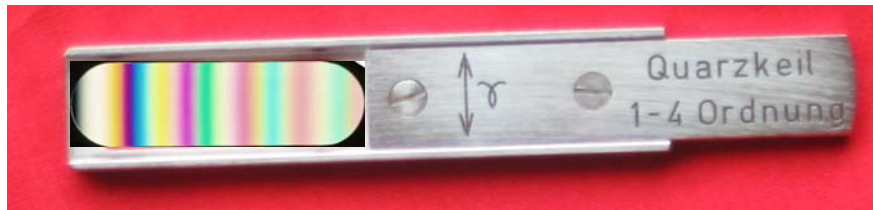
2. *Mica Plate*

- o Retardation of 147 nm, the interference colour is a first order white.



3. Quartz Wedge

- o Wedge shaped and produces a range of retardations.

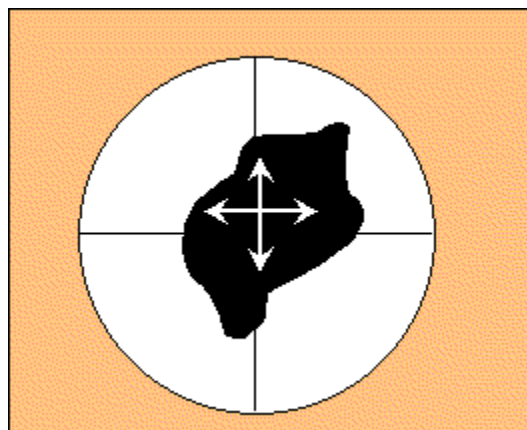


o

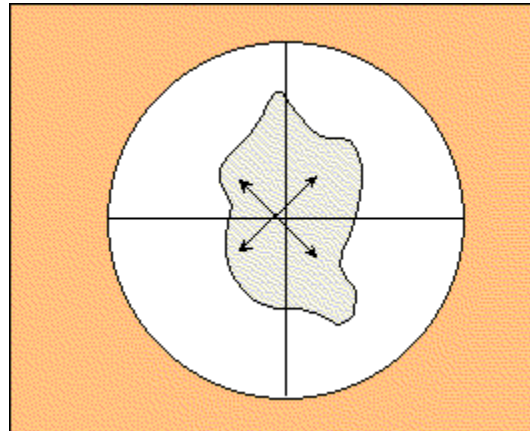
VIBRATION DIRECTIONS IN A MINERAL

To Determine the Vibration Direction in a Mineral.

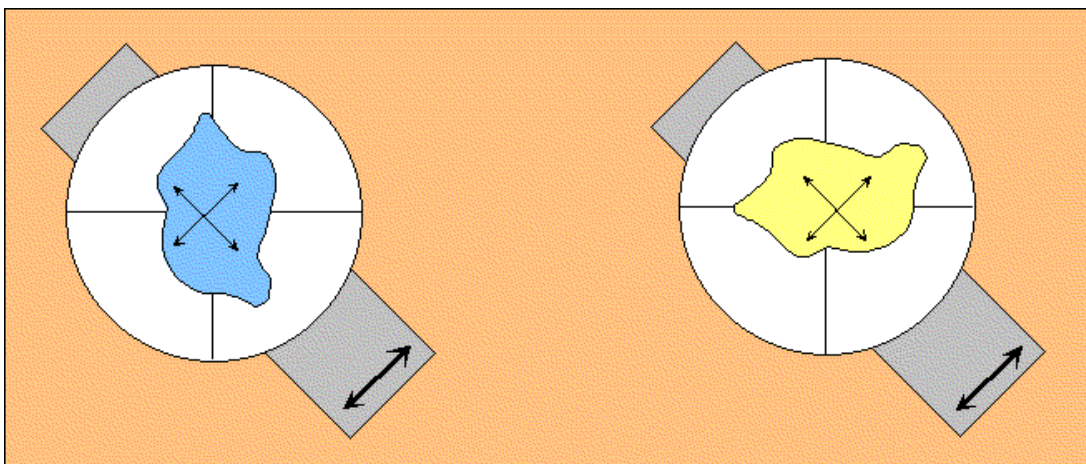
1. Rotate the grain on the stage to extinction. In this position the vibrations directions of the grain are parallel to the crosshairs of the microscope which are themselves parallel to the polarization directions of the microscope.



2. Rotate the stage 45° , clockwise. The vibration direction that was parallel to the NS crosshair is now aligned NE-SW. The grain should be brightly illuminated at this point. Note the interference colour exhibited by the grain and locate this colour on Plate 1 and record its retardation.



3. Insert the Gypsum Plate. The slow ray vibration direction of the plate is aligned NE-SW. Is the interference colour now exhibited by the grain higher or lower than the recorded in step 2, i.e. has the colour moved up (to the right) or down (to the left) by 550 nm.



4. If the colour increased, went up the chart, then the slow ray in the accessory plate is parallel to the slow ray in the mineral grain. If the colour decreased, went down the chart, then the slow ray of the accessory plate is parallel with the fast ray of the grain.

SIGN OF ELONGATION

In the mineral descriptions found in the text book the terms **LENGTH FAST** and **LENGTH SLOW** are encountered.

Length fast means that the fast ray of the mineral vibrates parallel with the length of the elongate mineral or parallel to the single cleavage, if present. This is also referred to as **NEGATIVE ELONGATION**, as the overall total retardation is less than that exhibited by the mineral prior to the accessory plate being inserted.

Length slow means that the slow ray of the mineral vibrates parallel with the length of the mineral or the single cleavage, if present - **POSITIVE ELONGATION**, the total overall retardation is greater than that exhibited prior to the accessory plate being inserted.

Only minerals which have an elongate habit exhibit a sign of elongation.

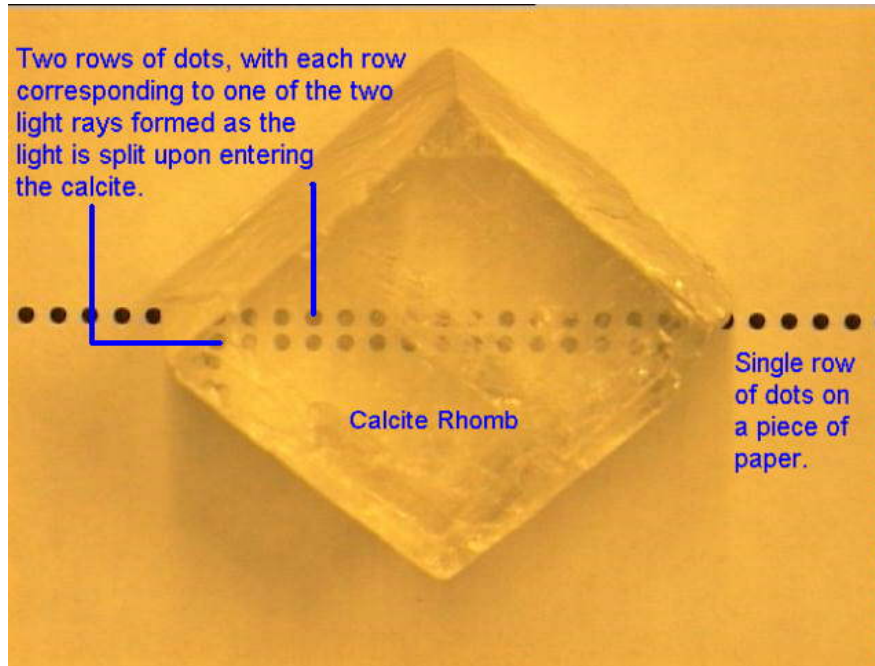
UNIAXIAL OPTICS

Uniaxial minerals have only one optic axis, and belong to the hexagonal and tetragonal systems.

Minerals in this group include:

- nepheline NaAlSiO_4
- apatite $\text{Ca}_5(\text{PO}_4)_3(\text{F}, \text{Cl}, \text{OH})$
- calcite CaCO_3
- dolomite $(\text{Ca}, \text{Mg})\text{CO}_3$
- quartz SiO_2
- zircon ZrSiO_4
- tourmaline - borosilicate

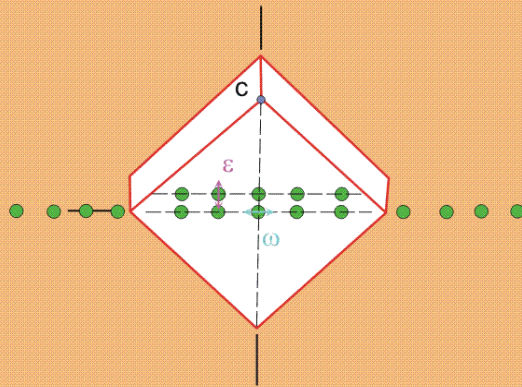
In the last lab you examined the calcite rhomb and the two rays formed by the light travelling through the rhomb, with each ray corresponding to a different RI of the calcite.



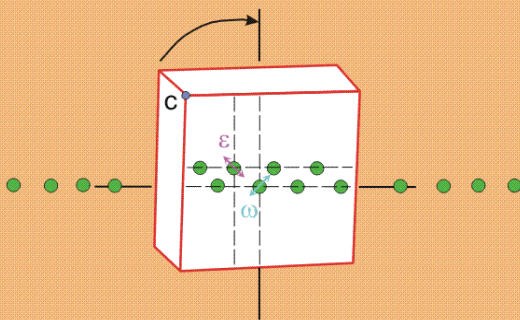
On rotating the calcite rhomb one dot remained stationary but the other dot rotated with the calcite about the stationary dot.

- The ray corresponding to the image which moved is called the Extraordinary Ray - epsilon.
- The ray corresponding to the stationary image, which behaves as though it were in an isotropic mineral is called the Ordinary Ray - omega.

Double Refraction - Calcite Why?



The two images produced by laying a piece of clear calcite on a single row of dots. The vibration directions for the two images are mutually perpendicular, one vibrates parallel to c , one vibrates perpendicular to c . We did this in the lab.



When the calcite is rotated one image of the dots stays stationary and one image of dots rotates with the calcite. The image which stays stationary corresponds to the ordinary ray (ω) which vibrates perpendicular to the c -axis.

The image which rotates with the calcite corresponds to the extraordinary ray (ϵ) and vibrates parallel to the c -axis.

(File = Calcite.ds4)

The vibration direction of the ordinary ray lies in the $\{0001\}$ plane of the calcite and is at right angles to the c -axis.

The extraordinary ray vibrates perpendicular to the ordinary ray vibration direction in the plane which contains the c -axis of the calcite.

If instead of using a calcite rhomb we had used a slab of calcite which had been cut in a random orientation and placed that on the dots, two images would still appear.

If the random cuts were such that they were perpendicular to the c-axis, then light travelling through the calcite, along the c-axis would produce only one image and would not become polarized.

The c-axis coincides with the optic axis, which is the direction through the mineral along which light propagates without being split into two rays.

For calcite,

1. The index of refraction for the ordinary ray is uniform $n_{\text{omega}} = 1.658$, regardless of the direction through the grain that the light follows.
2. The index of refraction for the extraordinary ray, n_{epsilon} , is variable ranging from 1.486 to 1.658. The index is dependant on the direction that the light travels through the mineral.
 - o If light travels perpendicular to c-axis, $n_{\text{epsilon}} = 1.486$.
 - o If the light travels along the the c-axis, $n_{\text{epsilon}} = 1.658$.
 - o For intermediate directions through the grain n_{epsilon} will fall between the two extremes.

Calcite is used as an example of the formation of the two rays because of the large difference between the refractive indices (birefringence (Δ)).

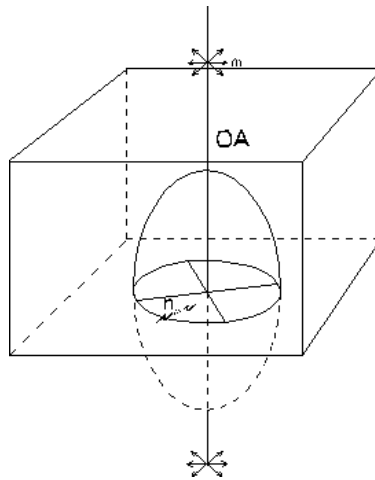
- for calcite, $\Delta = 0.172$.

For minerals with a lower birefringence, e.g. quartz, $\Delta = 0.009$, the two images are still produced but show very little separation. The quartz would have to be 20-25X as thick as the calcite to see the same separation of the dots.

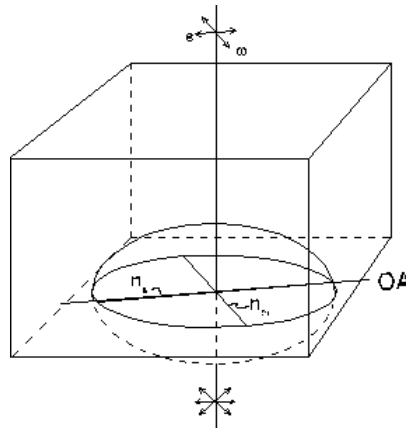
BIREFRINGENCE AND INTERFERENCE

COLOURS

Birefringence, difference between the index of refraction of the slow and fast rays and the interference colours for uniaxial minerals is dependant on the direction that light travels through the mineral.

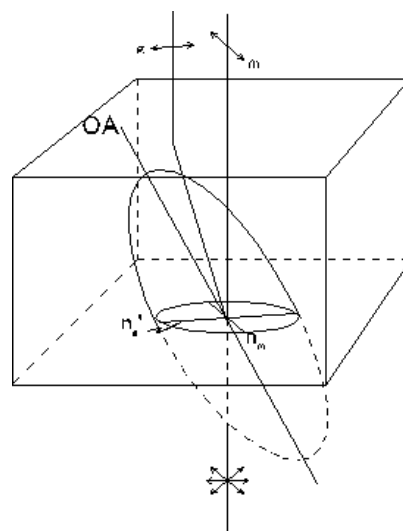


1. In a sample which has been cut perpendicular to the optic axis, the bottom and top surfaces will be parallel. The angle of incidence for the light entering the crystal = 0° and the wave front are not refracted at the interface and remain parallel to the mineral surface.
 - o A cut through the indicatrix, parallel to the bottom of the mineral, will yield the indices and vibration directions of the light. A slice through the indicatrix is a circular section, with radius n_{omega} .
 - o No preferred vibration direction, so light passes along the optic axis as an ordinary ray and retains whatever vibration direction it had originally.
 - o Between crossed polars the light passing through the mineral is completely absorbed by the upper polar and will remain black on rotation of the stage, The birefringence = 0.



2. Cutting the sample such that the optic axis is parallel to the surface of the section the following is observed.

- o The indicatrix section is a principle section, as it contains the optic axis. The indicatrix forms an ellipse with axes = n_{ω} and n_{ϵ} , with the incident light being split into two rays such that:
 - the ordinary ray vibrates perpendicular to the optic axis,
 - the extraordinary ray vibrates parallel to the optic axis.
- o The birefringence is at a maximum, and in thin section this grain orientation will display the highest interference colour.



3. A mineral cut in a random orientation, with normally incident light;

- o The ordinary ray produced has an index, n_{omega} and vibrates perpendicular to the optic axis.
- o The extraordinary ray has an index n_{epsilon}' and vibrates in the plane containing the optic axis.
- o $n_{\text{epsilon}}' < n_{\text{omega}}$ maximum or minimum, the birefringence is intermediate between the two extremes.

Examination of Minerals under Petrological Microscope:

- 1. Using Ordinary Light**
- 2. Under Polarized Light**
- 3. Under Crossed Nicols**
- 4. Using Convergent Light**

1. Using Ordinary Light

- a. Crystalline Form**
- b. Cleavage**
- c. Inclusions**
- d. Transparency**
- e. Colour**
- f. Refractive Index**

2. Under Polarized Light

- a. Pleochroism**
- b. Pleochroic Halos**
- c. Twinkling**

3. Under Crossed Nicols

- a. Isotropism and Anisotropism**
- b. Extinction and Polarization Colours**
- c. Twinning**
- d. Alteration**
- e. Elongation**

4. Using Convergent Light

- a. Interference Figures**
- b. Determination of the Optic Sign**

ROCK FORMING MINERALS

1. Silicates

- **Structures -Independent tetrahedral**
- **Single Chain**
- **Double Chain**
- **Sheet structure**
- **Framework silicates**

2. Non-silicates

a. Metallic, b. Non-metallic

- **Oxides**
- **Sulphides**
- **Sulphates**
- **Chlorides**
- **Carbonates**
- **Phosphates**
- **Halides**

Table 2–5 Common rock-forming silicate minerals

Silicate mineral	Composition	Physical properties
Quartz	Silicon dioxide (silica, SiO_2)	Hardness of 7 (on scale of 1 to 10); will not cleave (fractures unevenly); specific gravity: 2.65
Potassium feldspar group	Aluminosilicates of potassium	Hardness of 6.0–6.5; cleaves well in two directions; pink or white; specific gravity: 2.5–2.6
Plagioclase feldspar group	Aluminosilicates of sodium and calcium	Hardness of 6.0–6.5; cleaves well in two directions; white or gray; may show striations on cleavage planes; specific gravity: 2.6–2.7
Muscovite mica	Aluminosilicates of potassium with water	Hardness of 2–3; cleaves perfectly in one direction, yielding flexible thin plates; colorless; transparent in thin sheets; specific gravity: 2.8–3.0
Biotite mica	Aluminosilicates of magnesium, iron, potassium, with water	Hardness of 2.5–3.0; cleaves perfectly in one direction, yielding flexible thin plates; black to dark brown; specific gravity: 2.7–3.2
Pyroxene group	Silicates of aluminum, calcium, magnesium, and iron	Hardness of 5–6; cleaves in two directions at 90° ; black to dark green; specific gravity: 3.1–3.5
Amphibole group	Silicates of aluminum, calcium, magnesium, and iron	Hardness of 5–6; cleaves in two directions at 56° and 124° ; black to dark green; specific gravity: 3.0–3.3
Olivine	Silicate of magnesium and iron	Hardness of 6.5–7.0; light green; transparent to translucent; specific gravity: 3.2–3.6
Garnet group	Aluminosilicates of iron, calcium, magnesium, and manganese	Hardness of 6.5–7.5; uneven fracture, red, brown, or yellow; specific gravity: 3.5–4.3

METALLIC MINERALS			
Step 1: What is the mineral's hardness?	Step 2: What is the mineral's streak?	Step 3: Compare the mineral's physical properties to other characteristic properties below.	Step 4: Find mineral name(s) and check the mineral database for additional properties (Figure 2.25)
HARD ($H > 5.5$) Scratches glass Not scratched by masonry nail or knife blade	Dark gray	Color brass yellow; Tarnishes brown	Pyrite
		Color dark gray to black; Tarnishes gray; Attracted to a magnet and may also be magnetized	Magnetite
	Brown	Color silvery black to black; Tarnishes gray to black	Chromite
	Red to red-brown	Color silvery gray, black, or brick red; Tarnishes red	Hematite
	Dark gray	Color brass yellow; Tarnishes dark brown or purple	Chalcopyrite
		Color iridescent blue, purple, or copper-red; Tarnishes dark purple	Bornite
		Color silvery gray; Tarnishes dull gray; Cleavage good to excellent	Galena
		Color dark gray to black; Can be scratched with your fingernail	Graphite
	Yellow-brown	Color yellow-brown to dark brown, (rusted iron); Tarnishes yellow to brown; Amorphous	Limonite
		Color dark brown to black; Forms layers of radiating microscopic crystals	Goethite
	White to pale yellow-brown	Color brown to yellow-brown or dark red; Tarnishes brown; May appear nonmetallic or metallic; Cleavage excellent to good	Sphalerite
	Copper	Color copper; Tarnishes dark brown or green; Malleable	Copper (Native Copper)
SOFT ($H \leq 5.5$) Does not scratch glass Scratched by masonry nail or knife blade			

FIGURE 2.22 Flowchart for identification of minerals having a metallic luster.

LIGHT-COLORED NONMETALLIC MINERALS			
Step 1: What is the mineral's hardness?	Step 2: What is the mineral's cleavage?	Step 3: Compare the mineral's physical properties to other distinctive properties below.	Step 4: Find mineral name(s) and check the mineral database for additional properties (Figure 2.25).
HARD (H > 5.5) Scratches glass Not scratched by masonry nail or knife blade	Cleavage excellent or good	White or gray; 2 cleavages at nearly right angles and with striations; H 6	Plagioclase feldspar
		Orange, brown, white, gray, green, or pink; H 6; 2 cleavages at nearly right angles; exsolution lamellae	Potassium feldspar
		Pale brown, white, or gray; Long slender prisms; 1 excellent cleavage plus fracture surfaces; H 6–7	Sillimanite
		Blue, very pale green, white, or gray; Crystals are blades; H 4–7	Kyanite
	Cleavage poor or absent	Colorless, white, gray, or other colors; Greasy luster; Massive or hexagonal prisms and pyramids; Transparent or translucent; H 7	Quartz Milky Quartz (white var.), Citrine Quartz (yellow var.), Rose Quartz (pink var.)
		Opaque gray or white; Luster waxy; H 7	Chert (variety of quartz)
		Colorless, white, yellow, light brown, or pastel colors; Translucent or opaque; Laminated or massive; Cryptocrystalline; Luster waxy; H 7	Chalcedony (variety of quartz)
		Pale olive green to yellow; Conchoidal fracture; Transparent or translucent; Forms short stout prisms; H 7	Olivine
SOFT (H ≤ 5.5) Does not scratch glass Scratched by masonry nail or knife blade	Cleavage excellent or good	Colorless, white, yellow, green, pink, or brown; 3 excellent cleavages; Breaks into rhombohedrons; Effervesces in dilute HCl; H 3	Calcite
		Colorless, white, gray, creme, or pink; 3 excellent cleavages; Breaks into rhombohedrons; Effervesces in dilute HCl only if powdered; H 3.5–4	Dolomite
		Colorless or white with tints of brown, yellow, blue, black; Short tabular crystals and roses; Very heavy; H 3–3.5	Barite
		Colorless, white, or gray; Massive or tabular crystals, blades, or needles; Can be scratched with your fingernail; H 2	Gypsum
		Colorless, white, gray, or pale green, yellow, or red; Spheres of radiating needles; Luster silky; H 5–5.5	Natrolite
		Colorless, white, yellow, blue, brown, or red; Cubic crystals; Breaks into cubes; Salty taste; H 2.5	Halite
		Colorless, purple, blue, gray, green, yellow; Cubes with octahedral cleavage; H 4	Fluorite
		Colorless, yellow, brown, or red-brown; Short opaque prisms; Splits along 1 excellent cleavage into thin flexible transparent sheets; H 2–2.5	Muscovite mica
	Cleavage poor or absent	Yellow crystals or earthy masses; Luster greasy; H 1.5–2.5	Sulfur
		Opaque pale blue to blue-green; Amorphous crusts or massive; Very light blue streak; H 2–4	Chrysocolla
		Opaque green, yellow, or gray; Dull or silky masses or asbestos; White streak; H 2–5	Serpentine
		Opaque white, gray, green, or brown; Can be scratched with fingernail; Greasy or soapy feel; H 1	Talc
		Opaque earthy white to very light brown; H 1–2	Kaolinite
		Colorless to white, orange, yellow, brown, blue, gray, green, or red; May have play of colors; Conchoidal fracture; H 5–5.5	Opal
		Colorless or pale green, brown, blue, white, or purple; Brittle hexagonal prisms; Conchoidal fracture; H 5	Apatite

FIGURE 2.23 Flowchart for identification of light-colored minerals with nonmetallic luster.

DARK-COLORED NONMETALLIC MINERALS			
Step 1: What is the mineral's hardness?	Step 2: What is the mineral's cleavage?	Step 3: Compare the mineral's physical properties to other distinctive properties below.	Step 4: Find mineral name(s) and check the mineral database for additional properties (Figure 2.25).
HARD (H > 5.5) Scratches glass Not scratched by masonry nail or knife blade	Cleavage excellent or good	Translucent dark gray, blue-gray, or black; may have silvery iridescence; 2 cleavages at nearly 90° and with striations; H 6	Plagioclase feldspar
		Translucent brown, gray, green, or red; 2 cleavages at nearly right angles; exsolution lamellae; H 6	Potassium feldspar
		Opaque dark green in long prisms or needles; 2 cleavages at about 60° and 120°; H 5.5	Actinolite (Amphibole)
		Opaque black; 2 cleavages at about 60° and 120°; H 5.5	Hornblende (Amphibole)
		Opaque black; 2 cleavages at nearly 90°; H 5.5–6	Augite (Pyroxene)
	Cleavage poor or absent	Transparent or translucent gray, brown, or purple; Greasy luster; Massive or hexagonal prisms and pyramids; H 7	Quartz Smoky Quartz (black/brown var.), Amethyst (purple var.)
		Transparent, translucent, or opaque red-gray, or gray; Short hexagonal prisms with striated flat ends; H 9	Corundum
		Opaque red-brown or brown; Luster waxy; Cryptocrystalline; H 7	Jasper (variety of quartz)
		Transparent to translucent dark red to black; H 7	Garnet
		Opaque gray; Luster waxy; Cryptocrystalline; H 7	Chert (variety of quartz)
		Opaque black; Luster waxy; Cryptocrystalline; H 7	Flint (variety of quartz)
		Black or dark green; Long striated prisms; H 7–7.5	Tourmaline
		Transparent or translucent olive green; Conchoidal fracture; Transparent or translucent, H 7	Olivine
		Opaque green; Poor cleavage; H 6–7	Epidote
		Opaque brown prisms that interpenetrate to form crosses; H 7	Staurolite
	Cleavage excellent or good	Translucent to opaque yellow-brown to brown; may appear submetallic; Octahedral cleavage; H 3.5–4	Sphalerite
		Purple cubes or octahedrons with octahedral cleavage; H 4	Fluorite
		Black short opaque prisms; Splits easily along 1 excellent cleavage into thin sheets; H 2.5–3	Biotite mica
		Green short opaque prisms; Splits easily along 1 excellent cleavage into thin sheets; H 2–3	Chlorite
	Cleavage poor or absent	Opaque rusty brown or yellow-brown; Massive and amorphous; Yellow-brown streak; H 1.5–5.5	Limonite
		Opaque rusty brown to brown-gray rock with shades of gray, yellow, and white; Contains pea-sized spheres that are laminated internally; Pale brown streak; H 1–3	Bauxite
		Deep blue; Crusts, small crystals, or massive; Light blue streak; H 3.5–4	Azurite
		Opaque green or gray-green; Dull or silky masses or asbestos; White streak; H 2–5	Serpentine
		Opaque green in laminated crusts or massive; Streak pale green; Effervesces in dilute HCl; H 3.5–4	Malachite
		Translucent or opaque dark green; Can be scratched with your fingernail; Feels greasy or soapy; H 1	Talc
		Opaque earthy red; red to red-brown streak; H 1.5–6	Hematite
SOFT (H ≤ 5.5) Does not scratch glass Scratched by masonry nail or knife blade	Cleavage poor or absent	Transparent or translucent green, brown, blue, or purple; Brittle hexagonal prisms; Conchoidal fracture; H 5	Apatite

FIGURE 2.24 Flowchart for identification of dark-colored minerals with nonmetallic luster.

MINERAL DATABASE (Alphabetical Listing)					
Mineral	Luster	Hardness	Streak	Distinctive Properties	Some Uses
ACTINOLITE (amphibole)	Nonmetallic (NM)	5.5–6	White	Color dark green or pale green; Forms needles, prisms, and asbestose fibers; Good cleavage at 56° and 124°; SG = 3.1	Gemstone (Nephrite), Asbestose products
AMPHIBOLE: See HORNEBLEND and ACTINOLITE					
APATITE $\text{Ca}_5\text{F}(\text{PO}_4)_3$ calcium fluorophosphate	Nonmetallic (NM)	5	White	Color pale or dark green, brown, blue, white, or purple; Sometimes colorless; Transparent or opaque; Brittle; Conchoidal fracture; Forms hexagonal prisms; SG = 3.1–3.4	Used for pesticides and fertilizers
ASBESTOSE: fibrous varieties of AMPHIBOLE and SERPENTINE					
AUGITE (pyroxene) calcium ferromagnesian silicate	Nonmetallic (NM)	5.5–6	White to pale gray	Color green to black; Forms opaque, short, 8-sided prisms; Two good cleavages that intersect at 87° and 93° (nearly right angles); SG = 3.2–3.5	Some pyroxene mined as an ore of lithium, for making steel
AZURITE $\text{Cu}_3(\text{CO}_3)_2(\text{OH})_2$ hydrous copper carbonate	Nonmetallic (NM)	3.5–4	Light blue	Color a distinctive deep blue; Forms crusts of small crystals, opaque earthy masses, or short and long prisms; Brittle; Effervesces in dilute HCl; SG = 3.7–3.8	Ore of copper for pipes, electrical circuits, coins, ammunition, gemstone
BARITE BaSO_4 barium sulfate	Nonmetallic (NM)	3–3.5	White	Colorless to white, with tints of brown, yellow, blue, or red; Forms short tabular crystals and rose-shaped masses (Barite roses); Brittle; Cleavage good to excellent; Very heavy, SG = 4.5	Used in rubber, paint, glass, oil-well drilling fluids
BAUXITE Mixture of aluminum hydroxides	Nonmetallic (NM)	1–3	White	Brown earthy rock with shades of gray, white, and yellow; Amorphous; Often contains rounded pea-sized structures with laminations; SG = 2.3	Ore of Aluminum
BIOTITE MICA ferromagnesian potassium, hydrous aluminum silicate	Nonmetallic (NM)	2.5–3	Gray-brown	Color black, green-black, or brown-black; Cleavage excellent; Forms very short prisms that split easily into very thin, flexible sheets; SG = 2.7–3.1	Used for fire-resistant tiles, rubber, paint
BORNITE Cu_5FeS_4 copper-iron sulfide	Metallic (M)	3	Dark gray to black	Color opaque silvery blue or copper-red; Tarnishes to iridescent purple and blue; Forms dense, brittle masses; Cleavage poor to absent	Ore of copper for pipes, electrical circuits, coins, ammunition, brass, bronze
CALCITE CaCO_3 calcium carbonate	Nonmetallic (NM)	3	White	Usually colorless, white, or yellow, but may be green, brown, or pink; Opaque or transparent; Excellent cleavage in 3 directions not at 90°; Forms prisms, rhombohedrons, or scalenohedrons that break into rhombohedrons; Effervesces in dilute HCl; SG = 2.7	Used to make antacid tablets, fertilizer, cement; Ore of calcium
CHALCEDONY SiO_2 cryptocrystalline quartz	Nonmetallic (NM)	7	White	Colorless, white, yellow, light brown, or other pastel colors in laminations; Often translucent; Conchoidal fracture; Luster waxy; Cryptocrystalline; SG = 2.5–2.8	Used as an abrasive; Used to make glass, gemstones (agate, chrysoprase)

FIGURE 2.25 Mineral Database—alphabetical list of minerals and their properties and uses.

MINERAL DATABASE (Alphabetical Listing)					
Mineral	Luster	Hardness	Streak	Distinctive Properties	Some Uses
CHALCOPYRITE CuFeS_2 copper-iron sulfide	Metallic (M)	3.5–4	Dark gray	Color golden or brassy yellow; Tarnishes brown, or iridescent blue, green, and red; Forms elongate tetrahedra; Brittle; Cleavage poor; SG = 4.1–4.3	Ore of copper for pipes, electrical circuits, coins, ammunition, brass, bronze
CHERT SiO_2 cryptocrystalline quartz	Nonmetallic (NM)	7	White	Opaque gray or white; Luster waxy; Conchoidal fracture; SG = 2.5–2.8	Used as an abrasive; Used to make glass, gemstones
CHLORITE ferromagnesian aluminum silicate	Nonmetallic (NM)	2–2.5	White	Color dark green; Cleavage excellent; Forms short prisms that split easily into thin flexible sheets; Luster shiny or dull; SG = 2–3	Used for fire-resistant tiles, rubber, paint, art sculpture medium
CHROMITE FeCr_2O_4 iron-chromium oxide	Metallic (M)	5.5–6	Dark brown	Color silvery black to black; Tarnishes gray; Forms octahedrons; Brittle; No cleavage; May be weakly magnetic; SG = 4.6–4.8	Ore of chromium for making chrome, stainless steel, mirrors, paint and used in leather tanning
CHRYSOCOLLA $\text{CuSiO}_3 \cdot 2\text{H}_2\text{O}$ hydrated copper silicate	Nonmetallic (NM)	2–4	Very light blue	Color pale blue to blue-green; Opaque; Forms amorphous crusts or may be massive; Conchoidal fracture; Luster shiny or earthy; SG = 2.0–2.4	Ore of copper for pipes, electrical circuits, coins, ammunition; gemstone
COPPER (NATIVE COPPER) Cu copper	Metallic (M)	2.5–3	Copper	Color copper; Tarnishes brown or green; Forms distorted cubes octahedrons, and dendritic (root-like) masses; Malleable; Opaque; Cleavage absent; SG = 8.8–8.9	Ore of copper for pipes, electrical circuits, coins, ammunition, brass, bronze
CORUNDUM Al_2O_3 aluminum oxide	Nonmetallic (NM)	9	White	Color gray, blue, red, brown; Transparent or opaque; Forms short hexagonal prisms with striated flat ends; Cleavage absent; SG = 3.9–4.1	Used for abrasive powders to polish lenses; gemstones (red ruby, blue sapphire)
DOLOMITE $\text{CaMg}(\text{CO}_3)_2$ magnesian calcium carbonate	Nonmetallic (NM)	3.5–4	White	Color white, gray, creme, or pink; Usually opaque; Cleavage excellent in 3 directions; Breaks into rhombohedrons; Resembles calcite, but will effervesce in dilute HCl only if powdered; SG = 2.8–2.9	Ore of magnesium metal; soft abrasive; used to make paper
EPIDOTE complex silicate	Nonmetallic (NM)	6–7	White	Color pale or dark green to yellow-green; Massive or forms striated prisms; Cleavage poor, SG = 3.3–3.5	Gemstone
FELDSPAR: See PLAGIOCLASE (Na-Ca Feldspars) and POTASSIUM FELDSPAR (K-Spar)					
FLINT SiO_2 cryptocrystalline quartz	Nonmetallic (NM)	7	White	Color black to very dark gray; Opaque to translucent; Conchoidal fracture; Cryptocrystalline; SG = 2.5–2.8	Used as an abrasive; Used to make glass, gemstones
FLUORITE CaF_2 calcium fluoride	Nonmetallic (NM)	4	White	Colorless, purple, blue, gray, green, or yellow; Cleavage excellent; Crystals usually cubes; Transparent or opaque; Brittle; SG = 3.0–3.3	Source of fluorine for processing aluminum; flux in steel making

FIGURE 2.25 (Continued) Mineral Database—alphabetical list of minerals and their properties and uses.

MINERAL DATABASE (Alphabetical Listing)					
Mineral	Luster	Hardness	Streak	Distinctive Properties	Some Uses
GALENA PbS lead sulfide	Metallic (M)	2.5	Gray to dark gray	Color silvery gray; Tarnishes dull gray; Forms cubes and octahedrons; Brittle; Cleavage good in three directions, so breaks into cubes; SG = 7.6	Ore of lead for TV glass, auto batteries, solder, ammunition, paint
GARNET complex silicate	Nonmetallic (NM)	7	White	Color usually red, black, or brown; sometimes yellow, green, pink; Forms dodecahedrons; Cleavage absent; Brittle; Translucent to opaque; SG = 3.5–4.3	Used as an abrasive; gemstone
GOETHITE FeO (OH) hydrous iron oxide	Metallic (M)	5–5.5	Yellow-brown	Color dark brown to black; Tarnishes yellow-brown; Forms layers of radiating microscopic crystals; SG = 4.3	Ore of iron for steel, brass, bronze, tools, vehicles, nails and bolts, bridges, etc.
GRAPHITE C carbon	Metallic (M)	1	Dark gray	Color silvery gray to black; Forms flakes, short hexagonal prisms, and earthy masses; Greasy feel; Very soft, Cleavage excellent in 1 direction; SG = 2.1–2.3	Used as a lubricant (as in graphite oil), pencil leads, fishing rods
GYPSUM CaSO ₄ · 2H ₂ O calcium sulfate	Nonmetallic (NM)	2	White	Colorless, white, or gray; Forms tabular crystals, prisms, blades, or needles (satin spar variety); Transparent to translucent; Very soft; Cleavage good; SG = 2.3	Plaster-of-paris, wallboard, drywall, art sculpture medium (alabaster)
HALITE NaCl sodium chloride	Nonmetallic (NM)	2.5	White	Colorless, white, yellow, blue, brown or red; Transparent to translucent; Brittle; Forms cubes; Cleavage excellent in 3 directions, so breaks into cubes; Salty taste; SG = 2.1–2.6	Table salt, road salt; Used in water softeners and as a preservative; Sodium ore
HEMATITE Fe ₂ O ₃ iron oxide	Metallic (M) or Nonmetallic (NM)	1.5–6	Red to red-brown	Color silvery gray, black, or brick red; Tarnishes red; Opaque; Soft (earthy) and hard (metallic) varieties have same streak; Forms thin tabular crystals or massive; SG = 2.1–2.6	Red pigment; Ore of iron for steel tools, vehicles, nails and bolts, bridges, etc.
HORNBLende (amphibole) calcium ferromagnesian aluminum silicate	Nonmetallic (NM)	5.5	Gray-green or white	Color dark green to black; Opaque; Forms prisms with good cleavage at 60° and 120°; Brittle; Splintery or asbestos forms; SG = 3.0–3.3	Fibrous varieties used for fire-resistant clothing, tiles, brake linings
JASPER SiO ₂ cryptocrystalline quartz	Nonmetallic (NM)	7	White	Color red-brown, or yellow; Opaque; Waxy luster; Conchoidal fracture; Cryptocrystalline; SG = 2.5–2.8	Used as an abrasive; Used to make glass, gemstones
KAOLINITE Al ₂ (Si ₄ O ₁₀)(OH) ₂ hydrous aluminum silicate	Nonmetallic (NM)	1–2	White	Color white to very light brown; Commonly forms earthy, microcrystalline masses; Cleavage excellent but absent in hand samples; SG = 2.6	Used for pottery, clays, polishing compounds, pencil leads, paper
K-SPAR: See POTASSIUM FELSPAR					
KYANITE Al ₂ (SiO ₄)O aluminum silicate	Nonmetallic (NM)	4–7	White	Color blue, pale green, white, or gray; Translucent to transparent; Forms blades; SG = 3.6–3.7	High temperature ceramics, spark plugs

FIGURE 2.25 (Continued) Mineral Database—alphabetical list of minerals and their properties and uses.

MINERAL DATABASE (Alphabetical Listing)					
Mineral	Luster	Hardness	Streak	Distinctive Properties	Some Uses
LIMONITE $\text{Fe}_2\text{O}_3 \cdot n\text{H}_2\text{O}$ hydrous iron oxide	Metallic (M) or Nonmetallic (NM)	1.5–5.5	Yellow-brown	Color yellow brown to dark brown; Tarnishes yellow to brown; Amorphous masses; Luster dull or earthy; Hard or soft; SG = 3.6–4.0	Yellow pigment; Ore of iron for steel tools, vehicles, nails and bolts, bridges, etc.
MAGNETITE Fe_3O_4 iron oxide	Metallic (M)	6	Dark gray	Color silvery gray to black; Opaque; Forms octahedrons; Tarnishes gray; No cleavage; Attracted to a magnet and can be magnetized; SG = 5.2	Ore of iron for steel, brass, bronze, tools, vehicles, nails and bolts, bridges, etc.
MALACHITE $\text{Cu}_2\text{CO}_3(\text{OH})_2$ hydrous copper carbonate	Nonmetallic (NM)	3.5–4	Green	Color green, pale green, or gray green; Usually in crusts, laminated masses, or microcrystals; Effervesces in dilute HCl; SG = 3.9–4.0	Ore of copper for pipes, electrical circuits, coins, ammunition; gemstone
MICA: See BIOTITE and MUSCOVITE.					
NATIVE COPPER: See COPPER.					
NATIVE SULFUR: See SULFUR.					
NATROLITE (ZEOLITE) $\text{Na}_2(\text{Al}_2\text{Si}_3\text{O}_{10}) \cdot 2\text{H}_2\text{O}$ hydrous sodium aluminum silicate	Nonmetallic (NM)	5–5.5	White	Colorless, white, gray, or pale green, yellow, or red; Forms masses of radiating needles; Silky luster; SG = 2.2–2.4	Water softeners
MUSCOVITE MICA potassium hydrous aluminum silicate	Nonmetallic (NM)	2–2.5	White	Colorless, yellow, brown, or red-brown; Forms short opaque prisms; Cleavage excellent in 1 direction, can be split into thin flexible transparent sheets; SG = 2.7–3.0	Computer chip substrates, electrical insulation, roof shingles, facial makeup
OLIVINE $(\text{Fe}, \text{Mg})_2\text{SiO}_4$ ferromagnesian silicate	Nonmetallic (NM)	7	White	Color pale or dark olive-green to yellow, or brown; Forms short flat prisms; Conchoidal fracture; Cleavage absent; Brittle; SG = 3.3–3.4	Gemstone (peridot); Ore of magnesium metal
OPAL $\text{SiO}_2 \cdot n\text{H}_2\text{O}$ hydrated silicon dioxide	Nonmetallic (NM)	5–5.5	White	Colorless to white, orange, yellow, brown, blue, gray, green, or red; may have play of colors (opalescence); Amorphous; Cleavage absent; Conchoidal fracture; SG = 1.9–2.3	Gemstone
PLAGIOCLASE FELDSPAR $\text{NaAlSi}_3\text{O}_8$ to $\text{CaAl}_2\text{Si}_2\text{O}_8$ calcium-sodium aluminum silicate	Nonmetallic (NM)	6	White	Colorless, white, gray, or black; may have iridescent play of color from within; Translucent; Forms striated tabular crystals or blades; Cleavage good in two directions at nearly 90°; SG = 2.6–2.8	Used to make ceramics, glass, enamel, soap, false teeth, scouring powders
POTASSIUM FELDSPAR KAlSi_3O_8 potassium aluminum silicate	Nonmetallic (NM)	6	White	Color orange, brown, white, green, or pink; Forms translucent prisms with subparallel exsolution lamellae; Cleavage excellent in two directions at nearly 90°; SG = 2.5–2.6	Used to make ceramics, glass, enamel, soap, false teeth, scouring powders
PYRITE ("fool's gold") FeS_2 iron sulfide	Metallic (M)	6–6.5	Dark gray	Color brass yellow; Opaque; Tarnishes brown; Forms cubes or octahedrons; Brittle; No cleavage; SG = 5.0	Ore of sulfur, for sulfuric acid, explosives, fertilizers, pulp processing, insecticides

FIGURE 2.25 (Continued) Mineral Database—alphabetical list of minerals and their properties and uses.

MINERAL DATABASE (Alphabetical Listing)					
Mineral	Luster	Hardness	Streak	Distinctive Properties	Some Uses
PYROXENE: See AUGITE.					
QUARTZ SiO_2 silicon dioxide	Nonmetallic (NM)	7	White	Usually colorless, white, or gray but uncommon varieties occur in all colors; Transparent to translucent; Luster greasy; No cleavage; Forms hexagonal prism and pyramids; SG = 2.7	Used as an abrasive; Used to make glass, gemstones
SERPENTINE $\text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4$ hydrous magnesian silicate	Nonmetallic (NM)	2–5	White	Color pale or dark green, yellow, gray; Forms dull or silky masses and asbestos forms; No cleavage; SG = 2.2–2.6	Fibrous varieties used for fire-resistant clothing, tiles, brake linings
SILLIMANITE $\text{Al}_2(\text{SiO}_4)\text{O}$ aluminum silicate	Nonmetallic (NM)	6–7	White	Color pale brown, white, or gray; One good cleavage plus fracture surfaces; Forms slender prisms; SG = 3.2	High-temperature ceramics
SPHALERITE ZnS zinc sulfide	Metallic (M) or Nonmetallic (NM)	3.5–4	White to pale yellow-brown	Color usually yellow-brown to brown or black; Luster submetallic to non-metallic; Forms misshapen tetrahedrons or dodecahedrons; Cleavage excellent; SG = 3.9–4.0	Ore of zinc for die-cast automobile parts, brass, galvanizing, batteries
STAUROLITE iron magnesium zinc aluminum silicate	Nonmetallic (NM)	7	White to gray	Color brown to gray-brown; Tarnishes dull brown; Forms prisms that interpenetrate to form natural crosses; Cleavage poor; SG = 3.7–3.8	Gemstone crosses called “fairy crosses”
SULFUR (NATIVE SULFUR) S sulfur	Nonmetallic (NM)	1.5–2.5	Pale yellow	Color bright yellow; Forms transparent to translucent crystals or earthy masses; Cleavage poor; Luster greasy to earthy; Brittle; SG = 2.1	Used for drugs, sulfuric acid, explosives, fertilizers, pulp processing, insecticides
TALC $\text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_2$ hydrous magnesian silicate	Nonmetallic (NM)	1	White	Color white, gray, pale green, or brown; Forms cryptocrystalline masses that show no cleavage; Luster silky to greasy; Feels greasy or soapy (talcum powder); Very soft; SG = 2.7–2.8	Used for talcum powder, facial makeup, ceramics, paint, sculptures
TOURMALINE complex silicate	Nonmetallic (NM)	7–7.5	White	Color usually opaque black or green, but may be transparent or translucent green, red, yellow, pink or blue; Forms long striated prisms with triangular cross sections; Cleavage absent; SG = 3.0–3.2	Crystals used in radio transmitters; gemstone
ZEOLITE: A group of calcium or sodium hydrous aluminum silicates. See NATROLITE.					

FIGURE 2.25 (Continued) Mineral Database—alphabetical list of minerals and their properties and uses

METAMORPHIC ROCK ANALYSIS AND CLASSIFICATION								
STEP 1: What are the rock's textural features?			STEP 2: What are the rock's mineralogical composition and/or other distinctive features?		STEP 3: Metamorphic rock name	STEP 4: What was the parent rock?	STEP 5: What is the rock used for?	
FOLIATED	Fine grained	Slaty rock cleavage is better developed than foliation	Dull luster; breaks into hard flat sheets along the slaty rock cleavage (Figures 6.4, 6.5)		SLATE ¹	INCREASING METAMORPHIC GRADE ↓	Mudstone or shale	Roofing slate, table tops, floor tile, decorative stone
		Wavy foliation well developed more than rock cleavage	Breaks along wrinkled or wavy foliation surfaces that appear silky or glossy (Figure 6.6)		PHYLLITE ¹		Slate	Construction stone, decorative stone, sources of gemstones like rubies
	Medium to coarse grained	Schistosity: foliation formed by alignment of visible crystals; rock breaks along scaly foliation surfaces; crystalline texture	Visible crystals of platy minerals (chlorite, muscovite, biotite), bladed crystals (kyanite), or prismatic crystals (amphiboles, tourmaline, sillimanite); breaks along scaly foliated surfaces (Figure 6.7)		SCHIST ¹ Chlorite schist Muscovite schist Biotite schist Kyanite schist Amphibole schist Tourmaline schist Sillimanite schist		Phyllite	
		Gneissic banding: minerals segregated into alternating layers gives the rock a banded texture in side view; crystalline texture	Visible crystals of two or more minerals in distinct layers and bands (Figure 6.8)		GNEISS ¹		Schist	
			Gneissic texture in which some of the layers/bands are igneous rock (usually granite)		MIGMATITE		Gneiss	
			NONFOLIATED	Fine grained	Smooth texture; rock cleavage may be barely visible		Black glossy rock that breaks along uneven or conchoidal fractures (Figure 6.13)	
Smooth or sugary microcrystalline texture	Dull luster, usually dark-colored (Figure 6.12)				HORNFELS	Any rock type	Decorative stone	
Massive; may have smooth rock cleavage surfaces or asbestose form	Serpentine; dull or glossy; color usually shades of green				SERPENTINITE	Basalt, Gabbro, or Ultramafic igneous rocks		
Massive	Talc; can be scratched with your fingernail; shades of green, gray, brown, white				SOAPSTONE	Serpentinite		Art carvings, electrical insulators, talcum powder
Fine to coarse grained	Sandy texture or crystalline texture	Quartz sand grains fused together; grains will not rub off like sandstone		QUARTZITE ¹	Sandstone	Construction stone, decorative stone		
		Calcite or dolomite crystals fused together		MARBLE ¹	Limestone	Art carvings, construction stone, decorative stone, source of lime for agriculture		
	Conglomeratic	Pebbles stretched or cut by rock cleavage		META-CONGLOMERATE	Conglomerate	Construction stone, decorative stone		

¹Modify rock name by adding names of minerals in order of increasing abundance. For example, garnet muscovite schist is a muscovite schist with a small amount of garnet.

²May be porphyroblastic. Add name of mineral porphyroblasts to front of rock name as in Figures 6.11.

FIGURE 6.14 Five-step chart for metamorphic rock analysis and classification.

SEDIMENTARY ROCK ANALYSIS AND CLASSIFICATION							
STEP 1: What is the rock's composition?		STEP 2: What are the rock's textural and other distinctive properties?		STEP 3: Rock Name(s)			
DETRITAL	Mainly quartz grains, feldspar grains, rock fragments, and/or clay minerals	Gravel (≥ 2 mm)		Rounded grains	CONGLOMERATE		
				Angular grains	BRECCIA		
		Sand (0.0625–2.00 [1/16–2] mm)		Mostly quartz grains	QUARTZ SANDSTONE		
				Mostly feldspar grains	ARKOSE		
				Mostly rock fragments	LITHIC SANDSTONE		
				Sand is mixed with much silt and/or clay (mud)	WACKE		
		Mud	Mostly silt (0.0039–0.0625 [1/256–1/16] mm)		Nonfissile (compact)	SILTSTONE	
					Fissile (splits easily)	SHALE	
			Mostly clay (< 0.0039 [1/256] mm)		Nonfissile (compact)	CLAYSTONE	
					Fissile (splits easily)	SHALE	
BIOCHEMICAL	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 calcium carbonate, CaCO ₃ : so rock effervesces in dilute HCl	Shells or shell fragments (i.e., skeletal grains) well cemented to form dense rock)		Gravel (> 2 mm)	CALCIRUDITE		
				Sand (0.0625–2 mm)	CALCARENITE		
				Silt (0.0039–0.0625 mm)	CALCISILTITE		
				Clay (< 0.0039 mm)	MICRITE		
		Shells or shell fragments (i.e., skeletal grains) poorly cemented to form porous, earthy rock)		Gravel (> 2 mm)	COQUINA		
				Sand (0.0625–2 mm)	CALCARENITE		
				Silt and clay (< 0.0625 mm)	CHALK		
		Crystals formed as inorganic chemical precipitates		Crystals are coarse-grained (> 2 mm) to fine-grained (0.0039 mm)	CRYSTALLINE LIMESTONE		
				Crystals are very fine-grained (<0.0039 mm)	MICRITE		
		Spherical grains like tiny beads (< 2 mm) with concentric laminations		OOLITIC LIMESTONE			
	CHEMICAL	Mainly dolomite CaMg(CO ₃) ₂	Microcrystalline		Effervesces in dilute HCl only if powdered	DOLOSTONE	
		Mainly varieties of quartz, 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, CaSO ₄ · 2H ₂ 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 cryptocrystalline		Dark-colored, usually brown or red-gray	IRONSTONE		

FIGURE 5.8 Sedimentary rock analysis and classification. Follow the three steps to analyze and name a sedimentary rock. Refer to text explanation on page 90.

(...Contd.....from Pages **9 -12**....)

The 14 Bravais Lattices

When the crystal systems are combined with the various possible lattice centerings, we arrive at the Bravais lattices. They describe the geometric arrangement of the lattice points, and thereby the translational symmetry of the crystal. In three dimensions, there are 14 unique Bravais lattices which are distinct from one another in the translational symmetry they contain. All crystalline materials recognized until now (not including quasicrystals) fit in one of these arrangements. The fourteen three-dimensional lattices, classified by crystal system, are shown to the right. The Bravais lattices are sometimes referred to as *space lattices*.

The crystal structure consists of the same group of atoms, the *basis*, positioned around each and every lattice point. This group of atoms therefore repeats indefinitely in three dimensions according to the arrangement of one of the 14 Bravais lattices. The characteristic rotation and mirror symmetries of the group of atoms, or unit cell, is described by its crystallographic point group.

The 32 Point Groups

The crystallographic point group or *crystal class* is the mathematical group comprising the symmetry operations that leave at least one point unmoved and that leave the appearance of the crystal structure unchanged. These symmetry operations include

- *reflection*, which reflects the structure across a *reflection plane*
- *rotation*, which rotates the structure a specified portion of a circle about a *rotation axis*

- *inversion* which changes the sign of the coordinate of each point with respect to a *center of symmetry* or *inversion point*
- *improper rotation*, which consists of a rotation about an axis followed by an inversion.

Rotation axes (proper and improper), reflection planes, and centers of symmetry are collectively called *symmetry elements*. There are 32 possible crystal classes. Each one can be classified into one of the seven crystal systems.

The 230 Space Groups

The space group of the crystal structure is composed of the translational symmetry operations in addition to the operations of the point group. These include

- pure *translations* which move a point along a vector
- *screw axes*, which rotate a point around an axis while translating parallel to the axis
- *glide planes*, which reflect a point through a plane while translating it parallel to the plane.

There are 230 distinct space groups.

Defects or impurities in crystals

Real crystals feature defects or irregularities in the ideal arrangements described above and it is these defects that critically determine many of the electrical and mechanical properties of real materials. When one atom substitutes for one of the principal atomic components within the crystal structure, alteration in the electrical and thermal properties of the material may ensue.^[2] Impurities may also manifest as spin impurities in certain materials. Research on magnetic impurities demonstrates that substantial alteration of certain properties such as specific heat may be affected by small concentrations

of an impurity, as for example impurities in semiconducting ferromagnetic alloys may lead to different properties as first predicted in the late 1960s.^{[3][4]} Dislocations in the crystal lattice allow shear at lower stress than that needed for a perfect crystal structure.^[5]

Crystal symmetry and physical properties

Twenty of the 32 crystal classes are so-called piezoelectric, and crystals belonging to one of these classes (point groups) display piezoelectricity. All 21 piezoelectric classes lack a center of symmetry. Any material develops a dielectric polarization when an electric field is applied, but a substance which has such a natural charge separation even in the absence of a field is called a polar material. Whether or not a material is polar is determined solely by its crystal structure. Only 10 of the 32 point groups are polar. All polar crystals are pyroelectric, so the 10 polar crystal classes are sometimes referred to as the pyroelectric classes.

There are a few crystal structures, notably the perovskite structure, which exhibit ferroelectric behaviour. This is analogous to ferromagnetism, in that, in the absence of an electric field during production, the ferroelectric crystal does not exhibit a polarisation. Upon the application of an electric field of sufficient magnitude, the crystal becomes permanently polarised. This polarisation can be reversed by a sufficiently large counter-charge, in the same way that a ferromagnet can be reversed. However, it is important to note that, although they are called ferroelectrics, the effect is due to the crystal structure, not the presence of a ferrous metal. The angle between the normals to the two intersecting faces is called interfacial angle.

Incommensurate crystals have period-varying translational symmetry. The period between nodes of symmetry is constant in most crystals. The distance between nodes in an incommensurate crystal is dependent on the number of nodes between it and the base node.

Uses of Minerals

Minerals are essential to various needs within human society, such as minerals used for bettering health and fitness (such as mineral water or commercially-sold vitamins), essential components of metal products used in various commodities and machinery, essential components to building materials such as limestone, marble, granite, gravel, glass, plaster, cement, plastics, etc.^[32] Minerals are also used in fertilizers to enrich the growth of agricultural crops.

Modern mineralogy

Historically, mineralogy was heavily concerned with taxonomy of the rock-forming minerals; to this end, the International Mineralogical Association is an organization whose members represent mineralogists in individual countries. Its activities include managing the naming of minerals (via the Commission of New Minerals and Mineral Names), location of known minerals, etc. As of 2004 there are over 4,000 species of mineral recognized by the IMA. Of these, perhaps 150 can be called "common," another 50 are "occasional," and the rest are "rare" to "extremely rare."

More recently, driven by advances in experimental technique (such as neutron diffraction) and available computational power, the latter of which has enabled extremely accurate atomic-scale simulations of the behaviour of crystals, the science has branched out to consider more general problems in the fields of inorganic chemistry and solid-state physics. It, however, retains a focus on the crystal structures commonly encountered in rock-forming minerals (such as the perovskites, clay minerals and framework silicates). In particular, the field has made great advances in the understanding of the relationship between the atomic-scale structure of minerals and their function; in nature, prominent examples would be accurate measurement and prediction of the elastic properties of minerals, which has led to new insight into seismological behaviour of rocks and depth-related discontinuities in seismograms of the Earth's mantle. To this end, in their focus on the connection between atomic-scale phenomena

and macroscopic properties, the **mineral sciences** (as they are now commonly known) display perhaps more of an overlap with materials science than any other discipline.

(...Contd... from Page 17....)

Moh's hardness scale

1. Talc $\text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2$
2. Gypsum $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$
3. Calcite CaCO_3
4. Fluorite CaF_2
5. Apatite $\text{Ca}_5(\text{PO}_4)_3(\text{OH}, \text{Cl}, \text{F})$
6. Orthoclase KAlSi_3O_8
7. Quartz SiO_2
8. Topaz $\text{Al}_2\text{SiO}_4(\text{OH}, \text{F})_2$
9. Corundum Al_2O_3
10. Diamond C (pure carbon).

Unit-5 MINERAL GROUPS

Classification of Minerals based on Chemical properties

Minerals may be classified according to chemical composition. They are here categorized by anion group. The list below is in approximate order of their abundance in the Earth's crust. The list follows the Dana classification system^{[1][7]} which closely parallels the Strunz classification.

1. Silicate class

E.g. Quartz

The largest group of minerals by far are the **silicates** (most rocks are $\geq 95\%$ silicates), which are composed largely of silicon and oxygen, with the addition of ions such as aluminium, magnesium, iron, and calcium. Some

important rock-forming silicates include the feldspars, quartz, olivines, pyroxenes, amphiboles, garnets, and micas.

Table 2–1 Abundances of chemical elements in the earth's crust*

Element and symbol	Percentage by weight	Percentage by number of atoms	Percentage by volume
Oxygen (O)	46.6	62.6	93.8*
Silicon (Si)	27.7	21.2	0.9
Aluminum (Al)	8.1	6.5	0.5
Iron (Fe)	5.0	1.9	0.4
Calcium (Ca)	3.6	1.9	1.0
Sodium (Na)	2.8	2.6	1.3
Potassium (K)	2.6	1.4	1.8
Magnesium (Mg)	2.1	1.9	0.3
All other elements	1.5		
	100.0	100.0†	100.0†

*Note the high percentage of oxygen in the earth's crust.

†Includes only the first eight elements.

(Based on B. Mason, *Principles of Geochemistry*, New York, John Wiley & Sons, Inc., 1966.)

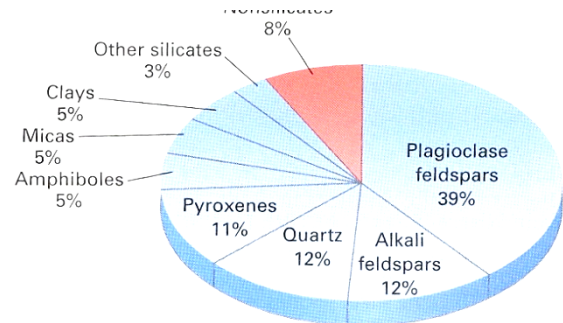


Figure 2.16 The silicate minerals compose 92 percent of the Earth's crust. Feldspar alone makes up about 50 percent of the crust, and pyroxene and quartz constitute another 23 percent. Source: Modified from Klein, *Manual of Mineral Science*, 22nd ed., John Wiley & Sons, Inc, 2002

Rock-Forming Minerals

MINERAL	COMPOSITION	PRIMARY OCCURRENCE
Ferromagnesian silicates		
Olivine	(Mg,Fe) ₂ SiO ₄	Igneous, metamorphic rocks
Pyroxene group		
Augite most common	Ca, Mg, Fe, Al silicate	Igneous, metamorphic rocks
Amphibole group		
Hornblende most common	Hydrous* Na, Ca, Mg, Fe, Al silicate	Igneous, metamorphic rocks
Biotite	Hydrous K, Mg, Fe silicate	All rock types
Nonferromagnesian silicates		
Quartz	SiO ₂	All rock types
Potassium feldspar group		
Orthoclase, microcline	KAlSi ₃ O ₈	All rock types
Plagioclase feldspar group	Varies from CaAl ₂ Si ₂ O ₈ to NaAlSi ₃ O ₈	All rock types
Muscovite	Hydrous K, Al silicate	All rock types
Clay mineral group	Varies	Soils and sedimentary rocks
Carbonates		
Calcite	CaCO ₃	Sedimentary rocks
Dolomite	CaMg(CO ₃) ₂	Sedimentary rocks
Sulfates		
Anhydrite	CaSO ₄	Sedimentary rocks
Gypsum	CaSO ₄ · 2H ₂ O	Sedimentary rocks
Halides		
Halite	NaCl	Sedimentary rocks

*Contains elements of water in some kind of union.

Table 2–5 Common rock-forming silicate minerals

Silicate mineral	Composition	Physical properties
Quartz	Silicon dioxide (silica, SiO_2)	Hardness of 7 (on scale of 1 to 10); will not cleave (fractures unevenly); specific gravity: 2.65
Potassium feldspar group	Aluminosilicates of potassium	Hardness of 6.0–6.5; cleaves well in two directions; pink or white; specific gravity: 2.5–2.6
Plagioclase feldspar group	Aluminosilicates of sodium and calcium	Hardness of 6.0–6.5; cleaves well in two directions; white or gray; may show striations on cleavage planes; specific gravity: 2.6–2.7
Muscovite mica	Aluminosilicates of potassium with water	Hardness of 2–3; cleaves perfectly in one direction, yielding flexible thin plates; colorless; transparent in thin sheets; specific gravity: 2.8–3.0
Biotite mica	Aluminosilicates of magnesium, iron, potassium, with water	Hardness of 2.5–3.0; cleaves perfectly in one direction, yielding flexible thin plates; black to dark brown; specific gravity: 2.7–3.2
Pyroxene group	Silicates of aluminum, calcium, magnesium, and iron	Hardness of 5–6; cleaves in two directions at 90° ; black to dark green; specific gravity: 3.1–3.5
Amphibole group	Silicates of aluminum, calcium, magnesium, and iron	Hardness of 5–6; cleaves in two directions at 56° and 124° ; black to dark green; specific gravity: 3.0–3.3
Olivine	Silicate of magnesium and iron	Hardness of 6.5–7.0; light green; transparent to translucent; specific gravity: 3.2–3.6
Garnet group	Aluminosilicates of iron, calcium, magnesium, and manganese	Hardness of 6.5–7.5; uneven fracture, red, brown, or yellow; specific gravity: 3.5–4.3

TABLE 2.3 Important Mineral Groups

Group	Member	Formula	Economic Use
Oxides	Hematite	Fe_2O_3	Ore of iron
	Magnetite	Fe_3O_4	Ore of iron
	Corundum	Al_2O_3	Gemstone, abrasive
	Ice	H_2O	Solid form of water
	Chromite	FeCr_2O_4	Ore of chromium
Sulfides	Galena	PbS	Ore of lead
	Sphalerite	ZnS	Ore of zinc
	Pyrite	FeS_2	Fool's gold
	Chalcopyrite	CuFeS_2	Ore of Copper
	Bornite	Cu_5FeS_4	Ore of copper
	Cinnabar	HgS	Ore of mercury
Sulfates	Gypsum	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	Plaster
	Anhydrite	CaSO_4	Plaster
	Barite	BaSO_4	Drilling mud
Native elements	Gold	Au	Electronics, jewelry
	Copper	Cu	Electronics
	Diamond	C	Gemstone, abrasive
	Sulfur	S	Sulfa drugs, chemicals
	Graphite	C	Pencil lead, dry lubricant
	Silver	Ag	Jewelry, photography
	Platinum	Pt	Catalyst
Halides	Halite	NaCl	Common salt
	Fluorite	CaF_2	Used in steel making
	Sylvite	KCl	Fertilizer
Carbonates	Calcite	CaCO_3	Portland cement
	Dolomite	$\text{CaMg}(\text{CO}_3)_2$	Portland cement
	Aragonite	CaCO_3	Portland cement
Hydroxides	Limonite	$\text{FeO}(\text{OH}) \cdot n\text{H}_2\text{O}$	Ore of iron, pigments
	Bauxite	$\text{Al}(\text{OH})_3 \cdot n\text{H}_2\text{O}$	Ore of aluminum
Phosphates	Apatite	$\text{Ca}_5(\text{F,Cl,OH})(\text{PO}_4)_3$	Fertilizer
	Turquoise	$\text{CuAl}_6(\text{PO}_4)_4(\text{OH})_8 \cdot 4\text{H}_2\text{O}$	Gemstone
Silicates	(Silicate minerals make up 92 percent of the Earth's crust. Figure 2.13 summarizes the rock-forming minerals.)		

Silicate Structures

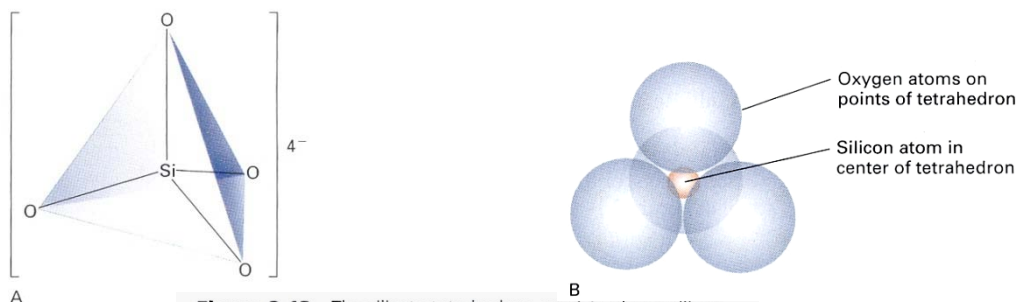
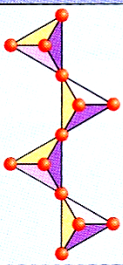
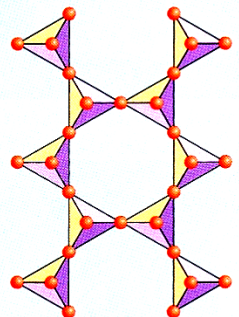
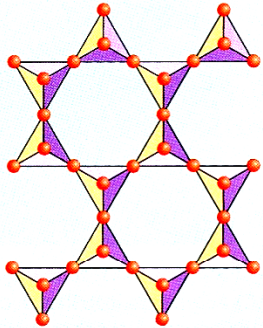
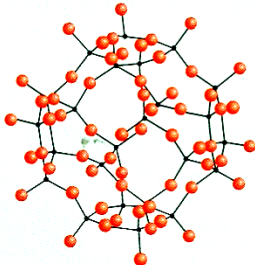


Figure 2.13 The silicate tetrahedron consists of one silicon atom surrounded by four oxygen atoms. It is the fundamental building block of all silicate minerals. (A) A schematic representation. (B) A proportionally accurate model.

Class	Arrangement of SiO_4 tetrahedron	Unit composition	Mineral examples
(A) Independent tetrahedra		$(\text{SiO}_4)^{4-}$	Olivine: The composition varies between Mg_2SiO_4 and Fe_2SiO_4
(B) Single chains		$(\text{SiO}_3)^{2-}$	Pyroxene: The most common pyroxene is augite, $\text{Ca}(\text{Mg, Fe, Al})(\text{Al, Si})_2\text{O}_6$
(C) Double chains		$(\text{Si}_4\text{O}_{11})^{6-}$	Amphibole: The most common amphibole is hornblende, $\text{NaCa}_2(\text{Mg, Fe, Al})_5(\text{Si, Al})_8\text{O}_{22}(\text{OH})_2$
(D) Sheet silicates		$(\text{Si}_2\text{O}_5)^{2-}$	Mica, clay minerals, chlorite, e.g.: muscovite, $\text{KAl}_2(\text{Si}_3\text{Al})\text{O}_{10}(\text{OH})_2$
(E) Framework silicates		SiO_2	Quartz: SiO_2 Feldspar: As an example, potassium feldspar is KAlSi_3O_8

Earth Science Now™ ACTIVE FIGURE 2.14 The five silicate structures are based on sharing of oxygen atoms among silicate tetrahedra. (A) Independent tetrahedra share no oxygen atoms. (B) In single chains, each tetrahedron shares two oxygens with adjacent tetrahedra, forming a chain. (C) A double chain is a pair of single chains that are cross-linked by additional oxygen atoms. (D) In the sheet silicates, each tetrahedron shares three oxygens with adjacent tetrahedra. (E) A three-dimensional silicate framework shares all four oxygens of each tetrahedron. **Interactive Question:** Discuss why mica has one perfect cleavage plane. Why does quartz have no cleavage?

Table 2–2 Structure of some geologically important elements

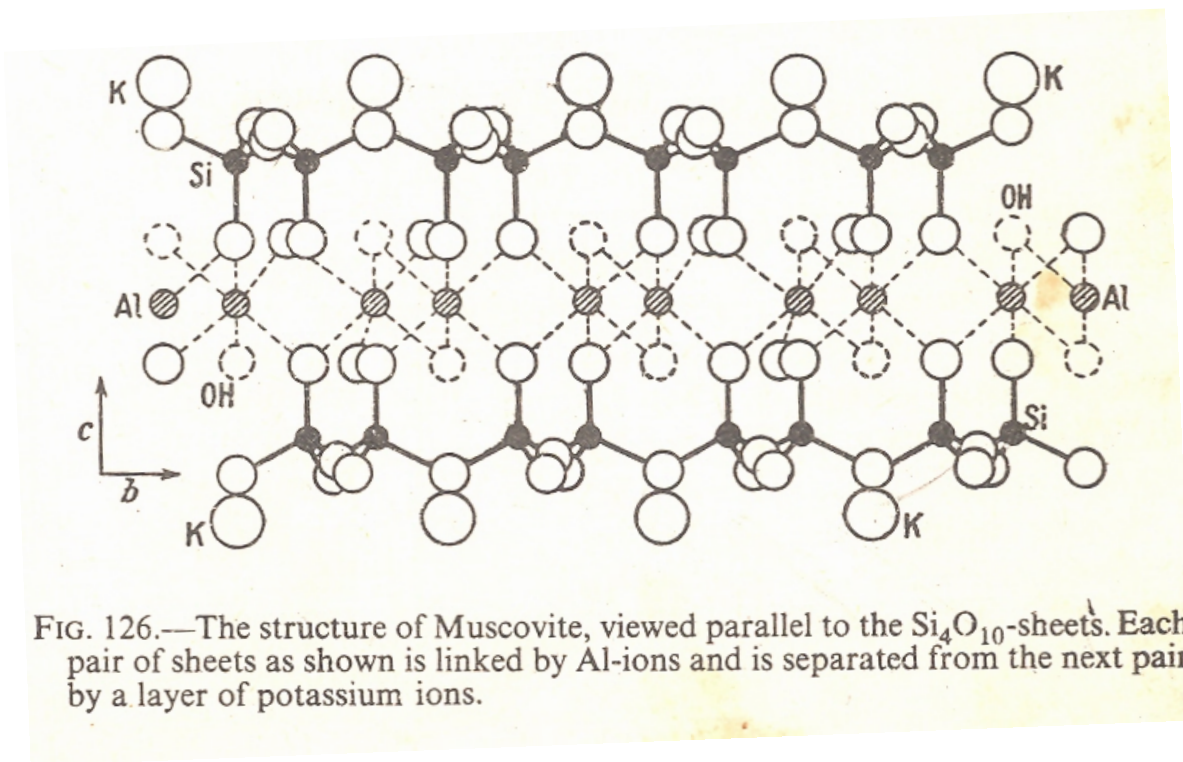
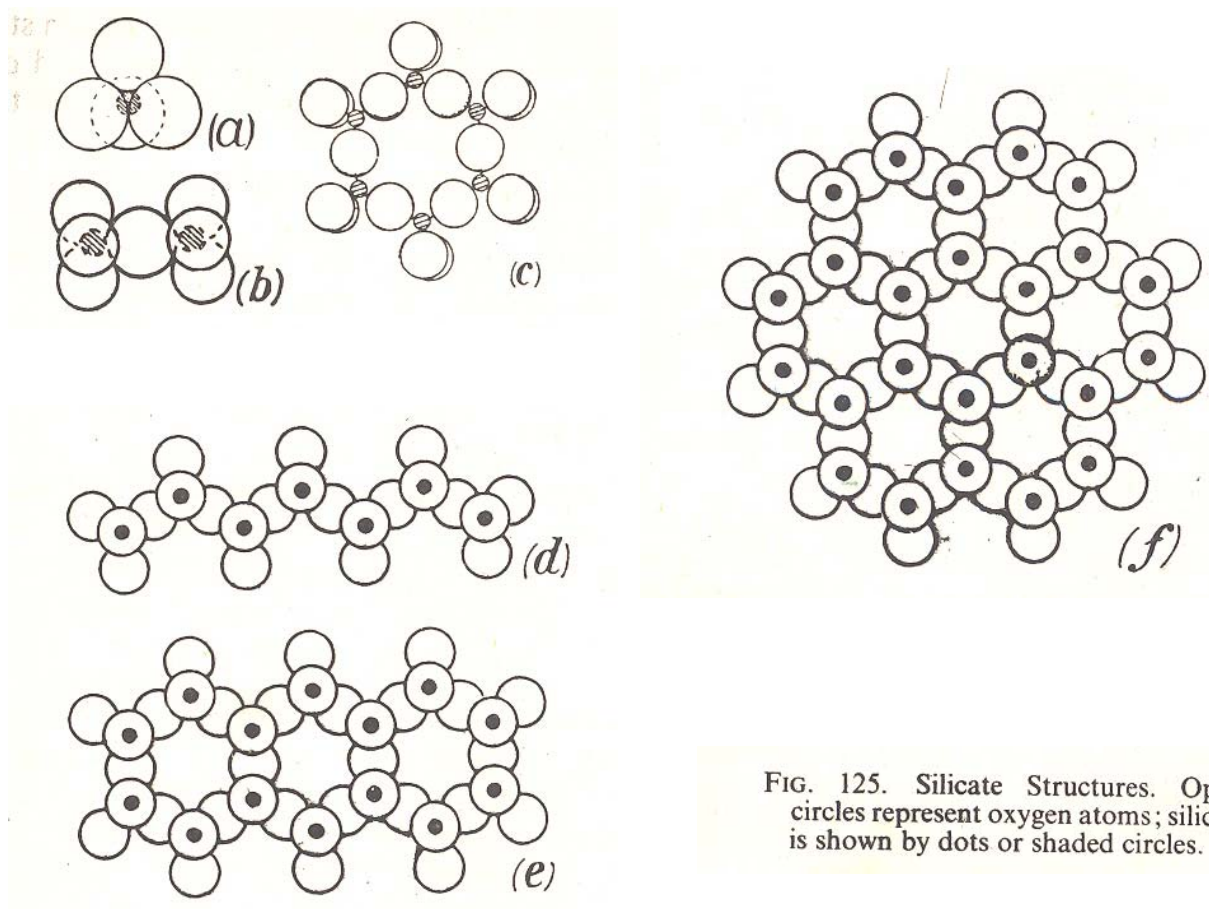
Element and symbol	Atomic number (number of protons in nucleus)	Number of neutrons in nucleus	Atomic mass	Electrons in various levels	Total number of electrons
Hydrogen (H)	1	0	1	1	(1)
Helium (He)	2	2	4	2	(2)
Carbon 12 (C)*	6	6	12	2–4	(6)
Carbon 14 (C)	6	8	14	2–4	(6)
Oxygen (O)	8	8	16	2–6	(8)
Sodium (Na)	11	12	23	2–8–1	(11)
Magnesium (Mg)	12	13	25	2–8–2	(12)
Aluminum (Al)	13	14	27	2–8–3	(13)
Silicon (Si)	14	14	28	2–8–4	(14)
Chlorine 35 (Cl)*	17	18	35	2–8–7	(17)
Chlorine 37 (Cl)	17	20	37	2–8–7	(17)
Potassium (K)	19	20	39	2–8–8–1	(19)
Calcium (Ca)	20	20	40	2–8–8–2	(20)
Iron (Fe)	26	30	56	2–8–14–2	(26)
Barium (Ba)	56	82	138	2–8–18–18–8–2	(56)
Lead 208 (Pb)*	82	126	208	2–8–18–32–18–4	(82)
Lead 206 (Pb)	82	124	206	2–8–18–32–18–4	(82)
Radium (Ra)	88	138	226	2–8–18–32–18–8–2	(88)
Uranium 238 (U)	92	146	238	2–8–18–32–18–12–2	(92)

*When two isotopes of an element are given, the most abundant is starred; for other elements, only the most abundant isotope is given. Note carefully that ordinary chemical atomic weights are not given; these are mixtures of isotopes and are therefore not whole numbers.

Table 2–3 Stable isotopes of oxygen*

Isotope	Number of protons	Number of neutrons	Atomic mass
^{16}O	8	8	16
^{17}O	8	9	17
^{18}O	8	10	18

*Isotopes of oxygen—oxygen 16, oxygen 17, and oxygen 18—are written ^{16}O , ^{17}O , ^{18}O , respectively. The superscript designates the sum of the protons and neutrons.



2. Non-silicate Groups

2.1 Carbonate class

The **carbonate minerals** consist of those minerals containing the anion $(\text{CO}_3)^{2-}$ and include calcite and aragonite (both calcium carbonate), dolomite (magnesium/calcium carbonate) and siderite (iron carbonate). Carbonates are commonly deposited in marine settings when the shells of dead planktonic life settle and accumulate on the sea floor. Carbonates are also found in evaporitic settings (e.g. the Great Salt Lake, Utah) and also in karst regions, where the dissolution and reprecipitation of carbonates leads to the formation of caves, stalactites and stalagmites. The carbonate class also includes the nitrate and borate minerals.

2.2 Sulfate class

Sulfates all contain the sulfate anion, SO_4^{2-} . Sulfates commonly form in evaporitic settings where highly saline waters slowly evaporate, allowing the formation of both sulfates and halides at the water-sediment interface. Sulfates also occur in hydrothermal vein systems as gangue minerals along with sulfide ore minerals. Another occurrence is as secondary oxidation products of original sulfide minerals. Common sulfates include anhydrite (calcium sulfate), celestine (strontium sulfate), barite (barium sulfate), and gypsum (hydrated calcium sulfate). The sulfate class also includes the chromate, molybdate, selenate, sulfite, tellurate, and tungstate minerals.

2.3 Halide class

E.g. Halite

The **halides** are the group of minerals forming the natural salts and include fluorite (calcium fluoride), halite (sodium chloride), sylvite (potassium chloride), and sal ammoniac (ammonium chloride). Halides, like sulfates, are

commonly found in evaporitic settings such as playa lakes and landlocked seas such as the Dead Sea and Great Salt Lake. The halide class includes the fluoride, chloride, bromide and iodide minerals.

2.4 Oxide class

Oxides are extremely important in mining as they form many of the ores from which valuable metals can be extracted. They also carry the best record of changes in the Earth's magnetic field. They commonly occur as precipitates close to the Earth's surface, oxidation products of other minerals in the near surface weathering zone, and as accessory minerals in igneous rocks of the crust and mantle. Common oxides include hematite (iron oxide), magnetite (iron oxide), chromite (iron chromium oxide), spinel (magnesium aluminium oxide - a common component of the mantle), ilmenite (iron titanium oxide), rutile (titanium dioxide), and ice (hydrogen oxide). The oxide class includes the oxide and the hydroxide minerals.

2.5 Sulfide class

Many **sulfide minerals** are economically important as metal ores. Common sulfides include pyrite (iron sulfide - commonly known as *fools' gold*), chalcopyrite (copper iron sulfide), pentlandite (nickel iron sulfide), and galena (lead sulfide). The sulfide class also includes the selenides, the tellurides, the arsenides, the antimonides, the bismuthinides, and the sulfosalts (sulfur and a second anion such as arsenic).

2.6 Phosphate class

The **phosphate mineral** group actually includes any mineral with a tetrahedral unit AO_4 where A can be phosphorus, antimony, arsenic or vanadium. By far the most common phosphate is apatite which is an important biological mineral found in teeth and bones of many animals. The phosphate class includes the phosphate, arsenate, vanadate, and antimonate minerals.

2.7 Element class

The elemental group includes metals and intermetallic elements (gold, silver, copper), semi-metals and non-metals (antimony, bismuth, graphite, sulfur). This group also includes natural alloys, such as electrum (a natural alloy of gold and silver), phosphides, silicides, nitrides and carbides (which are usually only found naturally in a few rare meteorites).

2.8 Organic class

The organic mineral class includes biogenic substances in which geological processes have been a part of the genesis or origin of the existing compound.^[2] Minerals of the organic class include various oxalates, mellitates, citrates, cyanates, acetates, formates, hydrocarbons and other miscellaneous species. Examples include whewellite, moolooite, mellite, fichtelite, carpathite, evenkite and abelsonite.

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