ELEMENTS
of
MINERALOGY
by
WINCHELL

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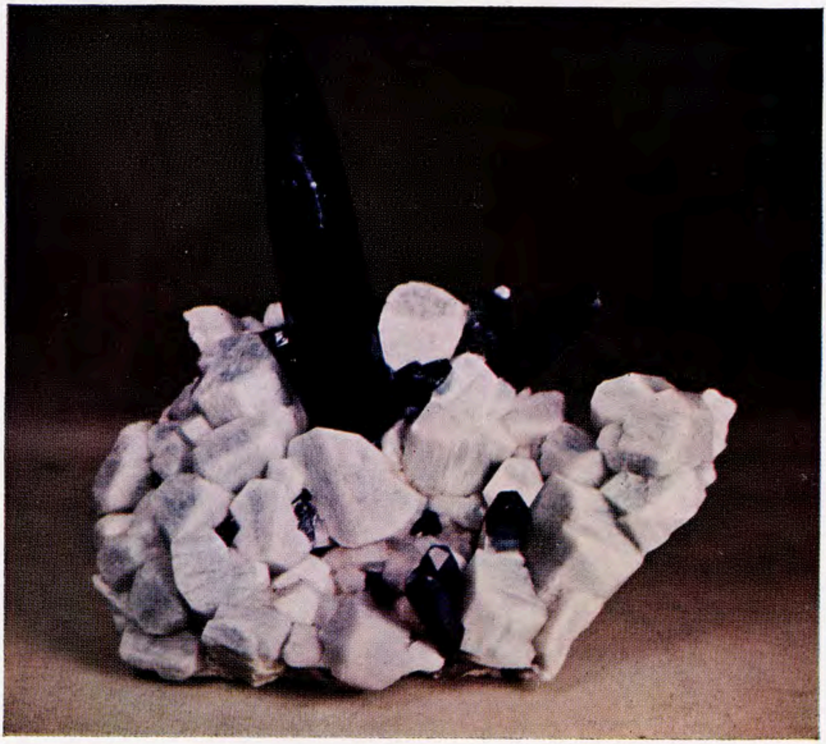

Top: Sulfur Crystals from Sicily. (*From a color photograph supplied by Ward's Natural Science Establishment.*)

Bottom: Smoky Quartz and Microcline from Crystal Peak, Colorado. ×0.9 (*A National Museum specimen. From a color photograph supplied by Dr. Sterling B. Hendricks.*)

ELEMENTS of MINERALOGY

Emphasizing the Variations in Minerals

by

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Preface

One purpose of this book is to advance the idea that many minerals are not fixed and simple in composition. Some years ago Professor D. Jerome Fisher of the University of Chicago pointed out that the writer's *Elements of Optical Mineralogy* had made such a treatment available to advanced students for some years, but that no elementary textbook, in any language, presented the subject in a similar way. A result of Dr. Fisher's suggestion has been the preparation of this volume.

About forty years ago, prominent petrographers like Fouqué did not accept the idea of continuous variation in composition from one formula to another for any mineral—not even for plagioclase. Perhaps the chief supporter of the idea at that time was the famous mineralogist of Vienna—Tschermak.

Ten years later, Bowen[1] proved that artificial plagioclase is a continuous series from one formula to a different one. Still ten years later this theory was accepted as possible for many minerals; Larsen and Glenn[2] used it in their study of melanterite and chalcanthite.

The development of the concept that many minerals vary considerably in composition (and properties) is illustrated by the fact that the first edition of the author's *Elements of Optical Mineralogy* in 1909 contained graphs correlating such variations for only two minerals (plagioclase, then called a series of minerals, and orthoclase-celsian); the second edition in 1928 contained thirty-nine such diagrams; the third edition in 1933 contained fifty-six; and this book contains sixty-three, although it deals only with the common minerals.

Great variations in the composition and properties of minerals are now accepted by all mineralogists, but many

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[1] N. L. Bowen: "The Melting Phenomena of the Plagioclase Feldspars," *American Journal of Science*, XXXV, 577 (1913).

[2] E. S. Larsen and M. L. Glenn: "Some Minerals of the Melanterite and Chalcanthite Groups," *American Journal of Science*, L, 225 (1920).

still cling to the old idea of a simple and (nearly) fixed composition for each mineral. In order to recognize the continuous variations, they tend to create a whole series of names for the different (arbitrarily defined) portions of a continuous series or system, and to consider that each name is that of a distinct mineral. Such names are useful in some cases, but to consider that each name is that of a distinct mineral makes it increasingly difficult, if not impossible, to define a mineral satisfactorily. It seems clear to the author that a single name is needed to designate the whole of any continuous series or system, and that it is desirable to consider that the name designates *one* mineral (of which there may be many varieties). The extent of possible variations in composition is unknown in some cases, but the variations of most of the common minerals are all known, at least approximately. Moreover, whether the extent of the variation is known or not, it is important that even the beginning student should understand that such variations are common.

In applying this idea of variations in composition and properties to all minerals, it has seemed necessary to use some new or unfamiliar names for certain minerals; but such names have been kept to a minimum, and the familiar names also are used as designations of end-members.

The author acknowledges gratefully the coöperation of his colleague, Professor R. C. Emmons, who offered valuable suggestions for the preparation of the Determinative Tables. He is likewise indebted to Erwin J. Lyons of the Wisconsin Institute of Technology for useful suggestions for the chapter on crystallography. Professor N. E. A. Hinds of the University of California suggested that X-ray studies of crystals should be described. Finally, the author is indebted to his son, Dr. Horace Winchell, crystallographer of the Hamilton Watch Company, for valuable contributions to the chapter on crystallography, especially the description and use of the Hermann-Mauguin symbols. He appreciates highly the courtesy of John Wiley & Sons, publishers of *Elements of Optical Mineralogy*, who allowed him to use freely many paragraphs and illustrations from that source.

ALEXANDER N. WINCHELL

Contents

Abbreviations and Symbols

For symbols of chemical elements, see page 183.
For Miller and Hermann-Mauguin symbols, see pages 10, 15, and 30.

A,B = optic axes of biaxial crystals.
a or a_1 = front and rear crystal axis.
a_2 = right and left crystal axis.
a_3 = vertical crystal axis.
α = angle between crystal axes b and c.
Ab = albite.
An = anorthite.
ang. = angle.
approx. = approximate.
At. = atom or atomic.
B = birefringence.
B.B. = before the blowpipe.
b = right and left crystal axis.
β = angle between crystal axes a and c.
°C. = degree Centigrade.
c = vertical crystal axis.
γ = angle between crystal axes b and c.
D (after index of refraction) = light of the D line of the spectrum.
d = difference.
E = extraordinary ray.
2E = apparent angle between the optic axes measured in air.
ϵ (epsilon) = index of refraction for the extraordinary ray.
e.g. = for example.
et al. = and others.
ext. = extinction.
F. = fusibility.
fig. = figure.
G. = specific gravity.
Gr. = gram.

H. = hardness.
hex. = hexagonal.
h,k,l are Miller symbols; see page 15.
inv. = inversion.
isom. = isometric.
Li (after index of refraction) = lithium (red) light.
λ (lambda) = wave length (of monochromatic light).
m = an indefinite number.
mm = millimeter.
μ (mu) = a thousandth of a millimeter, or a micron.
mμ = a millionth of a millimeter.
mol. = molecule or molecular.
mono. = monoclinic.
N = index of refraction.
n = an indefinite number.
Na (after index of refraction) = sodium (yellow) light.
N_e = index of refraction for the extraordinary ray.
N_g = greatest index of refraction (= γ of German writers).
N_m = middle index of refraction (= β of German writers).
N_o = index of refraction for the ordinary ray.
N_p = least ("petty") index of refraction (= α of German writers).
O = ordinary ray.
O.F. = oxidizing flame.
ω (omega) = index of refraction for the ordinary ray.
opt. = optic.
orth. = orthorhombic.
R.F. = reducing flame.
rel. = relative.
rhom. = rhombohedral.
prop. = properties.
sin = sine
sol. = solution.
tan = tangent.
T. or Temp. = temperature.
tetr. = tetragonal.
Tl (after index of refraction) = thallium (green) light.
tric. = triclinic.
$2V$ = the true angle between the optic axes.

X = the vibration direction of the fastest ray (= $\mathfrak{a}$ of the German writers).
Y = the vibration direction of the intermediate ray (= $\mathfrak{b}$ of the German writers).
Z = the vibration direction of the slowest ray (= $\mathfrak{c}$ of the German writers).
⬬ = axis of twofold symmetry.
▲ = axis of threefold symmetry.
■ = axis of fourfold symmetry.
⬢ = axis of sixfold symmetry.
$\wedge$ = angle; for example: $Z \wedge c$ = the angle between Z and c.
○ = center of symmetry.
$>$ = greater than.
$<$ = less than.
$\perp$ = normal to.
$\|$ = parallel; this may be replaced by " = " as in "$X = a$."
(+) or (−) before $2V$ signifies that the optic sign of the mineral is plus or minus.

1

Introduction

Relation of mineralogy to science

In a general sense the sciences dealing with inorganic nature may be arranged in a series based on the size of the smallest unit with which each is directly concerned. The smallest units in the field of physics are electrons, neutrons, and so on. The chemist's smallest unit of direct interest is the atom; he is interested in electrons only as they affect the atoms. In a similar way the crystallographer (and also the mineralogist) is interested primarily in the unit cell or crystule, which is the smallest group of atoms (or ions) that shows the complete structure of a crystal—he is concerned with atoms only as their varying arrangements produce different kinds of crystals. A rock (which is an aggregate of crystals) may be said to be the smallest unit of direct interest to the geologist; he is concerned with the crystals only as they affect the nature of the rock. Finally, the unit of study of the astronomer is the star or planet, such as the earth, which is an aggregate of many rocks. In this series the mineralogist occupies the central position. The unit of interest to the astronomer is enormously larger than that of the mineralogist just as the latter's is vastly greater than that of the physicist. But it is also true that the fields of interest of the different sciences overlap considerably and in increasing measure as the sciences develop. For example, astronomy began with a study of the stars and planets, but it now includes spectroscopic investigations to determine what elements are present in sun and stars. In a similar way a mineralogist is concerned primarily with minerals, but these are in the most favorable condition for exact study only when found as crystals, to understand the nature of which he must study atoms, ions, and even electrons.

The importance of mineralogy

Primitive man used minerals only to a very limited extent. He was concerned chiefly with the quest for food and shelter and these he obtained almost wholly from plant and animal sources. Like other animals, he only gradually learned that salt was useful as a mineral food. It was partly by learning to use minerals a little more freely that man advanced to a higher level. Thus, when he learned how to produce fire with flints and to destroy it with water, he took a very important step toward control of his environment. Gradually he learned to use native copper in tools and pipestone for pleasure. But man's extensive use of minerals may be said to have begun only a century or two ago, and it ushered in the industrial age. Man's use of many minerals on an unprecedented scale is absolutely essential to his present control of power. The minerals used in the production and application of power are numerous, but the most important are iron, coal, petroleum, and copper. It is largely through the use of minerals to produce power that North America has been changed from a region where one or two million Indians found a precarious living to the home of two hundred million people enjoying far the greatest economic advantages ever known anywhere in the world; this has been possible partly because the natural supplies of the most important industrial minerals are remarkably abundant on this continent—for example, more than half the known world's reserves of coal, including practically all of the anthracite, are in North America.

Definition of a mineral

For many years a mineral has been considered to be a substance produced in inorganic nature having a definite chemical composition and definite crystal structure leading to definite external forms and definite physical characters. This definition is simple and therefore convenient, but it does not correspond with the facts of nature. It has been known for some years that a few minerals vary considerably in composition and properties; they were considered to be exceptional. Gradually, and then more rapidly in recent years, such "exceptions" have been found in increasing number, so that now it is clear that nearly all minerals vary somewhat in composition, and many of them vary a great deal. Therefore a new definition of a mineral is necessary.[1] It is possible merely to modify the old definition to read: a mineral is a (natural inorganic) substance which is either definite in chemical composition and physical characters, or varies in these respects within natural limits. But these natural limits seem to be determined by the variations which are possible without destroying the crystal structure; therefore a mineral may be said to be characterized by a certain crystal structure. It is known that changes of composition may result in very slight changes of position of atoms in the crystal structure, but as long as this is accomplished gradually the structure may be considered to be unchanged. Under certain conditions all the atoms of one kind may move suddenly to new positions. This commonly results in a change in the symmetry, and a new mineral results. It is illustrated by the sudden change in the position of certain atoms when aragonite inverts to calcite.

In general, the simpler the composition, the less the variation in composition. If a mineral varies considerably in composition, as is common in many cases, the extremes, and also various intermediate ranges, are often recognized as minerals, but should be considered as varieties or subspecies. Most minerals assume a regular internal structure (and, if free to do so, a regular external form) when they are formed as solids either by cooling or by chemical reaction. A very few minerals, like opal, seem to be devoid of this power. The regular external forms assumed by minerals (and by many other substances) are called crystals. The regular internal arrangement characteristic of crystals is known as crystal structure; it may exist even in the absence of regular external forms. A group of minerals consists of two or more natural inorganic compounds which are related chemically and crystallographically, but cannot intercrystallize freely.

A mineral is typically alike in all its parts; therefore a fine-grained basalt, which appears to be homogeneous, is not a

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[1] A Russian (M. N. Godlevsky) has recently defined a mineral as a "part of the earth's crust which is homogeneous in the sense of a separate phase of physico-chemical systems." See *Min. Abst.* VII, 208 (1939).

mineral, since it can be seen under the microscope to be composed of different substances, each having characters of its own.

A mineral is either crystallized (as one substance) or capable of such crystallization. Therefore obsidian or volcanic glass is not a mineral since it cannot crystallize as one substance. (Even opal is *assumed* to be capable of crystallization.)

Strictly, a mineral is a product of nature; but the same, or even related, substances made by man are often called artificial minerals.

In general, minerals are inorganic compounds; but a few crystallized organic substances found in nature are accepted as minerals, as illustrated by hydrated calcium oxalate (known as whewellite).

In general, minerals are solids; but two liquids are recognized as minerals, perhaps because they solidify at temperatures familiar to man: they are water and mercury.

In the strict sense of the term, here described, it is obvious that coal is not a mineral, since it is neither fixed in composition nor crystallized; still less is petroleum a mineral, since it is a liquid; both of these, however, belong to what is often called the mineral kingdom.

Mineralogy and its divisions

Mineralogy is the science of minerals and has to do with their origin, their crystal forms, their composition, their physical characters, their description, their determination, their occurrence, and their uses. In the following pages, the subject is discussed under the following heads:

1. Crystallography. Typically, minerals, like most other solids, acquire regular internal structures and external forms at the very moment of their origin. Crystallography is a description of these internal structures and external forms.

2. Physical mineralogy deals with the physical characters of minerals, that is, those depending upon cohesion and elasticity, density, light, heat, electricity, and so forth.

3. Chemical mineralogy has to do with general concepts and principles of chemistry as applied to minerals; it also includes a description of chemical methods of studying minerals.

4. Descriptive mineralogy includes a classification of minerals and a discussion of their mutual relationships, as well as a description of them, as regards their crystal forms, chemical composition, physical characters, diagnostics, occurrence in nature, uses, and so on.

5. Economic mineralogy describes the uses of minerals and substances derived from minerals.

6. Determinative mineralogy describes methods of distinguishing minerals, and presents tables for their identification.

2

Crystallography

Crystallography is the science which deals with the nature of crystals (whether of minerals or not), of their origin, their internal structure, and their external forms; it includes the full description and classification of these external forms.

Basic Concepts

A crystal

A *crystal* is a solid bounded by smooth surfaces which result from a regular and definite arrangement of the constituent atoms or ions. Crystals are produced when a substance passes from the state of a fluid to that of a solid, under conditions favorable to the attainment of a state of equilibrium of the forces acting between the atoms or ions so that they form three-dimensional networks in which there is the same arrangement of atoms (or ions) about any atom (or ion) of one kind as about any other atoms (or ions) of that kind within the crystal. A space lattice is such a network that is composed of only one kind of atom or ion. In general, liquids and gases are composed of molecules, which are groups of atoms; while crystals (at least those of minerals) are built of atoms or ions, in some cases in such arrangement as to suggest the presence of radicals, or parts of molecules, like CO_3, but free from complete molecules, unless a whole crystal may be considered an enormous molecule.

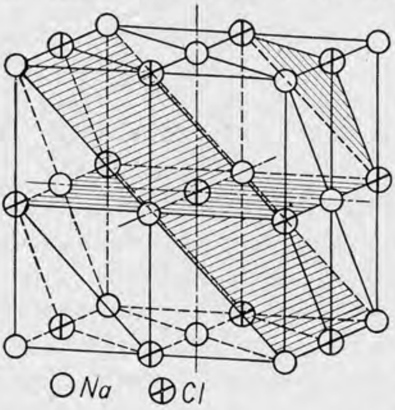

FIG. 1. Atomic structure of halite crystals.

One of the simplest types of networks is shown in Fig. 1: this is the arrangement in ordinary salt (sodium chloride or halite). Three kinds of planes passing through such crystals are shown by the shading. Another type of network, containing a group like a radical, is shown in Fig. 2: this is the arrangement of the atoms or ions in calcite and brown spar (magnesite, siderite, and rhodochrosite).

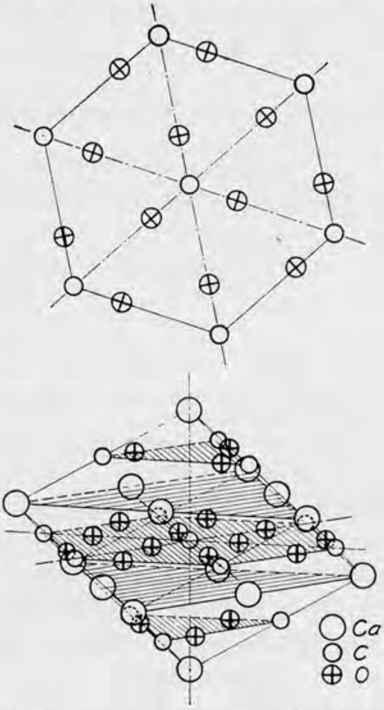

Fig. 2. Atomic structure of calcite crystals.

Crystalline and amorphous

If a mineral has the regular internal arrangement of its atoms without smooth external faces it is said to be *crystalline.* A compact aggregate of crystalline material is described as *massive.* A single unit having the same crystal structure throughout but devoid of crystal faces is called an *anhedron;* if it has imperfectly developed faces it is described as *subhedral;* if well developed faces, *euhedral.* A body which has neither the smooth external faces nor the regular internal arrangement of atoms is described as *amorphous.* Literally, this means without form, but it has come to mean having neither form nor crystal structure. This is the condition of a piece of glass, of opal, etc. Some substances solidify to the amorphous state if they are cooled very rapidly, because time is necessary to permit the atoms or ions to change from the molecular groupings of liquids or gases to the regular arrangements or networks in which the interatomic forces are in equilibrium.

Crystal faces

A crystal differs from a crystalline body in possessing smooth plane surfaces which have a simple relation to, and are a direct consequence of, the regular internal structure. These surfaces are called crystal faces. They are always related to the structure so as to include a high concentration of atoms or ions within them. For example, the network shown in Fig. 1 can be limited by the faces of a cube because those planes contain many atoms or ions per unit of area as compared with planes passing through the network in any indefinite direction.

Constancy of interfacial angles

The angles between like faces on all crystals of any one mineral (or other substance) are essentially constant. This is true although the sizes of like faces may vary enormously; it is true for natural minerals and for artificial minerals, as well as for crystals of organic compounds. It is true for all crystals of any one mineral no matter where that mineral may be found. Therefore these angles are used to help identify minerals; they are characteristic. Crystals may vary almost indefinitely in appearance, but the angles between corresponding faces remain constant. This is well shown in the series,[1] Figs. 242–271. The unequal development of crystal faces shown in these series is called *distortion*, but it is a distortion which does not change the angles between faces. Crystals are of all sizes, from those which are barely visible with a compound microscope to those which are measured in feet or even in yards. But the most nearly perfect crystals, that is, those with the smoothest faces, the greatest transparency, and the least distortion, are always small.

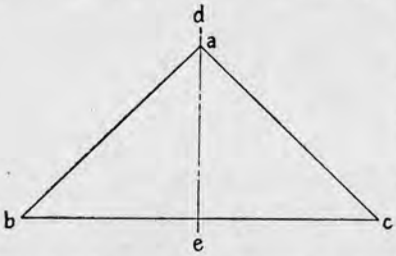

FIG. 3. Symmetry of a simple plane figure.

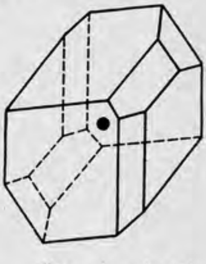

FIG. 4. A triclinic crystal of axinite with a center of symmetry.

Symmetry of crystals

All the faces of a crystal, as well as all the constituent atoms, are arranged in accordance with certain elements of symmetry,

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[1] See pages 112–113.

which are fixed in their position for a given crystal, and determine not merely its external form but also the distribution of all its internal physical characters. The essential feature of symmetry is repetition. Thus, a right triangle (*abc*, Fig. 3) may be divided symmetrically by a line (*de*), if every line, point, and angle on one side of it is repeated on the other side in the same position relative to that line (*de*). Three types of symmetry are commonly recognized in crystals, although a fourth is essential in one unimportant crystal class. These three types of symmetry are (1) the point, or center; (2) the line, or axis; and (3) the plane. All three, any two, any one, or none at all of these three symmetry elements may be present in a given crystal.

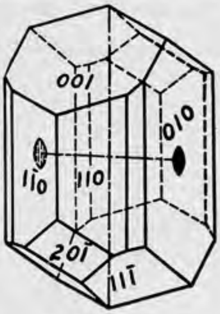

FIG. 5. A monoclinic crystal of orthoclase with an axis of twofold symmetry.

A crystal is symmetrical with respect to a point, or center, when for each face or edge on one side of that point, or center (also known as inverter), there is a similar face or edge at the same distance on the other side of the center. This is the only element of symmetry in triclinic crystals, as illustrated in Fig. 4. It may be represented by the symbol ○ in drawings, or by the symbol $\bar{1}$ in descriptions as proposed by Hermann and Mauguin, whose work has led to the so-called "international system," which is coming into wide usage.

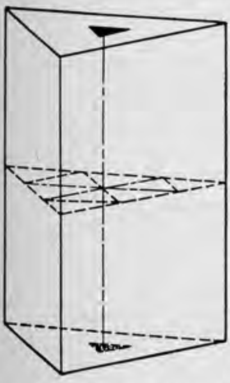

FIG. 6. A trigonal crystal with an axis of threefold symmetry.

A crystal is symmetrical with respect to a line (or axis) when a rotation of less than 360° about this axis causes the crystal to occupy a new position exactly the same as, and geometrically indistinguishable from, the original position. If a rotation of 180° produces the first repetition of position, there are two repetitions in a complete rotation, and the axis is said to be an axis of twofold, or binary, symmetry; it is illustrated in Fig. 5. The graphical symbol for such an axis is ●; the Hermann-Mauguin symbol is 2. An axis of threefold or ternary symmetry is present if the crystal repeats its position in space three times in a complete rotation (360°) about that axis. Its symbols are ▲ and 3; it is illustrated by the vertical axis in Fig. 6. An axis of fourfold, quaternary, or tetragonal symmetry is indicated by the symbol ■; and by the numeral 4; it is illustrated by the vertical axis in Fig. 7. An axis of sixfold, senary, or hexagonal symmetry is indicated by the symbol ⬢, or by the numeral 6; it is illustrated by the vertical axis in Fig. 8.

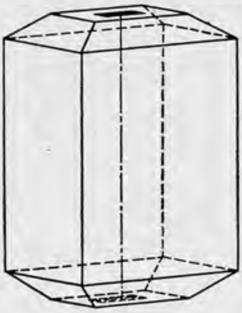
Fig. 7. A tetragonal crystal with a vertical axis of fourfold symmetry.

A crystal is symmetrical with respect to a plane when for each face or edge on one side of the plane there is a similar face or edge directly opposite on the other side of the plane, in such a position that one side is the mirror image of the other. Thus, the shaded plane is the plane of symmetry of the crystal of augite shown in Fig. 9. But crystals may have as many as nine planes of symmetry, as illustrated by those of a cube (Fig. 10), which has three principal planes of symmetry (Fig. 11) and six diagonal planes of symmetry (Fig. 12). In this book the plane of symmetry will be indicated by a full line in projections and by *m* (mirror) in descriptions.

In enumerating the three principal types of symmetry above, another type was mentioned, but not named. It is essential only in describing the tetartohedral class of the tetragonal system. This symmetry element is the axis of rotary-inversion, and it operates in such a way that by combining a rotation of 360°/p (where p is 1, 2, 3, 4, or 6) with a simultaneous inversion through a center of symmetry in the axis, the geometrical shape of the crystal repeats itself p times in the course of a complete rotation. It will be seen immediately that if p is 1, the "onefold" axis of rotary-inversion (Hermann-Mauguin symbol, $\bar{1}$) is identical with the center of symmetry described above.

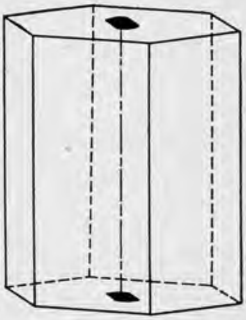
Fig. 8. A hexagonal crystal with a vertical axis of sixfold symmetry.

The twofold axis of rotary-inversion ($\bar{2}$) is the same as a simple plane of symmetry, already described and designated as *m* (mirror). The threefold axis of rotary-inversion ($\bar{3}$) operates in such a way that the result may also be described in terms of a simple threefold axis of symmetry (3) combined with a center ($\bar{1}$). The fourfold axis of rotary-inversion ($\bar{4}$) is said to be irreducible, since no possible combination of center, planes, and simple axes of symmetry can produce the equivalent configuration. This is found only in the tetartohedral class of the tetragonal system. A crystal belonging to this class is illustrated in Fig. 13. The sixfold possible axis of rotary-inversion, $\bar{6}$, may be duplicated with a combination of a simple threefold axis of symmetry, 3, and a plane normal thereto. The combina-

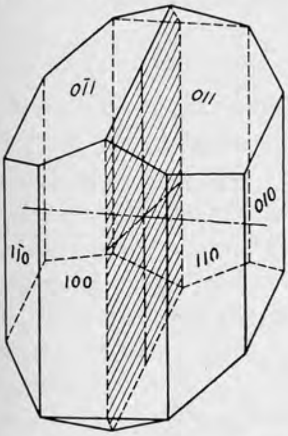

FIG. 9. A monoclinic crystal of augite with one plane of symmetry.

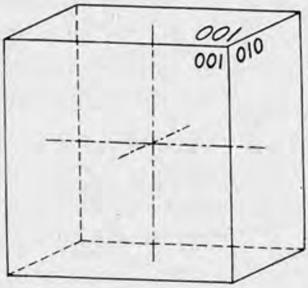

FIG. 10. A cubic crystal.

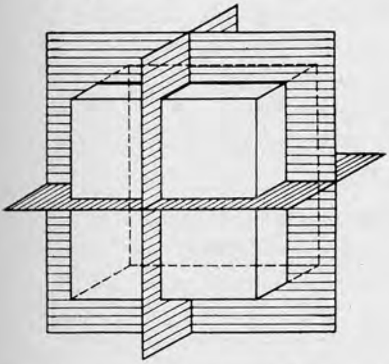

FIG. 11. Principal planes of symmetry of a cube.

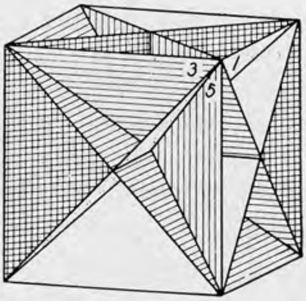

FIG. 12. Diagonal planes of symmetry of a cube.

tion might be indicated by the symbol $3/m$ or $\frac{3}{m}$. However, $\bar{6}$ is a single, simple symbol, and is usually preferred.

TABLE OF SYMMETRY ELEMENTS

Name	*Symbol*		*Composed of*
	Graphical	*Hermann-Mauguin*	
Axes—simple		1	
Binary axis	⬬	2	
Ternary axis	▲	3	
Quarternary axis	■	4	
Senary axis	⬢	6	
Axes—rotary-inversion			
Center	○	$\bar{1}$	Center only
Binary	(line)	$\bar{2}$ or m	Plane only
Ternary		$\bar{3}$	Ternary axis and center
Quaternary		$\bar{4}$	Irreducible
Senary		$\bar{6}$ or $3/m$	Ternary axis and plane

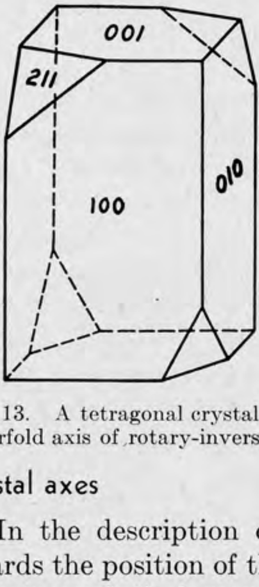

FIG. 13. A tetragonal crystal with fourfold axis of rotary-inversion.

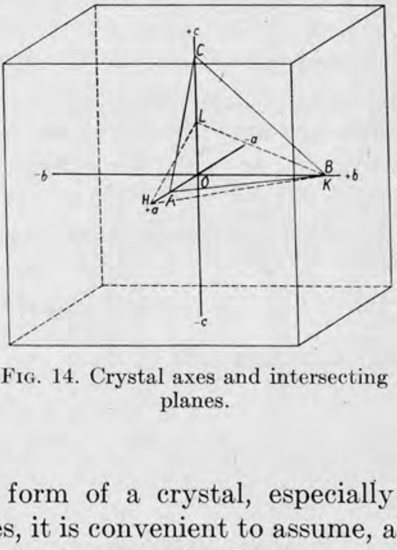

FIG. 14. Crystal axes and intersecting planes.

Crystal axes

In the description of the form of a crystal, especially as regards the position of the faces, it is convenient to assume, as is done in analytical geometry, certain axes of reference, passing through the center of the ideal form; these imaginary lines are called crystallographic axes. Their directions are more or less fixed by the symmetry of the crystal, since in most cases an axis of symmetry is a crystallographic axis,[2] and nearly always

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[2] Except in the hexagonal system (with four crystal axes) crystallographic axes are always three in number; whenever the symmetry axes exceed this number only certain ones (usually those of greatest symmetry) can be crystal axes.

the axes of the greatest symmetry are crystal axes. Such axes (denoted a, b, and c, if unequal in length) are shown in normal position in Fig. 14. The front and rear axis is always denoted by a. The right and left axis is also a if equal to that in length; otherwise it is designated b. The vertical axis is also a if equal to the first; otherwise it is c.

Coordinates and parameters

The position of any face of a crystal is conveniently expressed by stating the distances from the center at which the face (or its extension) cuts the crystallographic axes. These distances are known as the coordinates of the face, or plane. For example, in Fig. 14, the plane ABC cuts the axis a at a distance which may be 19 millimeters, the axis b at 36 millimeters, and the axis c at 32 millimeters; then 19, 36, and 32 are the coordinates of ABC. Another face may have coordinates which are entirely different, for example, 28.5, 27, and 12 millimeters. The coordinates are always written in the same order (a, b, c) and it is therefore unnecessary to write the axes. The second set of coordinates divided by the first set gives fractions which express the position of the second plane with respect to the first, as follows: $\frac{285}{190}$, $\frac{27}{36}$, $\frac{12}{32}$. In order to simplify these ratios either set of coordinates may be multiplied (or divided) by any suitable number (an operation which is equivalent to moving the plane parallel with itself, maintaining constantly the same *relative* position on the axes). For example, if the second set of coordinates be multiplied by $\frac{4}{3}$ so as to make the ratio unity on b, the fractions become $\frac{38}{19}$, $\frac{36}{36}$, $\frac{16}{32}$, which equal 2, 1, $\frac{1}{2}$. Again, if the second set of coordinates be multiplied by $\frac{8}{3}$, the fractions become $\frac{76}{19}$, $\frac{72}{36}$, $\frac{32}{32}$, or 4, 2, 1. This expresses the relative position of HKL (of Fig. 14) as compared with ABC. Numbers of this kind, which express in their simplest terms the relative positions of faces, are known as the parameters of the faces.

Now, it may be imagined that, after starting with random distances on the axes for the first plane, such as 19, 36, 32, it is very remarkable that the apparently equal random distances (28.5, 27, and 12) of the second plane should have a simple relationship to the first set, as disclosed by the ratios 4, 2, 1, obtained by a simple calculation. But this is not an accident; such a result is a necessary consequence of the relation of the faces to the internal structure of crystals. In order to simplify the matter we may consider the relation of faces to only two axes, say the axes *b* and *c*, as in Fig. 15. As already noted, the commonest and largest faces of crystals are so related to the structure that they contain the largest number of atoms or ions per unit of area; and the smaller this concentration is, the more improbable the plane is as an external crystal face. Accordingly, the planes *bb* and *cc* may be expected to be large; probably also *mm*; but *ll* and *nn* will be smaller ordinarily, and *rr* will be very small, if present at all. Finally, faces having no simple relation to the structure are practically never found and may be considered as almost impossible. Now if *mm* cuts *b* and *c* at distances which may be taken as units, the other faces, which are possible, cut the same axes at simple multiples of these units. Expressing this fact in another way: *A simple mathe-*

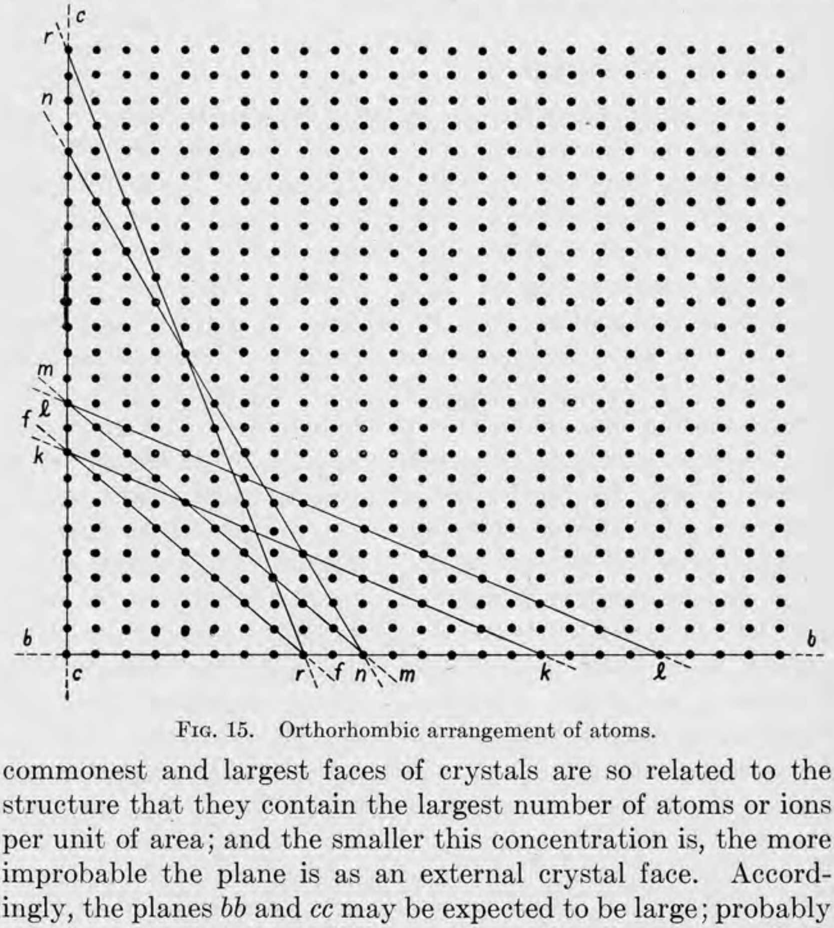

FIG. 15. Orthorhombic arrangement of atoms.

matical ratio exists between the coordinates of all planes which are possible as faces on all crystals of the same species. This is a fundamental law of crystallography.

Miller symbols

Crystal faces are completely defined as to their angular position by their parameters. However, it has been found that other numbers, derived from the parameters, are far more useful in mathematical computations than the parameters themselves. To obtain these other numbers it is only necessary to take the reciprocals of the parameters, and then clear of fractions, if necessary. Such numbers were first used by Miller and are therefore known as Miller symbols.[3] For example, if the parameters of a face are 4, 2, 1, the Miller symbols are 124, derived from the reciprocals, $\frac{1}{4}$, $\frac{1}{2}$, $\frac{1}{1}$, by clearing of fractions. Like the parameters, the symbols always refer to the axes in the order *a*, *b*, *c*, and it is therefore unnecessary to write the letters. A general expression for symbols of a face of indefinite position on a crystal having three unequal axes is *hkl*. In the hexagonal crystals, which have four crystal axes, this becomes *hkil*.

As shown in Fig. 14, there are + and − directions on each axis. If a face cuts any axis in the negative direction, that fact is expressed by writing a minus sign before the corresponding coordinate or parameter and over the corresponding Miller symbol. For example:

Parameters	**Symbols**
$4a: 2b: 1c$	124
$1a: -3b: -1c$	$3\overline{13}$
$\infty \mathrm{a}: 2b: -1c$	$01\overline{2}$

Crystal form

A crystal form includes all the faces of a crystal which are required by the symmetry if one of them is present. Thus, referring to Fig. 14, if the face *hkl*, which has the parameters: 421, and the Miller symbols: 124, is present on an orthorhombic crystal (which has three planes of symmetry each including two crystal axes), the crystal form of which it is a part consists of

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[3] In this book the symbols used for the hexagonal system are those proposed by Bravais as a modification of Miller's notation.

eight faces having the following Miller symbols: 124, $\bar{1}24$, $\bar{1}\bar{2}4$, $1\bar{2}4$, $12\bar{4}$, $\bar{1}2\bar{4}$, $\bar{1}\bar{2}\bar{4}$, $1\bar{2}\bar{4}$.

Zones

All the faces on any crystal which are parallel to a single line (through the center) are said to belong to one zone. All the intersections of these faces will necessarily be parallel to the line just mentioned, which is known as the *zone axis*. The Miller symbols of the face normal to the zone axis (except sometimes in the monoclinic and triclinic crystals) are used to express the axis;[4] when so used they are enclosed in brackets, as [*hkl*], to distinguish them from face symbols (not enclosed) and form symbols (enclosed in parentheses). For example, in Fig. 16 the faces $1\bar{1}0$, 110, 130 and 010 belong to the vertical zone whose axis is expressed as [001]; and $10\bar{1}$, $20\bar{1}$, and 001 belong to a lateral zone whose axis is [010].

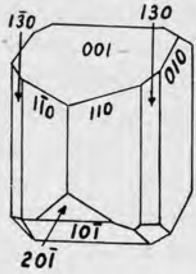

FIG. 16. Monoclinic crystal illustrating zones.

Drawings and Projections

Drawings of crystals are representations of solid objects in one plane, the plane of the paper, and therefore require a projection. The projection used in nearly all cases is not a true perspective, but assumes that the observer is at infinite distance, so that all lines which are parallel on the crystal are also parallel in the drawing. Furthermore, the observer is not supposed to be directly in front of the crystal, but above and to the right so that the top and right-hand side are in view as well as the front.

FIG. 17. A cube, photographed in clinographic projection.

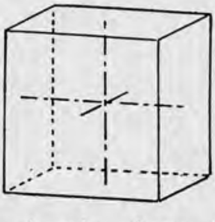

FIG. 18. A cube, drawn in clinographic projection.

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[4] The symbols of the face which would be normal to the zone axis if the crystal were orthorhombic are used in the case of monoclinic and triclinic crystals.

Ordinary crystal drawings, made in this way, are in *clinographic projection*, the observer having moved around to the right an angular distance of 18°26′, and also vertically upward through an angular distance of 9°28′. The relation between a photograph of a crystal model in its proper position for such a drawing and the drawing itself is illustrated by Figs. 17 and 18.

In all ordinary cases crystal drawings differ from photographs of natural crystals in one important respect, namely, they assume that the crystal has developed so as to have full geometrical symmetry, that is, corresponding faces are assumed to be at equal distances from the center as well as to be in their true angular position with respect to other faces and crystal axes.

Certain other types of projection do not give a picture of the crystal, but are very useful since they present a graphic expression of the symmetry and of all the angular relations of the crystal much more clearly and exactly than any picture.

Spherical projection

In *spherical projection* the crystal is supposed to have its center at the center of an enclosing sphere, as in Fig. 19. From the common center a line is drawn normal to each crystal face and this line is continued until it intersects the enclosing sphere. The point of intersection is known as the pole of the given face. The poles of all faces in one zone (that is parallel to one line in the crystal) are in one great circle in the sphere. Conversely, all faces whose poles are in one great circle belong to one zone in the crystal. A face whose pole falls at the intersection of two or more great circles belongs to two or more independent zones in the crystal. The angular relations between the faces are retained exactly on the sphere; the angles on the sphere, being the angles between normals to the faces, are the supplements of the actual interior angles between the faces of the crystals. These angles between the normals to the faces are the "normal interfacial angles" commonly recorded in all the literature on the subject.

It is customary to place the crystal so that the vertical axis is normal to the equatorial plane of the sphere; then an orthorhombic crystal has the pole of the face 001 at the north pole of the sphere and any crystal has the faces of the prism zone

(100, 110, 010, $\bar{1}10$, etc.) on the equatorial circle. Since crystals are commonly alike at the two ends of the vertical axis, it is

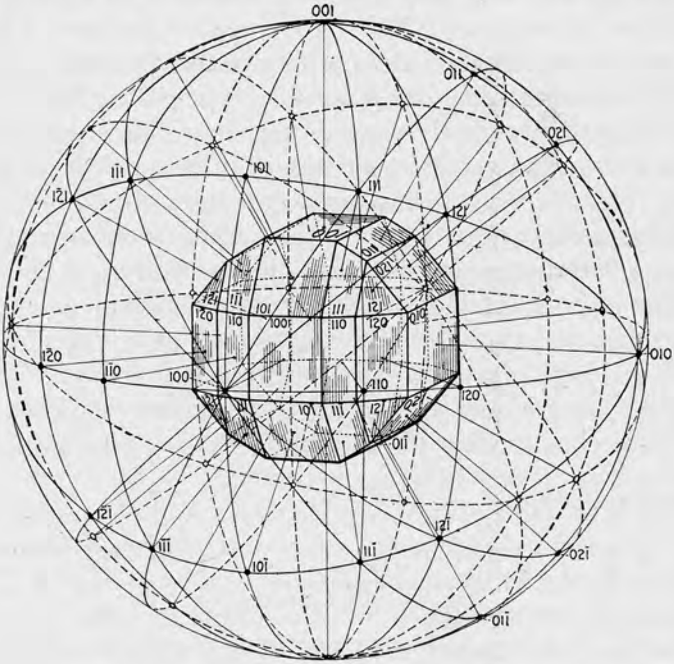

FIG. 19. Derivation of spherical projection.

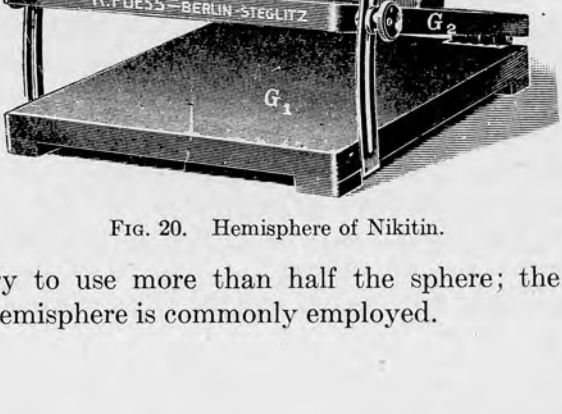

FIG. 20. Hemisphere of Nikitin.

unnecessary to use more than half the sphere; the upper or northern hemisphere is commonly employed.

The chief disadvantage of spherical projection is that the surface of projection is curved and therefore can be shown in a plane figure only pictorially or by means of another projection. To use the spherical projection directly an actual spherical surface is needed; a hemisphere, such as that of Nikitin[5] (Fig. 20), with movable graduated circles, serves the purpose well. The most important method used to convert a spherical projection into a plane figure is the stereographic projection.

Stereographic projection

The *stereographic projection* may be derived from the spherical projection by projecting each pole on the upper hemisphere onto the equatorial plane of the sphere by means of a straight line from the pole of the face to the south pole of the sphere, as shown in Fig. 21. In the figure it is evident that lines (of projection) are drawn from each pole on the upper hemisphere

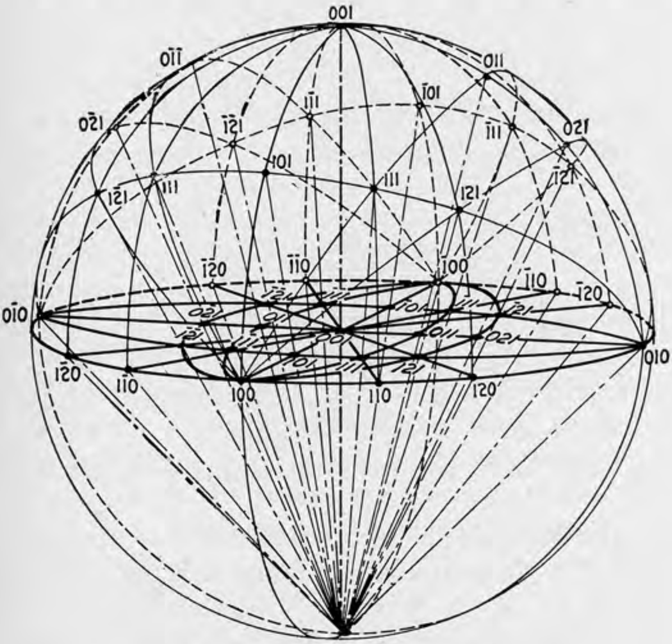

FIG. 21. Derivation of stereographic projection.

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[5] *Zeit. Kryst.*, XLVIII, 1910, p. 379.

to the south pole of the sphere; the points where these lines intersect the equatorial plane (which is the plane of projection) are the poles of their respective faces in a stereographic projection. The stereographic projection of the crystal of Fig. 19 derived from the spherical projection, as shown in Fig. 21, is represented in full view in Fig. 22. It is important to note that all great circles of the spherical projection appear as arcs of true circles in the stereographic projection, the only apparent exception being that all great circles passing through both the north and south poles of the spherical projection appear as straight lines in the stereographic projection (but such lines are arcs of circles of infinite radius). The poles of all faces which are parallel to the vertical axis of the crystal are on the equator of the spherical projection and remain at the same points on the boundary circle (equator) of the stereographic projection. The pole of a face normal to the vertical axis of the crystal is at the north pole of the spherical projection and at the center of the

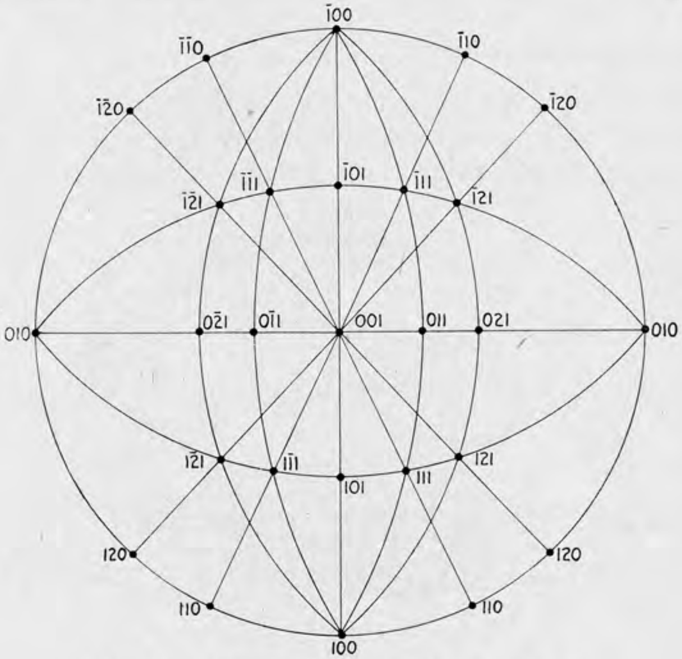

FIG. 22. Example of a stereographic projection.

stereographic projection. Penfield[6] devised convenient protractors for plotting and for measuring angles in stereographic projections of definite radius.

The stereographic projection is well adapted to show the symmetry of crystals, as illustrated in Fig. 22.

X-ray Study of Crystals

It has been stated that crystals are built of units which are regularly arranged throughout any single crystal. For many years such a statement could be made only as a theory derived from a study of the external faces and the cleavages of crystals. For many years, also, these units were supposed by nearly all mineralogists to be molecules, though one student of crystals (Groth) concluded that they were atoms. During this same period it was demonstrated mathematically that there are only fourteen possible arrangements of units (of one kind) in space of such a kind that there is exactly the same arrangement of units about any one as there is about any other one; and also such that a straight line passing through any two units will pass through a succession of similar units at equal intervals, and any parallel line drawn through any similar unit will do likewise. These are the fourteen *space-lattices* whose elementary cells are shown in Figs. 23–36, each cell consisting of the smallest number of units which completely determine[7] the space-lattice. These fourteen space-lattices have the same symmetry as is found in crystals of maximum symmetry in each of the six crystal systems and also in that of the trigonal division of the hexagonal system. Three of them belong to the isometric system, two to the tetragonal, one each to the hexagonal and trigonal divisions of the hexagonal system, four to the orthorhombic system, two to the monoclinic, and one to the triclinic.

These fourteen space-lattices served as a theoretical explanation of the structure and symmetry of seven classes or "point-groups" of crystals, but failed to explain the crystals of lower symmetry in each crystal system. The theory was successfully

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[6] *Am. Jour. Sci.*, CLXI, 1901, p. 10.

[7] In the hexagonal cell more units are shown than strictly necessary, because they make the pattern much more easily understood.

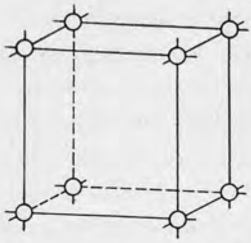

FIG. 23. Simple cubic space lattice.

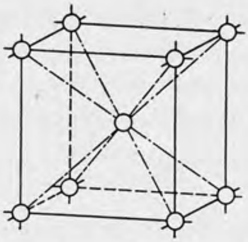

FIG. 24. Body-centered cubic space lattice.

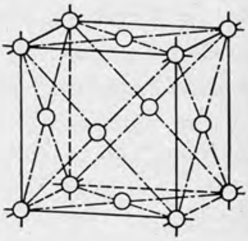

FIG. 25. Face-centered cubic space lattice.

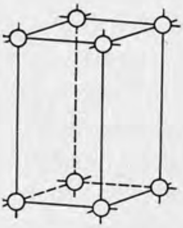

FIG. 26. Simple tetragonal space lattice.

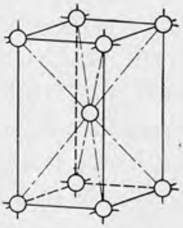

FIG. 27. Body-centered tetragonal space lattice.

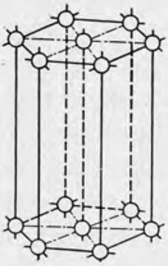

FIG. 28. Hexagonal space lattice.

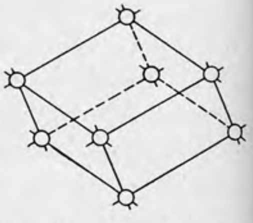

FIG. 29. Rhombohedral space lattice.

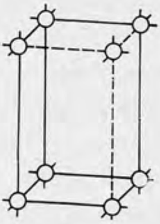

FIG. 30. Simple orthorhombic space lattice.

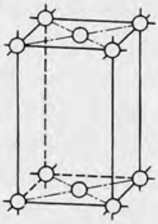

FIG. 31. Base-centered orthorhombic space lattice.

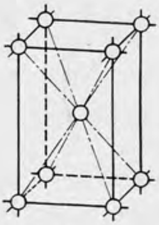

FIG. 32. Body-centered orthorhombic space lattice.

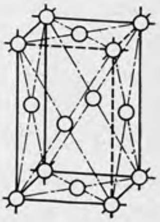

FIG. 33. Face-centered orthorhombic space lattice.

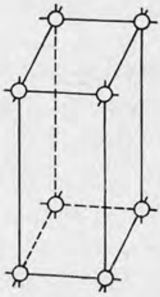

FIG. 34. Simple monoclinic space lattice.

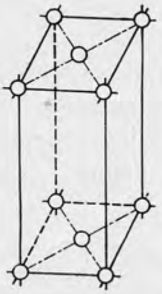

FIG. 35. Base-centered monoclinic space lattice.

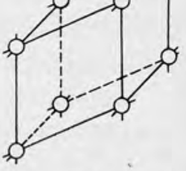

FIG. 36. Triclinic space lattice.

extended to include all types of symmetry which are possible by assuming that two or more space-lattices may interpenetrate according to definite laws. This extension led to the conclusion that just as there are three space-lattices, each having the symmetry of the normal class of the isometric system, so there are several (or even in some cases many) interpenetrating structures having the symmetry of a given class (or point-group). By working out the problem in detail it was proved that there are exactly 230 "space-lattice point-groups"—commonly called "space-groups."

Thirty years ago all of this interesting explanation of the structure of crystals was only a theory and there seemed to be no chance that it could ever be tested by observation, because the units of structure of crystals were obviously far too small to be visible even with the most powerful microscope, and no other method of direct observation or measurement was known. What was needed was some means of measuring the distances between the units in various directions so as to get exact information regarding their arrangement in space. These distances were obviously far too small to be measured by any "yard-stick" (or unit of measurement) then known.

It was in 1912 that Friedrich von Laue conceived the idea that the wave-length of the X rays (which Roentgen had discovered about fifteen years before) might serve as such a unit of measurement. Accordingly, he tried the experiment of passing these rays through a crystal (of sphalerite) knowing that if the distance between units of structure of crystals was about the same as the wave-length of the X rays, these rays would be diffracted by the crystal structure and interference phenomena would result. He used a beam of X rays of varying wave-length and caused the rays to pass through a crystal in a definite direction, such as parallel with an axis of fourfold symmetry of a cube. After passing through the crystal the rays were allowed to strike a photographic plate. It was known that a single beam of X rays will produce a spot on such a plate. It was hoped that the planes of units of structure in the crystal might reflect the rays *in phase* to produce other spots. The results were most satisfactory. As illustrated in Fig. 37 the

X rays passing through a crystal parallel with an axis of symmetry produce a pattern showing exactly that symmetry. Similar patterns produced by X rays passing through sphalerite along an axis of threefold and fourfold symmetry are shown in Figs. 38, 39. The pattern produced by X rays passing through beryl along the sixfold axis is shown in Fig. 40.

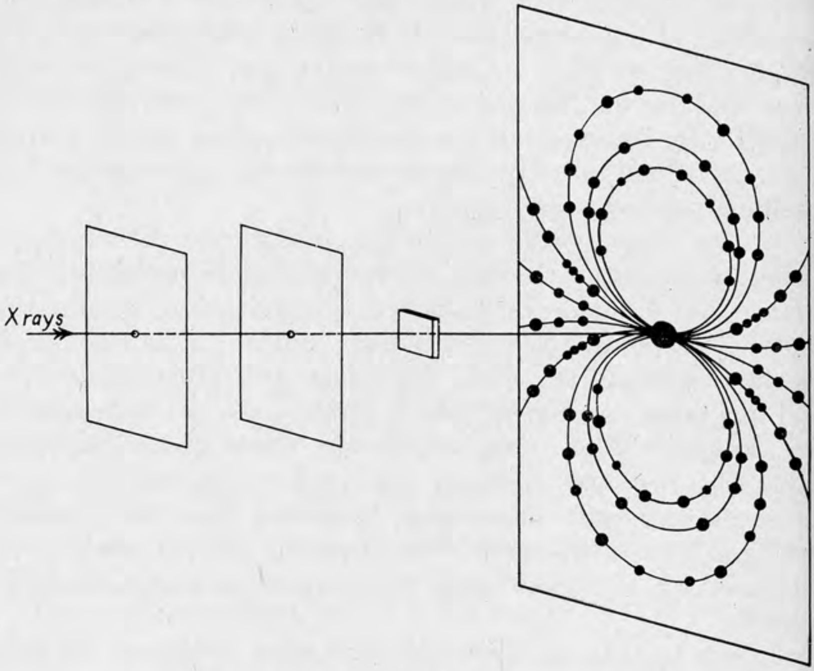

FIG. 37. Derivation of Laue X-ray pattern.

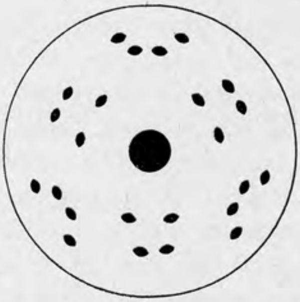

FIG. 38. Laue pattern of sphalerite along a threefold axis of symmetry.

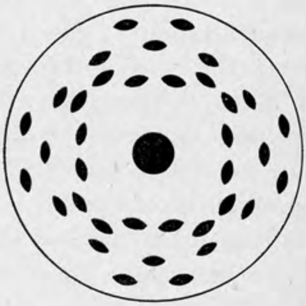

FIG. 39. Laue pattern of sphalerite along a fourfold axis of symmetry.

Not long afterward W. H. and W. L. Bragg (father and son) used X rays to learn the exact arrangement of the units of structure in halite, by reflecting monochromatic rays from a definitely oriented crystal face. Instead of recording the rays on a photographic plate they used them to discharge an electroscope. By measuring the angle of incidence at which the discharge took place they were able to calculate the distance between two adjacent layers or planes of the units of structure by means of the formula given below. Accordingly, by obtaining the distances between planes parallel to the cubic faces and then parallel to octahedral faces and also parallel to dodecahedral faces (assuming only that the intersections of these planes marked the actual positions of the units) they were able to calculate the exact positions of all the units.

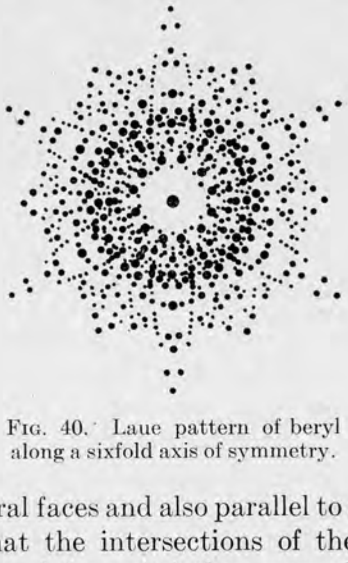

FIG. 40. Laue pattern of beryl along a sixfold axis of symmetry.

If X rays of wave-length λ are reflected from a crystal face FF at an angle of incidence θ (Fig. 41) it is easy to demonstrate geometrically that the two rays r and r' will differ in path by one wave-length when $\lambda = 2d \sin \theta$, if d is the distance between adjacent layers or planes of the units of structure. The difference of phase is equal to the difference of path and in traveling to O one ray has the path rO and the other has the path $rO' + O'O$. Now $rO = r'O' + O'P = r'O' + O'P'$; therefore the difference of path (and of phase) is $P'O$, or Pm, which equals $Om \sin \theta$ or $2d \sin \theta$.

Knowing the exact position in space of all the units of structure of a crystal, say of halite, it is easy to learn whether its units are atoms or molecules, since a cubic centimeter, for example, must contain n units of structure; if these units were molecules of NaCl the cubic centimeter would weigh $n \times (23 + 35.5)$; but the observed weight is only half that amount, which proves that these units are atoms.

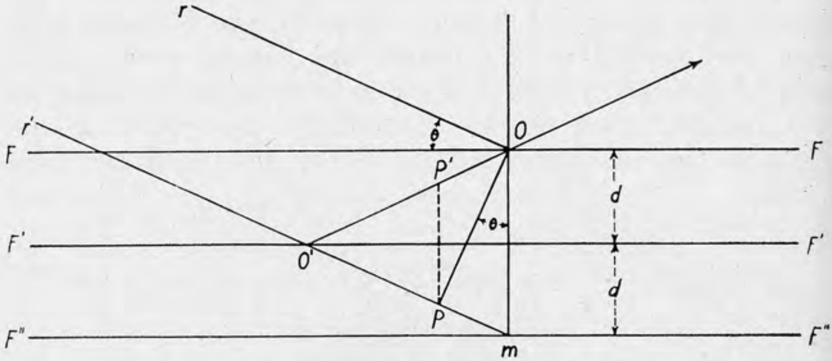

FIG. 41. Reflection of X rays by crystal structure.

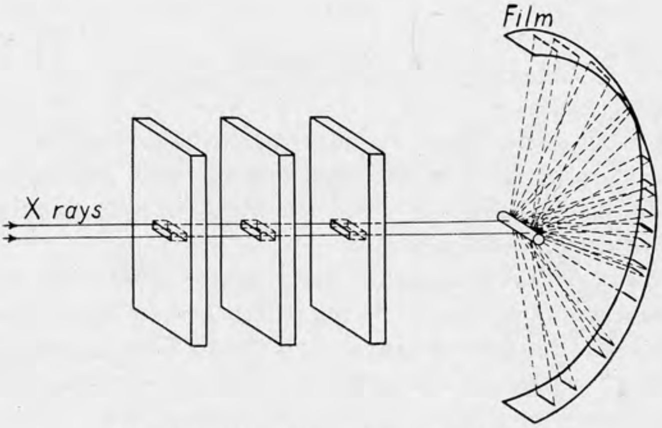

FIG. 42. Derivation of powder patterns.

A few years later (in 1917) Hull in America and Debye and Scherrer in Europe independently developed a method of X-ray study of crystal structure which does not require the use of well developed single crystals. Indeed, in this case the sample must be reduced to a fine powder, which is placed in a tiny capillary glass tube. Monochromatic X rays are passed through tiny slits in lead plates before striking the glass tube (which is parallel with these slits). The X rays are diffracted by the powder particles and recorded on semicircular photographic film at a uniform distance from the powder (Fig. 42). All particles which are not in suitable position to diffract the rays from any internal planes *in phase* produce no effect; all others aid in formation of the bands on the film, each band being produced by internal planes in one crystallographic position, with its own characteristic spacing. Accordingly, the structure can be determined by identifying the internal planes producing each band. This is usually easily accomplished with isometric, tetragonal, or hexagonal crystals. Each substance produces many reflections in the powder patterns, and each pattern is characteristic of one phase of one substance. Therefore this method is especially useful in identifying very fine-grained minerals or even mineral aggregates (assuming each constituent to be present in considerable quantity). A powder pattern (or "finger print") of pyrite (FeS_2) is shown in Fig. 43*A*, of halite (NaCl) in Fig. 43*C*, and of a mixture of pyrite and halite in Fig. 43*B*.

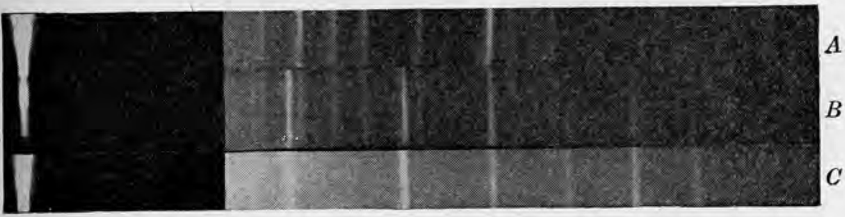

FIG. 43. Powder patterns.

These new X-ray methods of study of crystals very quickly completely transformed the situation regarding our knowledge of crystal structure. Whereas, beforehand it was possible only to theorize regarding the subject, it now became possible to obtain precise information. This new information promptly proved the correctness of Groth's theories regarding crystal structure and laid the foundation for the rapid extension of our knowledge of the structure of minerals, so that today the exact arrangement of the atoms is known for many minerals, even including some which are extremely variable and complicated. Illustrations of some of the simpler structures are given in Fig. 1 of halite (NaCl), Fig. 2 of calcite ($CaCO_3$), Fig. 44 of fluorite (CaF_2), Fig. 45 of sphalerite (ZnS), and Fig. 46 of cassiterite (SnO_2).

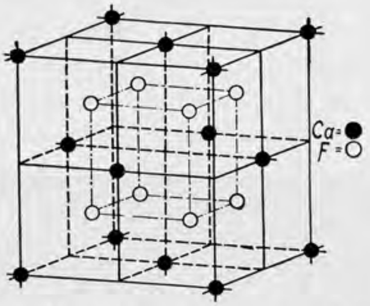

FIG. 44. Unit cell of fluorite, CaF_2.

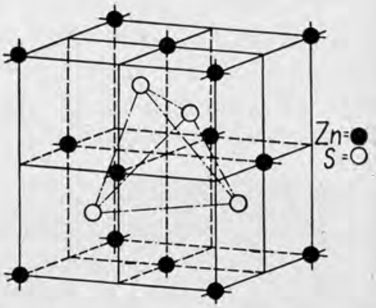

FIG. 45. Unit cell of sphalerite, ZnS.

The most important methods of X-ray study of crystal structures may be briefly summarized, as follows:

1. Using oriented single crystals or crystal plates.

A. *Laue method.* A pinhole beam of white X rays is passed through a stationary oriented crystal and diffracted by it to produce a pattern of spots on a photographic plate. This method is especially useful to determine the symmetry.

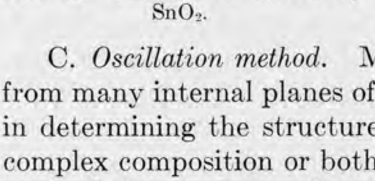

FIG. 46. Unit cell of cassiterite, SnO_2.

B. *Bragg method.* Monochromatic X rays are reflected from a single rotating crystal and used with an ionization chamber. This method is a direct means of calculating interplanar spacing of the crystal structure.

C. *Oscillation method.* Monochromatic X rays are reflected from many internal planes of atoms. This method is important in determining the structure of crystals of lower symmetry or complex composition or both.

2. Using finely powdered material.

A. *Hull, Debye-Scherrer, or powder method.* Monochromatic X rays are passed through a capillary glass tube filled with fine powder and the reflected rays are recorded on a semicircular photographic film. Only particles in proper position to reflect the rays *in phase* from some internal planes of atoms produce any effect, but a finely ground powder contains enough such particles to produce an excellent pattern. This method is very useful in identifying substances and in studying the structure of substances not available in good crystals.

Systems of Crystallization and Symmetry Classes

The study of crystals has shown that they can all be referred to six[8] crystal systems distinguished by the relative lengths and angular inclinations of the crystallographic axes which are properly assumed in each case; and, further, they can all be referred to thirty-two classes or "point-groups" on the basis of the symmetry which they possess. Each system includes two or more of the symmetry classes or point groups. In each system one class, which has the highest grade of symmetry and is most abundantly represented among minerals, is known as the normal class. The classes belonging to any one system not only may be referred to the same type of axes, but also include minerals with similar optical properties, and, with one exception, these optical properties may be used to distinguish the system to which the given mineral belongs.

The six crystal systems and their respective symmetry classes are given below, together with certain examples:

I. Isometric System includes the Normal, Pyritohedral, Tetrahedral, Plagihedral, and Tetartohedral Classes.

II. Tetragonal System includes the Normal, Hemimorphic, Tripyramidal, Pyramidal-Hemimorphic, Sphenoidal, Trapezohedral, and Tetartohedral Classes.

III A. Hexagonal System, Hexagonal Division includes the Normal, Hemimorphic, Tripyramidal, Pyramidal-Hemimorphic, Trapezohedral, Trigonal, and Trigonal-Tetartohedral Classes.

III B. Hexagonal System, Trigonal Division includes the Rhombohedral, Rhombohedral-Hemimorphic, Trirhombohedral, Trapezohedral, and Trigonal Tetartohedral Hemimorphic Classes.

IV. Orthorhombic System includes the Normal, Hemimorphic, and Sphenoidal Classes.

V. Monoclinic System includes the Normal, Hemimorphic, and Clinohedral Classes.

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[8] Some writers recognize seven crystal systems, considering each part of the hexagonal system (as described in this book) an independent system.

VI. Triclinic System includes the Normal and Asymmetric Classes.

The Hermann-Mauguin symbols, which are given in the following sections devoted to a description of the features of each crystal class or point group, are based upon certain conventions in each system. From these symbols it is possible to derive all the different elements of symmetry in each class, although the symbols themselves stand for only the minimum number of elements sufficient to define the class. The symbols themselves have been explained in the table on page 12. They are always arranged in a definite order, as follows:

Isometric system: the *a*-axis first; then the axis of the cubic body-diagonal normal to 111; then the axis of the cubic face-diagonal normal to 110.

Tetragonal system: the *c*-axis first; then the *a*-axis; then the direction normal to 110 at 45° to the *a*-axes and 90° to the *c*-axis.

Hexagonal system: the *c*-axis first; then the *a*-axis; then the direction normal to $11\bar{2}0$ at 30° to the *a*-axis and 90° to the *c*-axis.

Orthorhombic system: the *a*, *b*, and *c* axes in any order.

Monoclinic system: the *b*-crystallographic axis.

Triclinic system: (any direction).

Isometric System

All crystals which are referred to three equal rectangular axes belong to the isometric system (also known as cubic or regular system). Since these axes are equal in length and at right angles, they are interchangeable, and therefore all are designated by the letter *a*. When properly oriented for study an isometric crystal has any one of these in the vertical position, one extending right and left, and the other front and rear. Even in this case with interchangeable axes, the axes are always referred to in the same order as if the axes were unequal; that is, the first axis, a_1, has its positive direction in front and so may be said to "point" to the front; the second axis, a_2, points to the right; the third axis, a_3, points upward, as shown in Fig. 47.

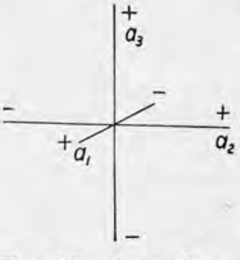

FIG. 47. Axes of an isometric crystal.

There are five symmetry classes in the isometric system. The normal class, which has the highest symmetry known among crystals, is far the most important. Two other classes, the pyritohedral and tetrahedral, are illustrated by important minerals and will be described. These classes may be listed as follows:

1. Normal class—center, 3 crystal axes 4-fold, 4 diagonal axes 3-fold, 6 diagonal axes 2-fold, 3 principal axial planes, 6 diagonal planes of symmetry. ($m\ 3\ m$)
2. Pyritohedral class—center, 3 crystal axes 4-fold, 4 diagonal axes 3-fold and 3 principal axial planes of symmetry. ($m\ 3$)
3. Tetrahedral class—3 crystal axes 2-fold, 4 diagonal axes 3-fold and 6 diagonal planes of symmetry. ($\bar{4}\ 3\ m$)
4. Plagihedral class—3 crystal axes 4-fold, 4 diagonal axes 3-fold and 6 diagonal axes of 2-fold symmetry. (4 3)
5. Tetartohedral class—3 crystal axes 2-fold and 4 diagonal axes of 3-fold symmetry. (2 3)

The Hermann-Mauguin or international symbols for the isometric system are easily recognized from the fact that they always have 3 in the second position, because all isometric crystals have four diagonal axes of threefold symmetry.

Normal or hexoctahedral class ($m\ 3\ m$)

Symmetry. All crystals of this class have a center of symmetry, thirteen axes of symmetry, and nine planes of symmetry. Since there is a center of symmetry, for any face present on a crystal there is a similar face directly opposite it on the other side of the center. The thirteen axes of symmetry are of three kinds. There are three axes of fourfold symmetry normal to the faces of a cube (Fig. 48). These are the crystal axes. There are four axes of threefold symmetry connecting

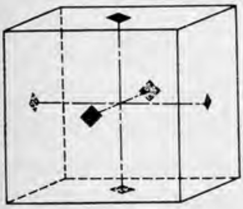

FIG. 48. Axes of fourfold symmetry of an isometric crystal.

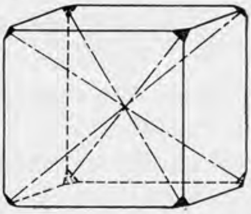

FIG. 49. Axes of threefold symmetry of an isometric crystal.

opposite solid angles of a cube and normal to octahedral faces (Fig. 49), and six axes of twofold symmetry connecting opposite midpoints on the edges of a cube and normal to the dodecahedral faces (Fig. 50). These lie in the principal planes of symmetry and bisect the angles between the crystallographic axes. Three of the nine planes of symmetry are called axial planes since they each include two crystallographic axes (Fig. 51); they are called also principal planes, since the crystal axes are equal; the six others (Fig. 52) are diagonal planes of symmetry bisecting the angles between the axial planes. All these elements of symmetry are shown in Fig. 53.

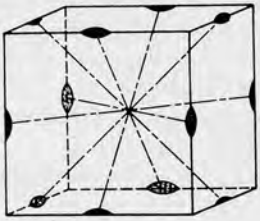

FIG. 50. Axes of twofold symmetry of an isometric crystal.

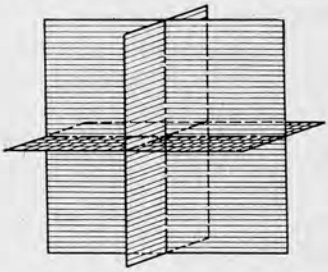

FIG. 51. Principal planes of symmetry of an isometric crystal.

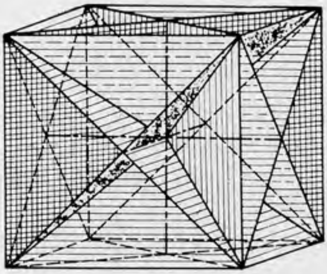

FIG. 52. Diagonal planes of symmetry of an isometric crystal.

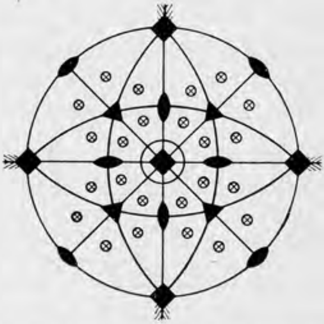

FIG. 53. Symmetry of the normal class of the isometric system.

The international symbol ($m\,3\,m$) for this symmetry class explicitly indicates only three of the 23 elements of symmetry enumerated above, but by operating on one another, these three are sufficient to derive the entire 23 belonging to the class. First, the axial plane of symmetry normal to a_1 indicated by the first m becomes three axial planes (Fig. 51) by the action of the threefold axis of symmetry lying parallel to the cubic body-diagonal, indicated by the "3." Then the single diagonal plane of symmetry specifically indicated by the last *m* becomes two diagonal planes by the action of the specifically indicated axial plane, and the threefold axis multiplies these two planes to form the six diagonal planes (Fig. 52). The axial planes moreover multiply the threefold axis to produce the four threefold axes of symmetry. Thus are developed all the nine planes of symmetry of the cube, and the four threefold axes. It can be proved that the line of intersection of two planes of symmetry at right angles to one another is a twofold axis of symmetry, and that the common line of intersection of four planes making angles of 45° and 90° with one another (for example, the two axial and the two diagonal planes, which all intersect an *a*-axis in the isometric normal class) is a fourfold axis of symmetry. These two theorems prove the existence of the three axial axes of fourfold symmetry and the six diagonal axes of twofold symmetry. Careful consideration will show that the three axial planes of symmetry operate in such a way that a center of symmetry must exist. Thus all 23 of the elements of symmetry described in the preceding paragraph can be derived from the three elements used in the international symbol.

Forms. The crystal forms belonging to this class may be found by a simple method. First, assume that a face cuts all three of the crystallographic axes at equal distances. Whatever the actual distance may be, it may be considered unit distance, since the size of a crystal is unimportant and only the angular positions of faces are significant; the angular positions depend upon *relative* distances on the axes, not on the actual distances. Next, find all the other faces required by the symmetry, if the one face is present. In this case, the principal (axial) planes of symmetry clearly require a total of eight faces, if one such face is present. For example, if the face 111 is present, then the vertical plane of symmetry containing a_1 and a_3 requires the presence of the face $1\bar{1}1$; if these two faces are present, the vertical plane of symmetry containing a_2 and a_3 requires the presence of the faces $\bar{1}11$ and $\bar{1}\bar{1}1$; if these four faces are present above the center, the horizontal plane of symmetry containing a_1 and a_2 requires the presence of the four faces below: $11\bar{1}$,

$1\bar{1}\bar{1}$, $\overline{111}$, and $\bar{1}1\bar{1}$. These eight faces are a complete crystal form, since they satisfy all the elements of symmetry which are present, although only three of those elements were used in deriving them. Since this form (Figs. 54 and 55) has eight faces it is called the *octahedron* (or eight-faced solid). Its Miller symbols are (111), since in this book symbols *alone* stand for one face (or its direction), while symbols (ordinarily of a face in the positive octant) *enclosed in parentheses* stand for a complete crystal form. Each face of the octahedron is an equilateral triangle; the angle between faces is 109° 28′ 16″; but in mathematical crystallography the angle between normals to faces (called normal interfacial angle) is far more important than the angle between faces; of course in this case the normal interfacial angle is 70° 31′ 44″. The crystallographic axes connect the opposite tetrahedral solid angles of the octahedron.

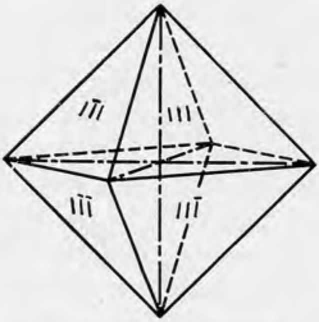

FIG. 54. The octahedron.

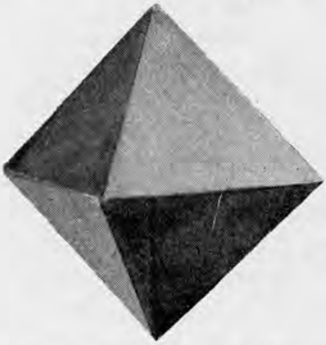

FIG. 55. Photograph of the octahedron.

What other forms are there which have the same symmetry as the octahedron? This question may be answered by considering all possible ways in which the position of the one face, 111, may be modified. It is clear that change in its position can be accomplished in only three ways, namely:

1. Increase[9] in the intercept on one axis, the other two remaining fixed.

2. Increase in the intercepts on two axes *at the same rate*, the other one remaining fixed.

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[9] Decrease in the intercept might be considered but would not change the final results.

3. Increase in the intercepts on two axes at *different rates*, the other one remaining fixed.

Increase in the intercepts on all three axes need not be considered, because no matter how much change there may be, one axis may always be assumed to be unity, since only *relative* distances are important.

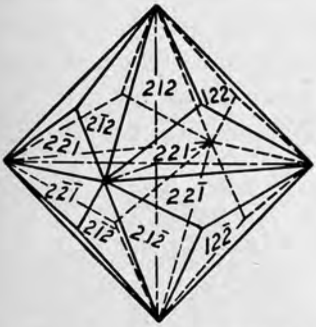

FIG. 56. The trisoctahedron (221).

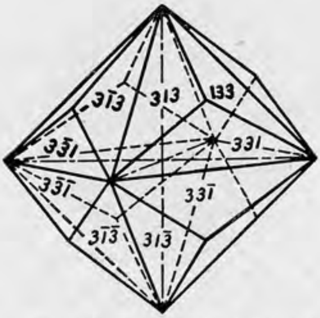

FIG. 57. The trisoctahedron (331).

1. Assuming the first case, if the original face be assumed to cut a_1 and a_2 at unity and a_3 at some simple multiple such as 2, its parameters are 112 and its Miller symbols are 221. If the face 221 (Fig. 56) is present, the threefold axis of symmetry normal to 111 requires the presence of two other faces, 212 and 122, in the same octant. If these three faces are present in the positive octant (= the space limited by the positive directions on the three crystal axes), then the principal plane of symmetry containing a_1 and a_3 requires the presence of the three faces, $2\bar{1}2$, $2\bar{2}1$, and $1\bar{2}2$, in the upper front left octant. If these six faces are present in front above the center, the principal plane of symmetry containing a_2 and a_3 requires the presence of three similar planes in each of the upper rear octants. And if these twelve faces are present above the center, the horizontal plane of symmetry containing a_1 and a_2 requires the presence of twelve faces below, three in each octant; this form has twenty-four faces, three in place of each one of the

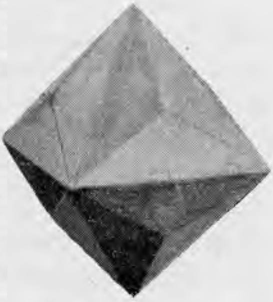

FIG. 58. Photograph of a trisoctahedron.

octahedron, and is called the *trisoctahedron.* (To distinguish it from the trapezohedron, sometimes called the tetragonal trisoctahedron, it is called the trigonal trisoctahedron.) Its Miller symbols in their general form are (hhl); common examples are (221) (Fig. 56) and (331) (Fig. 58).

Once again assuming the first case of an increase in the intercept on one axis, the other two remaining fixed, if this increase continues until the one axis is intersected at infinity, that is, until the face becomes parallel with one axis, a different form is produced. If the original face be assumed to cut a_1 and a_2 at unity and a_3 at infinity, its parameters are $1 1 \infty$ and its Miller symbols are 110. If the face 110 (Figs. 59 and 60) is present, the threefold axis of symmetry normal to 111 requires the presence of 011 and 101. If these three faces are present in the positive octant, the a_1 a_3 symmetry plane requires the presence of three similar faces, $1\bar{1}0$, $0\bar{1}1$, and 101, in the upper front left octant. But it may be noted that the face 101 extends continuously from the first octant into the second. Of course the other vertical symmetry plane requires faces in the rear above corresponding with those in the upper half. As in the one case already noted, it finally appears that each face of the form extends continuously from one octant to another octant. Therefore, while there are three faces in each octant, there are only twelve faces altogether and the form is known from this fact as the *dodecahedron.* Each face of this form (Figs. 59 and 60) is a rhomb with plane angles of 70½° and 109½°. The

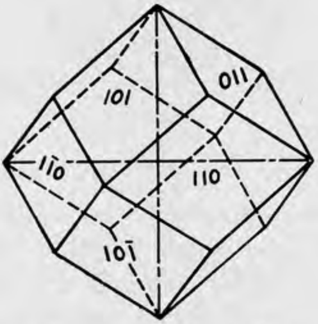

FIG. 59. The dodecahedron.

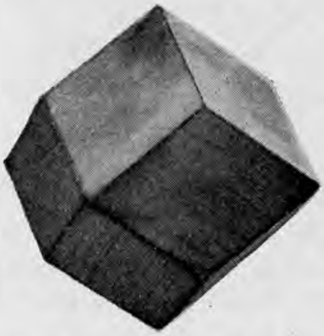

FIG. 60. Photograph of a dodecahedron.

normal interfacial angle is 60°. The crystallographic axes connect opposite tetrahedral solid angles.

2. Considering the second case, if the original face be assumed to cut the axis a_1 at unity and the axes a_2 and a_3 at some simple multiple, say 2, the parameters are 122 and the Miller symbols are 211. If the face 211 is present (Figs. 61 and 62), the threefold axis of symmetry requires the presence of two other faces, 121 and 112, in the positive octant. If these three faces are present in this octant, the vertical plane of symmetry containing a_1 and a_3 requires the presence of three similar faces in the upper front left octant. If these six faces are present in front above the center, the vertical plane of symmetry containing a_2 and a_3 requires the presence of three similar faces in each of the upper rear octants. And if these twelve faces are present above the center, the horizontal plane of symmetry requires the presence of twelve faces below, three in each octant. This form has twenty-four faces, like the trisoctahedron, but each face is a trapezium and the form is accordingly called a *trapezohedron* (also known as a *tetragonal trisoctahedron*). The Miller symbols in their general form are *hll*; common examples are (211) of Figs. 61 and 62 and (411) of Fig. 63.

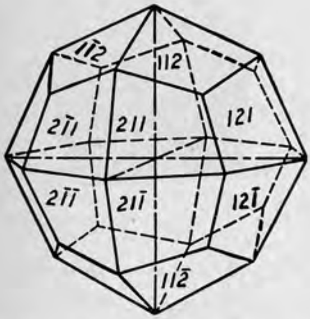

FIG. 61. The trapezohedron (211).

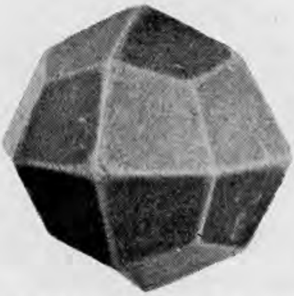

FIG. 62. Photograph of a trapezohedron (211).

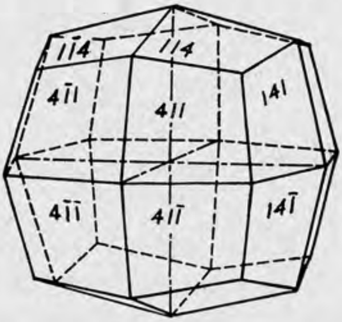

FIG. 63. The trapezohedron (411).

Again considering the second case, if the original face be assumed to cut the axis a_1 at unity and the axes a_2 and a_3 at infinity, it is possible to prove that there are three faces in each octant to satisfy the threefold axes of symmetry; but each face extends into four octants and therefore the number of faces is one fourth of twenty-four, or six. This form is called a hexahedron or merely a *cube*. The Miller symbols are (100). Each face is a square and the interfacial angles are 90°; the faces of the cube are parallel to the principal planes of symmetry and normal to the crystal axes, which are axes of fourfold symmetry, as shown in Figs. 64 and 65.

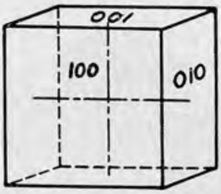

FIG. 64. The cube.

FIG. 65. The cube (photographed)

FIG. 66. The hexoctahedron (421).

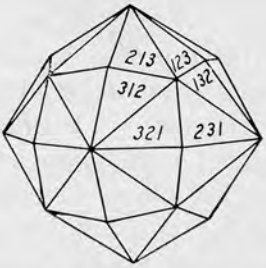

FIG. 67. The hexoctahedron (321).

3. Considering the third case, if the original face be assumed to cut a_1 at unity, a_2 at some simple multiple, say 2, and a_3 at a different multiple, say 4, the parameters are 124 and the Miller symbols are 421. If the face 421 is present (see Fig. 66), the diagonal plane of symmetry No. 1 of Fig. 12 requires the presence of the face 412; and if this face is present, the diagonal plane of symmetry No. 3 of Fig. 12 requires the presence of the face 214. If these three faces are present, the diagonal plane of symmetry No. 5 of Fig. 12 requires the presence of the faces 124,

142, and 241. If these six faces are present in the positive octant, the vertical planes of symmetry require the presence of six similar faces in each of the upper octants; and, if these are present, the horizontal plane of symmetry requires the presence of six faces in each of the four lower octants. Therefore each octant has six faces and the form is called the *hexoctahedron.* It is the most general form of this symmetry class. Each face is a scalene triangle intersecting the three axes at three different distances. The general symbol is (*hkl*): common forms are (421) of Fig. 66 and (321) of Fig. 67. The crystallographic axes connect opposite octahedral solid angles. Axes of threefold symmetry connect opposite hexahedral solid angles. Axes of twofold symmetry connect opposite tetrahedral solid angles.

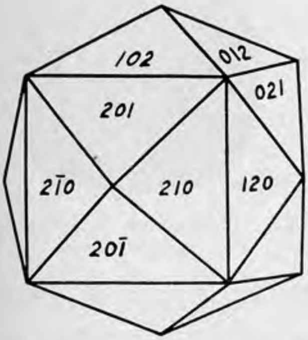

FIG. 68. The tetrahexahedron (210).

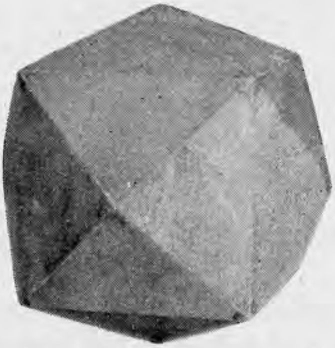

FIG. 69. Photograph of a tetrahexahedron (210).

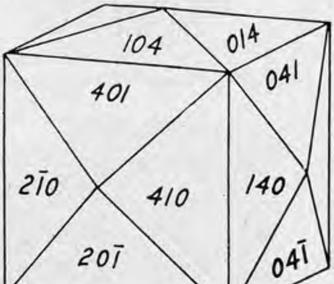

FIG. 70. The tetrahexahedron (410).

Once more considering the third case, if the original face be assumed to cut a_1 at unity, a_2 at some simple multiple, say 2, and a_3 at infinity, the parameters are 12∞ and the Miller symbols are 210 (Figs. 68 and 69). In this case, as with the hexoctahedron, the diagonal planes of symmetry require five other faces in the positive octant if one face is present. And the principal planes of symmetry require six faces in each octant if there are six faces in one octant. But the form has only twenty-four faces since each face belongs to two octants. The form has the outline of a hexahedron or cube and has four faces

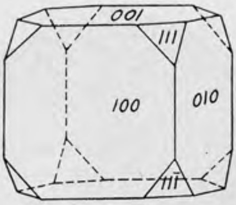

Fig. 71. The cube modified by octahedron.

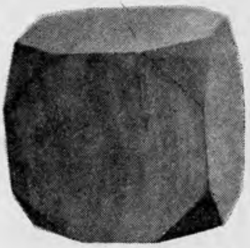

Fig. 72. Photograph of a cube modified by octahedron.

replacing each face of the hexahedron; therefore it is called the *tetrahexahedron*. The general symbol is ($hk0$): examples include (210) of Figs. 68 and 69 and (410) of Fig. 70.

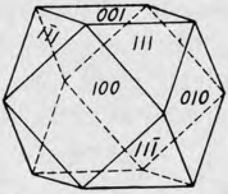

Fig. 73. Cube and octahedron.

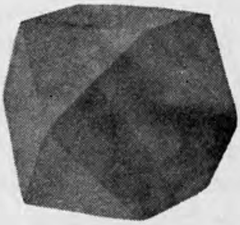

Fig. 74. Photograph of octahedron and cube (turned 45°).

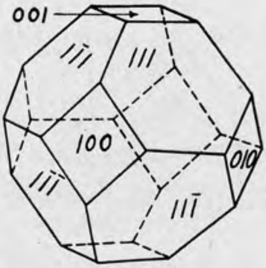

Fig. 75. Octahedron modified by cube.

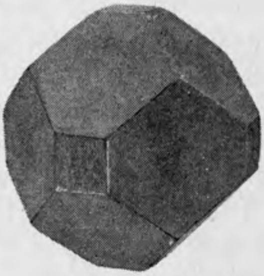

Fig. 76. Photograph of dodecahedron modified by cube.

Combinations. Single crystals often have more than one crystal form. For example, galena often exhibits combinations of the cube and octahedron in which the cube may dominate (Figs. 71 and 72), or the octahedron (Fig. 75), or neither

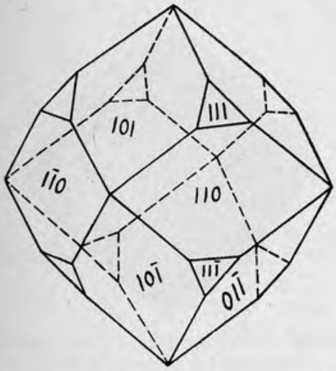

FIG. 77. Dodecahedron modified by octahedron.

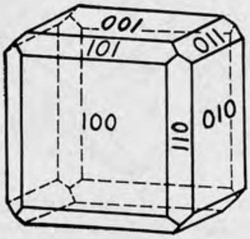

FIG. 78. Cube modified by dodecahedron.

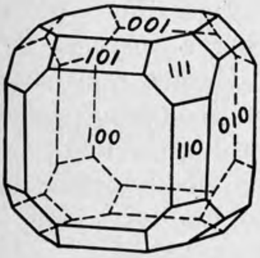

FIG. 79. Cube, octahedron, and dodecahedron.

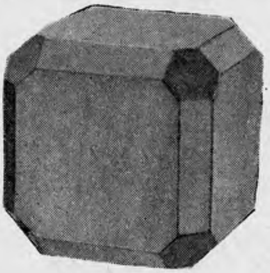

FIG. 80. Photograph of cube, octahedron, and dodecahedron.

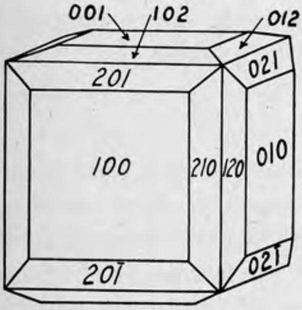

FIG. 81. Cube modified by tetrahexahedron.

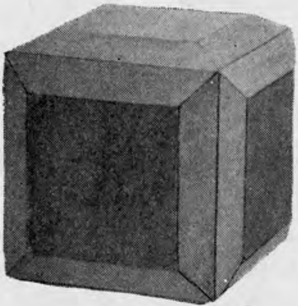

FIG. 82. Photograph of cube modified by tetrahexahedron.

(Figs. 73 and 74). Spinel often shows the dodecahedron modifying the octahedron. Magnetite may present the octahedron modifying the dodecahedron (Fig. 77). Fluorite shows the dodecahedron modifying the cube (Fig. 78). Galena often shows combinations of the three forms: cube, octahedron, and dodecahedron in varying prominence, as in Figs. 79 and 80. Halite may show the tetrahexahedron modifying a cube, as in Figs. 81 and 82. Garnet may show the trapezohedron modifying the dodecahedron, as in Figs. 83 and 84, or the hexoctahedron modifying the dodecahedron, as in Fig. 85. Many other combinations are found.

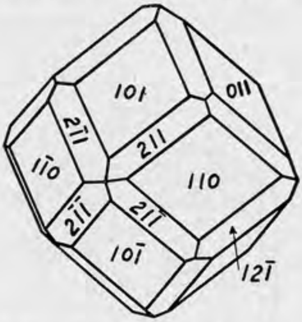

Fig. 83. Dodecahedron modified by trapezohedron.

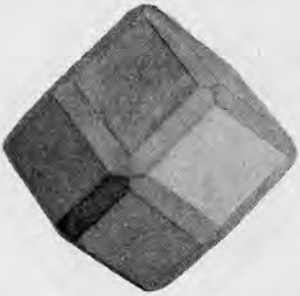

Fig. 84. Photograph of dodecahedron modified by trapezohedron.

Summary. The forms of the normal class of the isometric system are listed in the table shown on page 43, together with symbols, faces, angles, and symmetry.

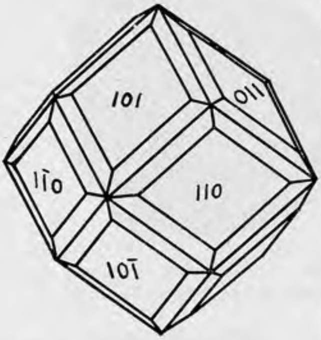

Fig. 85. Dodecahedron modified by hexoctahedron.

Pyritohedral class (m 3)

Symmetry. Crystals of the pyritohedral class have a center of symmetry, three axes of twofold symmetry which are at right angles to each other and coincide with the crystallographic axes, four axes of threefold symmetry which are normal to the faces of the octahedron, and only three planes of symmetry which are axial planes and parallel to the faces of the cube. In this class the axes of maximum symmetry are not the crystallographic axes. The elements of symmetry of this class are shown in Fig. 86.

Forms	Miller Symbols	Faces	Solid Angles				Normal Interfacial Angles
			Trihedral	Tetrahedral	Hexahedral	Octahedral	
Octahedron	(111)	8	—	6	—	—	70°31′44″
Trisoctahedron	(*hhl*)	24	8	—	—	6	*e.g.* 221 27°16′ and 38°56½′ *e.g.* 331 37°57¾′ and 26°31½′
Dodecahedron	(110)	12	8	6	—	—	60°
Trapezohedron	(*hll*)	24	8	6 + 12	—	—	*e.g.* 211 48°11½ and 33°33½′ *e.g.* 411 27°16′ and 60°0′
Hexahedron or cube	(100)	6	8	—	—	—	90°
Hexoctahedron	(*hkl*)	48	—	12	8	6	*e.g.* 321 21°47¼′, 31°0¼′, 21°47½′ *e.g.* 421 17°45¼′, 25°12½′, 35°57′
Tetrahexahedron	(*hk*0)	24	—	6	8	—	*e.g.* 210 36°52¼′ and 36°52¼′ *e.g.* 410 19°45′ and 61°55¼′

Symmetry	Center	Axes			Planes	
		4-fold	3-fold	2-fold	Axial	Diagonal
	1	3 ⊥ cubic faces	4 ⊥ octahedral faces	6 ⊥ dodecahedral faces	3	6

As in the normal class, so also in the pyritohedral class, the international symbol makes it possible to derive all the symmetry elements described in the preceding paragraph. The threefold axis of symmetry multiplies the specified axial plane to form the three axial planes of symmetry; these planes in turn multiply the threefold specified axis, forming all four of the threefold axes described above; the three axial planes of symmetry again produce the center of symmetry, as was the case in the normal class.

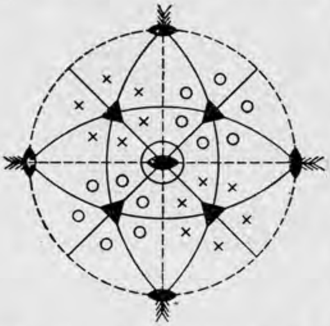
FIG. 86. Symmetry of the pyritohedral class.

Forms. Applying the same method to find the crystal forms as already used in the normal class it is evident that the same forms will be obtained in so far as the same elements of symmetry are used. A careful review will show that the three principal planes of symmetry and the threefold axes of symmetry were the only elements used to derive the following forms: octahedron, trisoctahedron, dodecahedron, trapezohedron, and hexahedron or cube. These forms are therefore not characteristic of the normal class since they belong also to the pyritohedral class. Indeed, the most general form (*hkl*) is the only one which is always characteristic of a class, and discloses its symmetry unmistakably. An octahedron (or other non-characteristic form) of this class cannot be distinguished geometrically from an octahedron (or other form) of the normal class; but X-ray studies prove that the symmetry of the internal structure of any crystal of this class is different from that of any crystal of the normal class.

To find the other forms of this class it is necessary to consider the third case described under the normal class. If the original face be assumed to cut a_1 at unity, a_2 at some simple multiple, say 1.5, and a_3 at some other simple multiple, say 3, the Miller symbols are 321. If the face 321 is present (Figs. 87 and 88), the threefold axis of symmetry normal to 111 requires two other faces, 213 and 132, in the positive octant, and the axial planes of symmetry require three similar faces in each octant. The faces are grouped in pairs and the form is therefore known as the *diploid*. Starting with another face of the hexoctahedron, such as 312, a complementary so-called *negative* diploid can be derived, as in Fig. 89. The positive diploid (321) and the negative diploid (312) together have all the faces of the hexoctahedron; either one has alternate faces of that form. The relation between the diploid and the hexoctahedron is shown in Fig. 90, where alternate faces of the hexoctahedron, indicated by shading, are extended to form the faces of the positive diploid.

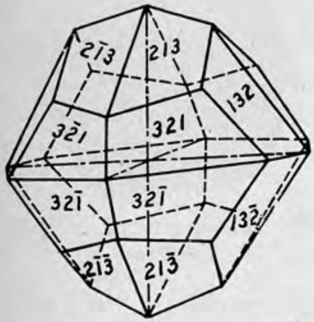

FIG. 87. The diploid (positive.)

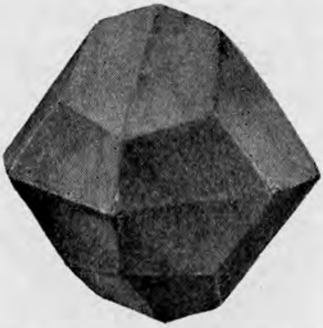

FIG. 88. Photograph of diploid (positive).

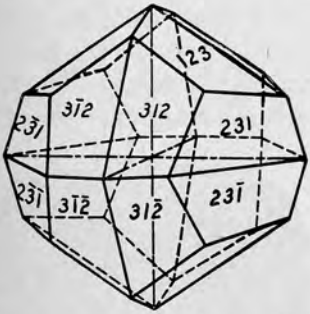

FIG. 89. The diploid (negative.)

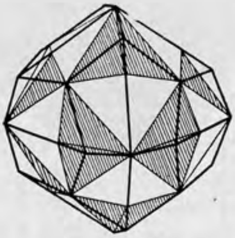

FIG. 90. Relation between diploid and hexoctahedron.

Considering once again the third case described under the normal class, if the original face cuts one axis, a_1, at unity, a second axis, a_2, at a simple multiple, say 2, and the third axis, a_3, at infinity, the symbols are 210. If this face is present

(Figs. 91 and 92), the threefold axis of symmetry normal to 111 requires the presence of 102 and 021 in the same octant. And the axial planes of symmetry require three similar faces in each octant. Each face extends from one octant into an adjoining octant, so the form has only twelve faces, each face having five sides. The form is sometimes called the *pentagonal dodecahedron*, but the five sides of each face are not all equal, so the form is not the same as the regular pentagonal dodecahedron of geometry, which is impossible in crystallography, since it must have an irrational intercept on one axis $[(1 + \sqrt{5})/2]$, an impossible condition in a crystal. The form (210) is called the *pyritohedron* because it is a common form of the ordinary mineral called pyrite (FeS_2). A negative pyritohedron is illustrated in Fig. 93.

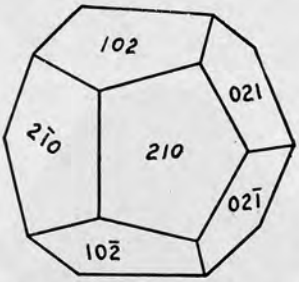

FIG. 91. The pyritohedron (positive).

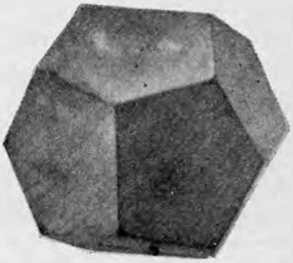

FIG. 92. Photograph of pyritohedron (positive).

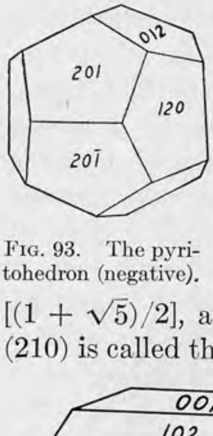

FIG. 93. The pyritohedron (negative).

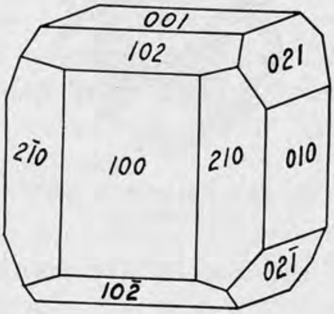

FIG. 94. Cube and pyritohedron.

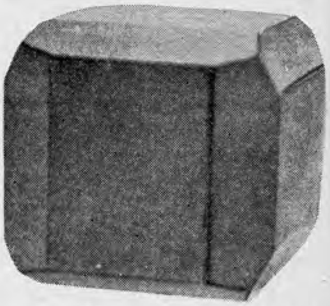

FIG. 95. Cube and pyritohedron, photographed.

Combinations. Pyrite (FeS_2) frequently shows more than one form in a single crystal; for example, the cube and pyritohedron may be present together, as in Figs. 94 and 95. Again, the pyritohedron may modify the octahedron, as in Figs. 96 and 97, or the two forms may be equally developed as in Figs. 98 and 99. This combination closely resembles the icosahedron or regular twenty-faced solid of geometry, but is not the same, since the eight octahedral faces are equilateral triangles while the twelve pyritohedral faces are isosceles triangles. The diploid faces modify the cube in Fig. 100. Pyrite often shows striations on cubic faces, as in Fig. 101, which demonstrate at once that each crystal axis is an axis of twofold and not fourfold symmetry.

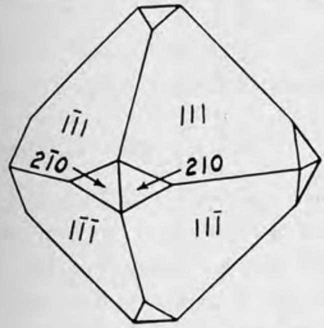

Fig. 96. Octahedron modified by pyritohedron.

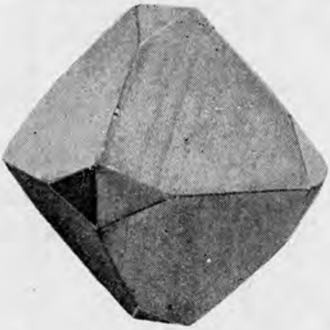

Fig. 97. Photograph of octahedron modified by pyritohedron.

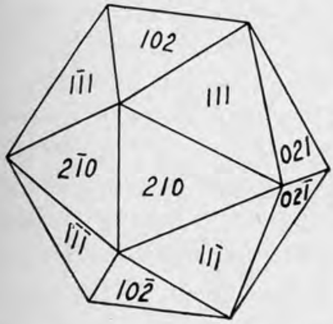

Fig. 98. Octahedron and pyritohedron.

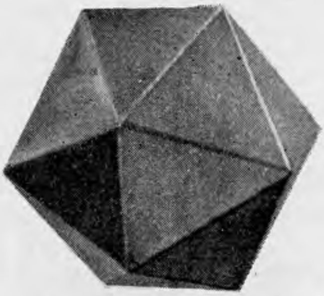

Fig. 99. Photograph of octahedron and pyritohedron.

Summary. The forms of the pyritohedral class of the isometric system are listed below together with symbols, faces, angles, and symmetry:

Forms	Miller Symbols	Faces	Solid Angles				Normal Interfacial Angles
			Trihedral		Tetrahedral		
			3 Equal Edges	2 + 1 Edges	2 + 2 Edges	2 + 1 + 1 Edges	
Octahedron	(111)	Geometrically the same as in the normal class					
Trisoctahedron	(hhl)						
Dodecahedron	(110)						
Trapezohedron	(hll)						
Hexahedron or cube	(100)						
Diploid Positive	(hkl)	24	8	—	6	12	*e.g.* 421 51°45¼′, 25°12½′, 48°11½′
Diploid Negative	$(h\bar{k}l)$						*e.g.* 531 60°56½′, 19°27¾′, 19°27¾′
Pyritohedron Positive	$(hk0)$	12	8	12	—	—	*e.g.* 210 53°7¾′ and 66°25¼′
Pyritohedron Negative	$(h\bar{k}0)$						*e.g.* 410 28°4¼′ and 76°23½′

Symmetry	Center	Axes			Planes	
		4-fold	3-fold	2-fold	Axial	Diagonal
	1	0	4 ⊥ octahedral faces	3 ⊥ cubic faces	3	0

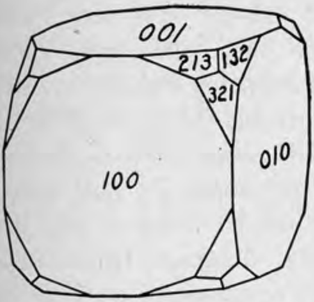

FIG. 100. Cube modified by diploid.

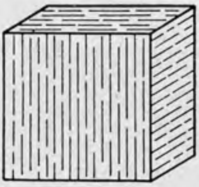

FIG. 101. Cube with striations.

Tetrahedral class ($\bar{4}\ 3\ m$)

Symmetry. Crystals of the tetrahedral class have no center of symmetry, but they have three axes of twofold symmetry which coincide with the crystallographic axes, four diagonal axes of threefold symmetry which are in the same position as in the preceding classes, and six diagonal planes of symmetry as in the normal class; but the axial planes of symmetry are not present. These elements of symmetry are shown in Fig. 102.

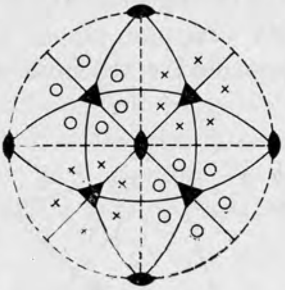

FIG. 102. Symmetry of the tetrahedral class.

In the tetrahedral class, the Hermann-Mauguin symbol is the fourfold axis of rotary-inversion. This symmetry element is more complicated than the ordinary four-

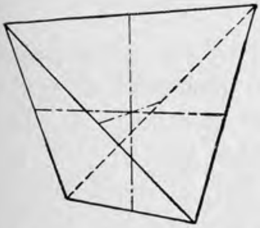

FIG. 103. Tetrahedron (positive).

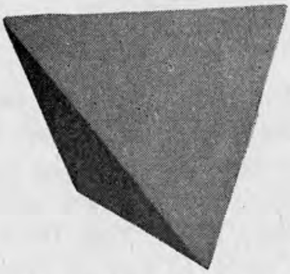

FIG. 104. Photograph of positive tetrahedron.

fold axis of symmetry, since with each rotation of a quarter turn, an "inversion" takes place as if through a center of symmetry. It is as if a fourfold axis of symmetry turned itself and its surroundings inside out with each quarter turn. The resulting symmetry is twofold, not fourfold; but it is a little more than twofold, since faces in the lower octants are produced by this element, complementary to those in the upper octants. The diagonal threefold axis of symmetry operates to produce three axes of fourfold rotary-inversion from the one specified, and these three axes coincide with the crystallographic axes. The four diagonal axes and the three crystallographic axes of symmetry then operate to produce the six diagonal planes of symmetry from the one diagonal one specified in the international symbol.

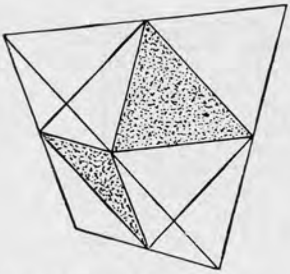
FIG. 105. Relation of tetrahedron to octahedron.

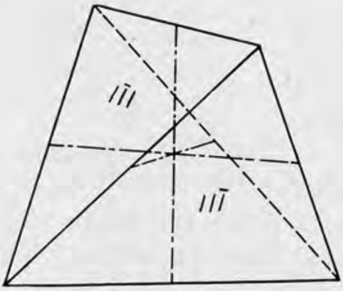

FIG. 106. Tetrahedron (negative).

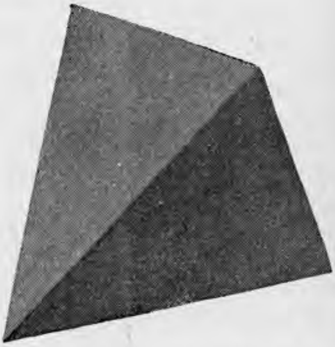
FIG. 107. Photograph of negative tetrahedron.

Forms. The forms can be derived by the same process as in the preceding classes, but different elements of symmetry must be used since the axial planes of symmetry are lacking. Beginning with a face which cuts all three axes at unit distance (namely 111 in Figs. 103 and 104) the axis a_1 requires the presence of $1\bar{1}\bar{1}$, and, if these two faces are present, the axis a_2 requires the presence of two similar faces, $\bar{1}1\bar{1}$ and $\bar{1}\bar{1}1$, in the rear. The relation of this form to the octahedron is shown in Fig. 105; it has the faces of alternate octants extended to meet. (Faces of the other set of alternate octants, if present at all, do not belong to the same form.) Having four faces the form is called a *tetrahedron*. Since it includes a face from the positive octant, it is easily understood that Fig. 103 is called a positive tetrahedron, and Fig. 106 (and 107), having no such face, is called a negative tetrahedron. If these two forms are present together and equally developed on one crystal, it can not be distinguished geometrically from an octahedron, but it differs in internal structure, as may be demonstrated by etch figures, X-ray studies, and other means. Both forms are shown in Figs. 108 and 109, but unequally developed.

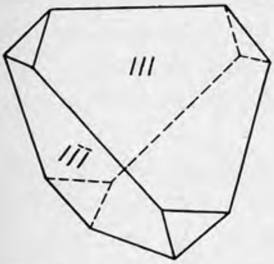

FIG. 108. Positive tetrahedron modified by negative tetrahedron.

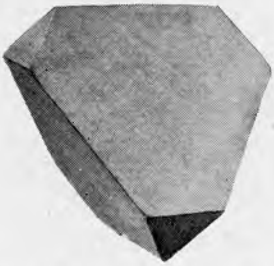

FIG. 109. Photograph of positive tetrahedron modified by negative tetrahedron.

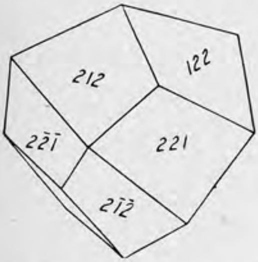

FIG. 110. Tetragonal tristetrahedron (positive).

FIG. 111. Photograph of tetragonal tristetrahedron (positive).

If the first way in which this face 111 can vary its position be considered, that is, by variation of the intercept on *one* axis, the variation can be to some simple multiple, such as 2, or to infinity. The first variation gives Miller symbols of 221 and the other gives symbols of 110. If the face 221 is present (see Figs. 110 and 111) the axis of threefold symmetry requires the presence of 212 and 122. Then, if these three faces are present, the twofold axis of symmetry, a_1, requires the presence of the faces $2\bar{1}\bar{2}$, $2\bar{2}\bar{1}$, and $1\bar{2}\bar{2}$; and, if these six faces are present, the twofold axis of symmetry, a_2, requires the presence of six similar faces in the rear. Since each face has four sides, and three faces take the place of one face of the tetrahedron, this form is known as the *tetragonal tristetrahedron*. The corresponding negative form is shown in Fig. 112.

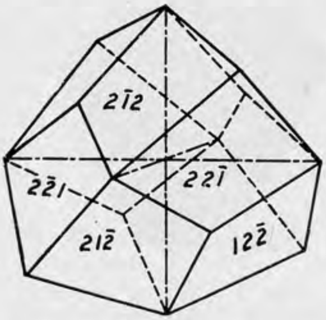

FIG. 112. Tetragonal tristetrahedron (negative).

If the original face is 110, the axis of threefold symmetry requires the presence of 101 and 011. Each of these faces extends from one octant into the next one because each is parallel to one axis. If these three faces are present, the twofold axis of symmetry, a_1, requires the presence of the faces $1\bar{1}0$, $10\bar{1}$, and $0\bar{1}\bar{1}$, and if these faces are present the twofold axis of symmetry, a_2, requires the presence of the faces in the rear. Thus all the faces of the *dodecahedron* are derived.

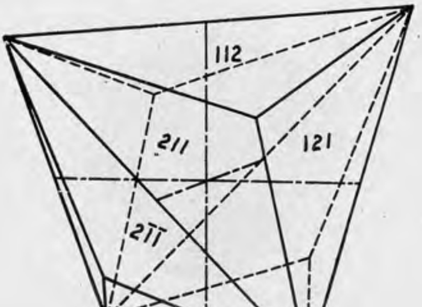

FIG. 113. Trigonal tristetrahedron (positive).

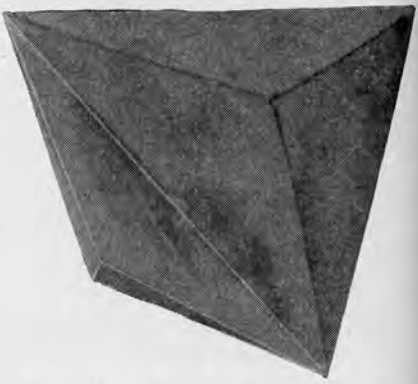

FIG. 114. Photograph of positive tristetrahedron.

Considering the second way in which 111 can vary its position, namely, by increasing the intercepts on two axes at the same rate, the variation can be to some simple multiple, say 2, or to infinity. The first variation leads to the Miller symbols 211 and the second to the symbols 100. If the face 211 is present (see Figs. 113 and 114), the threefold axis of symmetry requires the presence of the faces 112 and 121. If these three faces are present, the twofold axis of symmetry, a_1, requires the presence of the faces $2\bar{1}\bar{1}$, $1\bar{2}\bar{1}$ and $1\bar{1}\bar{2}$; and if these six faces are present, the twofold axis of symmetry, a_2, requires the presence of six similar faces in the rear. Since each face has three sides, and three faces take the place of one face of the tetrahedron, this form is known as the *trigonal tristetrahedron.* The corresponding negative form is shown in Fig. 115.

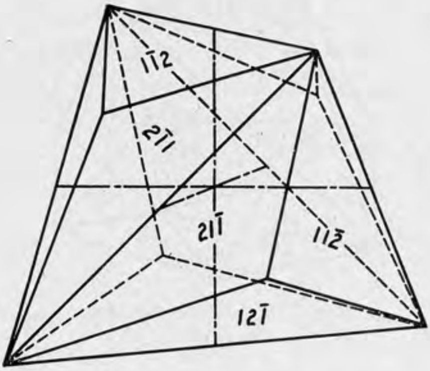

FIG. 115. Trigonal tristetrahedron (negative).

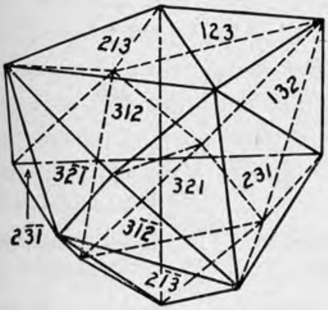

FIG. 116. Hextetrahedron (positive).

FIG. 117. Photograph of hextetrahedron (positive).

If the original face is 100, the axis of threefold symmetry requires the presence of 010 and 001. Each of these faces extends from one octant into three adjoining octants because each face is parallel to two crystal axes. If these three faces are present, the twofold axis of symmetry, a_1, requires the presence of $0\bar{1}0$ and $00\bar{1}$, and the twofold axis of symmetry, a_2, requires the presence of $\bar{1}00$ and $00\bar{1}$. Thus the form is the *hexahedron* or *cube*.

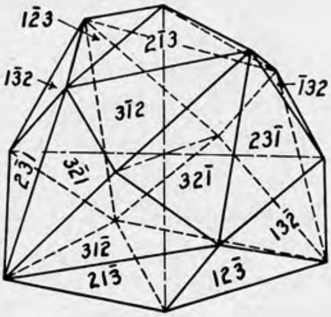

FIG. 118. Hextetrahedron (negative).

Considering the third way in which 111 can vary its position, namely, by increasing its intercepts on two axes at different rates, the variation can be to some simple multiples, say 1.5 and 3, or to one simple multiple, say 2, and to infinity. The first variation leads to the Miller symbols 321 and the second to the symbols 210. If the face 321 is present (see Figs. 116 and 117), the diagonal plane of symmetry requires the presence of the face 312. If these two faces are present, the axis of threefold symmetry, a_1, requires the presence of the faces 213, 123, 132, and 231. If these six faces are present, the axis of twofold symmetry, a_1, requires the presence of the six similar faces in the front lower left octant, namely, $3\overline{21}$, $3\overline{12}$, $2\overline{31}$, $1\overline{32}$, $1\overline{23}$, and $2\overline{13}$. If all these faces are present, the axis of twofold

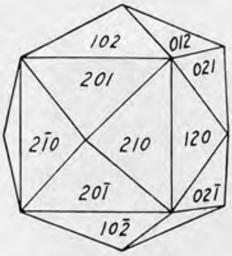

FIG. 119. Tetrahexahedron.

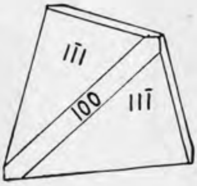

FIG. 120. Cube modifying tetrahedron.

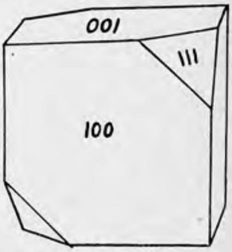

FIG. 121. Tetrahedron modifying cube.

symmetry, a_2, requires the presence of twelve similar faces in the rear. Since six faces take the place of one face of the tetrahedron, this form is known as the *hextetrahedron*. The corresponding negative form is shown in Fig. 118.

If the original face is 210 (see Fig. 119), the diagonal plane of symmetry requires the presence of the face 201. Each of these faces extends from one octant into an adjoining octant because each is parallel with one crystal axis. If these two faces are present, the threefold axis of symmetry requires the presence of the faces 102, 012, 021, and 120. If these six faces are present, the twofold axis of symmetry, a_1, requires the presence of the faces $2\bar{1}0$, $20\bar{1}$, $10\bar{2}$, $1\bar{2}0$, $0\bar{2}\bar{1}$, and $0\bar{1}\bar{2}$, and if all these faces are present, the twofold axis of symmetry, a_2, requires the presence of similar faces in the rear. (Since the faces extend from one octant to another many of these are already present.) Thus, all the faces of the *tetrahexahedron* are derived.

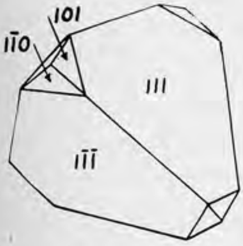

Fig. 122. Dodecahedron modifying tetrahedron.

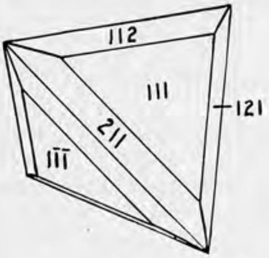

Fig. 123. Tristetrahedron modifying tetrahedron.

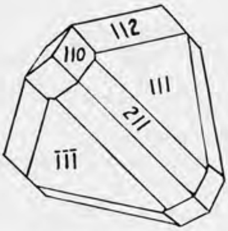

Fig. 124. Tetrahedron modified by tristetrahedron and dodecahedron.

Combinations. Tetrahedrite shows some interesting combinations of forms of this class; for example, Fig. 120 shows the cube modifying the tetrahedron, Fig. 121 shows the tetrahedron modifying the cube, Fig. 122 shows the dodecahedron modifying the tetrahedron, Fig. 123 shows the tristetrahedron beveling the edges of the tetrahedron, and Fig. 124 shows the tetrahedron modified by both the dodecahedron and the tristetrahedron.

Summary. The forms of the tetrahedral class of the isometric system are listed below together with symbols, faces, angles, and symmetry:

Forms	Miller Symbols	Faces	Solid Angles			Normal Interfacial Angles
			Trihedral	Tetrahedral	Hexahedral	
Tetrahedron....	(111)	4	4	—	—	109°28′16″
Tetragonal tristetrahedron...	(*hhl*)	12	4 + 4	6	—	*e.g.* 221 27°16′ and 90°0′ *e.g.* 331 37°51¾′ and 80°55
Dodecahedron..	Geometrically the same as in the normal class					
Trigonal tristetrahedron.	(*hll*)	12	4	—	4	*e.g.* 211 70°31¾′ and 33°33½′ *e.g.* 411 38°56½′ and 60°0′
Hexahedron or cube.........	Geometrically the same as in the normal class					
Hextetrahedron.	(*hkl*)	24	—	6	4 + 4	*e.g.* 321 21°47¼′, 69°4½′, 21°47¼′ *e.g.* 531 27°39⅔′, 57°7⅓′, 27°39⅔′
Tetrahexahedron	Geometrically the same as in the normal class					

Symmetry	Center	Axes			Planes	
		4-fold	3-fold	2-fold	Axial	Diagonal
	0	0	4 ⊥ tetrahedral faces	3 ⊥ cubic faces	0	6

Tetragonal System

All crystals which are referred to three rectangular axes of which two are equal in length and the third unequal belong to the tetragonal system (also called the quadratic system). The equal axes are always considered to be the horizontal axes, and are designated a_1 and a_2; the vertical axis is designated c (Fig. 125). The vertical axis may be either longer or shorter than the horizontal, which is always taken as unity. There are seven symmetry classes in the system, but only three need attention here, since the others are scarcely, if at all, represented among minerals.

The Hermann-Mauguin symbols applicable to the symmetry classes of the tetragonal system refer to (1) the c axis; (2) the a_1 axis; (3) the axis at 45 degrees, between the a_1 and a_2 axes. The tetragonal system is recognized in international symbols by the first symbol in the series, which is always 4—either 4 or $\bar{4}$.

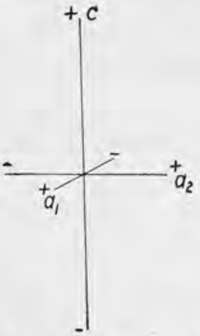

FIG. 125. Axes of a tetragonal crystal.

The seven classes are as follows:

1. Normal class—center, one axis 4-fold, 4 axes 2-fold, one principal plane, two vertical axial and two vertical diagonal planes of symmetry. ($4/m\ m\ m$)
2. Hemimorphic class—one vertical axis 4-fold and 4 vertical planes of symmetry. ($4\ m\ m$)
3. Tripyramidal class—one vertical axis 4-fold, horizontal plane, and center of symmetry. ($4/m$)
4. Pyramidal-hemimorphic class—vertical axis 4-fold symmetry. (4)
5. Sphenoidal class—three axes 2-fold and 2 diagonal planes of symmetry. ($\bar{4}\ 2\ m$)
6. Trapezohedral class—vertical axis 4-fold and 4 horizontal axes 2-fold symmetry. (4 2)
7. Tetartohedral class—vertical axis of 4-fold rotary-inversion symmetry. ($\bar{4}$)

Normal or ditetragonal dipyramidal class ($4/m\ m\ m$)

Symmetry. All crystals of this class have a center of symmetry, a vertical axis of fourfold symmetry coincident with the vertical crystal axis, two horizontal axes of twofold symmetry also coincident with the crystal axes, two horizontal axes of twofold symmetry bisecting the angles between the crystal axes, one horizontal plane of symmetry, which is the plane of the lateral crystal axes, two vertical axial planes of symmetry each including the vertical crystal axis and one lateral crystal axis, and two vertical diagonal planes of symmetry bisecting the angles between the axial planes. These elements of symmetry are shown in Figs. 126, 127, and 128.

The Hermann-Mauguin symbol $4/m$, standing in the first position, shows that there is not only a fourfold vertical axis of symmetry, but also a plane of symmetry normal to it. The second m in the symbol refers to the plane of symmetry which includes the a_2 and c axes. The third m specifically refers to the plane of symmetry which bisects the angle between the a_1 and the negative a_2 axes, and includes the c axis. The fourfold axis of symmetry requires that vertical planes of symmetry be multiplied to form four different planes instead of only the two specified. The four twofold axes of symmetry lying in the horizontal plane coincide with the intersections of the horizontal with the various vertical planes, and the center of symmetry may be derived from the three planes of symmetry each of which includes two crystallographic axes.

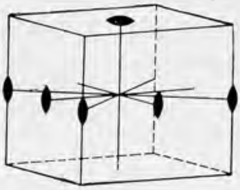

FIG. 126. Axes of symmetry of a tetragonal crystal.

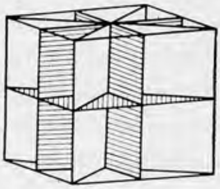

FIG. 127. Planes of symmetry of a tetragonal crystal.

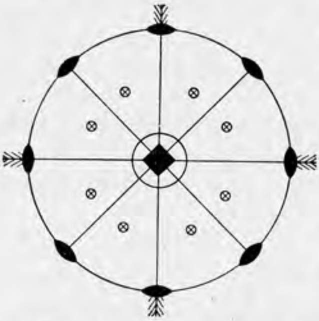

FIG. 128. Symmetry of the normal class of the tetragonal system.

Forms. Assuming that a face cuts all three crystal axes at their respective unit distances, what other faces are required by the symmetry? Also, if this face be assumed to vary in position in all possible ways, what faces (and form) result in each case?

Assuming the face 111 in Fig. 129, the symmetry plane a_1c requires the face $1\bar{1}1$; if these two faces are present, the symmetry plane a_2c requires the faces $\bar{1}11$ and $\bar{1}\bar{1}1$; if these four faces are present, the horizontal plane of symmetry a_1a_2 requires the presence of the four faces below the center. These eight faces satisfy all the elements of symmetry although only three have been used to derive them. In order to name this form it is necessary to take note that in all crystal systems except the isometric most crystal forms are commonly assigned to one of four types, which may be defined as follows:

1. A *pyramid* is a form each of whose faces cuts all three[10] crystal axes. If the form corresponds geometrically to two similar pyramids, base to base, it is properly called a *dipyramid.*

2. A *prism* is a form each of whose faces cuts the two lateral axes[11] and is parallel to the vertical axis.

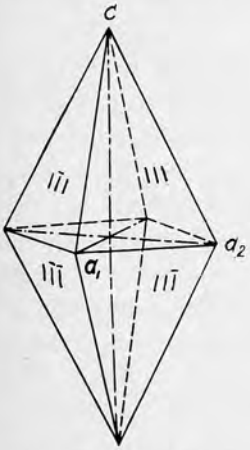

FIG. 129. First order dipyramid.

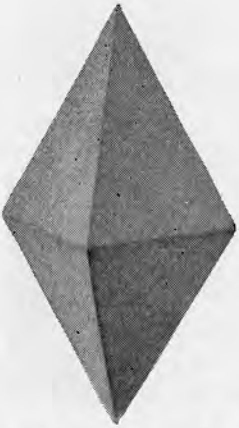

FIG. 130. Photograph of first order dipyramid.

3. A *pinacoid* is a form each of whose faces cuts one crystal axis and is parallel to the other two (or even three in hexagonal crystals).

4. A *dome* is a form each of whose faces cuts the vertical axis and one lateral axis and is parallel to the other lateral axis. This name is not used in the tetragonal and hexagonal systems, because the forms in question can be considered pyramids by a different (and reasonable) assumption as to the position of the lateral axes. A dome is sometimes called a horizontal prism.

It is clear that the form (111) is a pyramid, or better, a dipyramid. To distinguish it from pyramids of other crystal systems, it is called a *tetragonal dipyramid* (*of the first order*, as explained later). See Figs. 129 and 130.

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[10] Even in the hexagonal system any pyramid face cuts *three* axes, but not necessarily all (four) axes.

[11] Even in the hexagonal system any prism face cuts two lateral axes, but not necessarily all three.

In different minerals the length of the vertical axis (as compared with a) varies widely. For example, $c = 0.67$ ($\times a$) in cassiterite (SnO_2) and so the unit dipyramid is rather obtuse, as in Figs. 137 and 138, while $c = 1.78$ ($\times a$) in anatase (TiO_2) and the unit dipyramid is decidedly acute, as in Fig. 129. It is evident that the tetragonal dipyramid more closely approaches an octahedron as the length of c more nearly approaches equality with a. Chalcopyrite ($CuFeS_2$) crystals seem to be isometric, because $c = 0.98525$!

In the isometric system an increase in the intercept on one axis produces the same results as an increase on any other axis, since all the isometric axes are interchangeable; but in the tetragonal system the vertical axis is not interchangeable with the horizontal axes and must therefore be considered separately.

FIG. 131. First order prism and basal pinacoid.

FIG. 132. Photograph of first order prism and base.

If it be assumed that the original face changes its intercept on the vertical axis to any simple multiple or simple fraction, the form which results is in all cases a tetragonal dipyramid, with eight faces, each cutting all three of the crystal axes. The form (111), which cuts all three axes at their unit lengths, is called the *fundamental form:* other dipyramids include (113), (332), (221), and so on.

If the original face changes its intercept to infinity on the vertical axis, the Miller symbols become 110 and the form is no longer a pyramid, but a prism. If the face 110 is present, as in Figs. 131 and 132, the symmetry plane a_1c requires the presence of $1\bar{1}0$; if these two faces are present, the symmetry plane a_2c requires the presence of the two faces in the rear. These four faces satisfy all the elements of symmetry of this class. They are the faces of the *tetragonal prism* (*of the first order*, as explained later). The top and bottom faces do not belong to the prism; they form the basal pinacoid, as explained later.

If the original face changes its intercept on a_1 (or a_2) to some simple multiple, say 2, the Miller symbols become 122 (or 212). The face, unlike the original face 111, is not normal to the vertical diagonal plane of symmetry between a_1 and a_2, and that plane requires the presence of 212 (122 being assumed), as in Figs. 133 and 134. If these two faces are present, the axial plane of symmetry a_1c requires the presence of $2\bar{1}2$ and $1\bar{2}2$; with these four faces present the plane of symmetry a_2c requires the presence of four faces in the rear above; and with these eight faces present the horizontal plane of symmetry requires the presence of eight similar faces below the center. The form has twice as many faces as the tetragonal dipyramid and is therefore known as the *ditetragonal dipyramid.*

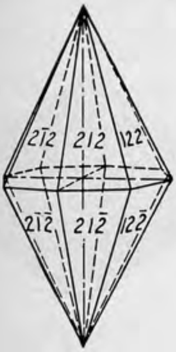

Fig. 133. Ditetragonal dipyramid.

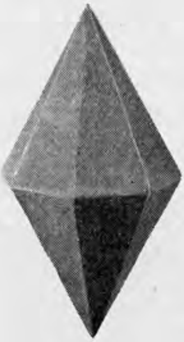

Fig. 134. Photograph of ditetragonal dipyramid.

If the original face changes its intercept to infinity on a_1 (or a_2), the Miller symbols become 011. If this face is present, as in Figs. 135 and 136, one diagonal plane of symmetry requires the presence of 101; if these two faces are present, the other diagonal plane of symmetry requires the presence of the faces in the rear above; and if these four faces are present, the horizontal plane of symmetry requires the presence of four similar faces below the center. The form corresponds with the definition of a dome, but it is not called a dome because it is geometrically

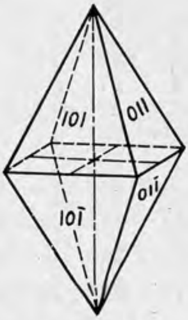

Fig. 135. Second order dipyramid.

Fig. 136. Photograph of second order dipyramid.

equivalent to a dipyramid and would be a dipyramid if the horizontal crystal axes were assumed to connect the tetrahedral solid angles instead of connecting the midpoints of opposite edges. Since a different and equally reasonable choice of the position of the horizontal axes would make this form a dipyramid, it is called a dipyramid in spite of its relation to the axes as chosen, and it is distinguished from the dipyramid first described by designating that one a dipyramid of the first order and this one a *tetragonal dipyramid of the second order*. A combination of first and second order dipyramids is illustrated in Figs. 137 and 138.

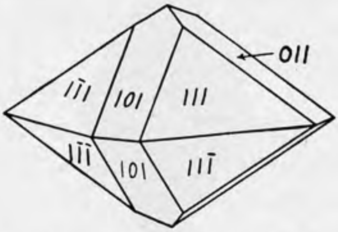

FIG. 137. First and second order dipyramids.

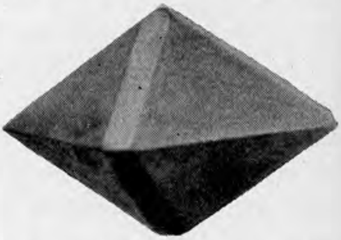

FIG. 138. Photograph of first and second order dipyramids.

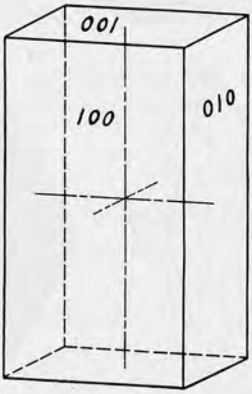

FIG. 139. Second order prism and basal pinacoid.

FIG. 140. Photograph of second order prism and base.

If the original face increases its intercepts on two axes at the same rate (in terms of the unit lengths) and if the two axes in question are a_1 and a_2, the form remains a tetragonal dipyramid as long as each face cuts all three crystal axes. If the two axes in question are a_1 (or a_2) and c the form is a ditetragonal dipyramid as long as all three axes are cut. But if the face becomes parallel with a_1 and a_2, the Miller symbols become 001. If this face is present, as in Figs. 131 and 139, the horizontal plane of symmetry requires the face $00\bar{1}$. These two faces alone satisfy all the elements of symmetry and therefore constitute a form. This form (001) is a pinacoid, since each face is parallel with two axes and cuts the other one. When the crystal is properly oriented, one of these faces is at its base; therefore this form is called a *basal pinacoid*, or merely a *base*.

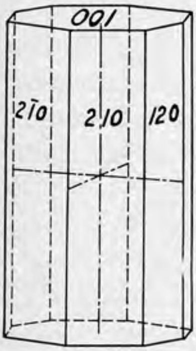

FIG. 141. Ditetragonal prism and base.

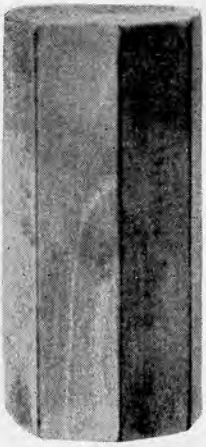

FIG. 142. Photograph of ditetragonal prism and base.

If the original face becomes parallel with a_1 (or a_2) and c, the Miller symbols become 010. If the face 010 is present, as in Figs. 139 and 140, one diagonal plane of symmetry requires the presence of 100; if these two faces are present the other diagonal plane of symmetry requires the presence of $0\bar{1}0$ and $\bar{1}00$. These four faces satisfy all the elements of symmetry and constitute a crystal form. They correspond with the definition of a pinacoid, but are not called a pinacoid because a different (and perfectly reasonable) choice of the position of the lateral axes would make them a prism. Accordingly, this form is called a *tetragonal prism of the second order*, the one first described being distinguished as first order. As in Fig. 131 the top and bottom faces do not belong to the prism, but to the basal pinacoid.

If the original face increases its intercepts on two axes at different rates (in terms of the unit lengths) and if the two axes in question are a_1 and a_2, the form is a *ditetragonal dipyramid*, as long as each face cuts all three axes. If the faces become parallel with a_1 (or a_2) while cutting the other two axes, the form is a tetragonal dipyramid of the second order. If the two axes in question are a_1 (or a_2) and c, the form is again a ditetragonal dipyramid of the first order, as long as each face cuts all three axes. If the face becomes parallel with a_1 (or a_2), the form is a tetragonal dipyramid of the second order. If the face becomes parallel with c while cutting a_1 at unity and a_2 at a simple multiple, say 2, the Miller symbols are 210. If the face 210 is present, as in Figs. 141 and 142, a diagonal symmetry plane requires the presence of 120. If these two faces are present the symmetry plane a_1c requires the presence of 2$\bar{1}$0 and 1$\bar{2}$0. If these four faces are present, the symmetry plane a_2c requires the presence of four similar faces in the rear. These eight faces satisfy all the elements of symmetry. Since there are twice as many faces as in the ordinary prism this form is called the *ditetragonal prism*.

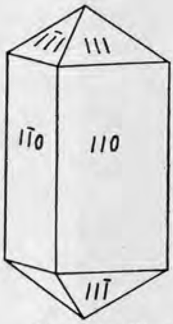

FIG. 143. First order prism and dipyramid.

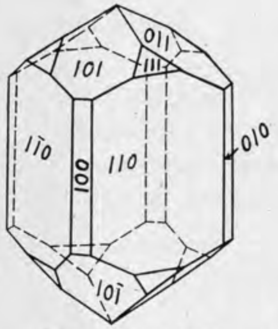

FIG. 144. First and second order prisms and dipyramids.

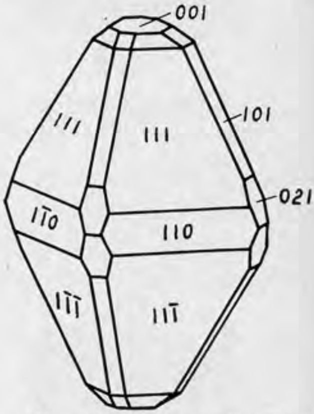

FIG. 145. First order prism, two first and three second order dipyramids and base.

Combinations. Each isometric crystal form and each tetragonal dipyramid completely encloses space and may occur alone; these are known as closed forms. But all prisms and pinacoids are open forms; no one of them completely encloses space; therefore no one can occur alone. Accordingly, nearly all tetragonal crystals are combinations of two or more forms. For example, Fig. 143 shows the first order prism and first order dipyramid in zircon ($ZrSiO_4$). Rutile (TiO_2) crystals may show first and second order prisms and dipyramids, as in Fig. 144. Anatase (also TiO_2) may show a first order prism and base with two first order and three second order dipyramids, as in Fig. 145. Zircon ($ZrSiO_4$) may show the first and second order prisms with the first order dipyramid and ditetragonal dipyramid, as in Figs. 146 and 147.

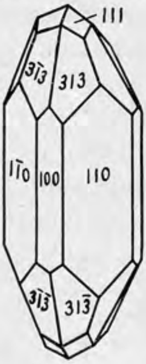

FIG. 146. First and second order prisms, first order pyramid and ditetragonal dipyramid.

FIG. 147. Photograph of first and second order prisms, first order pyramid and ditetragonal dipyramid.

Summary. The forms of the normal class of the tetragonal system are listed below together

Forms	Miller Symbols	Faces	Solid Angles	
			Tetrahedral	Octahedral
Tetragonal dipyramids of the first order (fundamental or unit form)	(111)	8	2 + 4	—
	(*hhl*)	8	2 + 4	—
Tetragonal prism of the first order	(110)	4	—	—
Ditetragonal dipyramids	(*hkl*)	16	4 + 4	2
Tetragonal dipyramids of the second order	(*h*0*l*)	8	2 + 4	—
Basal pinacoid	(001)	2	—	—
Tetragonal prism of the second order	(100)	4	—	—
Ditetragonal prism	(*hk*0)	8	—	—

Symmetry	Center	Axes		Planes	
		4-fold	2-fold	Axial	Diagonal
	1	1 vertical	2 axial 2 diagonal	1 horizontal 2 vertical	2 vertical

with symbols, faces, angles, and symmetry. Normal interfacial angles are not given because most of them vary with the length of the vertical axis.

Tripyramidal class ($4/m$)

Symmetry. Crystals of the tripyramidal class have only one axis of fourfold symmetry which coincides with the vertical crystal axis, one horizontal plane of symmetry (the plane a_1a_2), and a center of symmetry. These elements of symmetry are shown in Fig. 148.

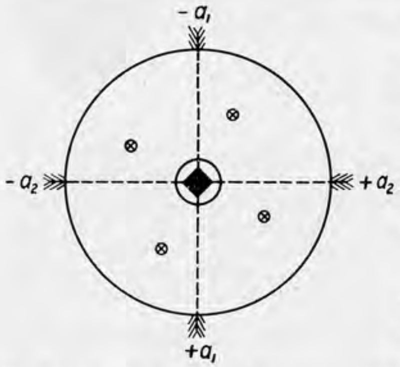

FIG. 148. Symmetry of tripyramidal class of tetragonal system.

The international symbol $4/m$ specifies all the symmetry except the center, which is present in this class. The center may be derived, however, from any one of the combinations $2/m$, $4/m$, $6/m$, and is therefore present in this instance.

Forms. Assuming the presence of the face 111, the vertical axis of fourfold symmetry requires the presence of the faces $\bar{1}11$, $\bar{1}\bar{1}1$, and $1\bar{1}1$; if these four faces are present, the horizontal plane of symmetry requires four similar faces below the center. Thus the tetragonal dipyramid of the first order is a form of this class.

If the original face be changed to 110, the vertical axis of fourfold symmetry requires the presence of $1\bar{1}0$, $\bar{1}\bar{1}0$, and $\bar{1}10$; this is the tetragonal prism of the first order.

If the original face be changed to 122, the vertical axis of fourfold symmetry requires the presence of $\bar{2}12$, $\bar{1}\bar{2}2$, and $2\bar{1}2$; and if these four faces are present, the horizontal plane of symmetry requires the presence of four similar faces below. This is called the *tetragonal dipyramid of the third order*—it corresponds with half of the faces of the ditetragonal dipyramid, alternately chosen. It is shown in Fig. 149, and the relation of the faces to those of the first and second order forms and to the horizontal crystal axes is shown in Fig. 150.

If the original face be changed to 011, the vertical axis of fourfold symmetry requires the presence of 101, $0\bar{1}1$, and $\bar{1}01$; if these four faces are present, the horizontal plane requires the four similar faces below. This is the tetragonal dipyramid of the second order.

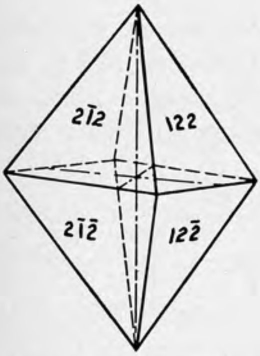

FIG. 149. Third order dipyramid.

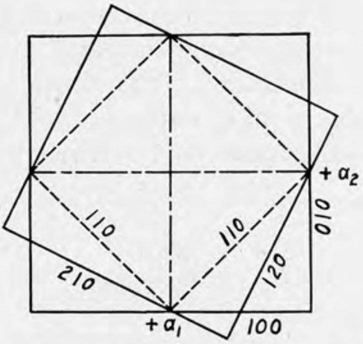

FIG. 150. Relation between prisms of first, second, and third orders.

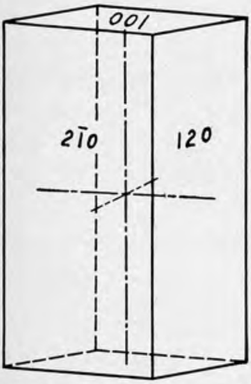

FIG. 151. Third order prism and base.

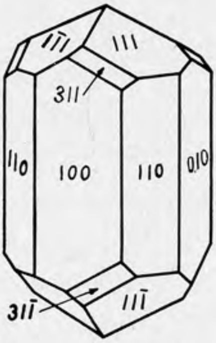

FIG. 152. First and second order prisms and first and third order dipyramids.

If the original face be changed to 001, the horizontal plane requires the presence of $00\bar{1}$, and the basal pinacoid is a form of this class.

If the original face be changed to 100, the vertical axis of fourfold symmetry requires the presence of 010, $\bar{1}00$, and $0\bar{1}0$. This is the tetragonal prism of the second order.

If the original face be changed to 210, the vertical axis of fourfold symmetry requires the presence of $\bar{2}10$, $\bar{1}\bar{2}0$, and $2\bar{1}0$. These are alternate faces of the ditetragonal prism; they have the same relation to the first and second order forms as shown in Fig. 150; they form the *tetragonal prism of the third order*, shown in Fig. 151.

Crystals of this type of symmetry are not common, but are illustrated by meionite ($CaCO_3 \cdot 3CaAl_2Si_2O_8$), as in Fig. 152.

Summary. The forms of the tripyramidal class of the tetragonal system are listed below together with their symbols, faces, angles, and symmetry:

Forms	Miller Symbols	Faces	Solid Angles	
			Tetrahedral	Octahedral
Tetragonal dipyramid of the first order (fundamental or unit form)	(111) (hhl)	8 8	2 + 4 2 + 4	— —
Tetragonal prism of the first order	(110)	4	—	—
Tetragonal dipyramid of the second order	$(h0l)$	8	2 + 4	—
Tetragonal dipyramid of the third order Positive	(hkl)	8	2 + 4	—
Negative	$(h\bar{k}l)$	8	2 + 4	—
Basal pinacoid	(001)	2	—	—
Tetragonal prism of the second order	(100)	4	—	—
Tetragonal prism of the third order Positive	$(hk0)$	4	—	—
Negative	$(h\bar{k}0)$	4	—	—

Symmetry	Center	Axes		Planes	
		4-fold	2-fold	Axial	Diagonal
	1	1 vertical	0	1 horizontal	0

Sphenoidal or tetragonal scalenohedral class ($\bar{4}\ 2\ m$)

Symmetry. Crystals of the sphenoidal class have no center of symmetry, but they have three twofold axes of symmetry coinciding with the crystal axes and they have two vertical planes of symmetry which bisect the angles between the horizontal crystal axes. These elements of symmetry are shown in Fig. 153.

The international symbols again are sufficient to derive all the above symmetry elements. $\bar{4}$ is itself an axis of twofold symmetry, and the diagonal vertical plane *m* requires the presence of the other horizontal axis of symmetry, parallel to a_2; the fourfold axis of rotary-inversion, and the specified horizontal axis of symmetry are each capable of multiplying the vertical diagonal plane of symmetry to produce the second one.

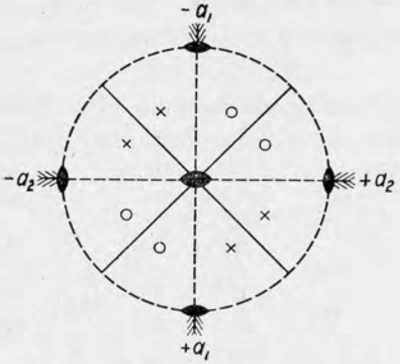

Fig. 153. Symmetry of the sphenoidal class of the tetragonal system.

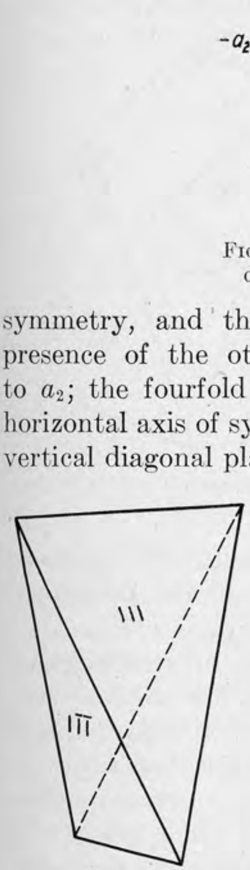

Fig. 154. Disphenoid (positive).

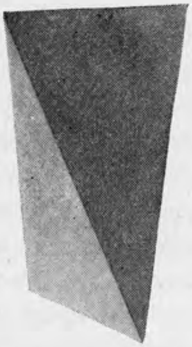

Fig. 155. Photograph of positive disphenoid.

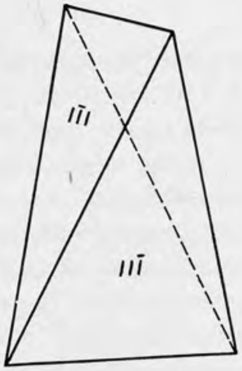

Fig. 156. Disphenoid (negative).

Forms. Assuming the presence of the face 111, the vertical axis of twofold symmetry requires the presence of the face $\bar{1}\bar{1}1$; if these two faces are present, either the axis a_1 or a_2, of twofold symmetry, requires the presence of $11\bar{1}$ and $\bar{1}1\bar{1}$. These four faces satisfy all the elements of symmetry. They correspond with half the faces of the first order dipyramid, but are given a different name, since the pyramidal shape is lost. They form a *disphenoid*, (Figs. 154 and 155). The other set of faces of the dipyramid gives a similar form, known as the negative disphenoid (Fig. 156).

If the original face be changed to 110, the axis a_1 of twofold symmetry requires the presence of $1\bar{1}0$; if these two faces are present, the axis a_2 of twofold symmetry requires the presence of $\bar{1}10$ and $\bar{1}\bar{1}0$. These four faces constitute the tetragonal prism of the first order.

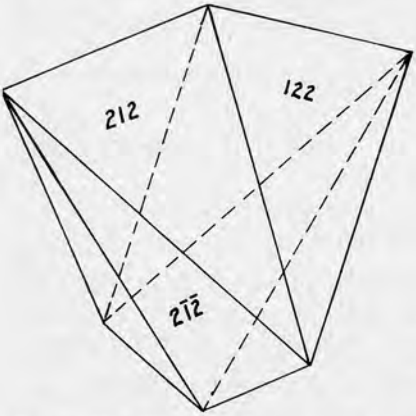

Fig. 157. Tetragonal scalenohedron (positive).

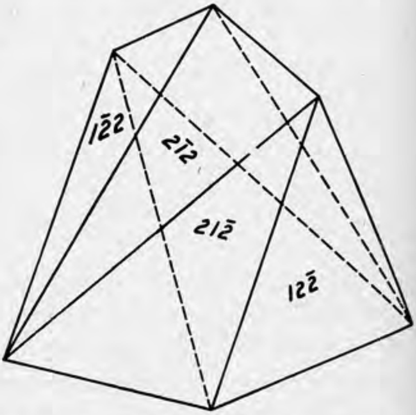

Fig. 158. Tetragonal scalenohedron (negative).

If the original face be changed to 122 (Fig. 157), the diagonal plane of symmetry requires the presence of 212; if these two faces are present, the vertical axis of twofold symmetry requires the presence of two faces in the rear; and if these four faces are present either the axis a_1 or a_2, of twofold symmetry, requires the presence of four faces converging below. Each face of this form is a scalene triangle and the form is known as the *tetragonal scalenohedron*. The faces correspond with faces of alternate octants of the ditetragonal dipyramid. The other set of faces gives a negative scalenohedron, as shown in Fig. 158.

If the original face be changed to 011, a diagonal plane of symmetry requires the presence of 101; if these two faces are present, the vertical axis of twofold symmetry requires the presence of $0\bar{1}1$ and $\bar{1}01$; if these four faces are present, either horizontal axis, a_1 or a_2, requires the presence of four faces below. This gives the tetragonal dipyramid of the second order.

If the original face be changed to 001, either horizontal axis of twofold symmetry requires the presence of $00\bar{1}$, and these two faces constitute the basal pinacoid.

If the original face be changed to 100, a diagonal plane of symmetry requires the presence of 010; if these two faces are present, the vertical axis of twofold symmetry requires the presence of $\bar{1}00$ and $0\bar{1}0$. This gives the tetragonal prism of the second order.

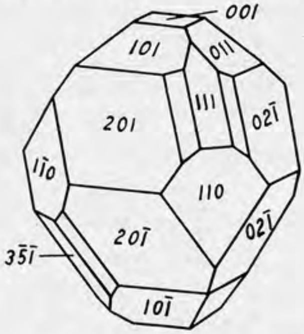

FIG. 159. First order prism, two second order dipyramids, base, disphenoid and positive tetragonal scalenohedron.

If the original face be changed to 210, a diagonal plane of symmetry requires the presence of 120; if these two faces are present a horizontal axis of twofold symmetry, a_1, requires the presence of $2\bar{1}0$ and $1\bar{2}0$; if these four faces are present, the vertical axis of twofold symmetry requires the presence of four similar faces in the rear. This gives the ditetragonal prism.

Chalcopyrite ($CuFeS_2$) crystals have the symmetry of this class, but they *seem* to be isometric because in them the vertical axis is so nearly equal to a lateral axis. A crystal of chalcopyrite may show the tetragonal prism of the first order, two tetragonal dipyramids of the second order, a positive disphenoid, a positive tetragonal scalenohedron, and a basal pinacoid, as in Fig. 159.

Summary. The forms of the sphenoidal class of the tetragonal system are listed below together with their symbols, faces, angles, and symmetry:

Forms		Miller Symbols	Faces	Solid Angles	
				Tri-hedral	Tetra-hedral
Tetragonal disphenoid	Positive	(111)	4	4	—
	Negative	$(1\bar{1}1)$	4	4	—
Tetragonal prism of the first order		(110)	4	—	—
Tetragonal dipyramid of the second order		$(h0l)$	8	—	2 + 4
Tetragonal scalenohedron	Positive	(hkl)	8	—	2 + 4
	Negative	$(h\bar{k}l)$	8	—	2 + 4
Basal pinacoid		(001)	2	—	—
Tetragonal prism of the second order		(100)	4	—	—
Ditetragonal prism		$(hk0)$	8	—	—

Symmetry	Center	Axes	Planes	
		2-fold	Axial	Diagonal
	0	1 vertical 2 axial	0	2 vertical

Hexagonal System

The hexagonal system includes all crystals which are referred to four crystal axes, three of them being equal intersecting axes at angles of 60° in the horizontal plane. These are the lateral axes which are designated by the letter *a*; being equal they are interchangeable. The fourth or principal axis, called *c*, is unequal to the others and is perpendicular to the plane thereof. When properly oriented for study and description the *c* axis is vertical, one *a* axis extends right and left, and the *a* axes are designated a_1, a_2, and a_3 with + and − directions, as in Fig. 160. The symbols always refer to the axes in this order, with *c* last. The length of the vertical axis *c* varies in different substances and is expressed in terms of unit length of the lateral axes. The position of a face cutting all the axes may be expressed as:

a_1/h, a_2/k, a_3/i, c/l; the Miller-Bravais symbols of the face are $hk\bar{i}l$, a_3 being considered negative in front, as shown in Fig. 160. Since a_3 is negative in front it is always true that $h + k + i = 0$.

There are two divisions of the hexagonal system, each including several symmetry classes. One is called the hexagonal division because in it the vertical axis (in most cases) is an axis of sixfold or hexagonal symmetry. The other is called the trigonal or rhombohedral division because in it the vertical axis is an axis of threefold or trigonal symmetry.

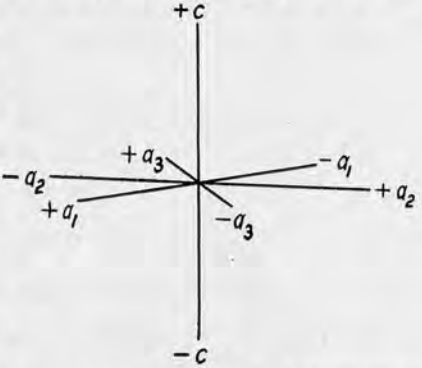

FIG. 160. Axes of a hexagonal crystal.

The Hermann-Mauguin symbols applying to the hexagonal system refer, first to the c axis, second, to the a_1 axis, and third, to an axis bisecting the angle between a_1 and (negative direction) a_2. The hexagonal and trigonal divisions of the hexagonal system are easily distinguished by means of these symbols, since in all cases the first symbol is 6 or $\bar{6}$ for the hexagonal division, and 3 or $\bar{3}$ for the trigonal or rhombohedral division. One of these four initial symbols is the mark of the hexagonal system itself, since they do not occur in the initial position of the symbols of any other system.

The twelve symmetry classes of the hexagonal system are:

A. Hexagonal Division
1. Normal class—center, vertical axis of 6-fold, 6 horizontal axes of 2-fold, horizontal principal plane and 6 vertical planes of symmetry. ($6/m\ m\ m$)
2. Hemimorphic class—center, vertical axis of 6-fold and 6 vertical planes of symmetry. ($6\ m\ m$)
3. Tripyramidal class—center, vertical axis of 6-fold and horizontal plane of symmetry. ($6/m$)
4. Pyramidal-hemimorphic class—vertical axis of 6-fold symmetry. (6)
5. Hexagonal trapezohedral class—vertical axis of 6-fold and 6 horizontal axes of 2-fold symmetry. (6 2)
6. Trigonal class—vertical axis of 3-fold, 3 horizontal axes of 2-fold, 3 vertical and one horizontal plane of symmetry. ($\bar{6}\ m\ 2$)

7. Trigonal tetartohedral class—vertical axis of 3-fold and horizontal plane of symmetry. $(\bar{6})$

B. Trigonal Division

8. Rhombohedral class—center, vertical axis of 3-fold, 3 horizontal axes of 2-fold and 3 vertical diagonal planes of symmetry. $(\bar{3}\ m)$
9. Rhombohedral-hemimorphic class—vertical axis of 3-fold and 3 vertical diagonal planes of symmetry. $(3\ m)$
10. Trirhombohedral class—center and vertical axis of 3-fold symmetry. $(\bar{3})$
11. Trigonal trapezohedral class—vertical axis of 3-fold and 3 horizontal axes of 2-fold symmetry. (3 2)
12. Trigonal tetartohedral hemimorphic class—vertical axis of 3-fold symmetry. (3)

Hexagonal Division

Normal or dihexagonal dipyramidal class $(6/m\ m\ m)$

Symmetry. Crystals of the normal class of the hexagonal system have a center of symmetry, one principal axis of sixfold symmetry (the vertical axis), six horizontal axes of twofold symmetry, three of which coincide with the lateral axes while the others bisect the angles between them, one principal plane of symmetry (the plane of the lateral axes), and six vertical planes of symmetry, three of which are axial planes each including one lateral axis and the vertical crystal axis, and the others bisecting the angles between these (see Fig. 161). The four axial planes of symmetry divide the crystal into twelve parts called dodecants. These elements of symmetry are shown in Fig. 162.

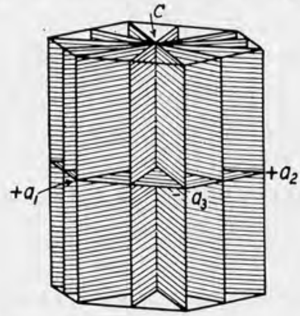

FIG. 161. Planes of symmetry of a hexagonal crystal.

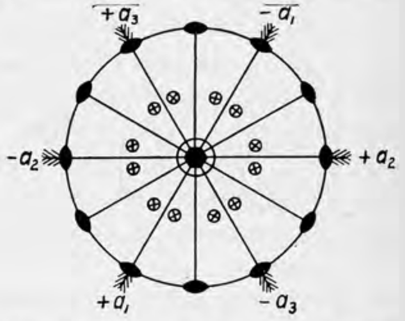

FIG. 162. Symmetry of the normal class of the hexagonal system.

As in all other crystal classes, the Hermann-Mauguin symbols contain the essentials for deriving all the different symmetry elements mentioned in the preceding paragraph. Thus, the combination $6/m$ leads to the identification of the center of symmetry; the combination of the horizontal plane of symmetry with each of the specified vertical planes leads to the two types of horizontal twofold axes of symmetry, namely, those which coincide with crystallographic axes, and those which bisect the angles between crystallographic axes.

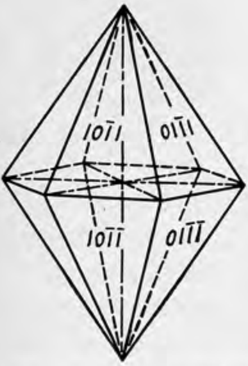

Fig. 163. First order dipyramid.

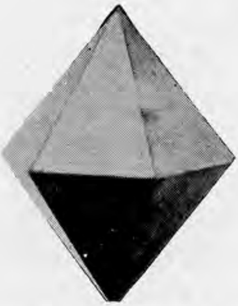

Fig. 164. Photograph of first order dipyramid.

Forms. It is impossible for any face to cut all four axes at their unit distances. Therefore the simplest assumption is a face cutting two lateral and the vertical axes at unit distances. Such a face is represented by the Miller-Bravais symbols $10\bar{1}1$. If this face is present (Figs. 163 and 164), the vertical axis of sixfold symmetry requires the presence of the faces $01\bar{1}1$, $\bar{1}101$, $\bar{1}011$, $0\bar{1}11$, and $1\bar{1}01$. If these six faces are present, the horizontal plane of symmetry requires six similar faces below. The form is called the *hexagonal dipyramid of the first order.* There may be two or more dipyramids of the first order on a given crystal: they cut the vertical axis at different simple multiples or simple fractions of the unit distance.

If the original face be changed to $10\bar{1}0$, cutting the vertical axis at infinity, the vertical axis of sixfold symmetry requires the faces $01\bar{1}0$, $\bar{1}100$, $\bar{1}010$, and $1\bar{1}00$, as in Figs. 165 and 166. This is the *hexagonal prism of the first order.*

If the original face be changed to 0001, parallel to the lateral axes, the horizontal plane of symmetry requires the face $000\bar{1}$, as in Figs. 165 and 166. This is the *basal pinacoid*.

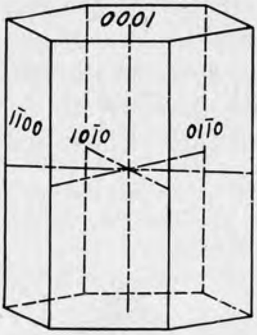

Fig. 165. First order prism and base.

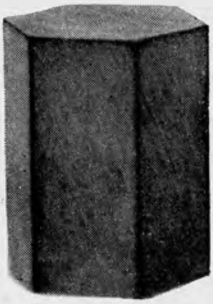

Fig. 166. Photograph of first order prism and base.

If the original face be changed to $11\bar{2}2$, the vertical axis of sixfold symmetry requires the faces $\bar{1}2\bar{1}2$, $\bar{2}112$, $\bar{1}\bar{1}22$, $1\bar{2}12$, and $2\bar{1}\bar{1}2$, as shown in Fig. 167; if these six faces are present, the horizontal plane of symmetry requires six similar faces below the center. This is the *hexagonal dipyramid of the second order*.

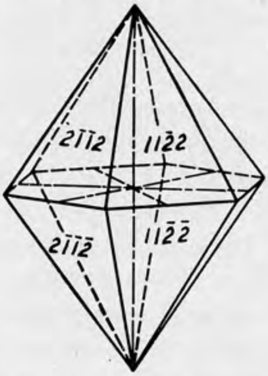

Fig. 167. Second order dipyramid.

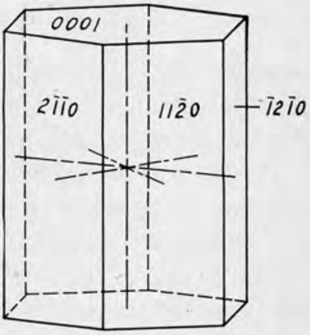

Fig. 168. Second order prism and base.

If the original face be changed to $11\bar{2}0$, the vertical axis of sixfold symmetry requires the face $\bar{1}2\bar{1}0$, $\bar{2}110$, $\bar{1}\bar{1}20$, $1\bar{2}10$, and $2\bar{1}\bar{1}0$, as in Fig. 168. This is the *hexagonal prism of the second order*.

If the original face be changed to $21\bar{3}1$, a diagonal plane of symmetry requires the face $12\bar{3}1$, as in Fig. 169; if these two faces are present, the vertical axis of sixfold symmetry requires a total of six pairs of such faces, namely: $21\bar{3}1$, $12\bar{3}1$, $\bar{1}3\bar{2}1$, $\bar{2}3\bar{1}1$, $\bar{3}211$, $\bar{3}121$, $\bar{2}\bar{1}31$, $\bar{1}\bar{2}31$, $1\bar{3}21$, $2\bar{3}11$, $3\bar{2}\bar{1}1$, and $3\bar{1}\bar{2}1$. If

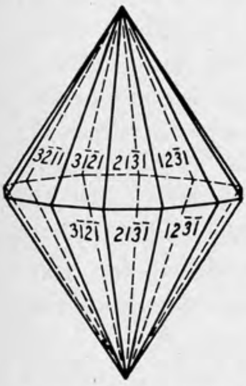

FIG. 169. Dihexagonal dipyramid.

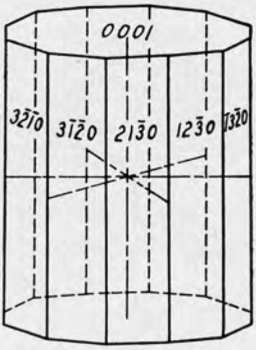

FIG. 170. Dihexagonal prism and base.

these faces are present, the horizontal plane of symmetry requires twelve similar faces below. This is the *dihexagonal dipyramid.*

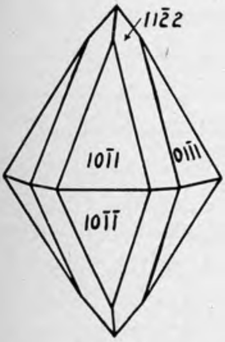

FIG. 171. First and second order hexagonal dipyramids.

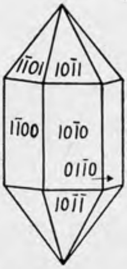

FIG. 172. Hexagonal prism and dipyramid.

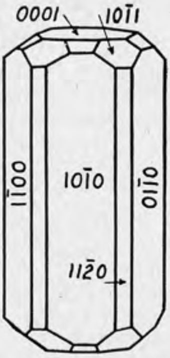

FIG. 173. Hexagonal base and first and second order prisms and dipyramids.

If the original face be changed to $21\bar{3}0$, a diagonal plane of symmetry requires the face $12\bar{3}0$, as in Fig. 170. If these two faces are present the vertical axis of sixfold symmetry requires a total of six pairs of similar faces, namely: $21\bar{3}0$, $12\bar{3}0$, $\bar{1}3\bar{2}0$, $\bar{2}3\bar{1}0$, $\bar{3}210$, $\bar{3}120$, $\bar{2}\bar{1}30$, $\bar{1}\bar{2}30$, $1\bar{3}20$, $2\bar{3}10$, $3\bar{2}\bar{1}0$, $3\bar{1}\bar{2}0$. These are the faces of the *dihexagonal prism.*

Combinations. Hexagonal dipyramids are closed forms and can occur alone; prisms and pinacoids are open forms and must occur with other forms. A combination of first and second order dipyramids is shown in Fig. 171. The hexagonal prism and dipyramid of the first order are shown in Fig. 172. The prism of the first order with the basal pinacoid is modified by the second order prism, and the first and second order pyramids in Fig. 173. One end of a crystal of beryl ($Be_3Al_2Si_6O_{18}$) is shown in Fig. 174. It has the first order prism, base, two first order pyramids, one second order pyramid, and a dihexagonal pyramid.

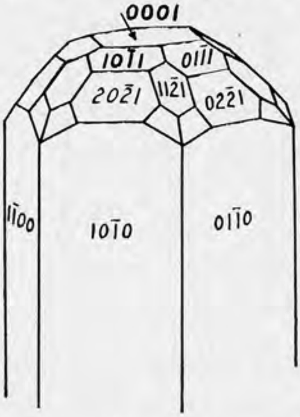

FIG. 174. First order prism and dipyramids, second order dipyramid, base and dihexagonal dipyramid.

Summary. The forms of the normal class of the hexagonal system are given below together with symbols, faces, angles, and symmetry. The generalized Miller-Bravais symbols are followed by a concrete example.

Forms	Miller-Bravais Symbols	Faces	Solid Angles		
			Tetra-hedral	Hexa-hedral	Dodeca-hedral
Hexagonal dipyramids of the first order (fundamental or unit form)	$(h0\bar{h}l)$ $(10\bar{1}1)$	12 12	6 6	2 2	— —
Hexagonal prism of the first order	$(10\bar{1}0)$	6	—	—	—
Basal pinacoid	(0001)	2	—	—	—
Hexagonal dipyramid of the second order	$(hh2\bar{h}l)$ $(11\bar{2}2)$	12 12	6 6	2 2	— —
Hexagonal prism of the second order	$(11\bar{2}0)$	6	—	—	—
Dihexagonal dipyramid	$(hk\bar{i}l)$ $(21\bar{3}1)$	24 24	6 + 6 6 + 6	— —	2 2
Dihexagonal prism	$(hk\bar{i}0)$ $(21\bar{3}0)$	12 12	— —	— —	— —

Symmetry	Center	Axes		Planes	
		6-fold	2-fold	Axial	Diagonal
	1	1 vertical	3 axial 3 diagonal	1 horizontal 1 vertical	3 vertical

Tripyramidal or hexagonal dipyramidal class ($6/m$)

Symmetry. Crystals of the tripyramidal class have a center of symmetry, one (vertical) axis of sixfold symmetry, and one (horizontal) plane of symmetry. These crystals are closely comparable to those of the tripyramidal class of the tetragonal system. These elements of symmetry are shown in Fig. 175.

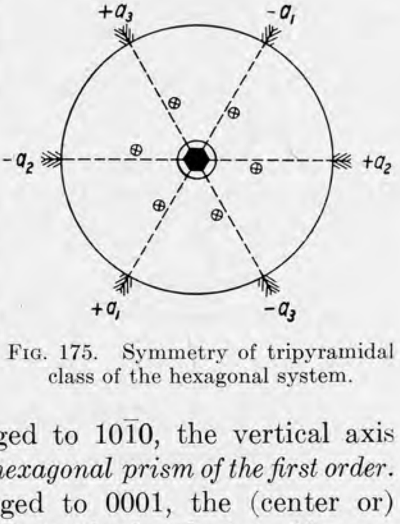

FIG. 175. Symmetry of tripyramidal class of the hexagonal system.

Forms. Assuming a face $10\bar{1}1$, the vertical axis of sixfold symmetry and the (center or) plane of symmetry lead to the *hexagonal dipyramid of the first order.*

If the original face be changed to $10\bar{1}0$, the vertical axis of sixfold symmetry leads to the *hexagonal prism of the first order.*

If the original face be changed to 0001, the (center or) horizontal plane of symmetry leads to the *basal pinacoid.*

If the original face be changed to $11\bar{2}2$, the vertical axis of sixfold symmetry and the (center or) horizontal plane of symmetry lead to the *hexagonal dipyramid of the second order.*

If the original face be changed to $11\bar{2}0$, the vertical axis of sixfold symmetry leads to the *hexagonal prism of the second order.*

If the original face be changed to $21\bar{3}1$, the vertical axis of sixfold symmetry and the (center or) horizontal plane of symmetry lead to the *hexagonal dipyramid of the third order.* This form is characteristic of the class; it includes alternate faces of the dihexagonal dipyramid, as shown in Fig. 176. The relation of the third order form to the first order prism is shown in Fig. 177.

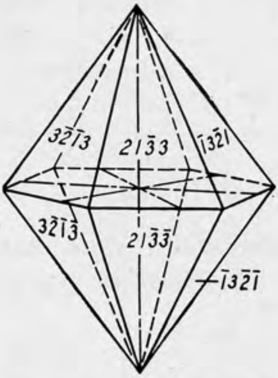

FIG. 176. Third order dipyramid.

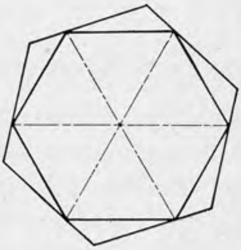

FIG. 177. Relation of third order prism to first order prism.

If the original face be changed to $21\bar{3}0$, the vertical axis of sixfold symmetry leads to the *hexagonal prism of the third order*, as shown in Fig. 178.

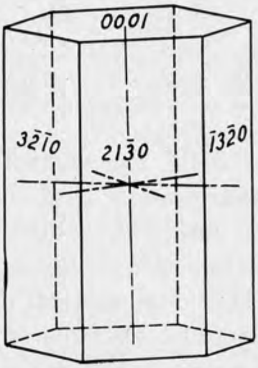

FIG. 178. Third order prism and base.

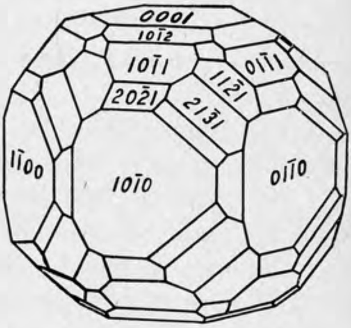

FIG. 179. First order prism, base and first, second, and third order dipyramids.

A typical crystal of this class is shown in Fig. 179. It represents a crystal of apatite with base (0001), first $(10\bar{1}0)$ and third $(21\bar{3}0)$ order prisms, three first order dipyramids $\{(10\bar{1}2), (10\bar{1}1), (20\bar{2}1)\}$, two second order dipyramids $\{(11\bar{2}1)$ and $(11\overline{22})\}$, and two third order dipyramids, $\{(21\bar{3}1)$ and $(31\bar{4}1)\}$.

Summary. The forms of the tripyramidal class of the hexagonal system are given below together with their symbols, faces, angles, and symmetry:

Forms	Miller-Bravais Symbols	Faces	Solid Angles	
			Tetrahedral	Hexahedral
Hexagonal dipyramids of the first order (fundamental or unit form)	$(h0hl)$	12	6	2
	$(10\bar{1}1)$	12	6	2
Hexagonal prism of the first order	$(10\bar{1}0)$	6	—	—
Basal pinacoid	(0001)	2	—	—
Hexagonal dipyramid of the second order	$(hh\overline{2hl})$	12	6	2
Hexagonal prism of the second order	$(11\bar{2}0)$	6	—	—
Hexagonal dipyramid of the third order	$(hk\bar{i}l)$	12	6	2
Hexagonal prism of the third order	$(hk\bar{i}0)$	6	—	—

	Center	Axes		Planes	
		6-fold	2-fold	Axial	Diagonal
Symmetry	1	1 vertical	0	1 horizontal	0

Trigonal Division

Rhombohedral or hexagonal scalenohedral class ($\bar{3}\ m$)

This class may be considered appropriately as the normal class of the trigonal division.

Symmetry. Crystals of the rhombohedral class have a center of symmetry, three horizontal axes of twofold symmetry coinciding with the crystal axes, one axis of threefold symmetry which is the axis *c*, and three vertical planes of symmetry which bisect the angles between the horizontal crystal axes. These elements of symmetry are shown in Fig. 180.

The international symbol for the rhombohedral class, $\bar{3}\ m$, indicates that the vertical axis is an axis of threefold rotary-inversion, which is the same as a threefold axis of rotation with a center of symmetry, and a vertical plane normal to the a_1 axis. The vertical axis of threefold symmetry requires the triplication of the vertical plane, which of course bisects the angles between the horizontal crystallographic axes, since it is normal to one of them.

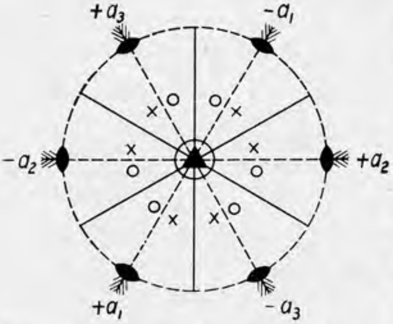

FIG. 180. Symmetry of the rhombohedral class of the hexagonal system.

Forms. Assuming a face $10\bar{1}1$, (see Fig. 181) the vertical axis of threefold symmetry requires the faces $\bar{1}101$, and $0\bar{1}11$. If these three faces are present, any one of the horizontal axes of twofold symmetry (or the center of symmetry) requires the presence of three faces in alternate position below—$0\bar{1}\bar{1}\bar{1}$, $\bar{1}01\bar{1}$, and $1\bar{1}0\bar{1}$. Such a form is a pyramid according to the general definition of that term. Further, it includes all the faces of alternate dodecants of the hexagonal dipyramid. However, as it has the lower faces in alternate position instead of directly below as in any ordinary dipyramid, it is given a special name; since each face is a rhomb, it is called a *rhombohedron*. Fig. 181 illustrates a positive rhombohedron; a corresponding negative rhombohedron is shown in Fig. 182. The angles of the rhombohedron vary widely as the faces make different angles with the vertical axis. Thus in Fig. 183 the angle is obtuse, since c is

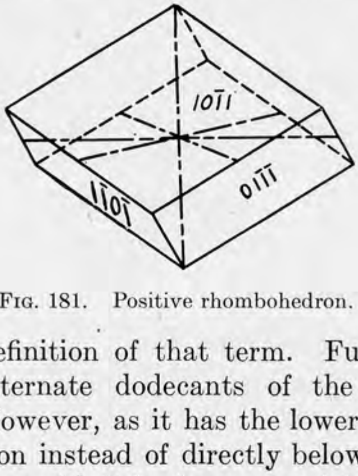

FIG. 181. Positive rhombohedron.

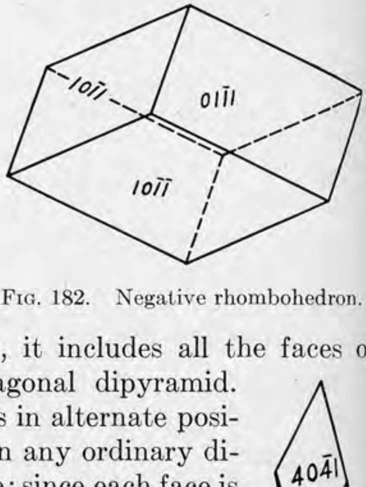

FIG. 182. Negative rhombohedron.

FIG. 183. Negative rhombohedron (obtuse).

Fig. 184. Positive rhombohedron (acute).

cut at $\frac{1}{2}$; whereas in Fig. 184 the angle is decidedly acute, since *c* is cut at 4. For a certain length of the vertical axis (1.2247+) the angle is 90° and the "rhombohedron" is a cube. A real cube has more symmetry than a rhombohedron, so this condition is not found among hexagonal crystals, though it is approached very closely in jarosite, in which $c = 1.2492$.

If the original face be changed to $10\bar{1}0$, the vertical axis of threefold symmetry requires the faces $\bar{1}100$ and $01\bar{1}0$; if these three faces are present any axis of twofold symmetry (or the center of symmetry) requires the presence of the faces $\bar{1}010$, $1\bar{1}00$, and $0\bar{1}10$. This is a *hexagonal prism of the first order.*

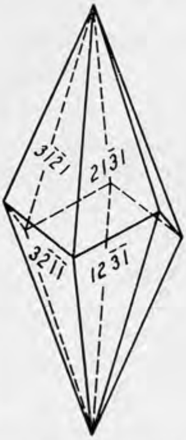

FIG. 185. Positive scalenohedron.

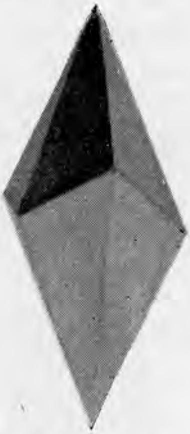

FIG. 186. Photograph of positive scalenohedron (turned 30°).

If the original face be changed to 0001, any horizontal axis of twofold symmetry (or the center of symmetry) requires the face $000\bar{1}$. This is the *basal pinacoid.*

If the original face be changed to $11\bar{2}2$, a diagonal plane of symmetry requires the face $\bar{1}2\bar{1}2$; if these two faces are present, the vertical axis of threefold symmetry requires the faces $\bar{2}112$, $\bar{1}\bar{1}22$, $1\bar{2}12$, and $2\bar{1}\bar{1}2$; if these faces are present any horizontal axis of twofold symmetry (or the center of symmetry) requires the corresponding faces below the center. This is the *hexagonal dipyramid of the second order.*

If the original face be changed to $11\bar{2}0$, a diagonal plane of symmetry requires the face $\bar{1}2\bar{1}0$; if these two faces are present the vertical axis of threefold symmetry requires the faces $\bar{2}110$, $\bar{1}\bar{1}20$, $1\bar{2}10$, and $2\bar{1}\bar{1}0$. This is the *hexagonal prism of the second order.*

If the original face be changed to $21\bar{3}1$, as in Figs. 185 and 186, a diagonal plane of symmetry requires the face $3\bar{1}\bar{2}1$; if these two faces are present the vertical axis of threefold symmetry requires the faces $\bar{2}3\bar{1}1$, $\bar{3}211$, $\bar{1}\bar{2}31$, and $1\bar{3}21$. If these six faces are present any horizontal axis of twofold symmetry (or the center of symmetry) requires the faces below: $12\bar{3}\bar{1}$, $\bar{1}3\bar{2}\bar{1}$, $\bar{3}12\bar{1}$, $\bar{2}\bar{1}3\bar{1}$, $2\bar{3}1\bar{1}$, and $3\bar{2}\bar{1}\bar{1}$. According to the definition, this form is a dipyramid, but it has two sets of terminal edges, one more obtuse than the other, and the lateral edges form a zigzag around the form, like that of a rhombohedron. Each face is a scalene triangle and the form goes under the special name, *scalenohedron*. This form has the faces of alternate dodecants of the dihexagonal dipyramid. As in the rhombohedron the faces of the lower half are in alternate position and not directly below the faces of the upper half. The corresponding negative scalenohedron is illustrated in Fig. 187. As in the case of the rhombohedrons, scalenohedrons may be acute or obtuse, depending on the length or intercept on the vertical axis.

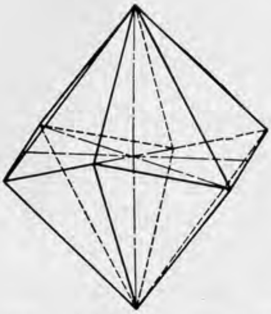

FIG. 187. Negative scalenohedron.

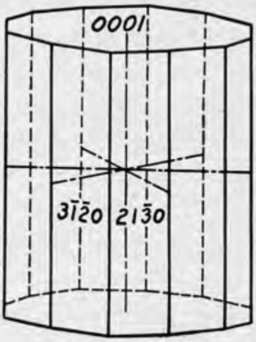

FIG. 188. Dihexagonal prism and base.

If the original face be changed to $21\bar{3}0$, as in Fig. 188, a diagonal plane of symmetry requires the face $3\bar{1}\bar{2}0$; if these two faces are present the vertical axis of threefold symmetry requires the faces $\bar{3}210$, $\bar{2}3\bar{1}0$, $\bar{1}\bar{2}30$, and $1\bar{3}20$; if these six faces are present a horizontal axis of twofold symmetry (or a center of symmetry) requires the faces $12\bar{3}0$, $\bar{1}3\bar{2}0$, $\bar{3}120$, $\bar{2}\bar{1}30$, $2\bar{3}10$, and $3\bar{2}\bar{1}0$. These are the faces of the *dihexagonal prism*.

Combinations. Many important minerals show the symmetry of this class, for example, calcite, hematite, corundum, siderite, chabazite, and so on. Calcite shows various combinations, for example, in Figs. 189 and 190, the positive rhombohedron

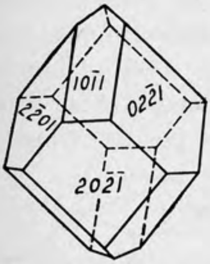

FIG. 189. Positive $(10\bar{1}1)$ and negative $(02\bar{2}1)$ rhombohedrons.

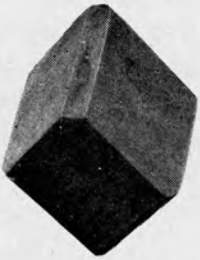

FIG. 190. Photograph of positive $(10\bar{1}1)$ and negative $(02\bar{2}1)$ rhombohedrons.

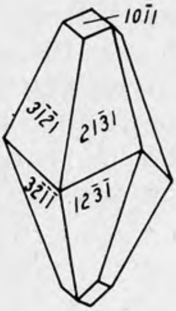

FIG. 191. Scalenohedron $(21\bar{3}1)$ modified by the rhombohedron $(10\bar{1}1)$.

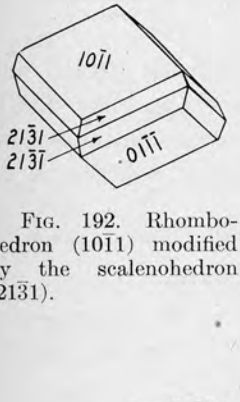

FIG. 192. Rhombohedron $(10\bar{1}1)$ modified by the scalenohedron $(21\bar{3}1)$.

FIG. 193. Hexagonal prism $(10\bar{1}0)$, rhombohedron $(10\bar{1}1)$, and scalenohedron $(21\bar{3}1)$.

FIG. 194. Photograph of hexagonal prism $(10\bar{1}0)$, rhombohedron $(10\bar{1}1)$, and scalenohedron $(21\bar{3}1)$.

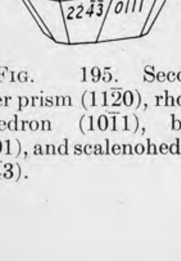

FIG. 195. Second order prism $(11\bar{2}0)$, rhombohedron $(10\bar{1}1)$, base (0001), and scalenohedron $(22\bar{4}3)$.

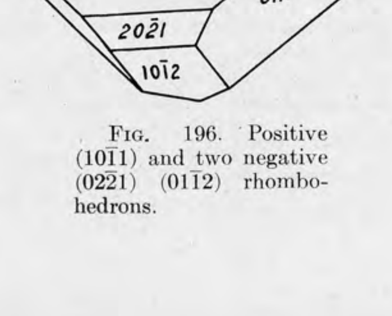

FIG. 196. Positive $(10\bar{1}1)$ and two negative $(02\bar{2}1)$ $(01\bar{1}2)$ rhombohedrons.

$(10\bar{1}1)$ and the negative rhombohedron $(02\bar{2}1)$; in Figs. 191 and 192, the rhombohedron $(10\bar{1}1)$ and the scalenohedron $(21\bar{3}1)$; in Figs. 193 and 194 the same forms with the hexagonal prism $(10\bar{1}0)$. Corundum may show the base (0001), rhombohedron $(10\bar{1}1)$, and scalenohedron $(22\bar{4}3)$ and second order prism $(11\bar{2}0)$ as in Fig. 195. Chabazite may show the positive rhombohedron $(10\bar{1}1)$, and two negative rhombohedrons $(01\bar{1}2)$ and $(02\bar{2}1)$, as in Fig. 196. Hematite may show the base (0001) and rhombohedron, as in Fig. 197, or two rhombohedrons $(10\bar{1}1)$ and $(10\bar{1}4)$ and second order dipyramid $(22\bar{4}3)$, as in Fig. 198.

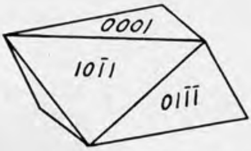

FIG. 197. Rhombohedron $(10\bar{1}1)$ and base (0001).

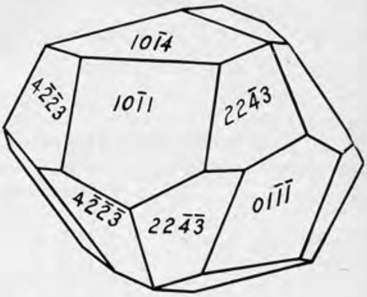

FIG. 198. Two rhombohedrons $(10\bar{1}1)$ $(10\bar{1}4)$ and scalenohedron $(22\bar{4}3)$.

Summary. The forms of the rhombohedral class are given below with their symbols, faces, angles, and symmetry:

Forms	Miller-Bravais Symbols	Faces	Solid Angles		
			Trihedral	Tetrahedral	Hexahedral
Rhombohedron Positive	*e.g.* $(10\bar{1}1)$	6	2 + 6	—	—
Negative	*e.g.* $(01\bar{1}1)$	6	2 + 6	—	—
Hexagonal prism of first order	$(10\bar{1}0)$	6	—	—	—
Basal pinacoid	(0001)	2	—	—	—
Hexagonal dipyramid of the second order	$(hh\overline{2h}l)$	12	6	2	—
Hexagonal prism of second order	$(11\bar{2}0)$	6	—	—	—
Scalenohedron Positive	$(hk\bar{i}l)$	12	—	6	2
Negative	$(kh\bar{i}l)$	12	—	6	2
Dihexagonal prism	$(hk\bar{i}0)$	12	—	—	—

Symmetry	Center	Axes		Planes	
		3-fold	2-fold	Axial	Diagonal
	1	1 vertical	3 axial horizontal	0	3 vertical

Rhombohedral hemimorphic or ditrigonal pyramidal class (3 *m*)

Crystals of the rhombohedral hemimorphic class differ from those of the preceding class in having no center of symmetry and no horizontal axes of symmetry. Therefore any form is complete when it has all the faces belonging above (or below) the plane of the horizontal axes. Minerals showing this symmetry (illustrated in Fig. 199) include such important ones as tourmaline and pyrargyrite.

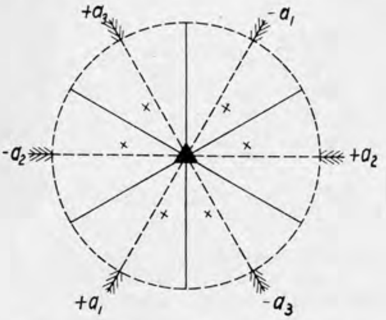

FIG. 199. Symmetry of the rhombohedral-hemimorphic class.

Symmetry. These crystals have three vertical planes of symmetry bisecting the angles between the horizontal crystal axes and one axis of threefold symmetry which is the axis *c*.

Forms. Assuming the face $10\bar{1}1$, the vertical axis of threefold symmetry requires the faces $\bar{1}101$ and $0\bar{1}11$, and these three faces are a complete form, since they satisfy all the elements of symmetry. Having three faces, they form (by definition) a *trigonal pyramid*. A similar group of three faces, if present, at the negative end of the vertical axis is another trigonal pyramid. Accordingly the dipyramid is not found in this class.

Also $(10\bar{1}1)$ is a positive trigonal pyramid. The faces $01\bar{1}1$, $\bar{1}011$, and $1\bar{1}01$ constitute the corresponding negative trigonal pyramid.

If the original face be changed to $10\bar{1}0$, the vertical axis of threefold symmetry requires the faces $\bar{1}100$ and $0\bar{1}10$ and these three faces constitute the positive *trigonal prism.* The corresponding negative trigonal prism has the faces $01\bar{1}0$, $\bar{1}010$, and $1\bar{1}00$.

If the original face be changed to 0001, no other face is required by the symmetry. This is a *basal pinacoid* (sometimes given a special name, *pedion,* since it consists of only one face). Of course $000\bar{1}$ is also a basal pinacoid (negative), but if both these faces are present they constitute *two* basal pinacoids.

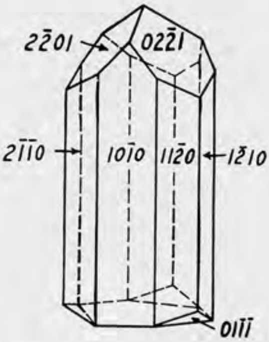

FIG. 200. Second order hexagonal prism $(11\bar{2}0)$, trigonal prism $(10\bar{1}0)$, two trigonal pyramids $(02\bar{2}1)$ $(01\bar{1}\bar{1})$ and base $(000\bar{1})$.

FIG. 201. Photograph of second order hexagonal prism $(11\bar{2}0)$, trigonal prism $(10\bar{1}0)$, two trigonal pyramids, $(02\bar{2}1)$ and $(01\bar{1}\bar{1})$ and base $(000\bar{1})$.

If the original face be changed to $11\bar{2}2$, a diagonal plane of symmetry requires the face $2\bar{1}\bar{1}2$; if these two faces are present, the vertical axis of threefold symmetry requires the faces $\bar{1}2\bar{1}2$, $\bar{2}112$, $\bar{1}\bar{1}22$, and $1\bar{2}12$. These six faces constitute the *hexagonal pyramid of the second order.* This is not a dipyramid, since no faces below the plane of the horizontal axes are included.

If the original face be changed to $11\bar{2}0$, a diagonal plane of symmetry requires the face $2\bar{1}\bar{1}0$; if these two faces are present, the vertical axis of threefold symmetry requires the faces $\bar{1}2\bar{1}0$, $\bar{2}110$, $\bar{1}\bar{1}20$, and $1\bar{2}10$. These six faces constitute the *hexagonal prism of the second order.*

If the original face be changed to $21\bar{3}1$, a diagonal plane of symmetry requires the face $3\bar{1}\bar{2}1$; if these two faces are present, the vertical axis of threefold symmetry requires the faces $\bar{2}3\bar{1}1$, $\bar{3}211$, $\bar{1}\bar{2}31$, and $1\bar{3}21$. These six faces constitute a *ditrigonal pyramid;* it is not a hexagonal pyramid because the interfacial angles belong to two unequal sets. The form has all the faces of the upper half of a positive scalenohedron or one fourth of the faces of a dihexagonal dipyramid.

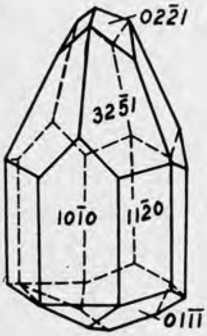

FIG. 202. Second order prism ($11\bar{2}0$), trigonal prism ($10\bar{1}0$), two trigonal pyramids ($02\bar{2}1$) ($01\bar{1}\bar{1}$), and ditrigonal pyramid ($32\bar{5}1$).

FIG. 203. Photograph of second order prism ($11\bar{2}0$), trigonal prism ($10\bar{1}0$), two trigonal pyramids ($02\bar{2}1$) ($01\bar{1}\bar{1}$), and ditrigonal pyramid ($32\bar{5}1$).

If the original face be changed to $21\bar{3}0$, a diagonal plane of symmetry requires the face $3\bar{1}\bar{2}0$; if these two faces are present, the vertical axis of threefold symmetry requires the faces $\bar{2}3\bar{1}0$, $\bar{3}210$, $\bar{1}\bar{2}30$, and $1\bar{3}20$. These six faces constitute the *ditrigonal prism.* It has two sets of unequal interfacial angles, just as the ditrigonal pyramid has. The form has half the faces of the dihexagonal prism. The corresponding negative ditrigonal prism has the remaining faces of the same form.

Combinations. A crystal of tourmaline, shown in Figs. 200 and 201, is a combination of a trigonal prism ($10\bar{1}0$), and a hexagonal prism of the second order ($11\bar{2}0$), a positive trigonal pyramid ($10\bar{1}\bar{1}$), a negative trigonal pyramid ($02\bar{2}1$), and a basal pinacoid ($000\bar{1}$). Another crystal (Figs. 202 and 203) shows the same forms, except the base, with a ditrigonal pyramid ($32\bar{5}1$).

Summary. The forms of the rhombohedral hemimorphic class are given with their symbols, faces, angles, and symmetry:

Forms		Miller-Bravais Symbols	Faces	Solid Angles		
				Tri-hedral	Tetra-hedral	Hexa-hedral
Trigonal pyramid	Upper +	$(10\bar{1}1)$	3	1	—	—
	Upper −	$(01\bar{1}1)$	3	1	—	—
	Lower +	$(10\bar{1}\bar{1})$	3	1	—	—
	Lower −	$(01\bar{1}\bar{1})$	3	1	—	—
Trigonal prism	+	$(10\bar{1}0)$	3	—	—	—
	−	$(01\bar{1}0)$	3	—	—	—
Basal pinacoid (or pedion)	+	0001	1	—	—	—
	−	$000\bar{1}$	1	—	—	—
Hexagonal pyramid of second order	+	*e.g.* $(11\bar{2}2)$	6	—	—	1
	−	*e.g.* $(11\bar{2}\bar{2})$	6	—	—	1
Hexagonal prism of second order		$(11\bar{2}0)$	6	—	—	—
Ditrigonal pyramid	Upper +	*e.g.* $(21\bar{3}1)$	6	—	—	1
	Upper −	*e.g.* $(12\bar{3}1)$	6	—	—	1
	Lower +	*e.g.* $(21\bar{3}\bar{1})$	6	—	—	1
	Lower −	*e.g.* $(12\bar{3}\bar{1})$	6	—	—	1
Ditrigonal prism	+	*e.g.* $(21\bar{3}0)$	6	—	—	—
	−	*e.g.* $(12\bar{3}0)$	6	—	—	—

Symmetry	Center	Axes		Planes	
		3-fold	2-fold	Axial	Diagonal
	0	1 vertical	0	0	3 vertical

Trirhombohedral or trigonal rhombohedral class ($\bar{3}$)

Symmetry. Crystals of the trirhombohedral class have a center of symmetry and a vertical axis, *c*, of threefold symmetry. They have no other elements of symmetry and so no planes of symmetry, as shown in Fig. 204.

Forms. Assuming the face $10\bar{1}1$, the vertical axis of threefold symmetry requires the faces $\bar{1}101$ and $0\bar{1}11$; if these three faces are present, the center of symmetry requires the faces $01\bar{1}\bar{1}$, $\bar{1}01\bar{1}$, and $1\bar{1}0\bar{1}$. These six faces constitute a positive *rhombohedron of the first order*.

If the original face be changed to $10\bar{1}0$, the vertical axis of threefold symmetry requires the faces $\bar{1}100$ and $0\bar{1}10$; if these three faces are present, the center of symmetry requires the faces $01\bar{1}0$, $\bar{1}010$, and $1\bar{1}00$. These six faces constitute the first order *hexagonal prism.*

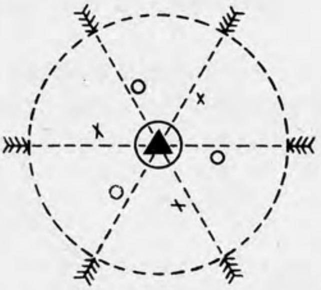

FIG. 204. Symmetry of the trirhombohedral class.

If the original face be changed to 0001, the center of symmetry requires $000\bar{1}$, which completes the *basal pinacoid.*

If the original face be changed to $11\bar{2}2$, the vertical axis of threefold symmetry requires the faces $\bar{2}112$ and $1\bar{2}12$; if these three faces are present, the center of symmetry requires the faces: $\bar{1}2\bar{1}\bar{2}$, $\bar{1}\bar{1}2\bar{2}$, and $2\bar{1}\bar{1}\bar{2}$. This completes the *rhombohedron of the second order.* Its faces are alternate faces of the hexagonal dipyramid of the second order.

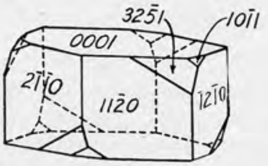

FIG. 205. Base (0001), second order prism ($11\bar{2}0$), first ($10\bar{1}1$) and third ($32\bar{5}1$) order rhombohedrons.

If the original face be changed to $11\bar{2}0$, the vertical axis of threefold symmetry requires the faces $\bar{2}110$ and $1\bar{2}10$; if these three faces are present, the center of symmetry requires the faces: $\bar{1}2\bar{1}0$, $\bar{1}\bar{1}20$, and $2\bar{1}\bar{1}0$. This completes the *hexagonal prism of the second order.*

If the original face be changed to $21\bar{3}1$, the vertical axis of the threefold symmetry requires the faces $\bar{1}3\bar{2}1$ and $\bar{3}211$; if these three faces are present, the center of symmetry requires the faces $\bar{1}\bar{2}3\bar{1}$, $2\bar{3}1\bar{1}$, and $3\bar{1}\bar{2}\bar{1}$. These six faces complete the *rhombohedron of the third order.* It has one fourth of the faces of the dihexagonal dipyramid or one half the faces of the scalenohedron.

If the original face be changed to $21\bar{3}0$, the vertical axis of threefold symmetry requires the faces $\bar{3}210$ and $1\bar{3}20$; if these three faces are present the center of symmetry requires the faces $\bar{1}3\bar{2}0$, $\bar{2}\bar{1}30$, and $3\bar{2}\bar{1}0$. This gives the *hexagonal prism of the third order.*

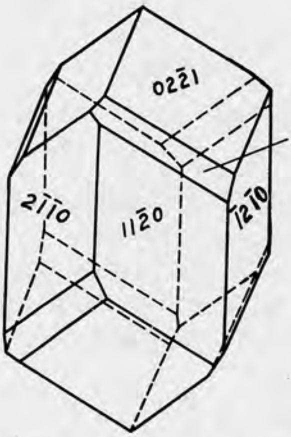

FIG. 206. Second order prism ($11\bar{2}0$), negative rhombohedron ($02\bar{2}1$), and third order rhombohedron ($13\bar{4}1$).

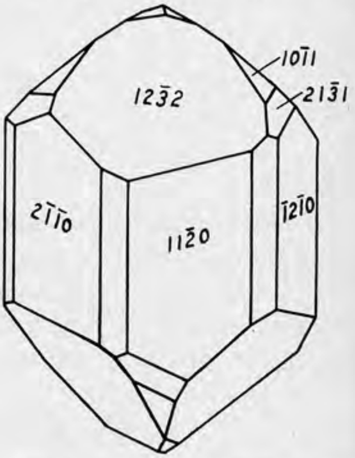

FIG. 207. First ($10\bar{1}0$) and second ($11\bar{2}0$) order prisms, two third order rhombohedrons ($12\bar{3}2$) ($21\bar{3}1$), and two first order rhombohedrons ($10\bar{1}1$) ($01\bar{1}2$).

Combinations. A crystal of dolomite ($CaMgC_2O_6$) may be limited by the base (0001), hexagonal prism of the second order ($11\bar{2}0$), first order rhombohedron ($10\bar{1}1$), and third order rhombohedron ($32\bar{5}1$), as in Fig. 205. Dioptase (H_2CuSiO_4) may show the second order hexagonal prism ($11\bar{2}0$), a negative first order rhombohedron ($02\bar{2}1$), and a third order rhombohedron ($13\bar{4}1$), as in Fig. 206. Phenacite (Be_2SiO_4) may show the first and second order hexagonal prisms ($10\bar{1}0$) and ($11\bar{2}0$), two first order rhombohedrons ($10\bar{1}1$) and ($01\bar{1}2$), and two third order rhombohedrons ($12\bar{3}2$) and ($21\bar{3}1$), as in Fig. 207.

Summary. The forms of the trirhombohedral class are given with their symbols, faces, angles, and symmetry:

Forms	Miller-Bravais Symbols	Faces	Solid Angles		
			Tri-hedral	Tetra-hedral	Hexa-hedral
Rhombohedrons of first order +	*e.g.* $(10\bar{1}1)$	6	2 + 6	—	—
Rhombohedrons of first order −	*e.g.* $(01\bar{1}1)$	6	2 + 6	—	—
Hexagonal prism of first order	$(10\bar{1}0)$	6	—	—	—
Basal pinacoid	(0001)	2	—	—	—
Rhombohedron of second order +	*e.g.* $(11\bar{2}2)$	6	2 + 6	—	—
Rhombohedron of second order −	*e.g.* $(\bar{1}2\bar{1}2)$	6	2 + 6	—	—
Hexagonal prism of second order	$(11\bar{2}0)$	6	—	—	—
Rhombohedrons of third order Right-handed +	*e.g.* $(21\bar{3}1)$	6	2 + 6	—	—
Rhombohedrons of third order Right-handed −	*e.g.* $(\bar{1}3\bar{2}1)$	6	2 + 6	—	—
Rhombohedrons of third order Left-handed +	*e.g.* $(3\bar{1}\bar{2}1)$	6	2 + 6	—	—
Rhombohedrons of third order Left-handed −	*e.g.* $(12\bar{3}1)$	6	2 + 6	—	—
Hexagonal prism of third order Right-handed	*e.g.* $(21\bar{3}0)$	6	—	—	—
Hexagonal prism of third order Left-handed	*e.g.* $(12\bar{3}0)$	6	—	—	—

Symmetry	Center	Axes		Planes	
		3-fold	2-fold	Axial	Diagonal
	1	1 vertical	0	0	0

Trigonal trapezohedral class (3 2)

Symmetry. Crystals of the trigonal trapezohedral class have no center of symmetry and no plane of symmetry; they have a vertical axis of threefold symmetry and three horizontal axes of twofold symmetry coinciding with the crystal axes, as shown in Fig. 208.

Forms. As described for the rhombohedral class, these symmetry elements lead to the *first order rhombohedrons* such as $(10\bar{1}1)$, *first order hexagonal prism* $(10\bar{1}0)$, and the *basal pinacoid* (0001).

If the original face be changed to $11\bar{2}2$, the vertical axis of threefold symmetry requires the faces $\bar{2}112$ and $1\bar{2}12$; if these three faces are present, each horizontal axis of twofold symmetry requires the faces directly below, namely: $11\bar{2}\bar{2}$, $\bar{2}11\bar{2}$, and $1\bar{2}1\bar{2}$. These six faces complete the *second order trigonal* *dipyramid*, called right-handed. A complementary left-handed trigonal dipyramid $(2\bar{1}\bar{1}2)$ has all the remaining faces of the hexagonal dipyramid $(11\bar{2}2)$ shown in Fig. 167.

If the original face be changed to $11\bar{2}0$, the vertical axis of threefold symmetry requires the faces $\bar{2}110$ and $1\bar{2}10$. These three faces constitute a *trigonal prism*, also called right-handed. The complementary left-handed trigonal prism $(2\bar{1}\bar{1}0)$ has all the other faces of the second order hexagonal prism $(11\bar{2}0)$.

If the original face be changed to $21\bar{3}1$, the vertical axis of threefold symmetry requires the faces $\bar{3}211$ and $1\bar{3}21$; if these three faces are present, each horizontal axis of twofold symmetry requires the faces $12\bar{3}\bar{1}$, $\bar{3}12\bar{1}$, and $1\bar{3}2\bar{1}$. These six faces complete a form called a *trigonal trapezohedron* (since each face is a trapezium); this is the positive right-handed form. The horizontal axes of twofold symmetry connect opposite midpoints of the zigzag edges.

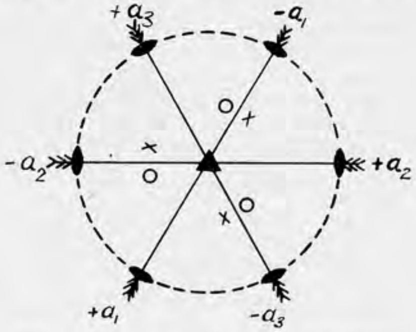

FIG. 208. Symmetry of the trapezohedral class of the hexagonal system.

If the original face be changed to $21\bar{3}0$, a horizontal axis of twofold symmetry requires the face $12\bar{3}0$; if these two faces are present, the vertical axis of threefold symmetry requires the faces $\bar{3}210$, $\bar{3}120$, $1\bar{3}20$, and $2\bar{3}10$. These six faces complete the right-handed *ditrigonal prism.*

Crystals of ordinary quartz (SiO_2) (the low temperature α-form) illustrate this class of symmetry. Some such crystals may appear to have normal hexagonal symmetry, since the rhombohedrons $(10\bar{1}1)$ and $(01\bar{1}1)$ may be equally developed, but often one rhombohedron differs in size or luster from the other, and the difference can always be demonstrated by etching;

if characteristic forms are present, the symmetry is apparent at once, as in Figs. 209–212. The first order hexagonal prism and the two rhombohedrons $(10\bar{1}1)$ and $(01\bar{1}1)$ are modified by the right trigonal pyramid $(11\bar{2}1)$ and right positive trapezohedron $(51\bar{6}1)$ in Figs. 209 and 210, and by the left trigonal pyramid $(2\bar{1}\bar{1}1)$ and left positive trapezohedron $(6\bar{1}\bar{5}1)$ in Figs. 211 and 212. Such crystals rotate the plane of polarized light to the right (clockwise) in the first case and to the left in the second case.

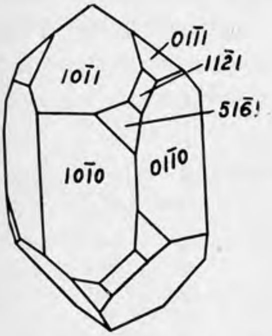

Fig. 209. Prism $(10\bar{1}0)$, two rhombohedrons $(10\bar{1}1)$ $(01\bar{1}1)$, right trigonal dipyramid $(11\bar{2}1)$, and right positive trapezohedron $(51\bar{6}1)$ of quartz.

Fig. 210. Photograph of prism $(10\bar{1}0)$, two rhombohedrons $(10\bar{1}1)$ $(01\bar{1}1)$, right trigonal pyramid $(11\bar{2}1)$, and right trapezohedron $(51\bar{6}1)$.

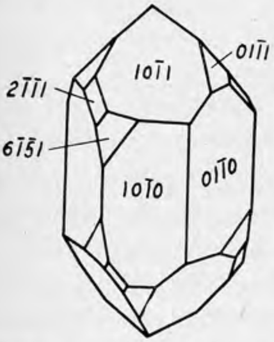

Fig. 211. Prism $(10\bar{1}0)$, two rhombohedrons $(10\bar{1}1)$ $(01\bar{1}1)$, left trigonal dipyramid $(2\bar{1}\bar{1}1)$, and left trapezohedron $(6\bar{1}\bar{5}1)$ of quartz.

Fig. 212. Photograph of prism $(10\bar{1}0)$, two rhombohedrons $(10\bar{1}1)$ $(01\bar{1}1)$, left trigonal dipyramid $(2\bar{1}\bar{1}1)$, and left trapezohedron $(6\bar{1}\bar{5}1)$.

Summary. The forms of the trigonal trapezohedral class follow, with their symbols, faces, angles, and symmetry:

Forms		Miller-Bravais Symbols	Faces	Solid Angles		
				Trihedral	Tetrahedral	Hexahedral
Rhombohedrons	Positive $(h0\bar{h}l)$	*e.g.* $(10\bar{1}1)$	6	2 + 6	—	—
	Negative $(0h\bar{h}l)$	*e.g.* $(01\bar{1}1)$	6	2 + 6	—	—
Hexagonal prism of first order		$(10\bar{1}0)$	6	—	—	—
Basal pinacoid		(0001)	2	—	—	—
Trigonal dipyramids of the second order	Positive $(hh\overline{2h}l)$	*e.g.* $(11\bar{2}2)$	6	2 + 6	3	—
	Negative $(2h\bar{h}\bar{h}l)$	*e.g.* $(2\bar{1}\bar{1}2)$	6	2 + 6	3	—
Trigonal prisms of second order	Positive $(hh\bar{2}\bar{h}0)$	$(11\bar{2}0)$	3	—	—	—
	Negative $(2h\bar{h}\bar{h}0)$	$(2\bar{1}\bar{1}0)$	3	—	—	—
Trigonal trapezohedrons	Right + $(hi\bar{k}l)$	*e.g.* $(21\bar{3}1)$	6	2 + 6	—	—
	Right − $(ih\bar{k}l)$	*e.g.* $(\bar{1}3\bar{2}1)$	6	2 + 6	—	—
	Left + $(k\bar{i}\bar{h}l)$	*e.g.* $(3\bar{1}\bar{2}1)$	6	2 + 6	—	—
	Left − $(k\bar{h}\bar{i}l)$	*e.g.* $(12\bar{3}1)$	6	2 + 6	—	—
Ditrigonal prisms	+ $(hi\bar{k}0)$	*e.g.* $(21\bar{3}0)$	6	—	—	—
	− $(\bar{k}ih0)$	*e.g.* $(\bar{3}120)$	6	—	—	—

Symmetry	Center	Axes		Planes	
		3-fold	2-fold	Axial	Diagonal
	0	1 vertical	3 horizontal axial	0	0

Orthorhombic System

Those crystals which have three unequal axes at right angles to each other belong to the orthorhombic system. The front and rear axis is designated *a*, as before, the right and left axis is *b*, and the vertical axis is *c*, as shown in Fig. 213. Any one of the axes may be chosen as *c*, but the right and left axis, *b*, must be chosen so as to be longer than the front and rear axis, *a*. From this fact the *b* axis is known as the macro-axis and the *a* axis as the brachy-axis. The length of the *b* axis is taken as unity and the lengths of the other axes are expressed in terms

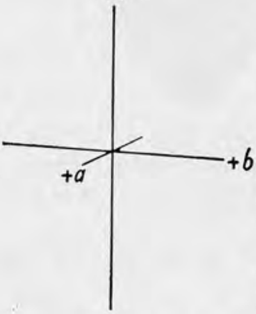

FIG. 213. Axes of an orthorhombic crystal.

of that unit. For example, in barite the axial ratio is $a:b:c: = 0.815:1:1.31$. Negative directions on the axes are to the rear on a, to the left on b, and downward on c, as before. The Hermann-Mauguin symbols identify the crystal system in this case by the fact that they consist of either two or three symbols, none indicating more than twofold symmetry.

There are three classes of symmetry in the orthorhombic system, as follows:

1. Normal class—center, three twofold axes and three planes of symmetry. (*m m m*)
2. Hemimorphic class—vertical axis and two vertical planes of symmetry. (*m m*)
3. Sphenoidal class—three twofold axes of symmetry. (2 2 2)

All these classes are represented among minerals, but the normal class is far the most important.

Normal or rhombic dipyramidal class (*m m m*)

Symmetry. Crystals of the normal class have a center of symmetry, three twofold axes of symmetry coinciding with the crystal axes, and three planes of symmetry each containing two crystal axes. These elements of symmetry are shown in Fig. 214.

The Hermann-Mauguin symbols, *m m m*, indicate immediately the three planes of symmetry; since these planes are all at right angles to one another, there is also a center of symmetry; and since these planes intersect one another in pairs, always at right angles, there are three axes of twofold symmetry, coinciding with the crystallographic axes.

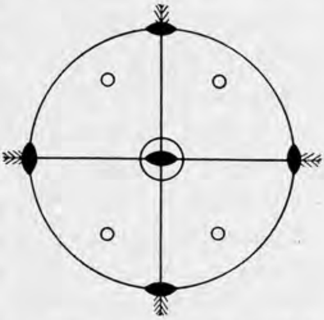

FIG. 214. Symmetry of an orthorhombic crystal (normal class).

Forms. Assuming the original face 111, as in Fig. 215, the *ac* plane of symmetry requires the face $1\bar{1}1$; if these two faces are present, the *bc* plane of symmetry requires the faces $\bar{1}11$ and $\bar{1}\bar{1}1$; if these four faces are present, the horizontal plane requires the four corresponding faces below the center. These eight faces constitute a *rhombic* (or orthorhombic) *dipyramid.*

This dipyramid, which cuts all the axes at their respective unit distances, is known as the *fundamental form.*

In the orthorhombic system the form remains a dipyramid as long as the assumed face cuts all three axes, no matter how the intercepts are changed. But there are three varieties of dipyramids depending upon the intercepts. If the change from 111 involves only the vertical axis (the intercept on that axis becoming a simple fraction or multiple of unity) the form resulting is called a *unit dipyramid,* which means that the intercepts on *a* and *b* are both unity. (For the respective axes it is not true that these intercepts are equal.) The general symbols are (*hhl*). There may be several unit dipyramids on a single crystal with different intercepts on the vertical axis; all the faces of such forms lying in the positive octant have parallel intersections and are said to form a *zone*—with the base (001) and the unit prism (110).

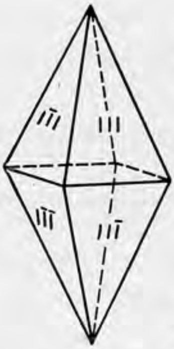

FIG. 215. Rhombic dipyramid (111) of sulfur.

All dipyramids which cut the brachy-axis, *a*, at a multiple (even including those cutting *c* at a multiple) are called *brachydipyramids,* and all those cutting the macro-axis, *b*, at a multiple are called *macrodipyramids.* Each set of such dipyramids having a common ratio on the lateral axes belongs to a zone; for example, the brachydipyramids (124), (123), (122), (241), etc., belong to a single zone—between the base (001) and the brachyprism (120).

If the original face becomes parallel with the vertical axis *c*, the symbols become 110; thus in Fig. 216 the *ac* plane of symmetry requires the face 1$\bar{1}$0 and the *bc* plane of symmetry requires 1$\bar{1}$0 and $\bar{1}\bar{1}$0. These four faces complete the *unit prism.* If the face changes position so as to cut the brachy-axis, *a*, at a multiple (symbols then, for example, 120) the form is called a *brachyprism,* and if it cuts the macro-axis, *b*, at a multiple, it is a *macroprism.*

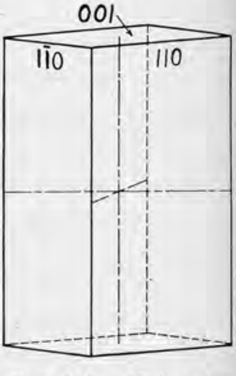

FIG. 216. Unit prism and base.

If the original face becomes parallel with the brachy-axis, *a*, the symbols become 011, as in Figs. 217 and 218; then the *ac* plane of symmetry requires $0\bar{1}1$ and the *ab* plane of symmetry requires $01\bar{1}$ and $0\bar{1}\bar{1}$. These four faces constitute a dome, called a *brachydome*, because the faces are parallel with the brachy-axis.

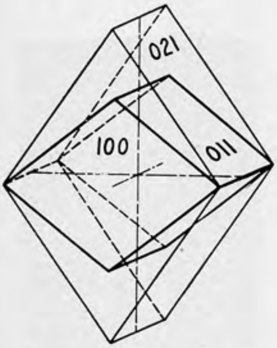

FIG. 217. Brachydomes and macropinacoid.

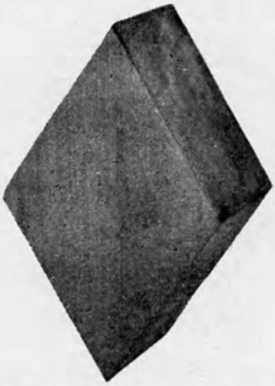

FIG. 218. Photograph of brachydome and macropinacoid.

If the original face becomes parallel with the macro-axis, *b*, the symbols become 101, as in Fig. 219; then the *bc* plane of symmetry requires $\bar{1}01$ and the *ab* plane of symmetry requires $10\bar{1}$ and $\bar{1}0\bar{1}$. These four faces make another dome, which is the *macrodome*, because the faces are parallel with the macro-axis.

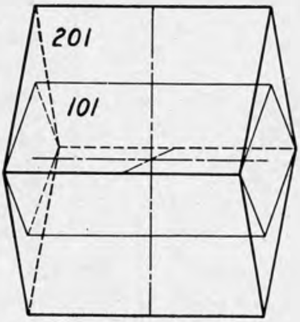

FIG. 219. Macrodomes and brachypinacoid.

If the original face becomes parallel with two axes, say *a* and *b*, the symbols are 001; then the *ab* plane of symmetry requires $00\bar{1}$, and these two faces complete the *basal pinacoid* (see Figs. 220 and 221).

If the original face becomes parallel with *a* and *c*, the symbols are 010; then the *ac* plane of symmetry requires $0\bar{1}0$, and these two faces complete another pinacoid, called the *brachypinacoid*, because the faces are parallel with the brachy-axis (see Figs. 220 and 221).

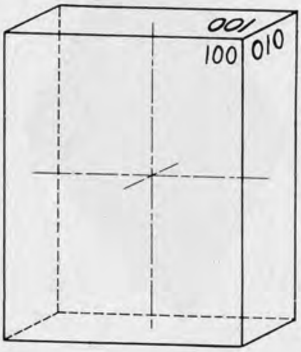

FIG. 220. Basal, brachy- and macropinacoids.

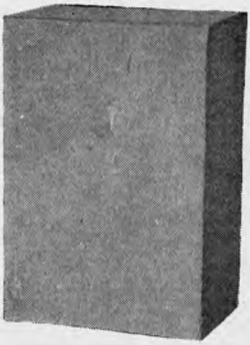

FIG. 221. Photograph of basal, brachy- and macropinacoids.

If the original face becomes parallel with *b* and *c*, the symbols are 100; then the *bc* plane of symmetry requires $\bar{1}00$, and these two faces complete a third pinacoid, called the *macropinacoid*, because the faces are parallel with the macro-axis (see Figs. 220 and 221).

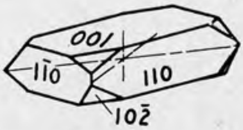

FIG. 222. Crystal forms of barite.

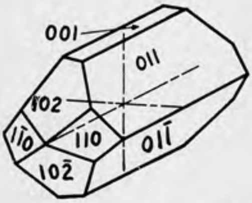

FIG. 223. Crystal forms of barite.

Combinations. A crystal of barite ($BaSO_4$) may show the base (001), unit prism (110), and macrodome (102), as in Fig. 222, or the brachydome (011), macrodome (102), unit prism (110), and base (001), as in Fig. 223, and so on. A crystal of chrysolite may show the brachydome (021), unit prism (110), brachyprism (120), brachypinacoid (010), macrodome (101), and unit pyramid (111), as in Fig. 224. A crystal of hypersthene may have the macropinacoid (100), unit prism (110), brachypinacoid (010), unit pyramid (111), two macrodipyramids (212) and (211), brachydome (014), and brachydipyramid (232), as in Fig. 225. Cordierite ($Mg_2Al_4Si_5O_{18}$) may show the base (001), macropinacoid (100), brachypinacoid (010), unit prism (110), brachyprism (130), two unit dipyramids (111) and (112), and two brachydipyramids (131) and (134), as in Fig. 226. An orthorhombic crystal may have only one form, as sulfur, in Fig. 215, but is much more likely to have at least two forms, as in Fig. 227.

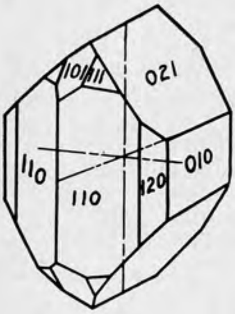

FIG. 224. Crystal forms in olivine.

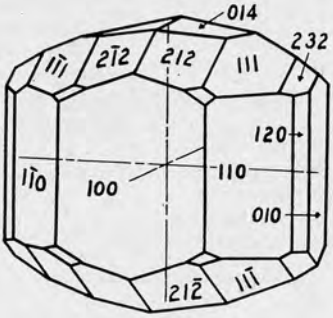

FIG. 225. Crystal forms in enstenite.

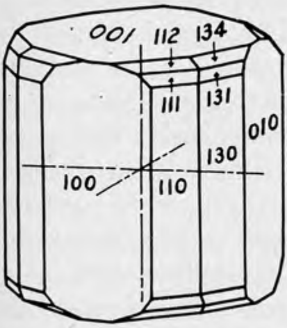

FIG. 226. Crystal forms in cordierite.

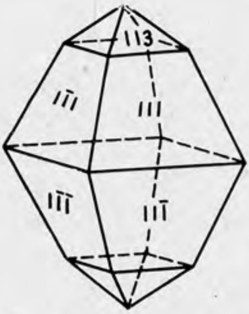

FIG. 227. Two rhombic dipyramids (111) (113) of sulfur.

Summary. The forms of the normal class of the orthorhombic system follow, with their symbols, faces, angles, and symmetry:

Forms		Miller Symbols	Faces	Tetrahedral Solid Angles
Rhombic dipyramids (*hkl*)	Fundamental form	(111)	8	2 + 2 + 2
	Unit dipyramid	*e.g.* (112)	8	2 + 2 + 2
	Brachydipyramid	*e.g.* (121)	8	2 + 2 + 2
	Macrodipyramid	*e.g.* (211)	8	2 + 2 + 2
Rhombic prisms (*hk*0)	Unit prism	(110)	4	—
	Brachyprism	*e.g.* (120)	4	—
	Macroprism	*e.g.* (210)	4	—
Brachydome (0*kl*)		*e.g.* (011)	4	—
Macrodome (*h*0*l*)		*e.g.* (101)	4	—
Basal pinacoid		(001)	2	—
Brachypinacoid		(010)	2	—
Macropinacoid		(100)	2	—

Symmetry	Center	Axes	Planes
	1	3 axial	3 axial

Monoclinic System

All crystals which are referred to three unequal axes, one being at right angles to the other two, which are not at right angles to each other, belong to the monoclinic system. The axis at right angles to the other two is called the ortho-axis and is always considered the *b* axis; either of the other two axes may be selected as the vertical axis *c*, but it is required that the third axis, *a*, shall extend downward to the front. Since this axis is not normal to the *c* axis, it is known as the clino axis. As before, the *b*-axis length is taken as unity and the lengths of the other axes are expressed in terms of that unit. Furthermore, the angle between *a* and *c*, known as the angle β, varies in different monoclinic minerals and must be expressed in order to have a complete statement of the axes. For example, in orthoclase ($KAlSi_3O_8$) $a:b:c = 0.66:1:0.55, \beta = 64°$. Of course

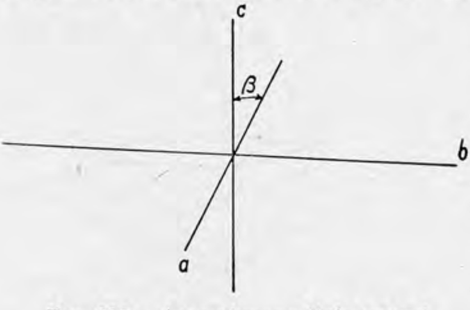

FIG. 228. Axes of monoclinic crystal.

the obtuse angle β (the angle between a and c in the positive octant) is 116°. In the monoclinic system the acute angle β is usually recorded. These axes and β are shown in Fig. 228.

Since there is only one direction in monoclinic crystals which is completely unique (which cannot be replaced by any other direction), this is the direction of reference for the Hermann-Mauguin symbols. It is the direction of the b-axis. In the normal class, both an axis and a plane are associated with this unique direction, and the symbol is written $2/m$, indicating a twofold axis of symmetry and a plane of symmetry normal thereto.

There are three classes of symmetry in the monoclinic system, as follows:

1. Normal class—center, one twofold axis, b, and one plane, ac, of symmetry. $(2/m)$
2. Hemimorphic class—one axis, b, of twofold symmetry. (2)
3. Clinohedral class—one plane, ac, of symmetry. (m)

The normal class is the only one needing detailed description.

Normal or prismatic class $(2/m)$

Symmetry. Crystals of the normal class have a center of symmetry, one axis, b, of twofold symmetry, and one plane of symmetry, which is the plane of the axes a and c, normal to the axis of symmetry. These elements of symmetry are shown in Fig. 229.

Forms. Assuming the original face 111, the plane of symmetry requires the face $1\bar{1}1$; if these two faces are present, the axis of twofold symmetry (or the center) requires the faces $\bar{1}1\bar{1}$ and $\overline{111}$. These four faces satisfy all the elements of symmetry and are therefore a complete crystal form. Geometrically this is a hemidipyramid, since it has half the faces of a dipyramid; crystallographically it suffices to call it merely a *pyramid*. It requires two such pyramids to represent all the faces corresponding with a dipyramid.

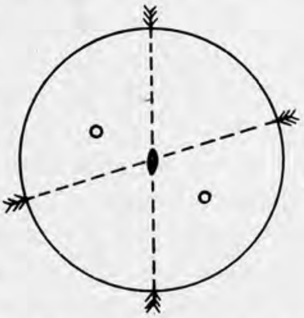

FIG. 229. Symmetry of the normal class of the monoclinic system.

One is the positive pyramid (111) and the other is the negative pyramid $(\bar{1}11)$.

As in the orthorhombic system all pyramids which cut the lateral axes at their unit lengths (or at the same multiple thereof) are called *unit pyramids;* of these the one which also cuts the vertical axis at its unit length is called the *fundamental form.* Of course there may be several unit pyramids on a single crystal having different intercepts on the vertical axis.

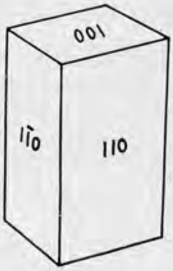

Fig. 230. Unit prism (110) and base (001).

Fig. 231. Photograph of unit prism (110) and base (001).

All the pyramids which cut the clino-axis, *a*, at a multiple are known as *clinopyramids,* for example, (122), no matter what the intercept is on *c*. And all the pyramids which cut the ortho-axis, *b*, at a multiple are called *orthopyramids*, illustrated by (213).

If the original face becomes parallel to the vertical axis, *c*, the symbols become 110, the plane of symmetry requires the face $1\bar{1}0$; if these two faces are present, the twofold axis of symmetry (or the center) requires the faces $\bar{1}10$ and $\bar{1}\bar{1}0$. These four faces make the *unit prism* (Figs. 230 and 231.) If the original face cuts the clinoaxis, *a*, at a multiple, a *clinoprism* results; and if it cuts the orthoaxis, *b*, at a multiple, an *orthoprism* results.

If the original face becomes parallel to the clino-axis, *a*, the symbols become 011, the plane of symmetry requires the face $0\bar{1}1$, and then the axis of twofold symmetry (or the center) requires the faces $01\bar{1}$ and $0\bar{1}\bar{1}$. Since these faces are parallel with the clino-axis, the form is the *clinodome.*

If the original face becomes parallel with the ortho-axis, *b*, the symbols become 101; the axis of twofold symmetry (or the center) requires the face $\bar{1}0\bar{1}$. These two faces satisfy all the elements of symmetry and constitute a form; since the faces are parallel with the ortho-axis, *b*, the form is the *orthodome* (geometrically a hemiorthodome). Another orthodome $(\bar{1}01)$ has the other set of faces. Both clinodomes and orthodomes may cut the vertical axis at a simple multiple (or simple fraction) of unity.

If the original face becomes parallel with two axes, say *a* and *b*, the symbols are 001; the axis of twofold symmetry or the center requires $00\bar{1}$. These two faces form the *basal pinacoid* or *base* (see Figs. 230 and 231).

FIG. 232. Prism (110), clinopinacoid (010), and pyramid (111).

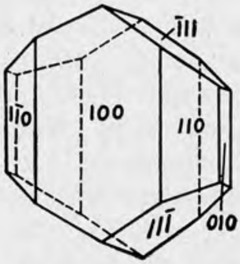

FIG. 233. Orthopinacoid (100), prism (110), clinopinacoid (010), and pyramid $(\bar{1}11)$ of augite.

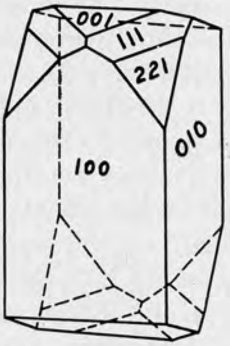

FIG. 234. Orthopinacoid (100), clinopinacoid (010), base (001), and two pyramids (111) (221) of pyroxene.

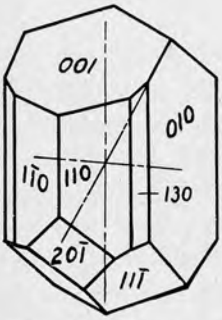

FIG. 235. Base (001), clinopinacoid (010), prisms (110) (130), orthodome $(20\bar{1})$, and pyramid $(11\bar{1})$ of orthoclase.

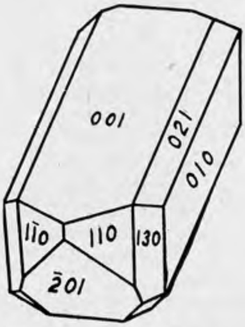

FIG. 236. Base (001), prisms (110) (130), clinopinacoid (010), clinodome (021), and orthodome $(\bar{2}01)$ of orthoclase.

If the original face becomes parallel with *a* and *c*, the symbols are 010; this face with $0\bar{1}0$ completes a form; it is called the *clinopinacoid*, because the faces are parallel with the clino-axis, *a*.

If the original face becomes parallel with *b* and *c*, the symbols are 100; the symmetry requires only $\bar{1}00$; these two faces are called the *orthopinacoid*, because they are parallel with the ortho-axis, *b*.

Combinations. Gypsum ($CaSO_4 \cdot 2H_2O$) may show a rather simple combination of clinopinacoid (010), unit prism (110), and unit pyramid (111), as in Fig. 232. Augite may show the orthopinacoid (100), unit prism (110), clinopinacoid (010), and unit pyramid ($\bar{1}11$), as in Fig. 233, or it may show the orthopinacoid (100), clinopinacoid (010), orthodome ($\bar{1}01$), base (001), and two unit pyramids (111) and (221), as in Fig. 234. Orthoclase ($KAlSi_3O_8$) may show the base (101), clinopinacoid (010), unit prism (110), clinoprism (130), and orthodome ($20\bar{1}$), as in Fig. 235, or the same forms with different development and with the clinodome (021), as in Fig. 236.

Summary. The forms of the normal class of the monoclinic system are given below with their symbols, faces, and symmetry:

Forms		Miller Symbols	Faces
Pyramids (*hkl*)	Fundamental form	(111)	4
	Unit pyramid	*e.g.* (112)	4
	Clinopyramid	*e.g.* (121)	4
	Orthopyramid	*e.g.* (211)	4
Prisms (*hk*0)	Unit prism	(110)	4
	Clinoprism	*e.g.* (120)	4
	Orthoprism	*e.g.* (210)	4
Clinodome (0*kl*)		*e.g.* (011)	4
Orthodome (*h*0*l*)	Positive	*e.g.* (101)	2
	Negative	*e.g.* ($10\bar{1}$)	2
Basal pinacoid		(001)	2
Clinopinacoid		(010)	2
Orthopinacoid		(100)	2

	Center	Axes	Plane
Symmetry	1	1 (*b* axis)	1 (*ac* plane)

Triclinic System

The triclinic system includes all crystals which are correctly referred to three unequal crystal axes intersecting each other at unequal angles. In general all three angles are oblique, but *by chance* one of them may be a right angle. The three axes are designated as in the orthorhombic system, namely, a, the brachy-axis;[12] b, the macro-axis; and c, the vertical axis. But any one of the axes may be taken as the vertical axis (preferably, however, the one parallel with the principal zone); then the shorter lateral axis, a, should extend downward to the front, and the other should extend downward to the right. The angle between b and c is α, between a and c is β, and between a and b is γ. These angles should be measured in the positive octant, and are therefore usually greater than 90°. These relations are shown in Fig. 237. A complete expression of the variable features of any triclinic crystal requires the axial ratio and also the angles, α, β, and γ.

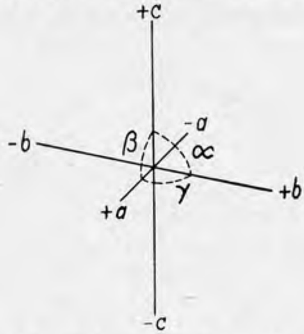

FIG. 237. Axes of a triclinic crystal.

Since every direction is unique in any triclinic crystal, there is no need to specify any particular direction of reference for the Hermann-Mauguin symbol. The symbol itself is a non-directional, non-unique symbol, since any and every direction is an axis of "onefold symmetry." The axis of onefold rotary-inversion ($\bar{1}$) is simply a center of symmetry, and the axis of onefold rotation (1) is simply used to designate a complete lack of symmetry.

There are only two classes of symmetry in the triclinic system, as follows:

1. Normal class—center of symmetry. ($\bar{1}$)
2. Asymmetric class—no element of symmetry. (1)

---

[12] By exception a may be the longer lateral axis, as in rhodonite with $a:b = 1.073:1$.

The normal class will be described briefly. It is worthy of emphasis that crystals of the asymmetric class are not mere products of chance in spite of their entire lack of symmetry, since they still have definite axial ratios and axial angles and simple relations between the positions of all faces.

Normal or pinacoidal class ($\bar{1}$)

Symmetry. Crystals of the normal class have only one element of symmetry and that is the center, as shown in Fig. 238; accordingly each and every form consists of two faces, no more and no less, and these are always the assumed face and the face opposite it.

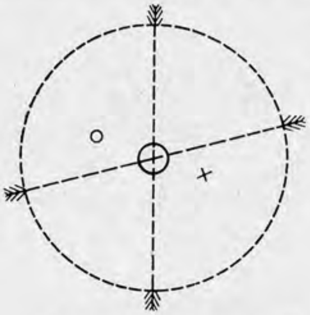

FIG. 238. Symmetry of the normal class of the triclinic system.

Forms. Beginning, as before, with 111, the center requires $\bar{1}\bar{1}\bar{1}$. These two faces are geometrically a tetartodipyramid, but crystallographically they are merely *pyramids*, since each face cuts all three axes. As in the orthorhombic system there are unit pyramids, such as (111) and (223), brachypyramids, such as (321) and (422), and macropyramids, such as (141) and (132).

Similarly, there are *unit prisms*, as illustrated by (110) and ($1\bar{1}0$), and also brachyprisms, such as (310) and (210), and macroprisms, such as (140) and (130).

The other forms are the *macrodomes*, such as (101) and (201), the *brachydomes*, such as (011) and (021), the *base* (001), the *brachypinacoid* (010), and the *macropinacoid* (100).

Illustrations. Albite ($NaAlSi_3O_8$) may show the base (001), brachypinacoid (010), two unit prisms (110) and ($1\bar{1}0$), and two unit pyramids $(11\bar{1})$ and $(1\bar{1}\bar{1})$, as in Fig. 239. Rhodonite ($MnSiO_3$) crystals may be limited by the base (001), brachypinacoid (010), macropinacoid (100), two unit prisms (110) and $(1\bar{1}0)$, and four unit pyramids $(11\bar{1})$, (221), $(22\bar{1})$, and $(2\bar{2}\bar{1})$, as in Fig. 240. An anorthite crystal ($CaAl_2Si_2O_8$) may have the base (001), brachypinacoid (010), two unit prisms (110) and $(1\bar{1}0)$, two brachyprisms (130) and $(1\bar{3}0)$, two macrodomes (201) and $(\bar{2}01)$, three brachydomes (021), (061), and $(0\bar{2}1)$, and four pyramids (111), $(1\bar{1}1)$, $(\bar{1}\bar{1}1)$ and $(\bar{2}11)$, as in Fig. 241.

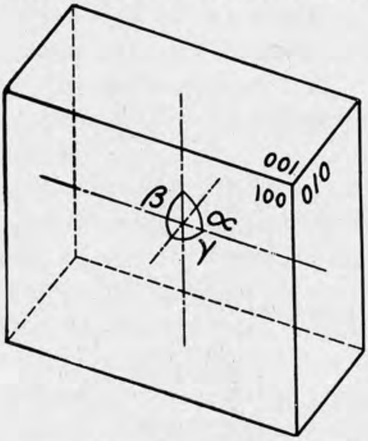

FIG. 239. Macropinacoid (100), base (001), and brachypinacoid (010) of albite.

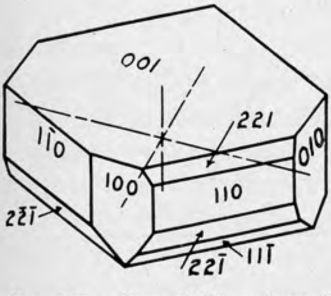

FIG. 240. Base (001), prisms (110) $(1\bar{1}0)$, pinacoids (100) (010), and pyramids (221) $(11\bar{1})$ of rhodonite.

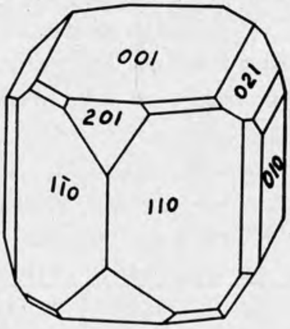

FIG. 241. Unit prisms (110) $(1\bar{1}0)$, base (001), brachypinacoid (010), two brachydomes (021) pyramid and macrodome (201) of anorthite.

Summary. The forms of the normal class of the triclinic system are given below with their symbols, faces, and symmetry:

Forms			Miller Symbols	Faces
Pyramids (hkl)	Fundamental forms	Upper right	(111)	2
		Upper left	$(1\bar{1}1)$	2
		Lower right	$(11\bar{1})$	2
		Lower left	$(1\bar{1}\bar{1})$	2
	Unit pyramids	Upper right	*e.g.* (112)	2
		Upper left	*e.g.* $(1\bar{1}2)$	2
		Lower right	*e.g.* $(11\bar{2})$	2
		Lower left	*e.g.* $(1\bar{1}\bar{2})$	2
	Brachypyramids	Upper right	*e.g.* (121)	2
		Upper left	*e.g.* $(1\bar{2}1)$	2
		Lower right	*e.g.* $(12\bar{1})$	2
		Lower left	*e.g.* $(1\bar{2}\bar{1})$	2
	Macropyramids	Upper right	*e.g.* (211)	2
		Upper left	*e.g.* $(2\bar{1}1)$	2
		Lower right	*e.g.* $(21\bar{1})$	2
		Lower left	*e.g.* $(2\bar{1}\bar{1})$	2
Prisms ($hk0$)	Unit prisms	Positive	(110)	2
		Negative	$(1\bar{1}0)$	2
	Brachyprisms	Positive	*e.g.* (120)	2
		Negative	*e.g.* $(1\bar{2}0)$	2
	Macroprisms	Positive	*e.g.* (210)	2
		Negative	*e.g.* $(2\bar{1}0)$	2
Brachydome ($0kl$)	Positive		*e.g.* (011)	2
	Negative		*e.g.* $(0\bar{1}1)$	2
Macrodome ($h0l$)	Positive		*e.g.* (102)	2
	Negative		*e.g.* $(10\bar{2})$	2
Basal pinacoid			(001)	2
Brachypinacoid			(010)	2
Macropinacoid			(100)	2

Symmetry	Center	Axes	Planes
	1	0	0

Crystal Habit

Crystals vary not only in their angular relations and symmetry, but also in their size, the relative development of their faces, and the number and kind of faces or forms that are present. Variations in the angular relations of the faces and the symmetry of the forms are of fundamental importance and constitute the chief differences between the six crystal systems just described. Variations in the size of crystals, the relative development of their faces, and the number and kind of faces or forms that are present are of no fundamental significance; crystals of any substance always show such variations to some extent, and in some cases these variations produce a great variety in the crystals of one substance. Such variations are said to produce different *crystal habits.* It should be emphasized that variation in crystal habit occurs without the slightest variation in angular relations of the faces and therefore without the slightest variation in the crystallographic symmetry.

The relative development of the faces and the number and kind of faces or forms of crystals vary so greatly when different substances are compared and are so nearly constant in different crystals of one substance (in some cases) that they furnish data of considerable value in the study of crystals. The relative development of the faces of crystals is one of the chief factors in determining their general shape. If the faces are all of nearly the same size, the crystal is likely to be nearly equidimensional: such crystals are said to be *equant.* If a pair of opposite faces are decidedly larger than the other faces, the crystals are necessarily *flattened* and are said to be *tabular;* if this tendency is carried to an extreme they are called *lamellar* or even *foliated.* If three or more faces belonging to one zone, that is, all parallel to any one line, are decidedly larger than the other faces, the crystal is necessarily *elongated* in that direction and is described as *columnar;*[13] if this tendency is carried to an extreme the crystal is described as *acicular,* or even *fibrous.* Crystals of any crystal system may be equant, tabular, lamellar, columnar, or fibrous, but isometric crystals are usually equant; tetragonal and hexagonal crystals are equant or flattened normal to the vertical axis or elongated parallel thereto; other crystals may be flattened parallel with any pinacoid (or even any other pair of opposite faces) or elongated parallel with any crystal axis (or, rarely, parallel with some other crystal direction).

Crystals which show only one crystal form, or have the faces of one form decidedly larger than those of any other, are easily described as characterized by that form; for example, isometric crystals may be cubic, octahedral, dodecahedral, and so on;

---

[13] Some writers describe columnar and acicular crystals as prismatic; this is correct geometrically, but incorrect crystallographically unless the long faces are prisms; they may be domes or pinacoids, or even pyramids.

Isometric *Tetragonal* *Hexagonal*

Acicular

Columnar

Equant

Tabular

Lamellar

FIG. 242.

FIG. 243.

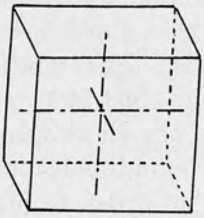

FIG. 244.

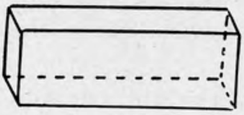

FIG. 245.

FIG. 246.

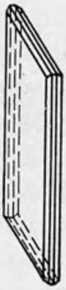

FIG. 247.

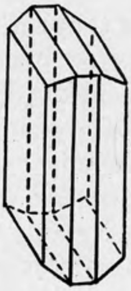

FIG. 248.

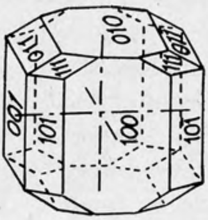

FIG. 249.

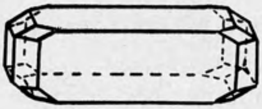

FIG. 250.

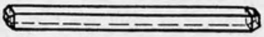

FIG. 251.

FIG. 252.

FIG. 253.

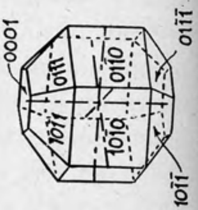

FIG. 254.

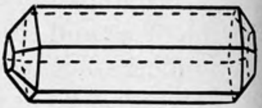

FIG. 255.

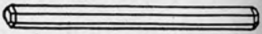

FIG. 256.

Orthorhombic

FIG. 261.

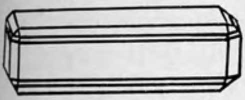

FIG. 260.

FIG. 259.

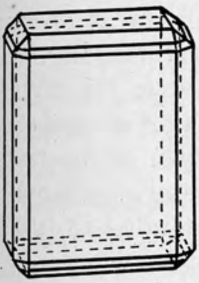

FIG. 258.

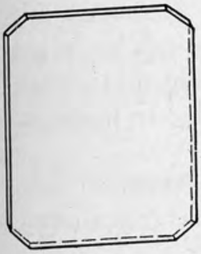

FIG. 257.

Monoclinic

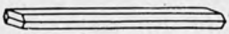

FIG. 266.

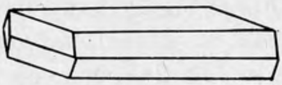

FIG. 265.

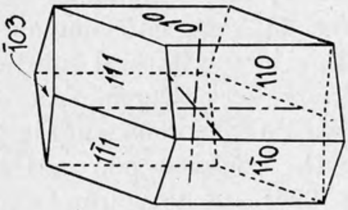

FIG. 264.

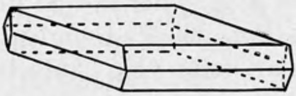

FIG. 263.

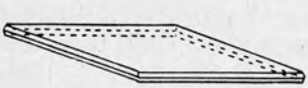

FIG. 262.

Triclinic

FIG. 271.

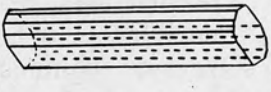

FIG. 270.

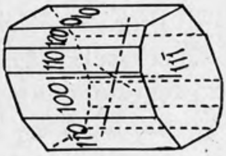

FIG. 269.

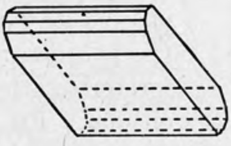

FIG. 268.

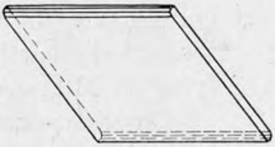

FIG. 267.

tetragonal crystals may be pyramidal, prismatic, or pinacoidal; hexagonal crystals may be pyramidal, prismatic, pinacoidal, rhombohedral, or scalenohedral; orthorhombic, monoclinic, and triclinic crystals may be pyramidal, prismatic, domatic, or pinacoidal.

A cubic isometric crystal (Fig. 244) may be flattened to a tabular habit as in Fig. 243; by more flattening it may become lamellar as in Fig. 242, or even foliated; by elongation it may become columnar as in Fig. 245, or even acicular as in Fig. 246. Isometric crystals are usually equant or nearly so. An equant tetragonal crystal of calomel (Hg_2Cl_2) is shown in Fig. 249; this substance often forms crystals of columnar habit as in Fig. 250; acicular crystals (Fig. 251) are not common; tabular crystals (Fig. 248) are not rare in the natural substance, but lamellar crystals (Fig. 247) are very scarce. An equant hexagonal crystal of apatite ($Ca_5FP_3O_{12}$) is shown in Fig. 254; the columnar habit (Fig. 255) is the common one in this substance, but acicular forms (Fig. 256) are not rare; tabular crystals (Fig. 253) and lamellar crystals (Fig. 252) are very rare or unknown in this substance. An equant orthorhombic crystal of olivine [$(Mg,Fe)_2SiO_4$] is shown in Fig. 259; natural olivine is often tabular parallel to 100 as in Fig. 258, while natural iron olivine or fayalite is likely to be lamellar in that direction as in Fig. 257; the columnar habit (Fig. 260) is found in magnesian olivine or forsterite; the acicular habit (Fig. 261) is unknown or rare in olivine. Fig. 264 shows an equant monoclinic crystal of gypsum ($CaSO_4 \cdot 2H_2O$); such crystals are often tabular parallel to 010 as in Fig. 263; the lamellar habit (Fig. 262) is less common; a columnar habit (Fig. 265) is shown by crystals formed in a $MgCl_2$ solution; a fibrous habit (Fig. 266) is also known in the natural mineral. An equant triclinic crystal of chalcanthite[14] ($CuSO_4 \cdot 5H_2O$) is illustrated in Fig. 269; such crystals are often columnar as in Fig. 270, or even fibrous as in Fig. 271; when formed artificially on a glass slide they are tabular to lamellar, lying on 110, as shown in Figs. 267 and 268.

Crystals which are much flattened or much elongated tend to be simpler, that is, have fewer faces, than corresponding

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[14] The orientation differs from that of Tutton and Barker by reversing the *c* axis so as to make the *b* axis incline downward to the *right*, as usual in triclinic crystals.

equant crystals; this tendency is illustrated in Figs. 247, 248, and 251 as compared with Fig. 249, Figs. 257 and 261 as compared with Fig. 259, and Figs. 267 and 271 as compared with Fig. 269.

Some crystals show both elongation and flattening; such crystals are described as *bladed* if developed as in Fig. 272 or *lath-shaped* if similar to Figs. 273 or 274 in development.

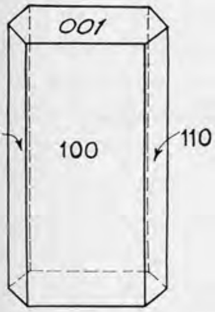

FIG. 272. A bladed crystal of kyanite, Al_2SiO_5.

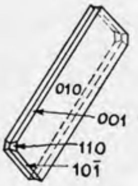

FIG. 273. Lath-shaped crystal of feldspar.

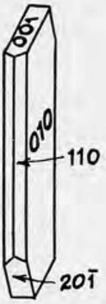

FIG. 274. Lath-shaped crystal of feldspar.

Groups of Crystals

A single crystal is a polyhedron whose interfacial angles are all less than 180°; the presence of a re-entrant angle on a crystal surface is therefore evidence of the presence of more than one individual. Crystals frequently grow in groups or aggregates which may have random position with respect one to another, or may have exactly parallel positions, or may even have partially parallel positions. Such partial parallelism is present when certain directions in one crystal unit are exactly parallel with the corresponding directions in an adjoining crystal but others are not. These conditions can be found in groups of crystals of one kind and also in groups of crystals of unlike composition. Such groups may therefore be arranged under seven types, as follows:

I. Homogeneous groups (all the crystals of the same substance)

1. Parallelism complete	Parallel growths
2. Parallelism partial	Twin crystals
3. Parallelism approached	Subparallel aggregates
4. Parallelism wanting	Irregular aggregates

II. Heterogeneous groups (crystals of different substances)	
5. Parallelism nearly complete	Zonal growths
6. Parallelism partial	Regular growths
7. Parallelism wanting	Irregular heterogeneous aggregates

These seven types may be described briefly with special attention given to twin crystals, because of their importance.

Homogeneous groups

Parallel growths. Parallel growths often consist of many crystals rather than merely two, and the units sometimes form along the axes of a much larger crystal of the same kind. Such *skeleton crystals* may continue to grow and fill out to form one large crystal. Snowflakes are excellent examples of skeleton crystals, and they show a wonderful variety. When a flake fills out, it forms one hexagonal crystal of ice. The same tendency is shown in some groups of parallel crystals of calcite and also of quartz.

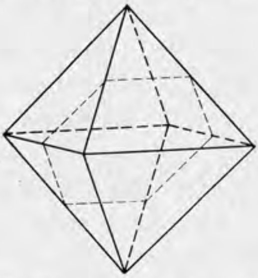

Fig. 275. Simple octahedron of spinel.

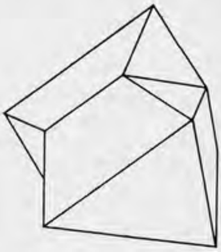

Fig. 276. Spinel octahedron in twinning position.

Twin crystals. Two crystals of the same substance which form an aggregate exhibiting partial parallelism are called a twin, and are said to be in twinning position. The relative position of the two crystals in twinning position may be most readily understood by *assuming* that one has been revolved through 180° about some direction or axis, which thus remains common to both. Thus, in Fig. 275, a crystal, say, of spinel, forms a simple octahedron.

If this octahedron be supposed to be cut in two parts along the dotted plane parallel to an octahedral face and the lower half be supposed to be revolved through 180° about an axis normal to this plane, the twinned form of Fig. 276 is produced. It should be emphasized that twins are not produced by such a revolution, but by regular growth (except the secondary twins produced by shearing, and so on); this is merely a convenient way to describe the relative positions.

The axis about which one part is supposed to be revolved is called the *twinning axis*,[14] and the plane normal to this is the *twinning plane.* The plane by which twinned crystals are united is called the *composition plane.* This is often the same as the twinning plane, but it is not necessarily so; when it is not the same as the twinning plane, the composition plane is likely to be parallel with the twinning axis, as in Carlsbad twins of feldspar (see Fig. 290). The twinning axis is nearly always a crystal axis or normal to a possible crystal face. If twins are simply adherent by the composition face, they are *contact twins;* if they interpenetrate more or less, they commonly have an irregular composition surface and are called *penetration twins,* as illustrated in Figs. 277 and 278. In many cases twins are composed of more than two parts, the mutual relations of any two adjacent parts being the same. In this case the twinning is described as *multiple* or *polysynthetic* if the composition faces are parallel, and *cyclic* or *symmetrical* if the composition faces are not parallel and therefore tend to turn in a circle. Repeated twinning of the cyclic type often gives rise to an apparent

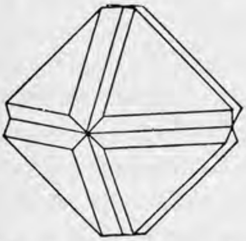

Fig. 277. Penetration spinel twin in hauynite.

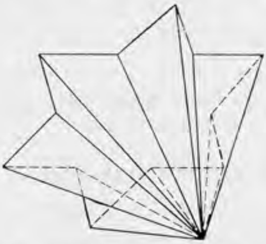

Fig. 278. Penetration spinel twin in tetrahedrite.

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[14] Some twins have no twinning axis, one part being related to the other as by reflection in a plane (the twinning plane), but not derivable from it by turning on any axis. This case is illustrated by quartz and is possible only in crystals of classes having no center of symmetry. Other crystals have a twinning axis but have no twinning plane (in the sense just described). This case is illustrated by tetrahedrite and is also possible only in crystals of classes having no center of symmetry.

symmetry, called *pseudosymmetry,* greater than that actually possessed by the crystal. Thus, orthorhombic cordierite may seem to be hexagonal on account of cyclic twinning.

Twinning may be produced artificially, in some cases, by shearing or other stresses; such twinning is called *secondary.* It is illustrated by some twinning in calcite and by some multiple twinning in feldspar and pyroxene.

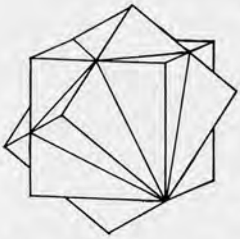

Fig. 279. Penetration spinel twin in fluorite.

Common twinning laws. The most important type of twinning, in crystals of the isometric system, is that illustrated in Fig. 276; this, like all other types of twinning, is most conveniently described by stating the crystallographic position ofthe twinning axis or the twinning plane, and such a statement is known as a twinning law. Twins whose twinning axis is normal to an octahedral face, as in Fig. 276, are especially common in spinel and are therefore known as spinel twins; they may be either contact twins, or penetration forms, as illustrated by Fig. 277 for hauynite, by Fig. 278 for tetrahedrite, and by Fig. 279 for fluorite. Fig. 277 requires two revolutions of 180° about different octahedral axes or one revolution of 180° about a dodecahedral axis.

In the tetragonal system, the most important type of twinning is that which corresponds to the spinel law, but in this case the twinning axis is normal to the face of a pyramid. Such twins are especially common in rutile and cassiterite; when simple they are described as *geniculated,* or knee-shaped, as in Fig. 280.

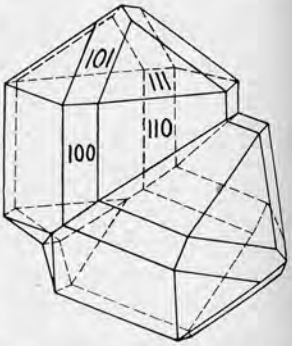

Fig. 280. Geniculated twin of cassiterite.

In the hexagonal system, twins are rare and unimportant in crystals of the hexagonal division, but are common in those of the trigonal division. Calcite twinned on 0001 is shown in Figs. 281 and 282. The calcite crystals and anhedra in rocks often show twinning lamellae (twinned on $01\bar{1}2$), which may be of secondary origin, as shown by the fact that a single cleavage piece of calcite may be changed, in part, into a twin by pressure with a dull knife on an obtuse edge of a piece of columnar form, the other obtuse edge resting on a firm support. This is illustrated in Fig. 283; the portion moved (that is, *abcd* to *a′b′cd*) takes a position as if twinned on $01\bar{1}2$ (or *edc*); it is not broken off, but is in a new position of stability.

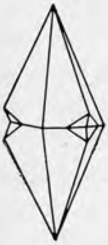

FIG. 281. Twinned scalenohedron of calcite.

FIG. 282. Photograph of twinned scalenohedron of calcite.

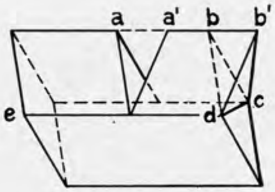

FIG. 283. Artificial twinning produced in calcite.

In the orthorhombic system the commonest type of twinning has the twinning axis normal to the face of a prism whose prismatic angle is about 60°. This is well illustrated in aragonite and in cordierite, as shown in Figs. 284 and 285 of aragonite, and 286 of cordierite. In staurolite, twinning on the face of a dome whose angle is nearly equal to 45° produces a group resembling a Greek cross. This is illustrated in Fig. 287.

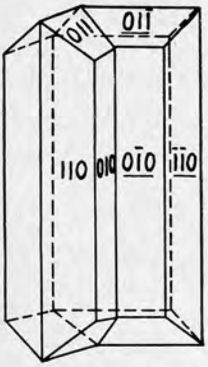

FIG. 284. Aragonite twinned on $1\bar{1}0$.

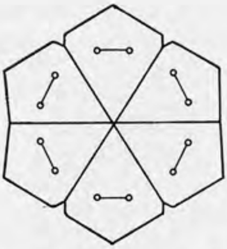

FIG. 285. Cross section of pseudohexagonal cyclic twin of aragonite.

Twinning is more important in the monoclinic and triclinic systems. The commonest type has the vertical axis as the twinning axis, as illustrated by Fig. 288 for augite and by Fig. 289 for gypsum. The same law gives the groups called *Carlsbad* twins in orthoclase, which are either contact forms or penetration twins, as shown in Figs. 290–292. This type of twinning may be explained equally well by referring it to the orthopinacoid, 100, as the twinning plane. In *Baveno* twins of orthoclase the twinning plane is the clinodome, 021, and since the angle between this face and the base is 44°56′, nearly square forms result, as illustrated in Fig. 293; they are commonly, however, elongated parallel to the *a* axis. A rare type of twinning in orthoclase is known as the *Manebach*, in which the basal plane is the twinning plane and also the composition face, as shown in Fig. 294. Multiple twinning, in the form

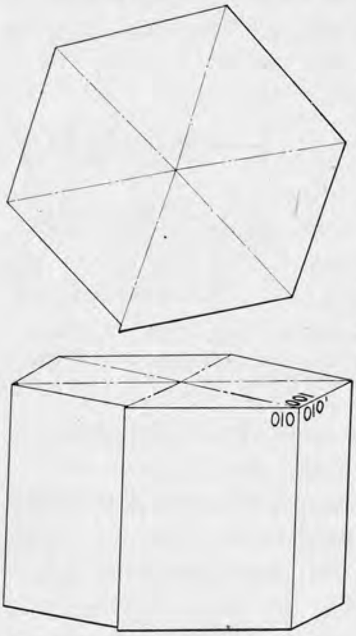

FIG. 286. Pseudohexagonal cyclic twin of cordierite.

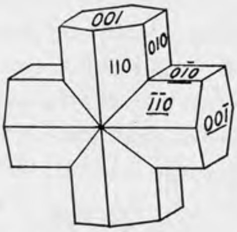

FIG. 287. Cruciform twin of staurolite.

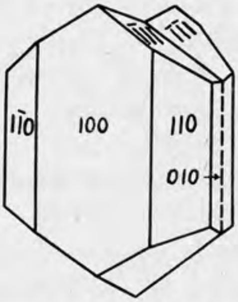

FIG. 288. Augite twinned on vertical axis.

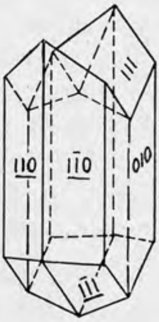

FIG. 289. Gypsum twinned on vertical axis.

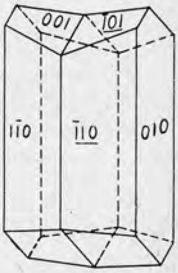

FIG. 290. Contact Carlsbad twin of albite.

of fine lamellae, producing striations on vertical faces and a parting parallel to 001, is common in monoclinic pyroxene; the twinning plane is the base. The aspect of such an aggregate is shown in Fig. 295.

FIG. 291. Partial penetration Carlsbad twin of orthoclase.

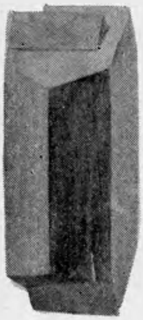

FIG. 292. Photograph of partial penetration Carlsbad twin of orthoclase.

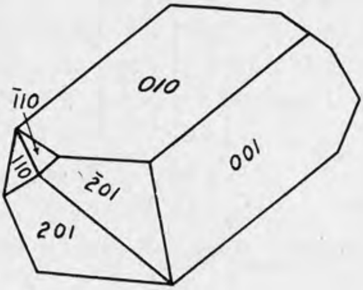

FIG. 293. Baveno twin of orthoclase.

The twinning peculiar to triclinic feldspar is of several types, the more abundant being the albite and pericline. The former type has 010 as the twinning plane, the latter has the b axis as the twinning axis. Both types are nearly always polysynthetic, producing narrow lamellae which are parallel to 010 in albite twinning and parallel to the axis b in pericline twinning. Therefore, albite twinning produces fine striations on a basal cleavage surface, and pericline twinning produces similar striations on the brachypinacoidal cleavage or face. A

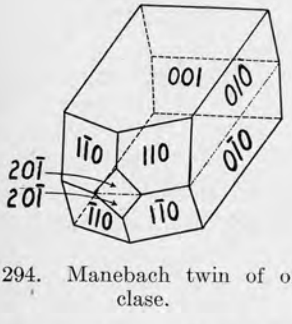

FIG. 294. Manebach twin of orthoclase.

FIG. 295. Multiple twinning on 001 in augite.

simple albite twin is shown in Fig. 296. This type of twinning is nearly always present, and many times repeated, in all kinds of plagioclase, and thus produces striations on the base parallel to

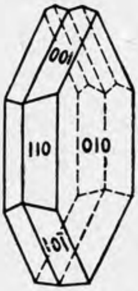

FIG. 296. Simple albite twin in albite.

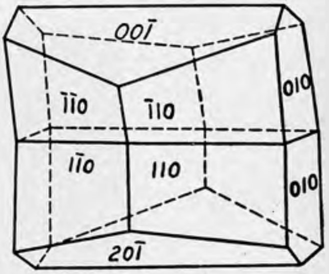

FIG. 297. Simple pericline twin in albite.

010, as illustrated in Figs. 298–300. A simple pericline twin is represented in Fig. 297; in such twins the composition plane passes through the crystal in such a direction that its intersections with the prismatic faces make an equilateral oblique-angled parallelogram or rhombus. The position of this "rhombic section" changes materially with small changes in the axial angle γ. It is always parallel to the axis b, and varies from parallel to the base in one type of andesine to an angle of plus 21°

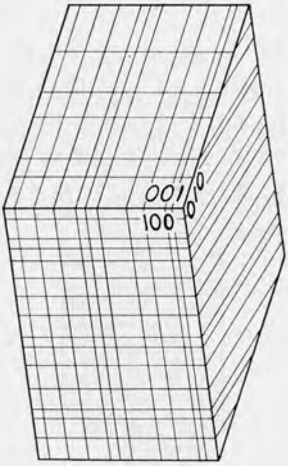

FIG. 298. External albite and pericline striations in albite.

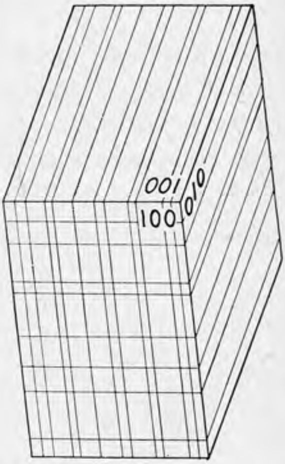

FIG. 299. External albite and pericline striations in andesine.

with the trace of the base in 010 in albite and to minus 18° with the same trace in 010 in anorthite, as shown in Fig. 301. Except rarely in albite, pericline twinning is polysynthetic and invisible without the microscope and polarized light; it produces striations on brachypinacoidal sections, as shown in Figs. 298–300. The plagioclase feldspars often show simple twinning of the same types known in orthoclase, in combination with these polysynthetic types. Microcline exhibits polysynthetic albite twinning combined with multiple twinning of the same kind as the pericline, except that the composition face is not a rhombic section, but is nearly normal to the base, as shown in Fig. 301.

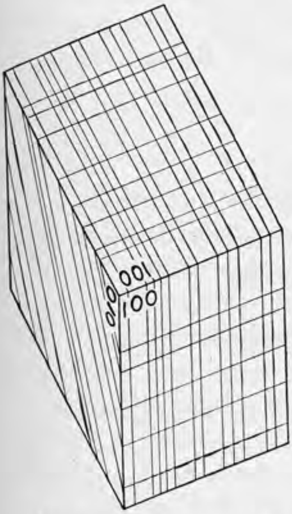

FIG. 300. External albite and pericline striations in anorthite.

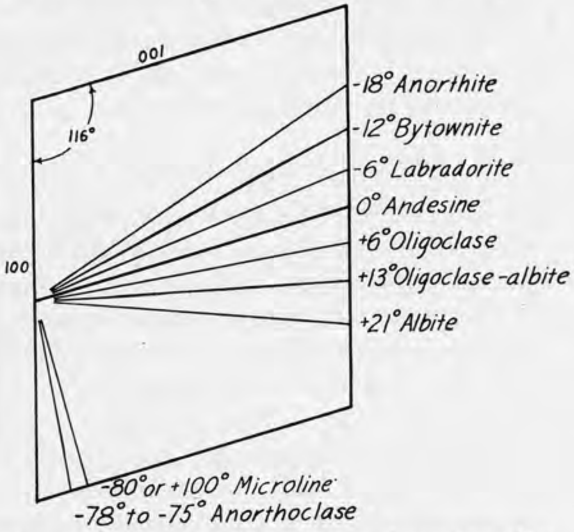

FIG. 301. Position of composition face of pericline (and microcline) twinning in triclinic feldspars.

Subparallel aggregates. Subparallel aggregates are very common in nature and in the laboratory. They may result from imperfect crystallization from a single center to form rosettes or spherulites, such as those of quartz, stilbite, and other minerals. Or they may result from crystallization of many independent crystals under similar conditions that tend to make all nearly parallel, as when crystals form on the flat surface of a vessel containing a supersaturated solution. In this case the flat surface of the vessel exerts a uniform influence which imperfectly controls the orientation of the crystals forming at different places, and the resulting aggregate when these crystals cover the surface may have many different crystal units in subparallel position. In some cases subparallel aggregates may even have partial parallelism, that is, as in the case of twins, one or more crystal directions may be exactly parallel, but, unlike twins, the other crystal directions are nearly parallel instead of being in twinning position.

Irregular aggregates. *Irregular homogeneous aggregates* are common in nature and in the laboratory. They result in many cases when one substance crystallizes from solution to form many crystals in a vein or amygdule, or in a beaker. Being irregular, they need no detailed description.

Heterogeneous groups

Zonal growths. It is obviously impossible for crystals of different systems to be completely, or even almost completely, parallel in position. Two substances must have almost exactly the same crystal axes and interfacial angles in order that their crystal faces may be almost completely parallel. Such substances are said to be *isostructural* (that is, they have the same crystal structure). For example, a crystal of deeply colored chromium alum suspended in a slightly supersaturated solution of potash alum will soon be completely coated with a colorless transparent layer of that salt which has just the same shape as the first crystal. This may be coated next with a layer of chromium alum, by suspending the body in a solution of that salt; and this process may be repeated indefinitely. The same development of a layer enclosing a crystal and retaining its shape occurs when a crystal of calcium carbonate is suspended in a solution of sodium nitrate. Such concentric zones of different substances not only retain the same shapes, but also have almost exactly the same crystal structures. They are called *zonal growths*, and are of frequent occurrence in nature, but commonly the zones are not only isostructural, but also *isomorphous*, that is they are capable of complete (or at least partial) intercrystallization to form one homogeneous substance; zonal growths are common in feldspars, pyroxenes, amphiboles, micas, tourmaline, garnet, and many other minerals.

Regular growths. Even though two substances are utterly unlike, both chemically and crystallographically, they may grow together with partial parallelism. For example, crystals of rutile (TiO_2) may be enclosed in crystals of chlorite (or mica) with their long axes parallel with the horizontal crystal axes of the chlorite (or mica). Again, triclinic kyanite (Al_2SiO_5) and orthorhombic staurolite may grow together so that their crystals have one face and one crystal axis in common. Many other examples of such partial parallelism are known.

Irregular aggregates. *Irregular heterogeneous aggregates* are the most indefinite and the commonest mode of grouping of crystals. Since the grouping is purely a matter of chance it needs no further description.

Crystalline Aggregates

Mineral masses are usually aggregates of units having crystal structure, but having no crystal faces. They are therefore crystalline aggregates. Such aggregates are usually characterized by the dominance of certain shapes even though no crystal forms are present. For example the shapes may be chiefly:

1. Fibers or columns, when the structure is *fibrous* or *columnar.*
2. Layers or laminae, when the structure is *lamellar* or *micaceous* (very thin laminae).
3. Grains when the structure is *granular.*

The external shape of such aggregates is described by such terms as *globular, oolitic* (egg-shaped), *reniform* (kidney-shaped), *botryoidal* (like a bunch of grapes), and so on.

3

Physical Mineralogy

The physical characters of minerals are numerous, but some of the most important are:

1. Specific gravity, or density as compared with water.
2. Cohesive properties, such as: cleavage, elasticity, hardness, and so on.
3. Electrical and magnetic properties.
4. Thermal properties.
5. Optical properties.

Specific Gravity

The specific gravity of a mineral is the ratio of its weight to that of the weight of an equal volume of water. For example, the statement that the specific gravity of graphite is 2, of hematite 5.2, and of gold 19, means that the weights of these minerals are 2, 5.2, and 19 times as much as that of an equal volume of water. Specific gravity is a definite characteristic which does not vary (at given temperature and pressure) so long as the composition of the mineral does not vary.

For high accuracy it is necessary to determine specific gravity at a fixed temperature and pressure since the volume of water (and of any mineral) varies with these conditions. Of course the mineral must be absolutely pure and free even of gaseous inclusions. But such accuracy is not needed in ordinary studies of minerals.

The specific gravity may be determined by weighing a substance in air (ideally in a vacuum) and then weighing it when suspended in water; the loss of weight in water is equal to the weight of an equal volume of water.

The Jolly balance is a convenient device to measure the specific gravity of minerals. An improved Jolly balance is shown in Fig. 302. It consists of a spiral spring attached to a movable tube which also carries a doubly graduated scale (shown in Fig. 302). One of these scales is used to read the position of the movable scale itself by means of the fixed vernier, W, and the other is used to read the position of the spring after the mineral is immersed in water. To use the balance it is necessary to adjust the two verniers, the scale, and the indicator of the position of the spring so that they shall all be at zero, the lower pan being immersed in water. This is done approximately by adjusting the position of the mirror by hand and more accurately by turning the micrometer screw directly below the spring. Then, after the mineral has been placed in the upper pan and the tube has been raised by means of the large milled head until the indicator is again at zero (as shown in the mirror), the vernier, W, records the elongation of the spring due to the weight of the mineral. The scale is then clamped in this position by means of the screw at its bottom, the mineral is transferred to the lower pan, where it is immersed in water, and the tube is lowered until the indicator is again at zero. The outer vernier has now moved down the scale to a position, L. This is the measure of the loss in weight due to immersion of the mineral in water. Therefore:

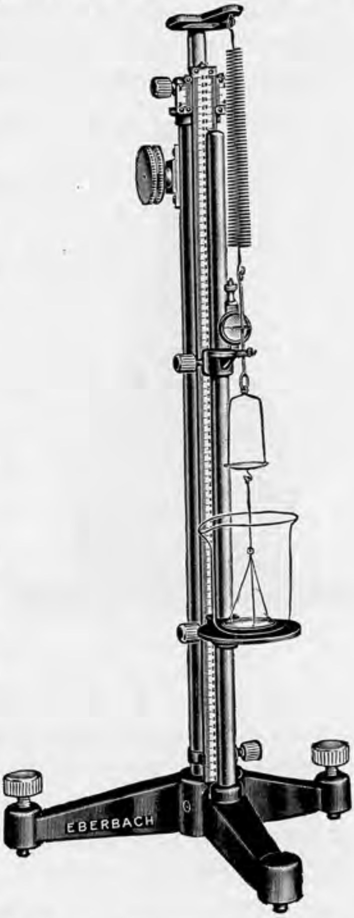

FIG. 302. Improved Jolly balance. *Courtesy of Eberbach & Son.*

$$\text{Specific gravity} = \frac{\text{Weight in air}}{\text{Loss of weight in water}} = \frac{W}{L}$$

In order to measure the specific gravity of a mineral in small fragments or grains, a pycnometer (Fig. 303) should be used. This is a small glass bottle with a ground-glass stopper pierced lengthways by a very small opening. The bottle is filled with distilled water, the stopper inserted, and the overflowing water carefully removed. It is then weighed on an ordinary balance. (Call this weight A.) Next a previously weighed portion of the mineral (call this weight B) is put in the bottle completely filled with water as before. The bottle containing the mineral is then weighed. (Call this weight C.) Then the weight of the water displaced is clearly, $A + B - C$, and the specific gravity of the mineral is:

$$\frac{B}{A + B - C}.$$

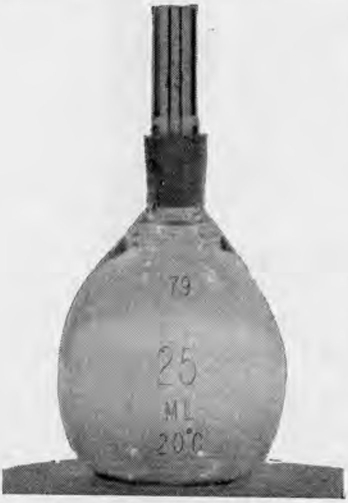

Fig. 303. Pycnometer.

To measure the specific gravity of very small amounts of mineral a micropycnometer[1] has been devised, but it is not suitable for use by a beginning student.

Another method of determining specific gravity is to weigh a crystal on an ordinary balance and then measure its volume by determining the exact amount of liquid displaced by immersion of the crystal in a suitable burette. From these measures the specific gravity can be calculated because one cubic centimeter of water weighs one gram.

In measuring specific gravity it is important to use pure material and to remove all the air from the fragments, under an exhaust pump, if needed.

Indirect methods of measuring specific gravity by comparison with that of liquids are of special importance because they also furnish methods of separating mineral aggregates into their constituent minerals. Several liquids are known to be heavier than the common rock-forming minerals. By dilution with an appropriate liquid, the density of these liquids may be lowered at will to any desired extent, and thus made equal to that of any mineral whose specific gravity is to be determined. This condition of equality is easily recognized by the fact that the mineral

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[1] Horace Winchell: *Amer. Mineral.* XXIII, 805 (1938).

stays indefinitely in any part of the liquid, neither rising nor sinking. The specific gravity of the liquid (and therefore of the mineral) may then be quickly determined by the use of the *Westphal balance,* shown in Fig. 304. By hanging suitable weights on the long arm at the end, or at a decimal division, until the sinker remains suspended in the liquid and the balance is in equilibrium, the specific gravity may be read from the number, kind, and position of the weights. Heavy liquids are used to separate the powdered constituents of a rock; when the powder is put into the liquid, the heaviest minerals will sink to the bottom and others will rise to the top. Those on top may be decanted off, or otherwise removed, and the process repeated with a lighter liquid. The most important "heavy solutions" for measuring specific gravity or separating powders are Thoulet's solution, methylene iodide, and Clerici's solution. A cheaper substitute for these is acetylene tetrabromide.

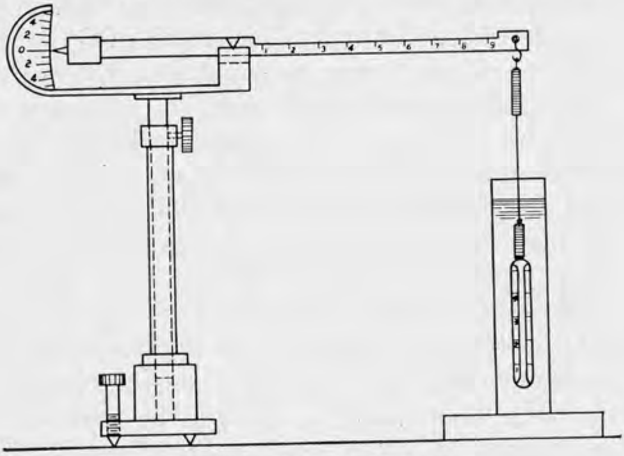

FIG. 304. Westphal balance.

Thoulet's solution is a very poisonous solution of iodide of potassium and mercury, which may be readily prepared by heating 270 grams of mercuric iodide and 230 grams of potassium iodide in 80 cubic centimeters of distilled water in a porcelain evaporating dish on a water-bath. After a little evaporation, a crystal of fluorite (G = 3.18) will float on the liquid, or a crystalline film will form on the surface. Upon cooling, the density reaches about 3.19. The liquid should be transparent and of a yellowish green color; it is stable, provided a few drops of mercury are added; otherwise, iodine slowly separates and darkens the color. It may be diluted with water in any proportions and subsequently reconcentrated by evaporation.

Methylene iodide is a thin, light-yellow fluid of high refractive index and maximum density of about 3.3, which cannot be diluted with water or alcohol (which spoil it), but mixes in all proportions with benzol or ether. It is stable in air, but slowly darkens in sunlight; mercury restores the color. It is so mobile that very fine powders may be separated—much finer than can be used in Thoulet's solution. The cleaning of the recovered powder is very simple, being accomplished by washing with benzol. Methylene iodide may be used in separating minerals which are soluble in water. It is rather expensive.

Clerici's solution is a mutual solution of thallium malonate, $CH_2(COOTl)_2$, and thallium formate $HCOOTl$, which is remarkable for its high density of 4.25 at ordinary temperature and about 4.65 at 50°C. It may be diluted with water in any quantity and reconcentrated by evaporation. It is more mobile than Thoulet's solution, odorless, and slightly amber colored. At ordinary temperature the solution is quite stable; it is able to attack sulphides when heated. It may be prepared by dissolving the dry salts in water; seven grams of each will dissolve completely in one cubic centimeter of water. It is rather expensive, but the high density and convenience of use make it indispensable for some purposes.

Acetylene tetrabromide has a maximum density of 3.0; it may be diluted with benzol, ether, or toluol, and restored to the maximum by evaporation, or by washing with acetone and then recovering by selective solution in excess of water. It is not decomposed by minerals, not even by ore minerals. Its chief advantage is its cheapness.

Cohesive Properties

Cleavage

Cleavage is the property of some crystals of breaking along definite smooth planes, which are called cleavage planes, and which are always possible crystal faces, since they are determined by the regular internal arrangement of the atoms. Cleavage planes, or briefly, "cleavages," (like crystal faces) occur parallel with planes in which the atoms are closely packed together, and normal to which the distance between adjacent layers of atoms is relatively great. Cleavage is described, according to its crystallographic direction, as cubic, octahedral, rhombohedral, basal, prismatic, and so on. It is also described, according to the ease with which it is obtained and the smoothness of the surfaces produced, as perfect or eminent, distinct, indistinct or imperfect, and difficult. Cleavage is perfect when it is obtained with great ease and yields smooth, lustrous surfaces, as in mica, calcite, and so on. The other terms express inferior degrees of cleavage.

Cleavage	*Number of Directions*	*Cleavage Angle*	*Mineral*
	ISOMETRIC SYSTEM		
Cubic	3	90°	Halite, galena
Octahedral	4	70° 31¾	Fluorite, diamond
Dodecahedral	6	60°	Sphalerite
	TETRAGONAL SYSTEM		
Basal	1	—	Apophyllite
Prismatic	2	90°	Rutile, wernerite
Pyramidal	4	Not 90°	Scheelite
	HEXAGONAL SYSTEM		
Basal	1	—	Beryl
Prismatic	3	60°	Nephelite
Rhombohedral	3	Not 90°	Calcite, dolomite
	ORTHORHOMBIC SYSTEM		
Basal	1	—	Topaz, barite
Brachypinacoidal	1	—	Stibnite
All three pinacoids	3	90°	Anhydrite
Prismatic	2	Not 90°	Barite, pyroxene
	MONOCLINIC SYSTEM		
Basal	1	—	Micas, chlorites, epidotes
Clinopinacoidal	1	—	Gypsum, stilbite
Orthopinacoidal	1	—	Borax
Basal and clinopinacoidal	2	90°	Orthoclase
Prismatic	2	Not 90°	Pyroxene, amphibole
	TRICLINIC SYSTEM		
Basal	1	—	Amblygonite
Brachypinacoidal	1	—	Axinite
Basal and brachypinacoidal	2	Not 90°	Plagioclase
All three pinacoids	3	Not 90°	Kyanite

In a crystal, cleavage is the same in quality in all directions which are crystallographically the same; conversely, if the crystallography of a given mineral is unknown, the cleavage provides a means by which identical crystal directions may be recognized. A single cleavage, crystallographically, may exist in a mineral in one, two, three, four, or even six different directions; thus, muscovite (isinglass) has basal cleavage in only one direction; pyroxene and amphibole have prismatic cleavage in two directions, parallel to the prism faces; calcite has rhombohedral cleavage in three directions; fluorite has octahedral cleavage in four directions; and sphalerite has dodecahedral cleavage in six directions, parallel to the dodecahedral faces.

Also, a mineral may have only one cleavage, or it may have two, or even more cleavages crystallographically unlike; they are then unlike in quality. Thus chlorite has only one perfect cleavage, which is parallel to the base; orthoclase has two cleavages, parallel to two of the pinacoids (001 and 010); and anhydrite has three pinacoidal cleavages.

The important cleavages in the different crystal systems may be summarized as shown in the table on page 131.

Parting

Cleavage is an inherent property which (if present at all) is always present in all crystals of a given kind. Parting is very similar, but it is not always present; it is due to a weakness produced by shearing (or other disturbance) after formation of the crystal. It is sometimes called false cleavage. It is found in some crystals of corundum, parallel with the base or rhombohedron or prism. It is important in some crystals of pyroxene (which even have a special name—*diallage*).

Fracture

Minerals which have no cleavage are said to fracture rather than to cleave. Further, the break of a cleavable crystal in any direction other than that of the cleavage is also fracture. Fracture differs from cleavage in being more or less irregular, uneven, or curved, and in no definite crystal direction. Fracture is described as *conchoidal* when the surfaces produced are smooth and curved, often concave, like those of some shells. It is described as *uneven* when the surface is rough and entirely irregular; this is the commonest type in minerals. It is described as *even* when the surface, though rough with many small irregularities, is approximately a plane.

Elasticity

As a consequence of variations in their elastic qualities minerals may be described as follows:

Elastic—thin layers of the mineral may be bent without breaking and they resume their original shape when the pressure is removed. Muscovite illustrates this condition.

Flexible—thin layers of the mineral are easily bent without breaking, but they do not resume their former shape when the pressure is removed. Talc illustrates this condition.

Ductile—the mineral may be drawn into wire, as illustrated by native copper or silver.

Malleable—the mineral may be hammered into thin sheets, as illustrated by gold.

Sectile—the mineral can be cut by a knife without powdering, but can nevertheless be powdered by a hammer. Gypsum illustrates this condition.

Brittle—the mineral breaks to fragments under a hammer and also when one attempts to cut it, as calcite.

Hardness

Hardness is a term ordinarily used with a rather vague meaning; as applied to crystals it is measured by the resistance offered to the production of a scratch on a smooth surface. In minerals there are all grades of hardness from that of talc, easily scratched with a fingernail, to that of diamond, which is the hardest substance known, either natural or artificial. For the rapid recognition of minerals hardness is very important because its approximate degree can be determined very quickly. Hardness (H) is always expressed in terms of the scale devised by Mohs, which is as follows:

1. Talc
2. Gypsum
3. Calcite
4. Fluorite
5. Apatite
6. Orthoclase
7. Quartz
8. Topaz
9. Corundum
10. Diamond

The numbers assigned to the scale express only *relative* hardness. It is not true that diamond is ten times as hard as talc; it is more than that. Nor is there a uniform difference in hardness between any number and the next. Indeed (as an extreme example) there is said to be a greater difference in hardness between 9 (corundum) and 10 (diamond) than between 1 (talc) and 9 (corundum)!

A crystal which scratches, and is also scratched by, one of the minerals of this scale has the same hardness as that mineral. A mineral which scratches one of the scale, say fluorite (and is not scratched by that), but does not scratch the next higher (being itself scratched by that), has an intermediate hardness, commonly expressed by the lower number with a fraction (usually one half); in this case the hardness would be 4.5. In testing hardness it is important to distinguish between a real scratch and a streak like a chalk mark: the latter is easily rubbed off; the former is not.

The determination of the approximate hardness is greatly simplified by noting that minerals with a hardness of 1 have a soft, usually greasy, feel to the hand; minerals with a hardness of 2 are easily scratched with the fingernail; those with a hardness of 3 may be scratched with a copper coin; those with a hardness of 4 are easily scratched with a knife; those with a hardness of 5 are scratched with some difficulty with a knife or window glass; those with a hardness of 6 are scratched with a file, but will scratch glass. Minerals harder than 6 are not numerous, so that these devices are very useful.

In testing the hardness of minerals it is ordinarily assumed that any one mineral has one hardness. Actually the hardness varies in different crystallographic directions. However, with very rare exceptions, like kyanite (H. = 4–5 parallel to elongation and 6–7 normal thereto), the difference in hardness in different crystal directions can be recognized only by using methods of precision, such as measuring the pressure necessary to produce a scratch.

Taste

A few minerals which are soluble in water have more or less characteristic taste, described as follows:

Acid, or *sour:* the taste of sulfuric acid.

Alkaline: the taste of soda or potash.

Astringent: the taste of vitriol, which causes a puckering.

Bitter: the taste of Epsom or bitter salts.

Cooling: the taste of potassium or sodium nitrate.

Pungent: the taste of ammonium chloride, sharp and bitter.

Saline or *salty:* the taste of common salt or sodium chloride.

Odor

In general minerals have no odor; but friction, moistening with the breath, crushing, heating or attack by acids may cause odors, which are described as follows:

Argillaceous: the odor of moistened or heated clay.

Bituminous: the odor of minerals containing bitumen, such as asphalt.

Fetid: the odor of rotten eggs (sulfuretted hydrogen), obtained by friction from some samples of barite, quartz, limestone.

Garlic or *alliaceous:* the odor from arsenic, obtained by friction or heat from arsenopyrite.

Horse-radish odor: obtained by heating ores of selenium.

Sulfurous, the odor of sulfur dioxide obtained by rubbing pyrite or heating many sulfides.

Feel

The touch or feel of some minerals is rather distinctive, and may be described as follows:

Cold: the feel of good conductors of heat such as metals and gems.

Greasy or *soapy:* the slippery feel of talc.

Harsh or *meager:* the rough feel of chalk.

Smooth: the feel of sepiolite.

Porosity

Some porous minerals are described as *hygroscopic* because they absorb water freely (they may even adhere to the tongue in consequence).

Electrical and Magnetic Properties

Electrical conductivity

Electrical conductivity is of some importance, because the development of electrostatic charges depends upon it. Most minerals are very poor conductors of the electric current, but strictly opaque minerals are commonly good conductors. Electrostatic charges may be produced, under suitable conditions, in good conductors, which may thus be separated from bad conductors. For example, if a mixture of ilmenite and monazite, or of pyrite and quartz or calcite, is placed on a good conducting surface, such as a copper plate, and dried thoroughly, and a flattened stick of sealing wax, which has been previously excited by rubbing, is brought near, grains of the former mineral (in each case) will be attracted to the sealing wax, and may be thus entirely separated. The method may be applied to rock and ore powders. Muscovite is a better electric insulator than glass.

Frictional electricity

All sorts of substances become electrified by friction, but the electrification is slight in many cases. Polished gem stones are commonly positively electrified by friction. They will then attract bits of paper.

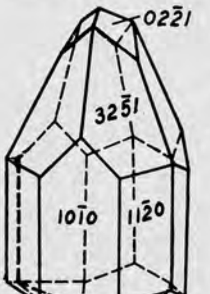

Fig. 305. Crystal of tourmaline.

Pyroelectricity

The development of electric charges on different parts of a single crystal by heating (or cooling) is called pyroelectricity. It is found only on crystals of low symmetry, especially those usually called hemimorphic. Tourmaline is an excellent example of a pyroelectric mineral. When a crystal is heated, the acute-angled end (see Fig. 305)—called the analogous end—becomes positively charged and the obtuse end becomes negatively charged. This is made manifest if the heated crystal is dusted with a mixture of finely powdered red lead and sulfur. The red lead is attracted to the negatively charged end and the yellow sulfur to the positively charged end. In similar fashion, opposite charges can be demonstrated at the opposite ends of the horizontal crystal axes of quartz when it is heated.

Piezoelectricity

Electric charges can be developed on crystals not only by heat, but also by pressure; this phenomenon is called piezoelectricity, and, like pyroelectricity it is marked along axes of unlike character of the two ends. Quartz is an important piezoelectric mineral because this property of quartz is used for frequency control in radio apparatus. A plate through a crystal of quartz which contains an *a* axis and the *c* axis, as in Fig. 306, is called a *Y* cut, while one containing the *c* axis and bisecting the angle between two *a* axes, as in Fig. 307, is called the *X* cut.

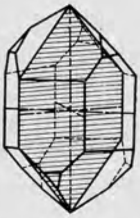

Fig. 306. A "Y" cut through a quartz crystal.

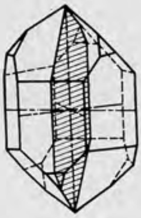

Fig. 307. An "X" cut through a quartz crystal.

Thermoelectricity

When two metals are put in contact each is electrified, one positively and the other negatively. If the point or plane of contact is heated while the other parts, connected by a wire, are kept cool, a continuous current of electricity is generated at the expense of the heat energy supplied. The current is reversed in direction if the point of contact is cooled instead of heated. This is called *thermoelectricity*, and the two metals are called a thermoelectric couple. Different metals (and conductors) can be arranged in a table, called the thermoelectric series, according to the direction and the electromotive force of the current set up on heating. It is important to note that natural metallic sulfides stand farther apart in the series than any metals and therefore produce a greater electromotive force.

Magnetism

By very accurate tests it can be shown that all minerals have magnetic charges, but many minerals have such weak charges that they cannot be discovered by mere use of a common horseshoe magnet. But between the poles of a powerful electromagnet some minerals are attracted and others are repelled. The former are called *paramagnetic* and the latter are called *diamagnetic*. All compounds of iron are paramagnetic; diamagnetic minerals include calcite, zircon, wulfenite, and so on. These properties lead to a useful method of electromagnetic separation of ores and other minerals.

Some (iron) minerals are attracted very much more powerfully than others; they have paramagnetism but of a different order of magnitude from that possessed by the others. They are sometimes distinguished as *ferromagnetic*. Certain samples of magnetite are even natural magnets and will themselves attract such substances as iron filings.

Thermal Properties

The most important thermal property for the identification of minerals is fusibility. The properties to be briefly described here are:

1. Heat of formation.
2. Heat of crystallization or latent heat of fusion.
3. Heat of inversion.
4. Thermal conductivity.
5. Thermal transmissibility.
6. Thermal diffusivity.
7. Thermal expansion.
8. Specific heat.
9. Heat of solution.
10. Fusibility.

Heat of formation

When two elements or compounds unite to form a single substance, heat is usually set free; in some cases heat is absorbed. The amount of heat set free or absorbed is a property of the mineral formed. It is usually expressed in calories per gram-molecule,[2] or it may be expressed in calories per gram of the

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[2] Gram-molecule = molecular weight in grams.

mineral formed. A calory is the amount of heat required to change one gram of water from 18° to 19° C. When heat is liberated in the process the heat of formation is considered to be +; when heat is absorbed it is −.

The heat of formation of many minerals is unknown. The following table gives the heat of formation of a few important minerals per gram-molecule and per gram:

HEAT OF FORMATION OF CERTAIN MINERALS

Mineral	*Reaction*	*Per Gram-Molecule*	*Per Gram*
Calcite	$Ca + C + 3O = CaCO_3$	+270,500	2705.
Calcite	$CaO + CO_2 = CaCO_3$	+ 42,600 (calculated)	430.
Galena	$Pb + S = PbS$	+ 20,400	85.
Halite	$Na + Cl = NaCl$	+ 97,700	1670.
Hematite	$2Fe + 3O = Fe_2O_3$	+195,600	1225.
Ice	$2H + O = H_2O$	+ 70,400	3910.
Quartz	$Si + 2O = SiO_2$	+180,000	2990.
Rutile	$Ti + 2O = TiO_2$	+218,400 (crystalline)	2725.
Rutile	$Ti + 2O = TiO_2$	+215,600 (amorphous)	2690.

Heat of crystallization

When a mineral crystallizes, a certain amount of heat is set free. The amount of heat set free when unit mass of a mineral under unit pressure changes from a liquid to a crystal at the same temperature is called the heat of crystallization, and is a characteristic of the crystal. The same amount of heat is absorbed without change of temperature when a crystal is liquefied; therefore it is often known also as the *"latent" heat of fusion.* When a mineral crystallizes from solution both the heat of crystallization and also the heat of solution are set free, but when crystallization occurs from fusion the heat liberated is solely the heat of crystallization. The following data illustrate our limited knowledge of the subject. The heat of crystallization is given in small calories per gram.

HEAT OF CRYSTALLIZATION OF CERTAIN MINERALS

Mineral	*Fusing Point*	*Heat of Crystallization in Calories per Gram*	*Authority*
Anorthite	1550°	105	Vogt.
Diopside	1391°	102	Vogt.
Enstatite	1375°	125	Vogt.
Forsterite	2130°	130	Vogt.
Ice	0°	80	
Microcline	1170°	83	Tammann
Nephelite	1105°	73	Tammann
Quartz	1625° ±	115	

Heat of inversion

Many minerals have a limited range of temperature and pressure conditions under which they are stable. Under other conditions of pressure and temperature they are unstable, and tend to change to some other form with absorption or evolution of heat. Such changes from one crystal form to another may be reversible or irreversible. The heat absorbed or set free is characteristic of the substance. Very few determinations of the heat of inversion of minerals have been made. The heat of inversion is said to be − when heat is absorbed and + when it is liberated. It is stated in small calories per gram-atom or gram-molecule.

Heat of Inversion of Certain Substances

Substance	*Change*	*Heat of Inversion*	*Temperature*	*Authority*
$Mg_6B_{14}O_{26}Cl_2$ (Boracite)	Orth. to isometric	+4.28	265°	Le Chatelier
	Orth. to isometric	+1.63	265°	Kröker
Carbon	Graphite to diamond	+0.50	—	Berthelot
$CaCO_3$	Aragonite to calcite	+0.39	—	Foote
H_2O	Ice-I to Ice-III	+0.054	—	Tammann
Quartz	α-form to β-form	+4.3 per gram	575°	White
Sulfur	Monoclinic to orth.	+0.081	96°	Reicher

When an amorphous solid changes to a crystalline solid the heat liberated may be regarded as heat of crystallization measured at a low temperature; or as a kind of heat of inversion, since the change is from one solid form to another solid form. It may differ from the heat of crystallization both because the latter varies slightly with temperature, and also because the crystal produced may not be the same as the one produced from fusion. The following determinations have been made:

Heat of Inversion, Amorphous to Crystalline

Substance	*Change*	*Heat of Inversion*	*Authority*
Carbon	Amorphous to graphite	+2.84	Berthelot
Carbon	Amorphous to diamond	+3.34	Berthelot
HgS	Amorphous to hexagonal cinnabar	+0.06	Varet
$SrCO_3$	Amorphous to orthorhombic strontianite	+1.1	Berthelot
Sulfur	Amorphous to orthorhombic	+0.91	Petersen

Thermal conductivity

The thermal conductivity of minerals has been studied especially by Senarmont, Jannetaz, Röntgen, and others. One method of study is to coat the face of a crystal with a thin film of wax or paraffin and observe the shape of the area melted by a hot wire placed in contact with the surface at a central point. It is found that isometric crystals conduct heat with equal speed in all directions, while tetragonal and hexagonal crystals conduct equally in all directions in the plane of their equal lateral axes, but unequally in the direction of the unequal vertical axis. Finally, all other crystals conduct unequally in the direction of their three unequal crystal axes. Thus crystals are divided into the same three classes as are established by a study of their optical characters. In other words the propagation of light and the conduction of heat are governed by the same laws and related in the same ways to the crystal structure.

The thermal conductivity is measured by determining the amount of heat in calories that passes per second through each square centimeter of surface of a plate one centimeter thick whose sides have a difference in temperature of 1°C. The conductivity varies with the temperature. Some determinations of conductivity follow:

THERMAL CONDUCTIVITY OF CERTAIN MINERALS

Mineral	*Temperature*	*Conductivity*	*Authority*
Copper	18°	0.8915	Jaeger and D.
Silver	18°	1.006	Jaeger and D.
Ice $\parallel c$	—	0.00223	Forbes
Ice $\perp c$	—	0.00213	Forbes
Quartz $\parallel c$	0° to 17°	0.0263	Tuchschmid
Quartz $\perp c$	0° to 17°	0.0160	Tuchschmid
Calcite $\parallel c$	0° to 17°	0.0096	Tuchschmid
Calcite $\perp c$	0° to 17°	0.0079	Tuchschmid
Halite	0°	0.014	Lees
Feldspar	16° to 69°	0.0058	Ayrton and Perry
Serpentine	0° to 40°	0.0024	Hecht

Thermal transmissibility

Heat passes through crystals in two different ways. It may be carried by the atoms of the body itself, or by the ether around these atoms. In the first case the heat is said to be conducted; in the second case it is said to be transmitted. Crystals which transmit heat waves freely are said to be diathermanous; that is, they are "transparent" to the heat waves. Those crystals which are "opaque" to heat waves are called athermanous.

The capacity of a mineral to transmit heat is measured by its thermal transmissibility. Heat, light, and electricity are all forms of wave motion of the ether. Light consists of very short waves, heat of longer, and electricity of very long waves. Substances which transmit light readily may be opaque to heat, and vice versa. Furthermore, crystals not isometric may transmit unequal quantities and kinds (wave-lengths) of heat in different directions, just as they may transmit unequal quantities and kinds of light.

Thus halite is transparent to light and diathermanous to a large part of the heat waves; alum is transparent to light and athermanous to heat, absorbing the infra-red waves and reflecting the waves of length 9μ and 30 to 40μ. A thin film of silver is practically opaque to light, but diathermanous to heat waves of length 32μ. Stibnite is also nearly opaque to light, but diathermanous to heat.

Thermal diffusivity

The transmission of temperature is of course not the same as the transmission of heat. The capacity of a body to transmit temperature is measured by its thermal diffusivity. It varies directly with the conductivity and inversely with the specific heat and the density. Indeed:

$$\text{Diffusivity} = \frac{\text{Conductivity}}{\text{Specific heat} \times \text{Density}}$$

Thermal expansion

Amorphous solids tend to expand equally in all directions when heated. But in crystals the expansion is equal or unequal in various directions depending upon the symmetry of the crystal concerned. Thus, isometric crystals expand equally in all directions. Further, tetragonal and hexagonal crystals expand equally in all directions in the plane of their equal lateral axes, but unequally in the direction of the vertical axis. Therefore the interfacial angles in the prism zone are unaltered, but the angles of pyramids are modified. Finally, orthorhombic, monoclinic, and triclinic minerals expand unequally in the direction of each crystal axis and therefore nearly all crystal angles suffer change with rise of temperature. Only pinacoids normal to crystal axes suffer no change in position.

Generalizing, it appears that there are three kinds of crystals as regards thermal expansion and these three groups correspond exactly with the three types based on optic properties (as described later).

The amount of increase (or, rarely, decrease) of volume per unit of volume for a rise in temperature from 0° to 1°C. is called the coefficient of expansion. This coefficient varies widely, depending not only on the mineral, but also on the direction in the crystal. In calcite the rhombohedral cleavage angle changes from 74°55′ to 83°32′ when the temperature changes from 0° to 100°C., the form thus approaching a cube. But expansion alone does not cause a change of symmetry. That is produced by a sudden inversion, accompanied by absorption of heat, during which there is no change of temperature and therefore no expansion from that cause.

The following table illustrates determinations of coefficients of expansion for a few minerals:

Coefficients of Thermal Expansion

Mineral	*Temp.*	*Coefficient Linear Expansion*	*Coefficient Cubic Expansion*	*Authority*
Calcite $\parallel c$	20°	0.00002561	0.00003685	Benoit
Calcite $\perp c$	20°	0.00000563		Benoit
Gold	20°	0.00001403	0.00004209	Matthiesen
Hematite $\parallel c$	20°	0.00000817	0.00002399	Bäckström
Hematite $\perp c$	20°	0.00000791		Bäckström
Quartz $\parallel c$	20°	0.00000748	0.00003492	Benoit
Quartz $\perp c$	20°	0.00001372		Benoit

Specific Heat

The specific heat of a body is the amount of heat required to raise unit mass of the substance one degree centigrade. Since one calory is by definition the amount of heat required to raise unit mass of water one degree centigrade (from 18° to 9°C.) the specific heat of water is unity. Determinations of specific heat have been made by White, Lindner, Ulrich, and others, and some of their results follow:

SPECIFIC HEAT OF CERTAIN MINERALS

Mineral	*Temperature*	*Specific Heat*	*Temp.*	*Specific Heat*	*Authority*
Albite	0°	0.177	500°	0.269	White
Anorthite	0°	0.174	500°	0.260	White
Augite	20–98°	0.1931			Ulrich
Calcite	0–100°	0.2005			Lindner
Diopside	0°	0.176	500°	0.262	White
Galena	0°–100°	0.0466			Tilden
Hornblende	20–98°	0.1952			Ulrich
Ice	−30°–0°	0.505			Person
Labradorite	20–98°	0.1949			Ulrich
Magnetite	24–99°	0.1678			Regnault
Microcline	0°	0.171	500°	0.258	White
Orthoclase	0–100°	0.1835			Lindner
Orthoclase	0–300°	0.1956			Lindner
Platinum	18–100°	0.0324			Behn
Quartz	0°	0.167	500°	0.294	White
Sphalerite	0–100°	0.1146			Lindner

Heat of solution

When a mineral is dissolved, heat is generally absorbed, and this heat includes not only the heat necessary to destroy the crystal structure, but also the heat necessary to cause the molecules of the mineral to mingle with those of the solvent. The latter alone is *properly* called the heat of solution, although the former is often included in the term. Consequently, the heat of solution should be determined by dissolving a mineral when it is in the liquid or the amorphous condition. The heat of solution of only a few minerals is known. It is expressed in the following table in small calories per gram-molecule dissolved in the stated number of gram-molecules of water. When heat is absorbed upon solution the quantity is marked −; when it is set free it is marked +.

HEAT OF SOLUTION OF CERTAIN MINERALS

Mineral	*Gr. Mol. of Water*	*Heat of Sol.*	*Temp.*	*Heat of Fusion*	*Authority*
Halite $NaCl$	100	− 1.2	18°C.	Included	Thomsen
Thenardite Na_2SO_4	400	+ 0.46	18	Excluded	Thomsen
Mirabilite $Na_2SO_4 + 10H_2O$	400	−18.8	18	Included	Thomsen
Anhydrite $CaSO_4$	—	+ 4.44	18	Included	Thomsen
Gypsum $CaSO_4 + 2H_2O$	—	− 0.3	18	Included	Thomsen
Barite $BaSO_4$	—	− 5.6?	18	Included	Thomsen
Epsomite $MgSO_4 + 7H_2O$	400	− 3.8	18	Included	Thomsen
Melanterite $FeSO_4 + 7\,H_2O$	400	− 4.5	18	Included	Thomsen
Chalcanthite $CuSO_4 + 5H_2O$	400	− 2.75	18	Included	Thomsen
Cerargyrite $AgCl$	—	−15.9	—	Included	Petersen

Fusibility

Under atmospheric pressure a few minerals, like many of the carbonates, are decomposed by heat and do not fuse; a few other minerals, like arsenic, calomel, and salmiac, vaporize without fusion; many minerals invert to other forms while still solid. All other minerals, including those produced by high temperature inversion, fuse when sufficiently heated. The temperature at which the mineral changes from the solid to the liquid state (or, more accurately, from the crystalline to the amorphous condition) is known as the fusing point. Exact measurements of the fusing points of minerals are difficult and of little importance in the determination of minerals, but they are interesting and significant in theoretical and petrographic studies. A few dimorphous substances invert so slowly that one substance (e.g. SiO_2) may have two fusing points, depending upon its crystal form.

FUSING POINTS OF IMPORTANT MINERALS

Mineral	*Day, et al.*	*Brun*	*Joly and Cusack*	*Doelter*
Actinolite		1190°	1272–1296°	1160°
Albite	1120°			
Almandite		1065°	1265°	1075–1145°
Anorthite	1550°	1550°		
Apatite		1550°	1227°	1285°
Argentite	842°			
Augite		1230°	1185–1200°	1080–1185°
Bronzite		1410°	1295–1300°	1330–1360°
Clino-enstatite	1557°			
Copper	1083°			
Corundum	2050°			
Diopside	1391°	1270°	1187–1195°	1255°
Galena	1120°	830°		
Gold	1062°			
Hornblende		1060°	1187–1200°	1075–1110°
Labradorite (Ab_1An_1)	1287–1450°	1370°	1230–1235°	1125–1180°
Magnetite	1580°	1260°	1250–1450°	1185–1210°
Muscovite				1230–1270°
Natrolite			960°	910°
Orpiment	320°			
Orthoclase	1170°	1270–1300°	1140–1175°	1160–1200°
Platinum	1755°			
SiO_2 Cristobalite	1713°	1780°	1425–1430°	
SiO_2 Tridymite	1670°			
Silver	960°			
Stibnite	546°		525°	
Sulfur	119°			
Tourmaline			1010–1100°	1020°

Accurate work in determining fusing points has been carried on recently at the Geophysical Laboratory in Washington. Earlier measurements were made by Brun, Joly, and Doelter. Some results are as shown in the table on page 145.

For practical rapid identification of minerals it is usually sufficient to determine the approximate or relative fusibility. For this purpose the *scale of fusibility* proposed by von Kobell is extensively used. As modified by Penfield this scale is as follows:

SCALE OF FUSIBILITY

Mineral	*Remarks*	*Approx. Temp.*
1. Stibnite Sb_2S_3	Fragments fuse easily in candle or gas flame. Fusible in closed tube below red heat.	546°C.
2. Chalcopyrite $CuFeS_2$	Standard size fragment fuses slowly in candle or gas flame. Fusible in closed tube at full red heat.	800° ±
3. Almandite $Fe_3Al_2Si_3O_{12}$	Standard size fragment fuses readily to a globule BB. In a candle or gas flame only the finest splinters are rounded.	1050°
4. Actinolite $H_2Ca_2(Mg,Fe)_5(SiO_3)_8$	Standard size fragment rounded easily BB.	1200°
5. Orthoclase[3] $KAlSi_3O_8$	Standard size fragment rounded on the edges with difficulty BB.	1300°
6. Bronzite $(Mg,Fe)SiO_3$	Only the finest points on thin splinters are rounded with difficulty BB.	1400°

Finally, there are many minerals which are wholly infusible before the blowpipe, as quartz and corundum.

A fragment of standard size is 1.5 mm. in diameter.

Optical Properties

Certain optical properties are of use in the rapid identification of minerals. Most of these are independent of crystallization; they include transparency, luster, color, and so on. Other optical properties are much more useful in studying minerals, but require special equipment, notably a polarizing microscope; they depend directly upon crystallization and include refringence, birefringence, extinction angles, and so forth.

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[3] Orthoclase fuses in the strict sense of losing crystalline condition at 1170°, but remains as a highly viscous glass to about 1300°.

Transparency

Transparency (or diaphaneity) of a mineral relates to the amount of light transmitted through it. If an object can be distinctly seen when looking through a mineral, the mineral is said to be *transparent*. Colorless quartz is a good example. When light is transmitted, but also refracted, so that objects cannot be seen through a mineral, the mineral is said to be *translucent*. A mineral which transmits no light even through the thin edges of splinters is *opaque*. But opaque is a relative term; thus gold is opaque, but extremely thin films of gold transmit a greenish light.

Luster

The luster of a mineral depends upon the appearance of its surface in reflected light, and this in turn depends upon the transparency, refractivity, and structure of the surface layers. It is a property of great importance in the recognition of minerals. There are two main types of luster, the metallic and nonmetallic.

Metallic luster. Metallic luster is exhibited by all metals and some compounds resembling metals. As an arbitrary, but convenient and generally correct, method of distinguishing between metallic and nonmetallic lusters a mineral is not said to have metallic luster unless it is opaque, transmitting no light even through the edges of thin splinters. A few minerals have varieties with metallic luster and other varieties with nonmetallic luster. Hematite is a good example.

Nonmetallic luster. Nonmetallic luster includes all other types, such as

Adamantine: the very brilliant luster of diamond and some other minerals having a very high index of refraction.

Vitreous: the luster of glass and quartz. A very common kind of luster among minerals.

Resinous: the luster of resin and yellow sphalerite.

Greasy: the luster of oily glass, shown by nephelite.

Pearly: the luster of mother of pearl, shown by talc, and some other lamellar minerals.

Silky: the luster of silk and of some minerals having a fibrous structure.

Dull: the luster of chalk or kaolin. "Dull luster" is almost a contradiction of terms, because luster is due to reflected light and a surface is called dull when almost no light is reflected.

The intensity or brilliance of luster is described as *splendent, shining, glistening, glimmering,* or *dull* in decreasing order.

Color

The color of a mineral is due to the wave length (or combination of wave lengths) of the light reflected from it. It is one of the first physical properties to be observed. It is a very useful means of identifying minerals in spite of the fact that the color of many samples is not due to an inherent quality, but to a variable condition, such as a stain. Minerals which have an inherent color (due to some constituent) include: gold, which is yellow; malachite, which is green; azurite, which is blue; cinnabar, which is red; and magnetite, which is black.

Minerals which are colored by a stain or pigment may have almost any color. For example, pure quartz is colorless, but it may be colored golden yellow as in citrine, pink as in rose quartz, purple as in amethyst, red as in jasper, brown to black as in smoky quartz. The pigment may be quite uniformly distributed through the sample, or very irregularly in patches, as in some purple fluorite, or in regular but not uniform arrangement, as in bands or zones, or at one end of a crystal, as in tourmaline. Agate is a variety of quartz having colors in bands. In moss agate the pigment has an arrangement suggesting moss.

Streak. A mineral may have one color in a solid state and a different color when finely divided, as in a powder. This second color is known as the streak of the mineral, since it is conveniently produced if the mineral is not too hard by rubbing it on a rough white surface such as unglazed porcelain, thus leaving a mark or streak. Many minerals whose color varies greatly in mass have invariant or only slightly variant streak. Therefore the streak is an important means of identifying minerals. Furthermore minerals whose mass color is the same may have very different streaks; for example, some hematite and limonite and all magnetite samples are black, but hematite has a red streak, limonite a yellow brown streak, and magnetite a black streak.

Play of colors. Some minerals show different colors when slowly turned or viewed from different angles; they are said to exhibit a play of colors. This is illustrated by diamond, in which it is due to high dispersion and by labradorite, in which it is due to reflections from thin lamellar inclusions.

Opalescence is the milky or pearly appearance due to reflection from within the mineral, as in some opal and cat's eye; it is observed to best advantage from rounded and polished samples.

Iridescence is a play of bright colors due to a thin film on the surface or to reflection from cleavage cracks. It is well illustrated by some samples of limonite.

Tarnish. A mineral is said to exhibit tarnish when its surface shows a color different from that of a freshly broken piece; these tarnish colors are due to a thin surface film of alteration or incrustation. Bornite illustrates this condition.

Chatoyancy. A mineral exhibiting a changeable silky sheen is said to show chatoyancy (from the French "chat"—referring to the cat's eyes); it is due to a fibrous structure. The satin spar variety of gypsum is so named because it is chatoyant.

Asterism. Some minerals produce a starlike effect consisting of bright light along certain lines radiating from a center. This asterism is shown by some samples of sapphire when viewed in reflected light and by some samples of phlogopite in transmitted light. It is due to regularly arranged inclusions or twinning lamellae.

Luminescence. Some minerals transform various other forms of energy into light and thus become luminescent. When heat is thus transformed the mineral is said to show *thermoluminescence;* this is well illustrated by some samples of fluorite. If the luminescence is exhibited only during exposure to heat (or other forms of energy) it is called fluorescence; if it continues after exposure it is called phosphorescence. Luminescence is also produced in some minerals by exposure to X rays, cathode rays, radium emanations, mercury vapor, and argon lamps, or by an iron arc apparatus. The light produced is often colored and the color has no relation to the mass color of the mineral. The display of such colors is quite spectacular in some cases, but is only rarely useful in identifying minerals. A few minerals become luminescent when rubbed or scratched; this phenomenon is called *triboluminescence* (tribo is from a Greek root meaning to rub). It is extraordinary to see how sphalerite in rare cases becomes triboluminescent under the influence of very slight rubbing as with a feather. In this case the experiment should be tried in the dark because the luminescence is slight.

Light

In addition to the foregoing optical properties of minerals which are easily observed in general without special apparatus, minerals (and other solids) have certain optical properties which are best studied with a microscope equipped with polarizing prisms to produce and use polarized light. In order to describe these properties satisfactorily it is desirable to consider first the nature of light.

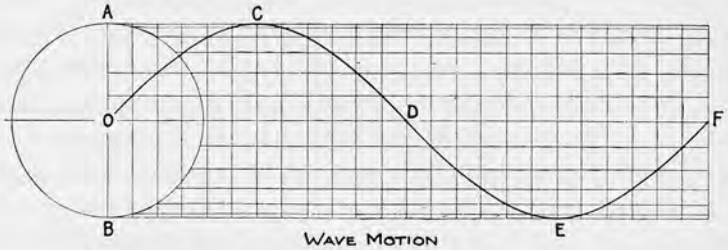

FIG. 308. Wave motion.

Light is a form of energy which may be considered to consist of an undulatory motion. This undulatory motion or vibration takes place at right angles to the direction of propagation. The *amplitude* of vibration is the distance from the point of rest to either point of reversal of motion. The *period* of vibration is the interval of time required for the particle to move from any point back to the same point, when moving in the same direction. The motion of any one particle is communicated to another and so on, each a little behind in its oscillation. So, while individual particles move back and forth in the same line, the wave moves forward. This is well illustrated when one end of a tight rope is given a sudden up and down motion, starting a wave along the rope. One *wave length* (denoted by λ) is the distance from any particle to the next which is in like position and traveling in the same direction. It is the distance *OF* in Fig. 308. The point of maximum upward displacement is called the *crest* of the wave and of maximum downward displacement, the *trough.* The *phase* of a wave at any instant is its distance measured as a fraction of a wave length from some given point taken as the origin of the motion. Two waves are in the same phase when they are at corresponding points of their vibrations. When two waves have a difference of phase of one-half a wave length ($\frac{1}{2}\lambda$) their vibrations are similar, but in opposite directions; if one is at the crest the other is at the trough.

Waves of light are very short: the wave length of the yellow light of sodium is 0.000023 of an inch or 0.000589 of a millimeter. The period of vibration of light is extremely short, about 510 million million vibrations of sodium light occurring in one second. Light travels with great velocity, about 186,000 miles per second. The velocity of light of all wave lengths is the same in a vacuum; therefore, the period of vibration is exactly inversely proportional to the wave length. Ether waves of different periods of vibration (and of different wave lengths) give rise to different colors of light. The wave length of violet light, at one end of the spectrum, is about 0.000380 mm., while that of red, near the other end, is about 0.000760 mm. The velocity of light is less in most substances than in a vacuum, and varies with the substance and also with the wave length; accordingly, in any medium whether gaseous, liquid, or solid, violet light has one velocity and red light another, which is greater.

Wave-surface. If wave motion of light be produced at a point in a vacuum, it will be transmitted outward from the point in all directions at the same velocity. Therefore, at any instant, all points in the same phase will be equally distant from the point of origin. The locus of all these points is called the wave-surface, and in this instance it is a spherical surface. If the wave motion originated in a plane instead of a point, it would be transmitted in spherical waves from every point of the plane; and the plane tangent to all these waves on each side of the plane of origin would be the wave-surface. If the wave motion were transmitted from a point at velocities varying gradually with the direction, the wave-surface would be a warped surface of some kind.

The line along which the wave motion travels from the point of origin to any other point is called a *ray.* In a vacuum the light ray from the point of origin to any point on the wave-surface is perpendicular to the tangent plane at that point.

Isotropic substances (and the ether of a vacuum) transmit light with equal velocity in all directions. They include all gases, most liquids, and all glasses and isometric crystals (when not under strain).

Anisotropic substances transmit light with unequal velocities in different directions; they include all crystals except those of the isometric system (which are unstrained). Glass under strain is also anisotropic. In non-isometric crystals the velocity varies gradually with the direction in such a way that most sections of the wave-surface are elliptical. In Fig. 309 it may be seen that the light ray from the point of origin to any point on the wave-surface is not perpendicular to the tangent plane at that point except when the ray coincides with the major or minor axis of the ellipse. The line (VW) perpendicular to the tangent plane is called the *wave-normal*. When the wave-surface is elliptical, as in Fig. 309, the wave-normal does not coincide with the light ray except in the directions of the principal axes of the ellipse. The plane tangent to the wave-surface at the point reached by any ray is called the wave-front of that ray.

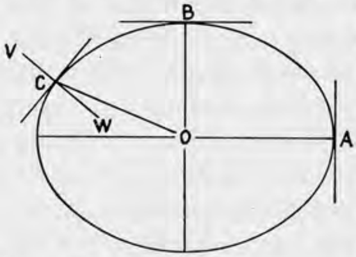

FIG. 309. Wave surface in an anisotropic substance.

In all unstrained isotropic minerals, light travels with equal velocity in all directions; therefore, in such minerals, the wave-front is always a sphere. The velocity of light in isotropic bodies varies, however, with the nature of the body, and also with the color of the light.

Reflection. When light reaches the boundary between two isotropic substances it is usually divided into two parts, one of which is turned back into the first medium while the other penetrates the second medium. That portion of the light which is turned back or reflected does not return along its original path, except in the case of a ray striking a reflecting surface perpendicularly. The path of the reflected ray can be deduced from the position of the new wave-front. Thus, if *Oa, Ob, Oc,* in Fig. 310, represent parallel rays (that is, a beam) of monochromatic light striking the boundary *MM′*—here, for simplicity of construction, a plane surface—between two isotropic substances, the wave-front of the light at the point *a* is the line *ad*, at right angles to the beam. During the time that the ray *Oc* travels from *d* to *c* it is evident that the ray *Oa*, turned back from *a* into the same medium in which *Oc* is moving, must go a distance equal to *dc*. Therefore, when *Oc* reaches *c*, *Oa* must be at some point on the semicircle *eqg*, whose radius is equal to *dc*. and the wave-front must be a line from *c* to the point of tangency, *t*. A similar construction gives the direction *bt′* of the ray *Ob* after reflection at *b*; in like manner the direction of any reflected ray can be found.

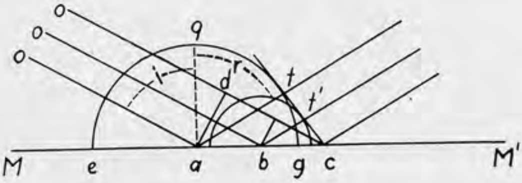

Fig. 310. Reflection of light.

If a perpendicular is erected at *a*, the angle *Oaq* is called the angle of incidence (*i*) and *qat* is called the angle of reflection (*r*). The right triangles *adc* and *atc* are equal, having one side in common and the side *at* equal to the side *dc*; therefore, the angle *dac* equals the angle *tca*, and the angle *Oaq* (= *dac*) equals the angle *qat* (= *tca*). That is, *the angle of reflection is equal to the angle of incidence.* Also, the incident and reflected rays lie in the same plane with the normal to the surface at the point of incidence if the medium is isotropic.

That light penetrates somewhat even those bodies called opaque is shown by the fact that the light reflected is less than the incident light. Many substances commonly called opaque are transparent in very thin flakes.

Refraction. When light strikes the boundary between two isotropic substances, that portion which penetrates the second medium is, in general, turned somewhat from its path. This is called refraction, and the property (of the substance) to which it is due is called refringence.

If a beam of light, *Oa, Ob, Oc,* in Fig. 311, strikes the plane surface *MM′* of a second medium, its velocity in this medium depends upon the relative densities of the two substances. Accordingly, while the ray *Oc* travels from *d* to *c,* the ray *Oa* will travel a shorter distance, say, *ae,* if the second medium is denser than the first. Therefore, the wave-front through the point *c* must pass through the point of tangency *e,* and the direction of the ray *Oa* in the second medium must be shown by *ae,* since it must be perpendicular to the wave-front *ec.* If a perpendicular *FF′* is erected at *a,* the angle *F′ae* is called the angle of refraction (*r*). Let *v* be the velocity of light in the first medium and *v′* that in the second. Then, by construction,

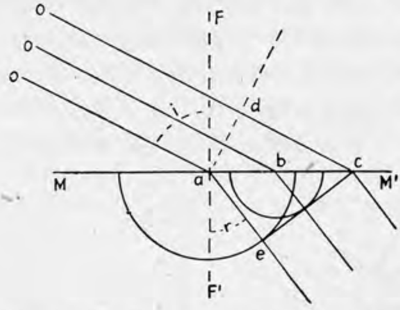

FIG. 311. Simple refraction of light.

$$\frac{v}{v'} = \frac{dc}{ae}.$$

Now, in the right triangles *adc* and *aec*:

$$dc = ac \sin dac = ac \sin OaF = ac \sin i$$
$$ae = ac \sin ace = ac \sin eaF' = ac \sin r$$

Therefore

$$\frac{v}{v'} = \frac{ac \sin i}{ac \sin r} = \frac{\sin i}{\sin r}.$$

For monochromatic light and isotropic substances, the velocity in one medium divided by the velocity in another medium is evidently constant. Let this constant be denoted by N. Then

$$\frac{v}{v'} = \frac{\sin i}{\sin r} = N;$$

that is, the sine of the angle of incidence bears a constant ratio to the sine of the angle of refraction, the ratio being the same as that between the velocities of light in the two substances. Further, the incident and refracted rays lie in a common plane with the normal to the surface.

The velocity of light is less, the denser the medium. Therefore, when the light passes from a rarer to a denser medium, the ratio $\frac{v}{v'} = \frac{\sin i}{\sin r}$ is greater than unity, the angle of refraction is less than the angle of incidence, and the refracted ray is bent toward the perpendicular. Also, when light passes from a denser to a rarer medium, the ratio $\frac{v}{v'} = \frac{\sin i}{\sin r}$ is less than unity, the angle of refraction is greater than the angle of incidence, and the refracted ray is bent away from the perpendicular.

The constant N is called the *index of refraction* of the second medium as compared with the first. The medium chosen as a standard and assigned a refractive index of unity is the ether of a vacuum. Air has an index (1.000294) so near unity that it is commonly used as a more convenient standard. After measurement of the index of a substance in any medium, as air, its index in a vacuum may be computed. It is equal to the index measured multiplied by the index (measured in a vacuum) of the medium used.

Examples of Indices of Refraction

Substance	*Index of Refraction*
Air	1.000294
Ice	1.309
Water	1.336
Alcohol	1.36
Clove oil	1.53
Light flint glass	1.54 ±
Canada balsam	1.54 ±
Quartz	1.547
Bromoform	1.59
α-Monobromnaphthalene	1.66
Methylene iodide	1.74
Methylene iodide saturated with sulfur	1.78
Sphalerite	2.37
Diamond	2.42
Rutile	2.71

The index of refraction of any substance varies for different colors of light, and increases as the wave length decreases; therefore, the index for violet light is greater than for red, while the index for the yellow light of sodium (Na) is commonly used as an approximate mean value. The difference in refraction in different colors is called the *dispersion*. It varies with the substance used.

Total reflection. In general, the index of refraction is measured from a rarer (ether or air) to a denser medium, so that the index is greater than unity, the refracted ray is bent toward the perpendicular, and light of any angle of incidence can enter the second medium. Thus, if the angle of incidence is 0°, then $\sin i = 0$, and since in this case $N = 0/\sin r$, $\sin r$ must also equal 0; that is, a ray of light striking a surface perpendicularly enters the new medium with no change in direction, but with a change in velocity. Also, if the angle of incidence is 90°, then $\sin i = 1$, and $N = 1/\sin r$, or $\sin r = 1/N$. For any substance, the sine of the angle of refraction for light whose angle of incidence is 90° is therefore the reciprocal of the index of refraction. For example, for water, $\sin r = 1/1.336$, and $r = 48°31'$; for Canada balsam, $\sin r = 1/1.54$, and $r = 40°29'$; for diamond, $\sin r = 1/2.42$, and $r = 24°24'$.

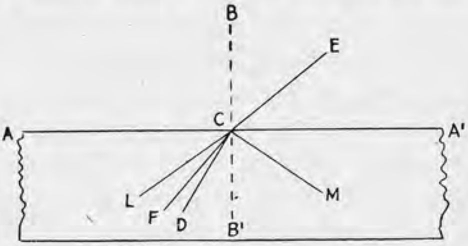

FIG. 312. Total reflection of light.

When light passes from a denser to a rarer medium, the refracted ray is bent away from the perpendicular and only light within a certain limiting angle of incidence can enter the second substance. In Fig. 312 let AA' be the upper surface of a plate of glass, and BB' the normal to the surface. Light from within the glass, as the ray DC, will be refracted in the air away from the perpendicular, to such a direction as CE. If the refractive index of the glass as compared with air is 1.54, the refractive index of air as compared with the glass must be 1/1.54; therefore

$$\frac{1}{1.54} = \frac{\sin DCB'}{\sin BCE'}$$

From this equation it is easy to calculate that, if the angle DCB' is 30°, the angle BCE must be 50°. Another ray, such as FC, at an angle of incidence of 40° 29' will be refracted in air at an angle of 90° along the path CA', grazing the surface of the glass. Any light from within the glass striking the bounding surface at an angle greater than 40°29' cannot enter the air, cannot obey the law of refraction, and must be wholly reflected. For example, the ray LC would be wholly reflected in the direction CM. This is called *total reflection*, and the angle of incidence at which the refracted light grazes the surface is called the *critical angle*.

It is evident that the critical angle for any substance, with respect to ether or air, is easily obtained (if its refractive index is known) from the equation $\sin r = 1/N$, in which r is the critical angle. Also, the index of refraction may be calculated from the same equation if the critical angle is known. The experimental measurement of the critical angle is frequently used as a means of determining the refractive index.

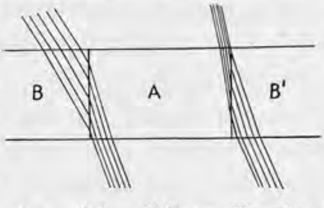

FIG. 313. Oblique illumination.

Refringence. The refringence of a substance is the power to produce refraction of light; it is measured by its index of refraction. Microscopic methods of measuring the index of refraction are not extremely accurate, but they are nevertheless important, and microscopic methods of comparing the indices of refraction of two substances in contact are of a high order of accuracy.

The relative refringence of transparent substances in contact can be determined with great accuracy either with normal illumination or oblique illumination. In the first case, if the boundary between the two substances is normal to the surface of the plate (or the object glass), total reflection is important in producing a white line next to the contact. This is called the Becke line. The Becke line moves toward the substance of higher index when the focus is raised and toward the substance of lower index when the focus is lowered. A high power objective should be used for this test. The Becke line is still plainer when oblique illumination is used (that is with a condenser and a device to shade part of the field). If the boundary between the two substances is normal to the plate the bright line can be understood from Fig. 313. If A is any mineral surrounded by a second mineral or liquid B and B' of higher index, an inclined beam of light passing from B' into A is refracted away from the perpendicular to the contact plane; it is thereby made narrower (and brighter). A similar beam of light passing from *A* into *B* is refracted toward the perpendicular and thereby made wider (and darker). If the mineral is above the focus of the condenser when the edge appears bright, as in passing from *B′* into *A*, the mineral of higher index is on the side of the boundary whence the light comes, and if the edge appears dark as in passing from *A* into *B*, the mineral of lower refringence is on the side whence the light comes. If the mineral is below the focus of the condenser the effects are reversed.

As compared with crystals or other solids, liquids in general have much greater dispersion, that is, they have much greater differences in indices for different parts of the spectrum. Therefore, if a crystal has exactly the same index of refraction as a certain liquid for yellow light, it will have greater refringence than the liquid for red light and less than the liquid for blue light. Under these conditions, if a fragment of the crystal is observed with inclined illumination in white light, one edge of the fragment is colored by blue light and the opposite edge by red light. The blue edge will be on that side of the crystal away from the shadow (the condenser being lowered), which is the side that is brightly illumined when the crystal is immersed in a liquid of higher refringence, or, without change of liquid, when monochromatic blue light is used instead of white light. Accordingly, the appearance of pale red and blue edges on opposite sides of a crystal is evidence that the fragment has a refringence equal to that of the liquid for some intermediate color. For some of the immersion liquids—notably cinnamon oil—the dispersion is very great and strongly colored borders are present even if the index for sodium light of the grain and the liquid differ in the second decimal place.

Immersion method. Schroeder van der Kolk brought into prominence a method to determine the refringence of minerals in fragments or grains. It consists essentially in immersing the fragment in a liquid of the same refringence, as determined by the method of normal or inclined illumination, and then measuring the index of refraction of the liquid. A liquid of the same refringence may be obtained by reducing the index by dilution or raising the index by evaporation, or it may be obtained approximately by preparing beforehand a set of liquids whose indices differ by only a small amount, for example, by 0.01. Changes of temperature or of concentration through evaporation modify the refringence of liquids and should be avoided during use. The liquids recommended for this use by Larsen[4] are given below. These liquids are selected partly because of relatively low dispersion. They may be kept conveniently in small dropping bottles with ground-glass dropper and cap, thus providing two ground joints to prevent evaporation. All the liquids, except as noted, will form suitable mixtures in any proportions with those next above and below them in the table. The index of refraction decreases with increase of temperature at the rate given (for 1° C.) in the column headed dN/dT.

Immersion Media and Their Properties

Substance	*N at 20° C.*	$\frac{dN}{dT}$	*Dispersion*	*Remarks*
Water	1.333	Slight	—	Dissolves many minerals of low index.
Acetone	1.357	—	Slight	—
Ethyl alcohol	1.362	0.00040	Slight	Dissolves many minerals of low index
Ethyl butyrate	1.381	—	Slight	—
Methyl butyrate	1.386	—	Slight	—
Ethyl valerate	1.393	—	Slight	—
Amyl alcohol[5]	1.409	0.00042	Slight	Dissolves many minerals of low index.
Kerosene	1.448	0.00035	Slight	—
Petroleum oil[6]				
Russian alboline	1.470	0.00040	Slight	—
American alboline	1.477	0.00040	Slight	—
Valvolene[7]	1.502	0.00040	Slight	Will not mix with clove oil.
Clove oil	1.531	0.00050	Moderate	Mixes with petroleum oil with difficulty; may be mixed readily with rapeseed oil, index of which is 1.471.
Cinnamon oil[8]	1.585–1.600	0.0003	Strong	—

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[4] *U. S. Geol Survey Bull.* 679, 1921, p. 15.

[5] Ordinary fusel oil may be used instead; it forms a milky emulsion with kerosene, which settles on standing, so that the clear liquid can be decanted off.

[6] Any of the medicinal oils may be used, such as Nujol.

[7] Any clean lubricating oil, such as used in automobiles, may be used.

[8] Less expensive than cinnamic aldehyde, but the index of commercial oil is not definite.

IMMERSION MEDIA AND THEIR PROPERTIES (*Continued*)

Substance	*N at 20° C.*	$\frac{dN}{dT}$	*Dispersion*	*Remarks*
Cinnamic aldehyde	1.615	0.0003	Strong	—
α-Monobromnaphthalene[9]	1.658	0.00048	Moderate	—
Methylene iodide	1.74 ±	0.00070	Rather strong	Expensive, discolors on exposure to light but a bit of Cu or Sn will prevent this change.
Methylene iodide saturated with sulfur.	1.778	—	Rather strong	—
Methylene iodide, sulfur and iodides.[10]	1.868	—	Rather strong	—
Piperine and iodides	1.68–2.10	—	—	—
Phosphorus	2.05			
Sulfur and selenium	2.0–2.7	—	Very strong	—
Selenium and arsenic selenide	2.72–3.17	—	Very strong	—

A set of prepared liquids with a regular difference of index of 0.005 may be obtained from mineral dealers, such as Ward's. This set begins preferably at about 1.440 and continues to 1.740; the liquids above 1.740 change in index so rapidly that only the sulfur-saturated methylene iodide (1.78) is desirable as permanent equipment. Such a set in bottles with ground-glass stoppers elongated as glass rods below and having flat tops is shown conveniently arranged in a substantial tray in Fig. 314.

FIG. 314. Set of index of refraction liquids.

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[9] Mixtures of α-monobromnaphthalene with clove oil give liquids with less dispersion than those with cinnamon oil.

[10] To 100 grams methylene iodide add 35 grams iodoform, 10 grams sulfur, 31 grams tin iodide (SnI_4), 16 grams arsenic iodide (AsI_3), and 8 grams antimony iodide (SbI_3), warm to hasten solution, allow to stand, and filter off undissolved solids. See H. E. Merwin: *Jour. Wash. Acad. Sci.*, III, 1913, p. 35.

A set of liquids convenient for approximate determinations, because preliminary measures of the indices of the liquids are unnecessary, is given below. Most of these are easily obtained. But for precise work the indices of the liquids must be measured, as different lots of the same material in some cases give results varying as much as 0.04.

Index	*Liquid*
1.33	Water
1.36	Ethyl alcohol
1.44	Chloroform
1.47	Glycerine
1.48	Castor oil
1.49	Xylol
1.50	Benzene
1.51	Cedar oil
1.53	Clove oil, or monochlorbenzol
1.54	Fennel oil
1.55	Nitrobenzene,[11] bitter almond oil, or anise oil
1.56	Monobrombenzene
1.59	Bromoform
1.60	Cassia oil
1.62	Monoiodobenzol
1.64	α-Monochlornaphthalene
1.66	α-Monobromnaphthalene
1.70	Cadmium borotungstate
1.74	Methylene iodide[12]
1.78	Methylene iodide saturated with sulfur

Immersion methods can be made much more accurate and useful by taking advantage of the thermal or thermal and chromatic variation in index of liquids, but this requires special apparatus.

Polarization. Ordinary light consists of vibrations in all directions normal to the direction of propagation. The process of resolving these complex vibrations into vibrations in definite planes is called *polarization.* Light may be polarized in several different ways:

Polarization by isotropic substances. When ordinary light, which is vibrating in all directions normal to the direction of propagation, strikes obliquely the surface of an isotropic medium, it is divided into a refracted and a reflected ray, both of which are partly polarized. It seems to be true that those vibrations of the incident light which are most nearly per-

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[11] Alters when exposed to light.

[12] The iodine which separates on exposure to light may be removed with copper.

pendicular to the surface of the medium penetrate it most easily, while those vibrations which are most nearly parallel to the same surface are reflected most abundantly. Also, vibrations of an intermediate position seem to be more or less completely resolved into two components, one vibrating parallel to the surface and being reflected, the other vibrating at right angles to the first and being refracted. The amount of the incident light which is polarized in this way varies with the angle of incidence: it should be none at all for absolutely normal incidence, and it increases to a maximum at that angle of incidence at which the reflected and refracted rays are at right angles. Therefore, at that angle of incidence which gives maximum polarization, $N = \tan i$.

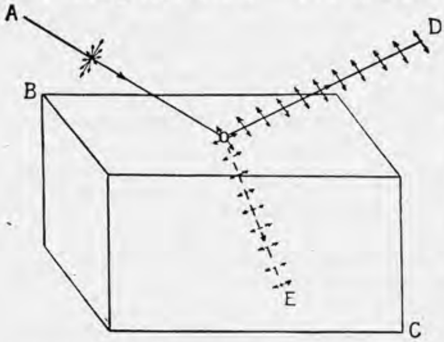

FIG. 315. Polarization by reflection and refraction.

In fig. 315, the incident ray AO is vibrating in all directions normal to the ray; upon striking the surface of the new medium BC at the angle which gives maximum polarization, it is divided into a reflected ray OD, vibrating parallel to the surface and normal to the ray, and a refracted ray OE, vibrating at right angles to the former and normal to the ray.

Polarization by anisotropic substances. The single plane surface of an isotropic substance produces polarization, which is commonly partial, but the innumerable regular layers of atoms of anisotropic substances produce complete polarization both in the reflected and refracted rays, except in a few special cases. In most cases, crystals produce plane polarized light, the position of the planes of vibration having a definite relation to the atomic structure of the substance. In some cases crystals produce circularly polarized or elliptically polarized light. Anisotropic crystals not only polarize the reflected and refracted rays, but they also generally divide the refracted light into two parts traveling at different rates and along different paths, and polarized in planes at right angles to each other. This division of the refracted light into two rays is called double refraction, and the ability of a crystal to separate the two refracted rays is measured by its birefringence. All anisotropic crystals produce double refraction, but only a few have sufficiently strong birefringence to be easily visible to the naked eye.

When a ray of light strikes the surface of an anisotropic crystal obliquely it is, in general, divided into two rays, which vibrate in planes at right angles to each other and travel with different velocities along different paths. For example, if the ray, R, strikes the surface, say of calcite, as in Fig. 316, one ray vibrates in the plane (called the principal section) containing the incident ray and the vertical crystal axis, and the other ray vibrates in the plane at right angles to this and also normal to the refracted ray (more accurately, the wave-normal). This production of two rays from one is called double refraction. It is a characteristic of all crystals except those of the isometric system. The ray vibrating normal to the principal section has a velocity which is constant no matter in what direction in the crystal it vibrates. It is called the *ordinary* or *O ray* since it obeys the ordinary law of refraction. The other is the *extraordinary* or *E ray;* its velocity depends upon its vibration direction, varying from equality with that of the ordinary ray to a maximum difference, either greater or less. The direction along which the two rays travel with the same velocity is known as the *optic axis*. The wave-surface of all the O rays (originating at a point within such a crystal) is a sphere, while that of all the E rays from the same point is an ellipsoid of rotation. If the O ray is a fast ray as compared with the E ray, the ellipsoid is inside the sphere, as in Fig. 317; in this case the mineral is said to be optically positive, or +. If the sphere is inside the ellipsoid, as in Fig. 318, it is negative, or −.

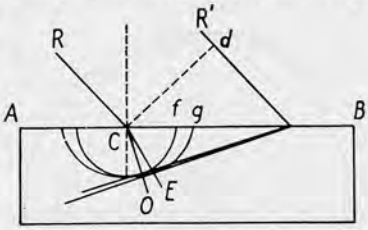

FIG. 316. Effect of a negative uniaxial crystal on light striking a basal plane obliquely, the plane of incidence being parallel to optic axis.

Isoaxial, uniaxial, and biaxial substances. In all isotropic substances, light travels with equal velocity in all directions, so that the wave-surface is a sphere all axes of which are equal; such substances are therefore called *isoaxial*. Those anisotropic crystals in which one part of the light travels with uniform velocity and another part moves with a velocity varying in different directions are called *uniaxial,* since in them there is one "axis," or direction, parallel to which all the light travels with the same velocity. Those bodies in which both parts of the light travel with velocities which vary with the direction are called *biaxial,* because in them there are two "axes," or directions, parallel to which all the light travels with the same velocity.

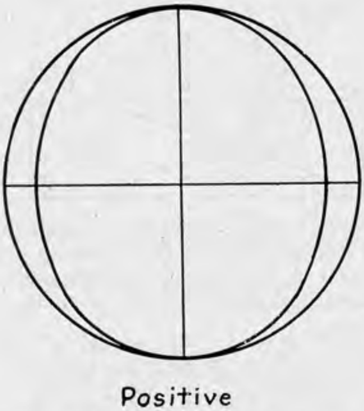

FIG. 317. Wave surface in a positive uniaxial crystal.

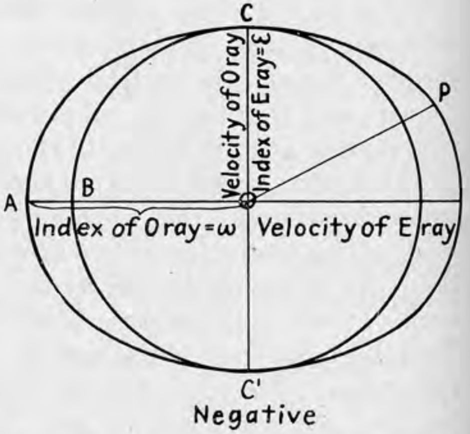

FIG. 318. Wave surface in a negative uniaxial crystal.

Isometric crystals are isoaxial; tetragonal and hexagonal crystals are uniaxial; and other crystals are biaxial. Uniaxial crystals have one principal axis of symmetry, which is the vertical crystallographic axis, parallel to which is the direction called the optic axis.

The index of refraction of a uniaxial crystal for the *E* ray varies with the direction of transmission, from equality with the index for the *O* ray in the direction of the optic axis, to its greatest deviation from this value in the direction normal to the vertical axis. The latter value is always implied when the index is referred to without statement of the direction; it is denoted by N_e, or by the Greek letter epsilon (ϵ). The index for the *O* ray is denoted by N_o, or by the Greek letter omega (ω).

The indices of refraction of two isotropic substances are inversely proportional to the velocities of light in them; also, the two indices of a uniaxial crystal are inversely proportional to the velocities of the two rays in that substance. Therefore, in negative crystals, in which the *E* ray travels faster than the *O* ray, the index of refraction for the *O* ray is more than that for the *E* ray, or $\omega > \epsilon$. In positive crystals, in which the *O* ray travels faster than the *E* ray, the index of refraction for the *O* ray is less than that for the *E* ray, or $\omega < \epsilon$.

Nicol prism. The most important and most distinctive feature of a petrographic microscope is the device for changing ordinary light into light polarized in a single plane. This instrument, called a Nicol prism, or simply a nicol, because it was first constructed and described by William Nicol (in 1828), consists of a cleavage rhombohedron of transparent calcite cut into two parts and then cemented together again with Canada balsam. In its original form the nicol is about three times as long as it is thick, and the natural angle of 70°52′ between the end faces and the obtuse vertical edges is changed by artificial means to 68°—that is, the natural form, *AB′CD′*, is changed to the shape

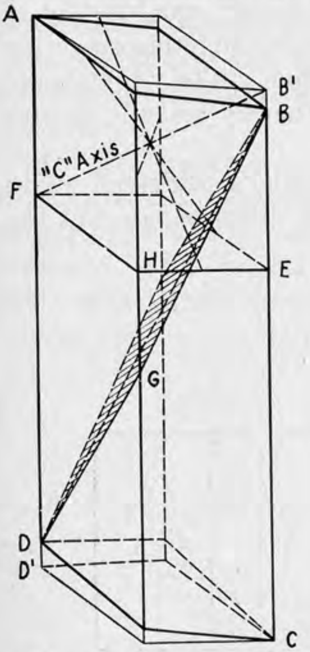

FIG. 319. Nicol prism in perspective.

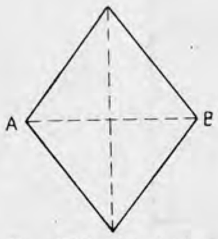

FIG. 320. End view of Nicol prism.

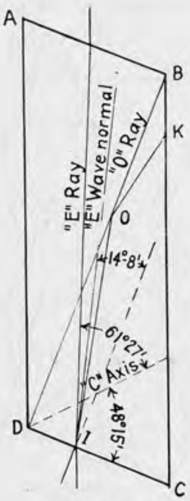

FIG. 321. Vertical section of Nicol prism.

ABCD of Fig. 319. It is then carefully sawed into two parts along the plane *BHDG*, which is perpendicular to the shorter diagonal of the end face. After being polished, the cut faces are cemented together in their original position. The prism faces are then covered by a black coating of some kind, and the nicol is ready for use. The top view of the nicol is given in Fig. 320, in which *AB* is the shorter diagonal.

If a ray of light parallel with the prism edges enters the lower end of the nicol, as in *I* in Fig. 321, it is immediately divided into two rays. The index of refraction of Canada balsam is about 1.54; the index of calcite for the *O* ray is 1.6586; therefore this ray, which strikes the layer of balsam at *O* at an angle of 76° 57′, will be totally reflected to, and absorbed in, the black coating of the prism *K*, since the angle of incidence is greater than the critical angle. The index (ϵ') of calcite for the *E* ray varies with the direction in the crystal, being 1.4864 at right angles to the vertical axis and equal to ω(1.6586) parallel thereto. In the direction taken by the *E* ray from the incident light mentioned, the index of calcite is 1.534, which is so nearly equal to that of balsam that the extraordinary ray passes through the cementing layer with practically no change in direction. The vibrations in the *E* ray are in the plane containing the ray and the shorter diagonal of the end face of the prism.

Polarizing prisms are sometimes made in different ways; thus, Ahrens' prism is cut in a different direction, so that the

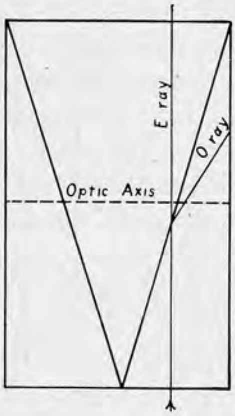

FIG. 322. Vertical section of Ahrens' prism.

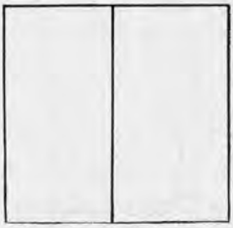

FIG. 323. Base of Ahrens' prism.

cross section becomes a rectangle whose sides are parallel and normal to the vertical crystal axis; such prisms usually have the end faces at right angles to the vertical edges and may be much shorter than Nicol's type in proportion to their width, as illustrated in Figs. 322 and 323. Several other forms are occasionally used. A given microscope may have its two nicols of unlike construction, but the complete polarization of the transmitted light in one plane is accomplished in all cases.

Every petrographic microscope has two such artificial prisms; one is placed below the stage, in the axis of the microscope, and is called the *polarizer;* the other, above the objective, is called the *analyzer.* The essential quality of these nicols consists in their power to eliminate one ray and to allow the passage of the other, vibrating in one plane. They are inserted in their places in such a way that the lower, and sometimes also the upper, can be easily rotated horizontally on its axis. One or both can, without difficulty, be entirely removed from the path of the light.

Interference colors. It is important to understand fully the action of the petrographic microscope upon parallel polarized light. If a section or fragment of the uniaxial mineral is in place between crossed nicols, the light is, in general,

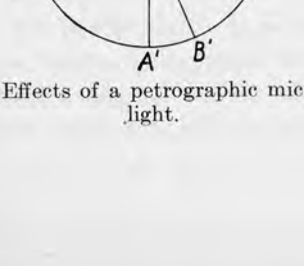

FIG. 324. Effects of a petrographic microscope on light.

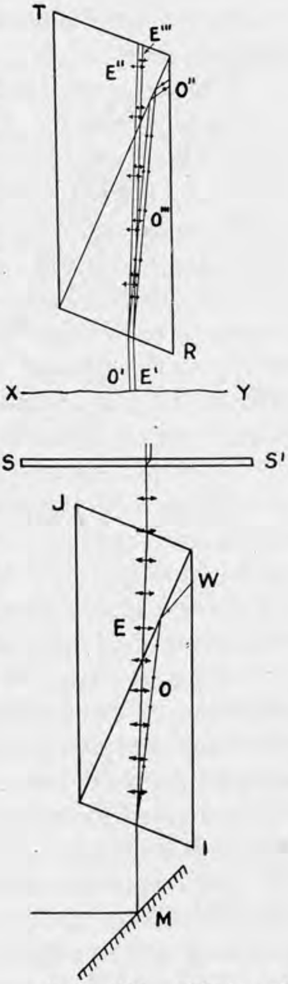

FIG. 325. Effects of a petrographic microscope on light.

doubly refracted and plane polarized three times. These facts are illustrated diagrammatically in the vertical section and plan of Figs. 324 and 325. After reflection from the mirror M, the ray of light enters the lower nicol, IJ, where it is doubly refracted, and completely polarized, one ray (the extraordinary) vibrating in the principal section, which is the plane of the paper in the drawing, and the other ray vibrating normal thereto. The E ray vibrates in the direction PP' of the plan and the O ray in the direction of AA'. The O ray is totally reflected by the Canada balsam to the black surface at W; only the E ray passes through the polarizer.

When the ray strikes an anisotropic mineral section, as SS', cut in an indefinite direction, it is, in general, divided into two rays, which may be called the ordinary (O') and extraordinary (E') rays for this crystal. In the drawing the mineral is supposed to be uniaxial and the O' ray is not refracted, since the incidence is normal. In general, in biaxial crystals, both rays are refracted. The rays O' and E' vibrate in planes at right angles to each other, the E' ray vibrating in the principal optic section of the mineral, which may be assumed to be in the position BB' in the plan, while the O' ray vibrates in the direction CC'. These two rays pass upward to the analyzer RT, where the third double refraction produces two rays from each of them. In the vertical section, the portion above XY is a section at right angles to the lower portion and in the direction AA' in the plan. If DO be taken to represent the vibration of the E ray after passing the polarizer, the two rays, O' and E', produced by the mineral have vibrations that may be represented by OG and FO respectively. In the upper nicol the ordinary ray (O'') derived from O' has a vibration represented by NO, and that (O''') derived from E', a vibration represented by HO. Also the extraordinary ray (E'') derived from O' has a vibration represented by LO, and that (E''') derived from E', a vibration represented by KO. Now the two ordinary rays (O'' and O''') are totally reflected to the dark wall of the upper nicol; therefore their vibrations, NO and HO, disappear. But the two extraordinary rays (E'' and E'''), whose vibrations are represented by LO and KO, pass through the analyzer; and since their vibrations are in the same plane and have a fixed phase relation, they "interfere" or combine. In monochromatic light this interference produces variation in the intensity of the light, depending upon the difference of phase of the two rays. As explained later, if the rays have no difference of phase, or if one is retarded an integral number of wave lengths behind the other, the amplitude of the resultant wave is zero, and darkness results. If the rays have a difference of phase of one-half wave length, or any uneven multiple thereof, the interference doubles the amplitude and also the intensity. In white light, since the different colors constituting the light have different wave lengths, the retardation which one ray suffers has different relations to the different colors, causing some to be in opposite phase and others to differ by an integral number of wave lengths; therefore, interference reduces the intensity of some colors (even to zero, as a limit), while increasing the intensity of others; thus, interference produces colors from white light. The color produced depends upon the difference of phase, or the relative retardation, and this in turn depends upon the birefringence of the mineral concerned, the direction in which the light travels through the crystal with respect to the optic axis (or optic axes), and the thickness of the section or fragment.

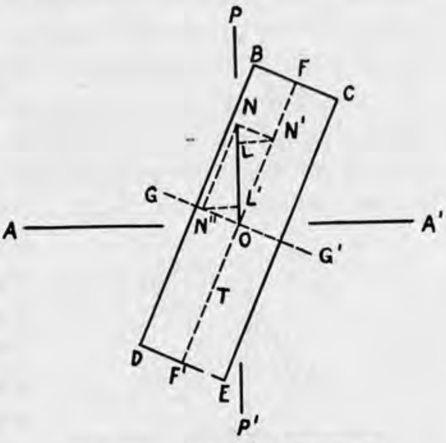

Fig. 326. Vibration directions.

In the simple combination of two light waves (without the microscope), darkness results when the phase difference is half a wave length, but when monochromatic light passes through crossed nicols and through a crystal plate between them, darkness results when the phase difference produced by the crystal is one wave length. This fact needs explanation. In Fig. 326 let PP' represent the plane of vibration of light which passes through the lower nicol or polarizer. Upon entering a crystal section $BCDE$, whose planes of vibration are FF' and GG', the vibration of a particle at O, which may be assumed to be at its crest at N, is resolved into two components, ON' and ON''. If these two waves pass through the crystal so as to have, at emergence, no difference of phase, or a difference of phase of any integral number of wave lengths, the wave ON'' will be at its crest N'' when the wave ON' is at its crest, N'. If, in passing through the crystal, they acquire a difference of phase of half a wave length, or any uneven multiple thereof, the wave ON'' will be at N'' when the wave ON' is at its trough, T.

Whatever the difference of phase which results from the difference in path and difference in velocity of the two waves in the crystal, when they enter the upper nicol, whose vibration plane is AA', each will be resolved into two components one of which, in the plane PP', will be totally reflected and absorbed in the walls of the analyzer, while the other, in the plane AA', will pass through the upper nicol. If they have a difference of phase of one wave length, the components which will be absorbed may be represented by OL and OL'. The more important components which pass through the analyzer are shown in Fig. 327 at OX and OY, which will be their positions if the phase difference is any integral number of wave lengths. It is clear that OX and OY are equal and opposite in direction; therefore these two waves will destroy each other and darkness will result if monochromatic light is being used. Also, if the difference of phase is half a wave length (or an uneven multiple thereof), when the wave vibrating in the plane GG' is at N'' the wave vibrating in the plane FF' will be at T, and the components of these waves vibrating in the plane AA' will be two waves (each OX) of equal amplitude and acting in the same direction; therefore the resultant wave will have double the amplitude.

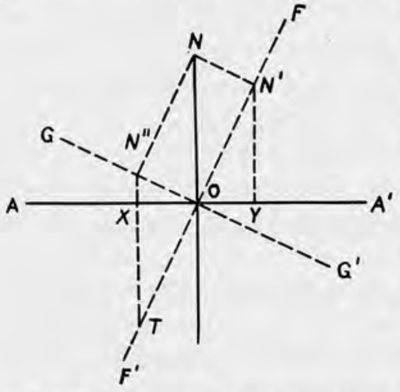

FIG. 327. Vibrations in the analyzer.

Wherever the difference of phase is neither a wave length nor a half wave length (nor a multiple thereof), the components in the plane AA' will be unequal, and the resultant will always have some amplitude varying between the limits named.

The difference of phase produced by any crystal depends upon the difference in velocity and the difference in path of the two waves within the crystal, and the latter varies with the thickness of the section (or fragment). Accordingly, a wedge-shaped section of a crystal will produce a difference of phase varying from zero at the thin edge to any desired amount at the other end. Hence, a wedge will alternately produce darkness or light upon its gradual insertion between crossed nicols, when monochromatic light is used. In Fig. 328, the relation between the thickness of the wedge and the difference in phase is shown; the difference in phase, *D*, is expressed in terms of fractions of the wave length, λ, of the light used. The thickness necessary to produce a given difference in phase varies with the mineral used, and also depends upon the way in which the wedge is cut, that is, the relation in position between the path of the light and the optic axis in the wedge.

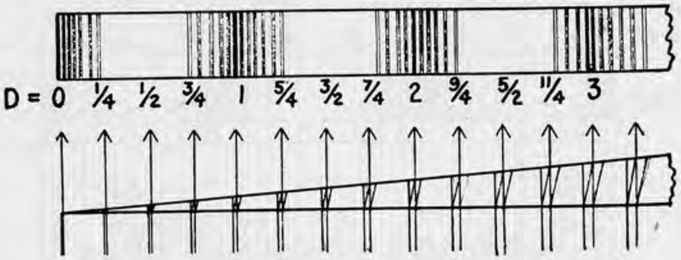

Fig. 328. A wedge between crossed nicols.

When white light is used, the difference of phase must be measured in some other unit than the wave length, because the white light has no definite wave length, but consists of waves whose length varies from about 380 to about 760 millionths of a millimeter, sometimes expressed as 380 to 760 millimicrons, or 380 to 760 mμ. In Fig. 329 the difference of phase, *D*, is given in millionths of a millimeter. The same figure shows the effect of any difference of phase from 0 to 2000 mμ on various kinds of monochromatic light. For each color a medium value of the wave length is chosen as follows: violet, 410mμ; blue, 460mμ; green, 510 mμ; yellow, 565 mμ; orange, 620 mμ; red, 690 mμ. When white light is used, the effect produced depends upon the relation of the difference of phase to the wave lengths of all parts of the white light; all these parts are approximately represented by the colors selected. Accordingly, the effect may be inferred by a study of the upper part of Fig. 329. It is modified somewhat by the fact that the intensity of various parts of the spectrum varies considerably, being greatest for yellow and

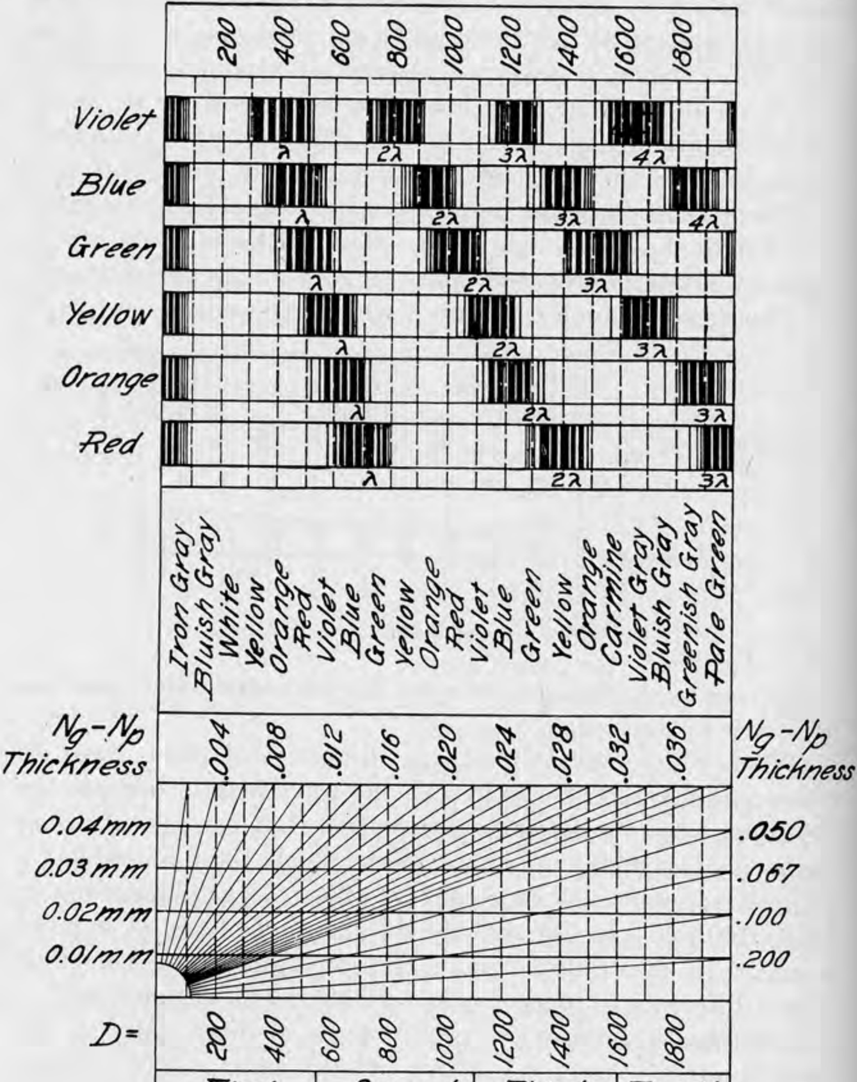

FIG. 329. Derivation of Newton's color scale.

least for violet. With no difference of phase, all parts of white light destroy each other in the upper nicol, as illustrated in

Fig. 327, and darkness results. From Figs. 327 and 329 it is clear that the intensity of the light increases as the difference of phase increases; accordingly, as D varies from 0 to 260 mμ, the effect varies from darkness to white light. At 300 mμ yellow light is produced, since yellow is near its maximum ($\frac{1}{2}\lambda$ for yellow) and violet is partly destroyed. At 400 mμ violet is wholly destroyed and blue and green are much weakened; yellow is considerably past its maximum, but on account of its greater relative intensity it dominates over red. For the same reason orange is found at 450 mμ and red at 530 mμ. At 575 mμ violet is produced, since green, yellow, and orange are practically destroyed, and the red and blue simply combine to increase the intensity of violet.

The interference color produced by any crystal plate depends upon three factors, namely, (1) the birefringence of the mineral, (2) the thickness of the plate, and (3) the direction of the plate with respect to the optic axis (or optic axes).

Determination of order of interference color. Any given color, except gray at the lower end of the first order, is found at least twice in the color scale, but only once in any single order. The precise shade of a color, say red, in one order is not exactly the same as in another order, but this difference is not sufficient to enable the order to be distinguished, especially by the beginner. There are two methods of determining the order to which a color belongs; one is by means of the quartz wedge, the other is by means of a beveled edge.

The quartz wedge is a wedge-shaped plate of quartz, as shown in Fig. 328, cut with its vertical axis parallel with the glass plates between which it is mounted. It is usually marked "quartz wedge," or "compensator"; the arrow at one end indicates the direction of vibration of the slow ray. When the quartz wedge is to be used to determine the order of an interference color, the mineral producing the color should be turned to a position at 45° from extinction, and the wedge should be inserted, thin edge forward, in the path of the light above the mineral. This will cause a series of changes in the interference color observed, owing to an increase or a decrease in the retardation produced by the mineral. It is convenient to call the ray which is more retarded in any anisotropic substance the slow ray, or the Z ray, in that medium, and to call the other ray the fast ray, or the X ray. If the slow ray in the mineral is the slow ray in the wedge, the colors observed will be in the order obtained by reading the colors of Newton's scale (Fig. 329) from left to right, and the colors are said to "rise," since they pass to higher orders. If the slow ray in the mineral is the fast ray in the wedge, the colors obtained will be in the reverse order. If the first result is secured, the stage should be turned 90°; then the insertion of the wedge as before will give the second result. When this is obtained the wedge should be inserted far enough to cause the colors to "fall" to the dark gray at the lower end of the first order. Since this color occurs in only one place in the scale the order to which it belongs is not in question. To obtain the order of any other interference color it is only necessary to find its relation to this dark gray.

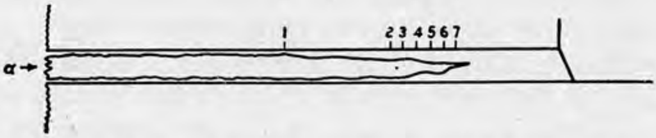

FIG. 330. Magnified section through a mounted mineral section.

The beveled edge, when present, is a simpler means of determining the order of an interference color. It can be used only when the mineral under examination has, somewhere along its border, an edge (in contact with balsam or a substance of weak birefringence) sufficiently beveled to produce a series of colors similar to those caused by an artificial wedge. It is only necessary to observe the relation between dark gray of the first order and the interference color produced by the full thickness of the mineral, as shown by the series of colors between them on the beveled edge, to determine the order to which the given color belongs. For example, if the mineral, *a*, in Fig. 330, gives a yellow interference color over the surface where it is of full thickness, as at 1, and if it produces a series of colors on a beveled edge that are as follows: 2, green; 3, blue; 4, red; 5, yellow; 6, white; 7, dark gray, the yellow interference color found over the main surface belongs to the second order. Frequently, the beveled edge is very narrow, so that it is impossible to distinguish all the colors; but, since red is the highest color of each order, if a single red band can be seen on the bevel, the color of the main surface is of the second order (or higher).

Measurement of birefringence. The birefringence of a mineral is always measured by the difference between its greatest and least indices of refraction, that is, with uniaxial minerals, the difference between ω and ϵ. The extraordinary ray has the index ϵ only when it is traveling at right angles to the vertical or optic axis. When propagated in any other direction it has an index, ϵ', nearer to ω than ϵ is. Therefore, a section of a uniaxial mineral must be parallel to the optic axis in order that the indices of refraction for light passing through normal to the surfaces may be ω and ϵ. The birefringence of a given crystal or grain, as cut in a section, is less than the birefringence of the mineral of which it is a sample, except when the given crystal or grain is cut parallel with its optic axis (or, in biaxial crystals, parallel to both optic axes), and with the same exception it is measured by the difference between ω and ϵ', which is always less than the difference between ω and ϵ.

The difference between the two indices, ω and ϵ, may be determined by accurate measures of those indices themselves, or it may be estimated from its effect in producing an interference color.

Determination of fast and slow rays. If a plate in which the direction of vibration of the slow ray is known is superposed over a section so that the vibration planes coincide, the interference color rises, provided the plane of vibration of the slow ray in the section is parallel with the plane of vibration of the slow ray in the plate, so that the same ray which is retarded in the section is further retarded in the plate. The interference color falls, provided the plane of vibration of the slow ray in the section is parallel with that of the fast ray in the plate, so that the ray which is retarded in the section is advanced in the plate. Consequently, by properly superposing such a plate over any mineral section, the position of the plane of vibration of the slow ray can be distinguished from that of the fast ray. This may be accomplished by means of: first, the quarter undulation mica plate; second, the sensitive tint plate; or third, the quartz wedge. In all these plates the arrow marks the position of the plane of vibration of the slow ray. The mica plate consists of a thin cleavage film of colorless mica of such thickness as to produce a retardation of a quarter of a wave-length of yellow (sodium) light, that is, about 150 mμ. It is usually mounted between glass plates and marked "mica" or $\frac{1}{4}\lambda$. Except with crystals producing very low or very high interference colors the mica plate is very convenient. For crystals giving very low interference colors the sensitive plate is most useful, while for those exhibiting very high interference colors the quartz wedge must be used. These plates are sometimes mounted with their vibration planes parallel with one edge of the glass plate and sometimes with their vibration planes at 45° with the edges, but in all cases they must be used with their vibration planes not parallel with the planes of the nicols.

If a plate or section of a crystal (which is not isometric) is examined between crossed nicols in parallel light, it is isotropic and dark in all positions of rotation of the stage, or it is anisotropic, and changes from "extinction" (or dark) at 0°, 90°, 180°, 270°, and 360° to some interference color at other positions. In either case, if a condenser is introduced below the stage so as to produce convergent light (preferably using a high power objective) and the ocular of the microscope is removed, the mineral is no longer visible. Instead there can be seen a telescopic image of the source of light showing the effect of the crystal plate upon all parts of the convergent beam of light passing through it. Such an image is called an interference figure.

Interference figures. A plate or section parallel with the basal pinacoid, and so normal to the optic axis of a uniaxial mineral, produces a characteristic interference figure (see Fig. 331). In monochromatic light this figure consists of a dark cross and concentric dark circles. In white light it consists of a dark cross and concentric color curves. The dark cross is called the isogyre and the others are the isochromatic curves. The color curves are produced by interference, just as the color bands of the quartz wedge are produced. The isogyres are the locus of all points at which the transmitted rays have zero amplitude of vibration.

A plate or section parallel with the vertical (and optic) axis of a uniaxial mineral produces a very different interference figure.

In it the isogyres are visible only at and very near the extinction position; they are broad and poorly defined; they move rapidly as the section is rotated; at extinction they form a dark cross filling much of the field. The color curves are not circular but nearly hyperbolic, and arranged in four quadrants, as in Fig. 332. In some cases only the central portion of this figure is visible. Two opposite quadrants have a lower interference color than the center of the field; the optic axis is in these quadrants.

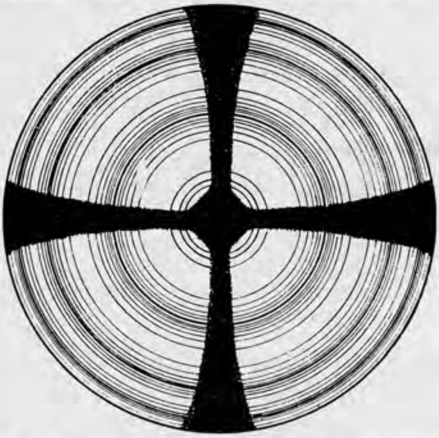

FIG. 331. Explanation of a uniaxial interference figure.

A plate or section neither normal to nor parallel with the optic axis of a uniaxial mineral produces an uncentered interference figure more or less resembling that from a basal section. In this case the whole figure rotates about the center of the field of view as the stage is rotated, but the isogyres are constantly parallel (or nearly parallel) with the planes of the nicols.

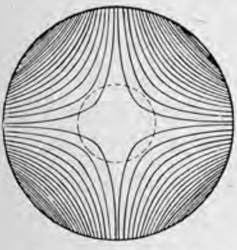

FIG. 332. Interference figure from a vertical section of calcite at 45° with nicols in monochromatic light.

Optic sign. The optical sign of uniaxial minerals can be determined conveniently from basal plates by superposing a mica plate, sensitive tint (or gypsum) plate, or quartz wedge over the interference figure. When a mica plate is used, the isogyres are replaced by a grayish white cross and two dark spots appear in opposite quadrants, as in Figs. 333 and 334. In the case illustrated the mineral has a negative sign; with a positive mineral the dark spots appear in the other two quadrants. It is very easy to remember how to interpret the effect of the mica plate when it is noticed that a line connecting the two dark spots makes a plus sign with the arrow on the plate when the mineral is positive and a minus sign when it is negative. In case a sensitive-tint plate is used, the dark cross is changed to a cross of violet, and the color between the arms and close to the cross falls from the sensitive tint to yellow in two quadrants, and rises to blue in the other two. It should be noticed that the yellow quadrants correspond to the dark spots produced by the mica plate, and may be used in the same way to deduce the sign of the mineral. Finally, if the quartz wedge is used, the color curves move toward the center in two quadrants, and away from it in the other two, as the wedge is gradually inserted, thin edge forward. Those quadrants in which the color curves move away from the optic axis correspond to the quadrants in which the dark spots appear when the mica plate is used, and may be used in the same way to obtain the sign of the mineral.


FIG. 333.

FIG. 334.

Determination of sign of a negative uniaxial mineral.

Orthorhombic, monoclinic, and triclinic crystals are biaxial, that is, they have two axes or directions along which all light travels with the same velocity. The bisector of the acute angle between these two directions is called the acute bisectrix Bx_a, and that of the obtuse angle is called the obtuse bisectrix Bx_o. These are the vibration directions of the rays traveling with the greatest and least velocities. The plane including these two optic axes and two bisectrices is called the plane of the optic axes, or, simply, the optic plane. The direction normal to this plane is that of the optic normal (Y). The direction of the acute bisectrix may be that of the slow ray, Z, or the fast ray, X; that of the obtuse bisectrix is then X or Z. The directions X, Y, and Z coincide with the crystal axes in orthorhombic crystals, but X, Y, or Z may coincide with a, or b, or c. In monoclinic crystals X or Y or Z must coincide with b, but no definitely named optical directions coincide with a or c, except by chance. In triclinic crystals there is no definite relationship in position between the axes X, Y, Z and a, b, c. The axes X, Y, and Z are exactly at right angles to each other in all cases. Crystals are said to be optically positive when Z is in the acute bisectrix and negative when X occupies this position. The slow ray, Z, has an index of refraction which is designated as N_g (the *greatest* index); the fast ray, X, has an index N_p (the *petty* index); the intermediate ray, Y, has an index N_m (the *medium* index).[13]

The acute angle between the two optic axes A and B is called the optic angle and is designated by $2V$. The angle between the optic axes is closely related to the three indices of refraction; indeed, as a close approximation:

Positive Crystals	*Negative Crystals*
$\tan V = \sqrt{\dfrac{N_m - N_p}{N_g - N_m}}$	$\tan V = \sqrt{\dfrac{N_g - N_m}{N_m - N_p}}$
$\sin^2 = \dfrac{N_m - N_p}{N_g - N_p}$	$\sin^2 V = \dfrac{N_g - N_m}{N_g - N_p}$

In biaxial crystals the amount and kind of light absorbed may vary along the three axes X, Y, Z. Accordingly, a mineral such as hornblende may absorb more light vibrating along Z than along Y, and more along Y than along X; very briefly this is expressed as: $X < Y < Z$. Also, the color of the unabsorbed light may be different for the different vibration directions, and this may be expressed as follows: X = clear yellow, Y = dark brown, Z = dark brownish green.

When the vibration directions of the mineral are parallel with the vibration planes of the nicols, the mineral is dark, or at extinction. The angle between this position and the direction of the trace of some crystal face or cleavage or twinning plane is called the extinction angle. In orthorhombic crystals the extinction is parallel with pinacoidal faces or cleavages in all plates or sections parallel with any crystal axis. It is symmetrical with respect to prismatic faces or cleavages in any plate or section parallel with a or with b. In monoclinic crystals the extinction is inclined with respect to pinacoidal or prismatic faces or cleavages except in plates or sections parallel with b. In triclinic crystals the extinction is inclined (except by mere chance) in all plates and sections.

Plates or sections of biaxial minerals normal to an optic axis produce an interference figure distinctly different from that produced by a basal plate of a uniaxial mineral. The chief difference is that the biaxial interference figure has a single line,

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[13] Some writers use γ for N_g, β for N_m, and α for N_p.

instead of a cross, as its isogyre. The isogyre is straight and parallel with one of the planes of the nicols in one position; it becomes curved and rotates clockwise when the stage is rotated anticlockwise, as shown in Figs. 335–337. A plate normal to the acute bisectrix produces an interference figure showing two optic axis figures, if the optic angle is not too large. It, thus, consists of two isogyres, which meet to form a cross each 90° of rotation. If the birefringence is strong, or the plate is thick, there are also color curves which may be nearly circular near the optic axes, but in general form symmetrical curves known as “Cassinian ovals,” as shown in Figs. 338–340. Obtuse bisectrix interference figures are similar except that the optic axis figures are not visible, being outside the field of view. A plate normal to Y, and therefore parallel with both optic axes, produces an interference figure very similar to that produced by a plate parallel to the optic axis of a uniaxial mineral. A plate inclined to all the chief optical directions of a biaxial mineral produces an uncentered interference figure whose isogyre may be curved and not parallel with either nicol when it passes through the center of the field of view. Such a condition proves that the mineral is

Fig. 335. Fig. 336. Fig. 337.

Figs. 335–336–337. Optic axis interference figure of a biaxial mineral.

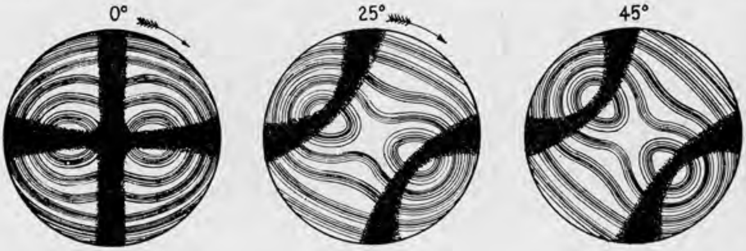

Fig. 338. Fig. 339. Fig. 340.

Figs. 338–339–340. Acute bisectrix interference figure of a biaxial mineral.

biaxial, but its absence does not prove that the mineral is uniaxial.

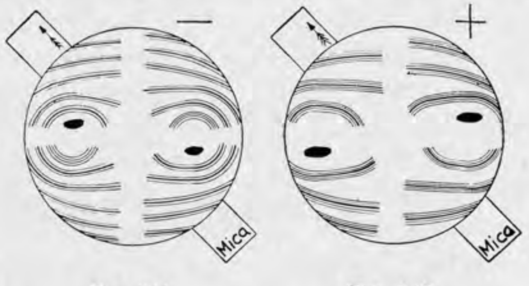

Fig. 341. Fig. 342.

Figs. 341–342. Determination of sign from the acute bisectrix interference figure.

If the optic angle is rather small, the optic sign of a biaxial mineral may be determined from the acute bisectrix interference figure in about the same way as that of a uniaxial mineral. Thus, a mica plate will produce two dark spots, as shown in Figs. 341 and 342; and a line joining the centers of the quadrants in which these spots lie makes a plus or minus sign with the arrow marking the slow ray of the plate according as the mineral is positive or negative.

Summary. Crystals, plates, sections, and fragments between crossed nicols:

REMAIN DARK THROUGH 360°

1. And give no interference figure in convergent light	Isotropic; have only one index, N	A. Have no regular form, structure or cleavage	Amorphous	
		B. Show regular form, structure or cleavage	Isometric	
2. Give optic axis interference figure in convergent light	Anisotropic	A. Uniaxial, two indices: N_o and N_e	Tetragonal Hexagonal	Positive if $N_o < N_e$ Negative if $N_o > N_e$
		B. Biaxial, three indices: N_g, N_m, N_p	Orthorhombic Monoclinic Triclinic	Positive, if $N_g - N_m > N_m - N_p$ Negative if $N_g - N_m < N_m - N_p$

REMAIN LIGHT THROUGH 360°

Anisotropic	1. Single crystals—normal to optic axis and have extreme birefringence or dispersion
	2. Aggregates—more than one substance in the thickness of the section

ALTERNATELY LIGHT AND DARK FOUR TIMES IN 360°

Anisotropic	1. Uniaxial, two indices: N_o and N_e		Tetragonal Hexagonal	Positive, if $N_o < N_e$ Negative, if $N_o > N_e$
	2. Biaxial, three indices: N_g, N_m, N_p	Common parallel or symmetrical extinction	Orthorhombic	Positive if $N_g - N_m > N_m - N_p$ Negative if $N_g - N_m < N_m - N_p$
		Both parallel and inclined extinction in plates ∥c	Monoclinic	
		Parallel extinction only by chance	Triclinic	

4

Chemical Mineralogy

A knowledge of the chemical composition of minerals is indispensable in their study since the very nature of a mineral and all its properties depend in large measure (but not wholly) upon its composition. Many minerals can be identified by means of their physical characters, but to complete the gradual process of determining unknown minerals by elimination, the use of both chemical and physical tests is often necessary. Accordingly, the proper study of minerals must include a study of their chemical nature. As a guide in such work this chapter will include a brief outline of some features of chemistry and a description of methods of testing minerals to learn the main facts as to their composition.

Elementary Concepts

An *element* is a substance which cannot be decomposed, or separated into unlike parts, by any process of chemical analysis; about ninety elements are now known, such as iron, gold, copper, oxygen, hydrogen, carbon, and so on. Most of these are given with their symbols, atomic weights, and atomic domains in the table on page 183.

An *atom* is the smallest portion of an element which can enter into combinations; each element is believed to have an atom of definite and characteristic weight,[1] and of nearly definite domain (for any fixed valence) in oxygen salts and halides. The atomic domain is the space required by the atom in a crystal structure. With rare exceptions an atom cannot exist alone (more than momentarily), but forms a regular crystal structure with other atoms, or combines with other atoms to form molecules (in fluids).

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[1] Disregarding isotopes, which are not important in minerals.

A *molecule* is the smallest portion of any substance which can exist alone. The symbol of an element is the initial letter (or letters) of its Latin name, by which it is represented in chemical notation. This symbol, as O for oxygen, Al for aluminum, and Fe for iron (Latin, *ferrum*) stands not merely for the element, but for a definite amount of the element, namely, one atom. In order to express more than one atom the appropriate number is written as a subscript after the symbol, thus: Al_3 means three atoms of aluminum, and Al_2O_3 means a molecule consisting of two atoms of aluminum and three atoms of oxygen. From the atomic weights of aluminum and oxygen (given in the table below) it is evident that the compound consists of 54 parts, by weight, of aluminum and 48 parts, by weight, of oxygen. An expression such as Al_2O_3 is known as a chemical *formula*.

The following table gives an alphabetical list of most of the elements with their symbols, atomic weights and radii of their

ALPHABETICAL LIST OF CHEMICAL ELEMENTS

Name	Symbol	Atom. Wt.	Valence	Atomic Domain	Name	Symbol	Atom. Wt.	Valence	Atomic Domain
Aluminum	Al	27.0	+3	0.55	Molybdenum	Mo	96.0	+6	0.62
Antimony	Sb	121.8	+5	0.62	Nickel	Ni	58.7	+2	0.74
Arsenic	As	74.9	+5	0.47	Nitrogen	N	14.0		
Barium	Ba	137.4	+2	1.43	Oxygen	O	16.0	−2	1.40
Beryllium	Be	9.1	+2	0.34	Palladium	Pd	106.7		
Bismuth	Bi	209.0	+5	0.74	Phosphorus	P	31.0	−5	0.34
Boron	B	10.8	+3	0.20	Platinum	Pt	195.2		
Bromine	Br	79.9	−1	1.95	Potassium	K	39.1	+1	1.33
Cadmium	Cd	112.4	+2	1.03	Rhodium	Rh	102.9		
Caesium	Cs	132.9	+1	1.65	Rubidium	Rb	85.5	+1	1.49
Calcium	Ca	40.1	+2	1.06	Ruthenium	Ru	101.7		
Carbon	C	12.0	+4	0.15	Scandium	Sc	45.1		
Cerium	Ce	140.1	+3	1.10	Selenium	Se	79.0	−2	1.91
Chlorine	Cl	35.5	−1	1.81	Silicon	Si	28.1	+4	0.41
Chromium	Cr	52.0	+3	0.64	Silver	Ag	107.9	+1	1.13
Cobalt	Co	59.0	+2	0.82	Sodium	Na	23.0	+1	0.98
Copper	Cu	63.6	+1	0.96	Strontium	Sr	87.6	+2	1.27
Erbium	Er	167.2			Sulfur	S	32.1	−2	1.74
Fluorine	F	19.0	−1	1.36	Tantalum	Ta	180.9		
Gold	Au	197.2	+1	1.37	Tellurium	Te	127.6	−2	2.12
Hydrogen	H	1.0	−1	2.08	Thallium	Tl	204.4	+1	1.50
Iodine	I	126.9	−1	2.20	Thorium	Th	232.1	+4	1.10
Iridium	Ir	193.1			Tin	Sn	118.7	+4	0.71
Iron	Fe	55.8	+2 +3	0.80 0.61	Titanium	Ti	47.9	+2 +4	0.76 0.68
Lanthanum	La	138.9	+3	1.15	Tungsten	W	183.9	+4	0.68
Lead	Pb	207.2	+2	1.32	Uranium	U	238.1	+4	1.05
Lithium	Li	6.9	+1	0.78	Vanadium	V	51.0	+4	1.05
Magnesium	Mg	24.3	+2	0.75	Yttrium	Y	88.9	+3	0.93
Manganese	Mn	54.9	+2	0.91	Zinc	Zn	65.4	+2	0.83
			+3	0.70	Zirconium	Zr	91.2	+4	0.80
Mercury	Hg	200.6	+2	1.12					

atomic domains,[2] in Ångstrom units (in oxygen salts and halides) for the valence specified. The atomic (or often, the ionic) domain is the space necessary for the presence of the atom (or ion) in a crystal structure. Certain radicals sometimes take the place of atoms in crystal structures; these are NH_4, with a radius almost the same as that of rubidium, and OH, with a radius about the same as that of oxygen.

The relative abundance of the different elements in the earth's crust is extremely different; thus, two elements (oxygen and silicon) make up more than 70 per cent of the crust (by weight), and aluminum, iron, calcium, magnesium, sodium and potassium are the only other elements which exceed one per cent. These elements together with titanium, hydrogen, phosphorus, carbon, manganese, sulfur, chlorine, barium, fluorine, and strontium make up 99.5 per cent of the crust. All the other elements (totaling about seventy) make up no more than 0.5 per cent, even though they include such important elements as gold, silver, copper, lead, zinc, tin, platinum, mercury, nickel, antimony, arsenic, bismuth, and nitrogen.

Elements are classified as *metals* and *nonmetals*, certain ones of intermediate characters being called *semimetals*. A metal possesses more or less completely the physical properties of opacity to light, metallic luster, malleability, and conductivity for heat and electricity. It is the positive, or basic, element in simple compounds. The nonmetals have none of these physical characters and are negative or acidic in chemical compounds. In writing chemical formulas it is customary to express the basic elements first.

The relations of the elements to one another are best understood from a study of the periodic classification, which is shown on page 185.

The *valence* of an element is measured by the capacity of an atom of the element to combine with atoms of some standard unit element, like hydrogen or chlorine. For example, the valence of sodium is one, since one atom of it combines with one atom of chlorine in ordinary salt, NaCl. Similarly, the formula $CaCl_2$ shows that the valence of calcium is two; H_2O shows that

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[2] Sizes of atomic domains are only approximately known, but they are important in understanding what elements can "proxy" for others in crystal structures.

THE PERIODIC CLASSIFICATION OF THE ELEMENTS

Period	Group 0	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8
1		Hydrogen H							
2	Helium He	Lithium Li	Beryllium Be	Boron B	Carbon C	Nitrogen N	Oxygen O	Fluorine F	
3	Neon Ne	Sodium Na	Magnesium Mg	Aluminum Al	Silicon Si	Phosphorus P	Sulfur S	Chlorine Cl	
4	Argon A	Potassium K	Calcium Ca	Scandium Sc	Titanium Ti	Vanadium V	Chromium Cr	Manganese Mn	Iron, Fe Cobalt, Co Nickel, Ni
5		Copper Cu	Zinc Zn	Gallium Ga	Germanium Ge	Arsenic As	Selenium Se	Bromine Br	
6	Krypton Kr	Rubidium Rb	Strontium Sr	Yttrium Y	Zirconium Zr	Columbium Cb	Molybdenum Mo	—	Ruthenium, Ru Rhodium, Rh Palladium, Pd
7		Silver Ag	Cadmium Cd	Indium In	Tin Sn	Antimony Sb	Tellurium Te	Iodine I	
8	Xenon X	Caesium Cs	Barium Ba	Lanthanum La					
					Lanthanides				
		Cerium Ce	Praseodymium Pr	Neodymium Nd	—	Samarium Sm	Europium Eu	Gadolinium Gd	
		Terbium Tb	Dysprosium Dy	Holmium Ho	Erbium Er	Thulium Tm	Ytterbium Yb	Lutecium Lu	
					Hafnium Hf	Tantalum Ta	Tungsten W	Rhenium Re	Osmium, Os Iridium, Ir Platinum, Pt
9		Gold Au	Mercury Hg	Thallium Tl	Lead Pb	Bismuth Bi	Polonium Po		
10	Radon Rn		Radium Ra		Thorium Th	Protactinium Pa	Uranium U		

the valence of oxygen is two; $AuCl_3$ shows that gold is trivalent; and $SnCl_4$ shows that tin is tetravalent. Some elements have more than one possible valence; thus, iron is divalent in FeO and trivalent in Fe_2O_3.

An *acid* is a compound of hydrogen or hydroxyl with a nonmetallic element or a radical containing such an element. A *base* is a compound of a metallic element (or radical) and hydroxyl. A *salt* is formed when the hydrogen of an acid is replaced by a metal; if all the hydrogen is replaced the salt is *normal;* if only a part is replaced the salt is *acidic;* if part of the acid radical is replaced by hydroxyl the salt is *basic.*

Hydrogen in minerals

Hydrogen, which upon chemical analysis of minerals is obtained in water, exists in them in various ways.[3] It occupies the place of a base in a few acid salts, like misenite, $HKSO_4$, and pharmacolite, $HCaAsO_4 + 2H_2O$. Much more commonly it is in combination with oxygen in the form of hydroxyl, and in that form replaces part of the acid so as to make a basic salt, as in malachite, $Cu_2(OH)_2CO_3$, and wavellite, $Al_3(OH)_3(PO_4)_2 + 4\frac{1}{2}H_2O$. In a few minerals hydroxyl is present to the entire exclusion of an acid; such minerals are hydroxides, as brucite, $Mg(OH)_2$, and hydrargillite, $Al(OH)_3$. In rare cases hydroxyl is present without a base, as in sassolite, $B(OH)_3$ or H_3BO_3, which is boric acid.

In all the preceding cases the minerals break up on analysis so as to yield water although the water molecule is probably not present as such in the original material. In other minerals, hydrogen is believed to be present in the molecule, H_2O. The water molecule is present in minerals either as "water of crystallization," or as "zeolitic water." Water of crystallization is clearly in some kind of chemical combination with the other constituents present, and the expulsion of the water (with the destruction of the crystal structure) occurs at a definite temperature with absorption of heat. But the exact mode of combination is not understood; it does not seem to be the same as the combination of the other constituents in most compounds, and

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[3] It probably occurs in a very small amount as the gaseous element either mechanically enclosed or in solution in certain minerals especially about volcanoes.

therefore the formula of the mineral is so written as to indicate a special mode of union. Thus gypsum, $CaSO_4 + 2H_2O$, contains two molecules of water of crystallization, three fourths of which may be expelled at about 130°C., and the remainder at about 165°C. The substance is abruptly changed in all its properties when it loses its water.

"Zeolitic water" is found in various minerals, but is most conspicuous and abundant in the zeolites. Such water is not present as part of a definite chemical compound, but is probably "in solution" (adsorbed?) in some crystallized compounds. It may be wholly expelled without destroying the crystal or radically altering its properties. The amount present is indefinite, depending upon the temperature and vapor pressure. It is not expelled at a definite temperature, but through a wide temperature range. The crystal upon cooling will take up water again, if it is in contact with water or water vapor. In the absence of water the crystal will take up (on cooling) almost any liquid or gas, even ordinary air. The crystal commonly absorbs many times its own volume of the fluid dissolved.

That this "solution" is a kind of chemical combination is indicated by the further fact that after a crystal has taken up some other fluid it will expel that fluid and absorb water if it is brought in contact with the latter.

Finally, more or less water is present in the pores of many minerals. Such "hygroscopic water" is clearly not an essential part of the mineral in any sense.

Calculation of formulas

Some minerals are practically pure simple chemical compounds, but many minerals are complicated compounds. Formulas for the simple compounds are derived in exactly the same way as those for artificial compounds; for example, an analysis of pyrargyrite from Andreasberg by Prior[4] led to:

Element	*Analysis Weight %*	*Atomic Weights*	*Relative Number of Atoms*	*Atomic Ratios*		
Silver Ag.	59.75	107.9	554	3.011	=	3
Antimony Sb.	22.45	121.8	184	1.000	=	1 approx.
Sulfur S.	17.81	32.1	555	3.016	=	3
	100.01					

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[4] G. T. Prior: *Min. Mag.* VIII, 94 (1888).

Therefore the formula is: Ag_3SbS_3

If the analysis is of an oxygen salt, the results are given in terms of various oxides, but the method is the same; for example, Rammelsberg[5] analyzed a sample of prehnite with the following results:

	Analysis Weight %	*Molecular Weights*	*Relative Number of Molecules*	*Molecular Ratios*			
SiO_2	43.40	60.1	722	2.996	=	3	approx.
Al_2O_3	24.53	102.0	241	1.000		1	
CaO	27.37	56.1	488	2.025		2	
H_2O	4.48	18.0	249	1.033		1	
	99.78						

Therefore the formula is $H_2O{\cdot}2CaO{\cdot}Al_2O_3{\cdot}3SiO_2$ or $H_2Ca_2Al_2Si_3O_{12}$.

Formulas for some complicated compounds can be calculated in a similar way, if it is understood that certain oxides replace certain others and must be included with them to get the formula. For example, Parsons[6] analyzed a garnet from Thetford with the following results:

	Analysis Weight %	*Molecular Weights*	*Relative Number of Molecules*			*Molecular Ratios*		
SiO_2	36.66	60.1	610			3.096	3	
Al_2O_3	4.18	102.0	41	197	=	1.000	1	approx.
Fe_2O_3	24.86	159.6	156					
MgO	0.25	40.3	6	613		3.112	3	
CaO	33.89	56.1	604					
MnO	0.20	70.9	3					
TiO_2	0.10	79.9	—					
	100.14							

Therefore the formula is: $3(Ca,Mg,Mn)O{\cdot}(Fe,Al)_2O_3{\cdot}3SiO_2$ or $(Ca,Mg,Mn)_3(Fe,Al)_2Si_3O_{12}$.

But the composition of other complicated compounds cannot be derived nor expressed as simply as this. For example, Meen[7] analyzed a plagioclase from Hawk's Harbor, Labrador, and obtained:

	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	H_2O	TiO_2	Total
Weight %	55.24	27.61	1.22	10.70	5.40	0.14	0.01	0.07	100.39
Mol. Wght.	60.1	102.	159.6	56.1	62.	94.2	18	79.9	
Rel. No. Mol.	919	271	8	191	87	1	—	—	
		279			88				

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[5] C. F. Rammelsberg: *Zeit. Geol. Ges.* XX, 79 (1868).

[6] A. L. Parsons: *Univ. Toronto Stud. Geol.* XXXVIII, 33 (1938).

[7] F. B. Meen: *Univ. Toronto Stud. Geol.* XXXV, 37 (1933).

Now the numbers: 919, 279, 191, and 88 yield no simple ratio, and, even if they did, it would be only by chance and of no importance. In order to derive the proper expression of this analysis it is necessary to make use of the facts that some crystals of plagioclase contain no calcium and others contain no sodium; that the former yield the formula $NaAlSi_3O_8$ and the latter the formula $CaAl_2Si_2O_8$; and that both in nature and artificially it can be proved that these two compounds can intercrystallize (to form one substance) in any proportions whatever. Therefore there is no reason for any simple ratio between $NaAlSi_3O_8$ (called albite, or Ab) and $CaAl_2Si_2O_8$ (called anorthite or An). The correct way to express this analysis is to give the percentage (either by weight or preferably by molecules) of these two compounds, which may be regarded as end-members of the plagioclase series. For this purpose it is necessary merely to learn how many molecules of each kind can be made from the analysis, and the method is shown below:

	SiO_2	Al_2O_3	CaO	Na_2O
Molecules	919	279	191	88
$NaAlSi_3O_8$ or $Na_2O{\cdot}Al_2O_3{\cdot}6SiO_2$	528	88		88
	391	191		✓
$CaAl_2Si_2O_8$ or $CaO{\cdot}Al_2O_3{\cdot}2SiO_2$	382	191	191	
	9	✓	✓	

The calculation indicates an excess of 9 SiO_2—easily within the limits of error. Since Na_2O contains two atoms of sodium it is clear that 88 Na_2O will make 176 $NaAlSi_3O_8$ molecules. After these have been made the remaining oxide molecules obviously yield 191 molecules of $CaAl_2Si_2O_8$. Therefore the analysis represents 48.2% $NaAlSi_3O_8$ and 51.8% $CaAl_2Si_2O_8$; briefly, it is $Ab_{48}An_{52}$.

End-members, or minals

Once the existence of such isomorphous series and systems is fully recognized, it becomes very important to learn the limits of the replacement (in a single kind of structure) of each element by each other element. Furthermore, since the structure remains essentially unchanged (though it is *slightly* and progressively modified with more and more replacement) and the physical characters are only gradually changed, the substance is essentially one kind of thing no matter how much replacement may occur. Such a substance is one *mineral*, as defined on page 3. The simple compounds which compose it are conveniently called *end-members* (also called *minals* by Alling). Since a few minerals are simple compounds, all minerals are commonly but incorrectly regarded as such, and many compounds which are actually end-members are commonly regarded as minerals. For example, the mineral, columbite, may reasonably be said to have four end-members, namely: $FeCb_2O_6$, $FeTa_2O_6$, $MnCb_2O_6$, and $MnTa_2O_6$. Each one of these end-members is commonly regarded as a mineral, but that is not correct according to the definition here used. Each simple compound is an end-member or minal. It is misleading to give names to these minals as if they were minerals. They are not even properly regarded as mineral subspecies (or varieties), since the latter should be considered to be certain arbitrary portions of an isomorphous series or system. For example, the mineral, plagioclase, is a series extending from the end-member, albite, $NaAlSi_3O_8$, to the other end-member, anorthite, $CaAl_2Si_2O_8$. The variety of plagioclase varying in composition from the pure end-member, $NaAlSi_3O_8$ to 90% $NaAlSi_3O_8$ + 10% $CaAl_2Si_2O_8$ is commonly called albite, but to avoid confusion, it would perhaps be better to call it sodaclase, as proposed by Johannsen.[8]

Chemical-Crystallographic Relationships

Homeomorphism

In general, compounds which are not related chemically are also not related crystallographically, and compounds which are chemically similar are often also crystallographically similar; however, there are interesting exceptions to both of these generalizations. For example, soda niter, $NaNO_3$, and calcite, $CaCO_3$, are not related chemically, but are very similar crystallographically, though they do not form mix-crystals. Such compounds are said to be *homeomorphous*. Again, chlorargyrite, AgCl, and iodyrite, AgI, are not related crystallographically (being isometric and hexagonal respectively), but are closely related chemically.

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[8] *Jour. Geol.* XXXIV, 840 (1926).

Isostructure and isomorphism

Two compounds may be similar as to symmetry and crystal habits whether they are chemically closely related or not. Moreover, they may have this relationship as to their external forms and still illustrate three different conditions as to their ability to intercrystallize; that is, they may illustrate no intercrystallization, limited intercrystallization, or intercrystallization in all proportions. If they are chemically related and crystallographically similar, but do not intercrystallize, they are merely *isostructural*, but not isomorphous. Whether they are chemically related or not, if they can intercrystallize, they are called *isomorphous*, and the isomorphism is limited if the intercrystallization is partial, and perfect (or complete) if it is unlimited. Thus, albite, $NaAlSi_3O_8$, and anorthite, $CaAl_2Si_2O_8$, are chemically dissimilar, but illustrate complete isomorphism. Again, fluorapatite, $Ca_{10}F_2P_6O_{24}$, and ellestadite, $Ca_{10}(OH)_2Si_3S_3O_{24}$, are widely different chemically, but intercrystallize, probably in all proportions. But a commoner condition is illustrated by forsterite, Mg_2SiO_4, and fayalite, Fe_2SiO_4, which are obviously closely related chemically and intercrystallize freely in all proportions, to form the olivine series. Orthoclase, $KAlSi_3O_8$, and albite, $NaAlSi_3O_8$, are also closely related chemically, but intercrystallize only within certain limits (except at high temperature).

The calcite group furnishes an interesting illustration of these relationships, because certain members of the group (namely, calcite, dolomite, and magnesite) are merely isostructural, while other members (namely, magnesite, siderite, and rhodochrosite) are at least partially isomorphous.

The garnet group furnishes another excellent illustration of isomorphism, because it supplies examples of limited miscibility and also of unlimited miscibility. The garnet group has at least six end-members, namely: $Ca_3Cr_2Si_3O_{12}$, $Ca_3Al_2Si_3O_{12}$, $Ca_3Fe_2Si_3O_{12}$, $Mg_3Al_2Si_3O_{12}$, $Fe_3Al_2Si_3O_{12}$, and $Mn_3Al_2Si_3O_{12}$. All garnets have (nearly) the same isometric structure. $Mg_3Al_2Si_3O_{12}$ is miscible in all proportions in $Fe_3Al_2Si_3O_{12}$ and the latter is miscible in all proportions in $Mn_3Al_2Si_3O_8$, but the former ($Mg_3Al_2Si_3O_{12}$) is miscible very slightly in $Mn_3Al_2Si_3O_{12}$. Furthermore, all the calcium garnet end-members probably have only limited miscibility in the non-calcium end-members. Therefore there seem to be two minerals in the garnet group, namely, the calcium garnet, ugrandite, and the non-calcium garnet, pyralspite. Garnets composed chiefly of $Ca_3Cr_2Si_3O_{12}$ are called uvarovite; chiefly of $Ca_3Al_2Si_3O_{12}$, grossularite; chiefly of $Ca_3Fe_2Si_3O_{12}$, andradite; chiefly of $Mg_3Al_2Si_3O_{12}$, pyrope; chiefly of $Fe_3Al_2Si_3O_{12}$, almandite; and chiefly of $Mn_3Al_2Si_3O_{12}$, spessartite.

The composition of garnet and other isomorphous minerals is best expressed in terms of the end-members. When these are known, it is easy to convert a chemical analysis into them. For example, Nováček[9] gives the following analysis of almandite from Bohemia:

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	MnO	Total
1. Weight %........	36.73	19.99	0.83	33.00	1.95	0.51	6.79	99.93
2. Mol. Wght........	60.1	102	159.6	71.8	40.3	56.1	70.9	
3. Rel. No. Mol......	611	196	5	459	48.	9	96	
4. $Fe_3Al_2Si_3O_{12}$.......	459	153		459				
	152	43		✓				
5. $Mn_3Al_2Si_3O_{12}$......	96	32					96	
	56	11					✓	
6. $Mg_3Fe_2Si_3O_{12}$......	15		5		15			
	41		✓		33			
7. $Ca_3Al_2Si_3O_{12}$......	9	3				9		
	32	8				✓		
8. $Mg_3Al_2Si_3O_{12}$......	33	11			33			
	−1	−3			✓			

The third line is obtained by dividing the numbers of the first line by those of the second, and multiplying by 1000, to avoid decimals. The number of FeO molecules determines the amount of $Fe_3Al_2Si_3O_{12}$ which can be made, and similarly for the other end-members. Finally, it is evident that 153 molecules of $Fe_2Al_2Si_3O_{12}$ have been made together with 32 of $Mn_3Al_2Si_3O_{12}$, 5 of $Mg_3Fe_2Si_3O_{12}$, 3 of $Ca_3Al_2Si_3O_{12}$, and 11 of $Mg_3Al_2Si_3O_{12}$, the total number being 204. Dividing each number of molecules by the total, the composition of this garnet in percentage number of molecules follows: $Fe_3Al_2Si_3O_{12}$—75.0, $Mn_3Al_2Si_3O_{12}$—15.7, $Mg_3Al_2Si_3O_{12}$—5.4, $Mg_3Fe_2Si_3O_{12}$—2.4, and $Ca_3Al_2Si_3O_{12}$—1.5. Being chiefly composed of $Fe_3Al_2Si_3O_{12}$, it is called almandite.

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[9] *Mineral. Abst.* 5, 220 (1933). Also 0.03 H_2O and 0.10 TiO_2.

Polymorphism

A substance which crystallizes in two different "forms" (more strictly, two different phases), crystallographically unlike and unrelated, is said to be dimorphous; if three phases are known the substance is trimorphous; or, in general, it is polymorphous, that is, it has many crystal phases. Since the crystal structures of two phases of the same substance are different, the physical characters are not the same, and may even be widely different. For example, carbon exists as diamond with a hardness of 10 and a specific gravity of 3.5 and as graphite with a hardness of 1 and a specific gravity of 2.2. Other examples are given in the table below:

Compound	Mineral	System	Spec. Grav.	N_o or N_m	Biref.
FeS_2	Pyrite	Isometric	5.0		
	Marcasite	Orthorhombic	4.85		
SiO_2	Quartz	Rhombohedral	2.65	1.544	0.009
	Tridymite	Orthorhombic	2.27	1.469	0.004
	Cristobalite	Tetragonal (?)	2.35	1.487	0.003
$CaCO_3$	Calcite	Rhombohedral	2.71	1.658	0.172
	Aragonite	Orthorhombic	2.95	1.681	0.155

Mineraloids

A few substances are commonly accepted as minerals even though they seem to have little, if any, crystallizing power and are therefore found in the condition of a hardened gel; they are sometimes called mineraloids. They are formed at low temperature, being secondary minerals produced commonly by weathering. Opal and limonite are good examples. They are often found in mammillary or botryoidal masses. Like gelatinous precipitates in test tubes they have a notable tendency (unlike crystals) to absorb foreign material, and this accounts for their decidedly variable composition.

Pseudomorphs

The internal structure of a crystal can change without any change in the external form. Whenever the internal structure does not correspond with the external form, the solid is called a *pseudomorph* (or false form). For example, siderite crystals alter easily to limonite; they are then said to be pseudomorphs of limonite after siderite. Pseudomorphs may be produced in several different ways; the most important probably are:

1. Inversion. Crystals of aragonite may change in crystal structure to calcite, there being no change whatever in composition. In this case the product is called a *paramorph* of calcite after aragonite. In some cases the external form is retained by means of complex twinning of the new structure; such inversions seem to occur easily and to produce less change in the physical characters, so that the new phase may be known by the same name as the old one. Thus, boracite is isometric above 265°, and retains the cubic shape after inversion at that temperature, by means of complicated twinning of an orthorhombic phase, also called boracite. Similarly, quartz inverts at about 575° from a high temperature phase (distinguished as β-quartz) with good cleavages to ordinary (low temperature) α-quartz having no cleavage.

2. Alteration. When a crystal is changed in composition by addition of some new substance or removal of some of the original material (or both) without loss of the external form a pseudomorph is produced. Good illustrations include the change of anhydrite, $CaSO_4$, to gypsum, $CaSO_4 \cdot 2H_2O$ (and also the reverse change), of galena, PbS, to anglesite, $PbSO_4$, and of pyrite, FeS_2, to limonite, $Fe_2O_3 \cdot nH_2O$.

3. Substitution. In some cases all the material of a crystal may be slowly removed in solution with simultaneous deposition of another substance; such pseudomorphs are illustrated by quartz in the form of fluorite, which it has replaced.

4. Incrustation and infiltration. Less common and less perfect pseudomorphs are sometimes produced by deposition of one mineral as a crust over a crystal of another mineral, as of quartz over fluorite, or by deposition (from solution) of one mineral so as to fill the cavities left by the removal in solution of the crystals of some other mineral.

Chemical Study of Minerals

A special technique has been developed for the chemical examination of minerals. It is not necessary to have all the apparatus and reagents of a chemical laboratory. The most important apparatus consists of a Bunsen burner and a blowpipe, but with these it is convenient to use forceps, charcoal blocks, plaster tablets, platinum wire, hammer, anvil, mortars, glass tubing, and so on.

Special apparatus

Bunsen burner. Some sort of steady flame is necessary for many tests. The flame of an ordinary candle can be used, but a candle with a flat wick is better. The flame from an alcohol or even a tallow lamp can be used; the addition of a little turpentine improves it. But these devices give a flame decidedly less satisfactory for the special purpose than that obtained by using a Bunsen burner (Fig. 343) with illuminating gas. This burner shoud have an additional inner tube, as shown, flattened at the upper end and cut off obliquely.

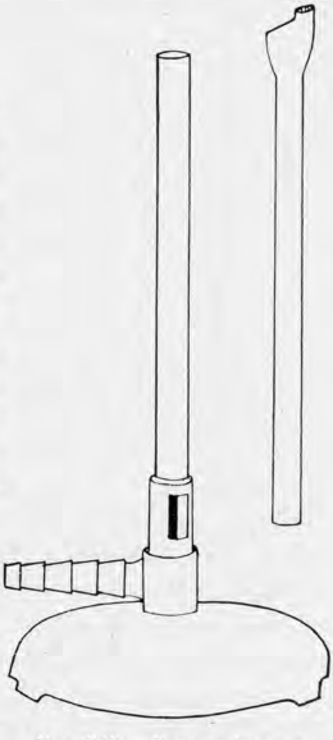


FIG. 343. Bunsen burner.

Blowpipe. The purpose of a blowpipe is to mix air with burning gas so as to produce more rapid and complete combustion and a hotter flame. A common type of blowpipe is shown in Fig. 344. It consists of a conical tube into the larger end of which a hard rubber mouthpiece fits, while the small end fits into a cylindrical chamber which serves to collect the moisture that condenses in the tube. From this chamber a side tube serves to conduct the air to the platinum tip, from which it escapes into the flame, as shown in Fig. 345. The blowpipe can be used to produce rapid oxidation by placing the mineral at the point *a* in the outer end of the flame or to produce strong reducing action by placing the mineral in the inner portion of the flame, as at *b*. Withdrawing the tip of the blowpipe slightly from the flame aids in producing a good reducing flame.

To produce a strong and continuous blowpipe flame some practise is usually necessary. One must learn to distend the cheeks so as to form a reservoir of air (under pressure) in the mouth. When the supply of air in the lungs is exhausted one must close the passage from the mouth into the throat (by raising the root of the tongue) long enough to refill the lungs by inhaling through the nose; during this interval the distended cheeks must maintain a steady stream of air through the blowpipe. In this way the flame can be kept constant and strong.

FIG. 344. Blowpipe.

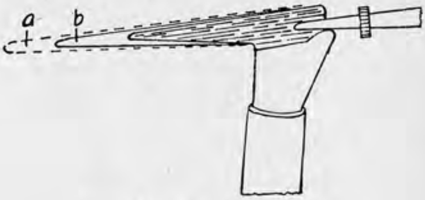


FIG. 345. Blowpipe flame.

A good blowpipe flame attains a temperature of about 1500° C. But this temperature is reached only in a small portion of the flame just beyond the tip of the inner cone. Therefore it is important to use a small fragment of a mineral, preferably with a sharp point, and this fragment should be held in platinum tipped forceps so that the sharp point (and not the forceps) is exactly at the hottest point of the flame. The blowpipe can be used to determine the fusibility of a mineral by comparing results with the table on page 146.

Heating on charcoal

Small pieces of charcoal about $\frac{1}{2} \times 1 \times 4$ inches are used as a support in many tests involving the use of the blowpipe. It is convenient to make a small depression (perhaps with the edge of a small coin) near the end of the charcoal. Place a fragment or powder of the mineral in it and hold the coal so that the flame passes along its length, in order to catch any sublimate. If the mineral decrepitates it should be powdered and made into a paste with water, and then heated slowly.

The reducing flame is used if the aim is to obtain a metal, as from sulfides. Otherwise, use the oxidizing flame for ignition, production of sublimates, etc. Possible changes to be observed are:

(1) Decrepitation, that is, breaking to pieces, as shown by fluorite, calcite, etc.

(2) Deflagration, that is burning with violence, as shown by some nitrates.

(3) Fusion. The mineral may fuse, or a metal from it may form globules. In some cases the fused mineral is absorbed in the charcoal.

(4) Intumescence, that is, swelling and bubbling after fusion.

(5) Fumes, as shown by some minerals containing S, As, Sb, etc.

(6) Odor, indicating S, As (garlic odor) or Se (horse-radish odor).

(7) Change of color, as shown by limonite, etc.

(8) Sublimate. (Ash from the coal is easily mistaken for a sublimate.)

(9) An infusible mineral or residue may glow brightly in the oxidizing flame, which indicates the presence of Ca, Mg, Sr, Sn, Zn, or Zr. Or, it may have an alkaline reaction after ignition, indicating Ba, Ca, Mg, Sr, Na, or K. Or, it may be magnetic, indicating the presence of Fe (or Ni).

A few metals can be obtained by reduction of certain minerals on charcoal. In some cases the reduction is possible only with the aid of a mixture of sodium carbonate and powdered charcoal in equal parts. Metallic globules that may be obtained are summarized in the following table:

METALLIC GLOBULES FROM REDUCTION ON CHARCOAL

Globule	Element	Comments
White, soft, not dull on cooling	Silver Ag	To distinguish from lead and tin, dissolve in nitric acid and add HCl to get white precipitate of AgCl.
White, soft, dull on cooling	Tin Sn	Globules obtained with difficulty; may be oxidized in nitric acid to white hydroxide.
Gray, soft, bright in R. F., iridescent in O. F.	Lead Pb	To distinguish from silver and tin, dissolve in nitric acid and add H_2SO_4 to get white $PbSO_4$ precipitate.
Yellow, soft, remains bright	Gold Au	Easily obtained from gold tellurides.
Red, soft, black surface when cold	Copper Cu	Copper minerals containing sulfur, arsenic or antimony must be roasted before treatment on charcoal.

The sublimates that may be obtained by heating minerals on charcoal are described in the following table:

SUBLIMATES ON CHARCOAL

Near Assay		Outer Fringe	Substance	Miscellaneous
Hot	Cold			
Silvery white		(Reddish) white	SeO_2 (white) Se (red)	Sublimate colors the reducing flame azure blue. Horse-radish odor.
Dense white		Gray to brownish	TeO_2 (white) Te (gray)	Volatile in reducing flame with pale bluish green flame color.
Dense white		Bluish	Sb_2O_3 and Sb_2O_4	Abundant near assay; less volatile than As_2O_3.
White		White to gray	As_2O_3	Abundant far from assay; garlic odor.
White		White to bluish	Chlorides of Cu, Pb, Hg, NH_4 and alkalies.	
Pale yellow to white	White	Faint white	SnO_2	Sublimate becomes bluish green if moistened with $Co(NO_3)_2$ and ignited.
Pale yellow	White	Bluish	MoO_3	Sublimate becomes azure blue in R. F. Cu-red MoO_2 next to assay.
Canary yellow	White	Faint white	ZnO	Sublimate becomes green if moistened with $Co(NO_3)_2$ and ignited.
Yellow	Pale yellow	White with bluish outer fringe	PbO, $PbSO_3$, $PbSO_4$	Produced by ignition of galena.
Dark yellow	Sulfur yellow	Bluish white	PbO	Yellowish green sublimate if heated with KI and $HKSO_4$.
Orange yellow	Light orange yellow	Greenish white	Bi_2O_3	Heated with KI and $HKSO_4$ gives yellow sublimate fringed with bright red.
Reddish brown to nearly black		Orange yellow	CdO	Iridescent if very thin.
Reddish to deep lilac			Ag with Pb and Sb	Ag alone gives slight brownish sublimate after long ignition.
Copper red		White	MoO_2, MoO_3	Sublimate becomes azure blue in the reducing flame.

Iodide sublimates

Iodides in some cases have an appearance quite different from the oxides. To produce iodide sublimates the mineral should be finely powdered and then moistened with HI or mixed with a flux composed of equal parts of KI and $HKSO_4$. Iodide sublimates can be formed on charcoal or on plaster or even on sheets of mica. To make suitable plaster plates it is only necessary to spread a layer of plaster of Paris about $\frac{1}{4}$ inch thick on an oiled glass plate, and cut it into strips about 1 × 4 inches while still soft. After it has hardened, the sheet can be easily broken into 1 × 4-inch strips and these can be conveniently supported on charcoal blocks during heating. Some iodides do not show on charcoal; others are plainer on plaster.

IODIDE SUBLIMATES ON PLASTER

Near Assay	Outer Fringe	Substance	Miscellaneous
Chrome yellow	Chrome yellow	PbI_2	Volatile.
Yellow to orange	Yellow to orange	AsI_3	Very volatile.
Orange to red	Orange to red	SbI_3	Disappears in strong NH_4OH fumes.
Black to dull yellow	Yellow to scarlet	HgI	Requires strong heat.
Red to crimson	Red to crimson	SeI_4	Volatile with reddish fumes and horse-radish odor.
Chocolate brown on scarlet	Chocolate brown on scarlet	BiI_3	NH_4OH fumes change it to yellow, then red. Bright red on charcoal.
Purplish brown	Dark brown	TeI_4	Volatile.
Deep ultramarine blue		MoI_4	Does not show on charcoal.

Flame colors

Some minerals produce distinct coloration of the flame when they are strongly heated in it. It is best to use the fine powder, and introduce it into the flame by means of a clean platinum wire. It is often an advantage to moisten the wire with water so that it will pick up more of the powder. Moistening with HCl or H_2SO_4 is desirable in some cases. The wire should be introduced into the flame slowly, first at the cooler base, and then it should be moved gradually up to the hottest central tip.

Light filters are useful in recognizing flame colors in some cases. Blue and green glasses may be used, but the Merwin color screen is better. It consists of strips of blue and violet

Flame Colors

Color	Tint	Substance	Merwin screen 1-blue, 2-both 3-violet	Miscellaneous
Red	Purple	Sr	1,2-invisible; 3-crimson	Green glass: faint yellow. Alkaline after ignition.
Red	Carmine	Li	1,2-invisible; 3-crimson	Green glass: no color. Not alkaline after ignition.
Reddish to yellow	Orange	Ca	1-green-yellow; 2-faint green; 3-pale crimson	Green glass: no color. Alkaline after ignition. Useful to moisten assay with HCl.
Yellow	Intense	Na	1,2,3-invisible. Blue glass: invisible	Intense and persistent.
Green	Yellowish	Ba	1-green; 2,3-pale green	Alkaline after ignition.
Green	Yellowish	B	1-green; 2,3-pale green	Use concentrated H_2SO_4. May need CaF_2 and $HKSO_4$.
Green	Yellowish	$MnCl_2$	1-emerald; 2-pale bluish green; 3-pale lavendar	Soda bead is green in oxidizing flame.
Green	Pale yellowish	Mo	Not necessary	Only from the oxide or sulfide.
Green	Pale	Sb	Not necessary	Platinum forceps must not be used. Best to heat on charcoal.
Green	Emerald	CuO CuI	Not necessary	With HCl, a blue flame tinged with green.
Green	Pale bluish	P	1-green; 2-pale green; 3-light violet red	Use concentrated H_2SO_4.
Green	Bluish	Zn	Not necessary	Bright streaks in the flame.
Blue	Azure	$CuCl_2$	1-bright green; 2-pale green; 3-blue with green border	Outer border is emerald green.
Blue	Pale azure	Pb	Not necessary	Outer border is greenish. Best to heat on charcoal.
Blue	Pale	As	Not necessary	Characteristic garlic odor.
Blue	Indigo	Se	Not necessary	Characteristic horse-radish odor.
Violet	Pale	K	1-blue-violet; 2-faint violet-red; 3-reddish violet	Blue glass: purplish red. Often necessary to use $CaSO_4 \cdot 2H_2O$ as a flux.

celluloid, partly overlapped, forming three screens. Hold the glass or celluloid close to the eye when using it.

The presence of sodium, even in minute amount, such as is commonly produced on any object touched by the fingers, produces a yellow flame color which obscures or even completely masks other colors. Light filters are especially useful in shutting out this yellow color.

Some minerals (especially some silicates) are so difficultly decomposed that they give no flame color even when they contain an element that produces color. In such cases it is necessary to fuse the powdered mineral on platinum wire with an equal volume of gypsum, or with fluorite and $HKSO_4$.

The colors produced and the substances which cause them are shown in the table on page 200.

Heating in the closed and open tubes

Minerals are examined in the closed or open tube chiefly to discover what volatile elements they may contain. The closed

SUBLIMATES IN THE CLOSED TUBE

Hot	Cold	Substance	Miscellaneous
Colorless liquid	Colorless liquid	H_2O	Neutral, acid, or rarely, alkaline.
Gray metallic liquid		Hg	May be tested on copper. See page 215.
White solid	White solid	$PbCl_2$, $SbCl_3$, As_2O_3, Sb_2O_3, NH_4 salts	
Pale yellow to colorless liquid	Colorless to white solid	TeO_2	Difficultly volatilized.
Dark yellow to red liquid	Pale yellow crystalline	S	Easily volatilized.
Dark red liquid	Reddish yellow solid	As_2S_3	Easily volatilized.
Black solid	Reddish brown solid	Sb_2S_2O	Difficultly volatilized.
Brilliant black metallic to gray crystalline		As	Break off closed end and heat for garlic odor.
Deep black and metallic		HgS	Rubbing gives a red powder.
Black globules	Black	Te	TeO_2 also likely to form; see above.
Black globules; smallest deep red	Black	Se	White crystalline SeO_2 may appear.

tube is used to heat the mineral without oxidation, since the small supply of air originally present is soon driven out. The open tube is used to heat the mineral under oxidizing conditions since a continual stream of hot oxygen passes over the assay.

Sublimates in the Open Tube

Hot	Cold	Substance	Miscellaneous
White crystalline	White	As_2O_3	Volatile; crystals octahedral
White crystalline	White	SeO_2	Usually radiating crystals; red. Se may be present. Volatile easily.
White crystalline	White	Sb_2O_3	Slowly volatile; crystals octahedral and prisms forming a ring on walls of tube.
Pale yellow to colorless liquid	Colorless to white solid	TeO_2	Difficultly volatilized.
Pale yellow	White, not volatile	$SbSbO_4$	White fumes; often with volatile Sb_2O_3.
Pale yellow	White	MoO_3	Tiny crystals near assay; volatile slowly. Crystals turn blue in reducing flame.
Gray metallic globules		Hg	Test on copper. See page 215.
If the assay is heated too rapidly the following sublimates may form (to avoid them, heat upper part of tube first and then heat the assay directly):			
Dark yellow to red liquid	Pale yellow crystalline	S	Easily volatilized.
Dark red liquid	Reddish yellow solid	As_2S_3	Easily volatilized.
Black solid	Reddish brown solid	Sb_2OSb_2	Difficultly volatilized.
Brilliant black metallic to gray crystalline		As	Test for garlic odor.
Deep black metallic		HgS	Rubbing gives a red powder.
Black globules, smallest deep red	Black	Se	Often with SeO_2—see above.

Sublimates in the closed tube. A small fragment of the mineral is placed in the closed tube and heating is begun in the ordinary Bunsen flame. Note carefully all the results, such as:

decrepitation, glowing, phosphorescence, change of color, fusion, fumes, or sublimates. To obtain sublimates the upper end of the tube must be kept cool, and this is accomplished most easily by holding the tube in the hand and keeping it nearly horizontal.

The most important sublimates obtained in the closed tube are shown in the table on page 201.

Sublimates in the open tube. The object in view in heating a mineral in the open tube is to do so under oxidizing conditions. Therefore it is desirable to have the tube nearly vertical, using a holder since the whole tube should be hot. Place the finely powdered mineral near the lower end and let the flame strike all (or most) of the tube, or move it frequently over all parts, to insure an ample supply of air. It may be worth while in some cases to blow air into the lower end of the tube with a blowpipe. Distribute the powdered mineral so as to be sure not to interfere with the flow of air through the tube.

The sublimates obtained in the open tube are shown in the table on page 202.

Heating the mineral with fluxes

In examining minerals the important fluxes to use are borax, sodium metaphosphate, and sodium carbonate. They are generally used with the platinum wire, but also at times on charcoal. To hold an appreciable amount of flux on the wire it is convenient to bend it (as around the tapering end of a pencil) into a small loop, which is heated to redness and dipped into the flux. The adhering powder may be fused to a bead. By repeating this process the loop may be filled. But sodium carbonate may be picked up more easily by using a cold moistened wire.

The hot bead is used to pick up a little of the finely powdered mineral, and heating is continued. Be careful not to use too much of the mineral. The bead should be heated first in the oxidizing flame and then in the reducing flame and the color noted when hot and when cold.

Minerals containing sulfur, arsenic, or antimony must be roasted (thoroughly oxidized) before testing with fluxes; otherwise no characteristic reactions will be obtained.

Borax bead reactions. The important borax bead reactions follow.

BORAX BEAD REACTIONS

Oxidizing flame		Reducing flame		Substance	Notes
Hot	Cold	Hot	Cold		
Colorless	Colorless	Colorless	Colorless	SiO_2, Al_2O_3, SnO_2	Any amount
Colorless	Colorless to opaque white	Colorless	Colorless to opaque white	CaO, SrO, BaO, MgO, ZnO, ZrO_2 Nb_2O_5	Any amount
Pale yellow	Colorless or white	Pale yellow	Colorless	PbO, Sb_2O_3, CdO	Large amount
Pale yellow	Colorless or white	Grayish or colorless	Brownish violet	TiO_2, Ti_2O_3	Large amount
Pale yellow	Colorless or white	Gray	Gray	Bi_2O_3, Bi	Large amount
Pale yellow	Colorless or white	Yellow	Yellow to yellowish brown	WO_3	Moderate amount
Pale yellow	Colorless or white	Brown	Brown	MoO_3	Large amount
Pale yellow to yellow	Colorless or nearly so	Pale green	Colorless or nearly so	Fe_2O_3, FeO, UO_3, U_2O_3	Small amount
Yellow	Yellowish green	Green	Green	Cr_2O_3	Small amount
Yellow	Pale yellowish green	Dirty green	Fine green	V_2O_5	Small amount
Yellow to brown	Yellow	Bottle green	Pale green	Fe_2O_3, FeO	Moderate to large amount
Yellow to brown	Yellow	Pale green	Colorless or nearly so	UO_3, U_2O_3	Moderate to large amount
Yellow to brown	Yellowish green	Green	Green	Cr_2O_3	Moderate to large amount
Green	Blue-green	Colorless to green	Bluish green	CuO, Cu_2O	Small to moderate amount
Blue	Blue	Blue	Blue	CoO	Small to moderate amount
Violet	Reddish brown	Gray, turbid	Gray, turbid	NiO, Ni	Small to moderate amount
Violet	Reddish violet	Colorless	Colorless	Mn_2O_3, MnO	Small amount

Sodium carbonate bead reactions. Borax and phosphate beads are glassy and transparent when pure, but sodium carbonate beads are opaque white. They are prepared in the same way as borax beads and give the following reactions:

Quartz or opal in fine powder when fused with an equal volume of sodium carbonate produces vigorous effervescence of CO_2 and the carbonate becomes silicate. The sodium silicate bead produced is glassy clear.

Chromium minerals when powdered and fused in the sodium carbonate bead color it yellow in the oxidizing flame.

Manganese minerals when powdered and fused in the sodium carbonate bead in the oxidizing flame color it green when hot and blue when cold; in the reducing flame the bead is colorless.

Sodium Metaphosphate bead reactions. These are as follows.

Sodium Metaphosphate Bead Reactions

Oxidizing flame		Reducing flame		Substance: oxide of	Notes
Hot	Cold	Hot	Cold		
Colorless	Colorless or opaque white	Colorless	Colorless or opaque white	Al, Ba, Ca, Mg, Sn, Sr, Zn, Zr	Insoluble. SiO_2 makes a skeleton in bead.
Pale yellow	Colorless	Pale yellow	Colorless	Cd	Large amount
Pale yellow (to yellow)	Colorless	Pale greenish yellow	Colorless	Fe	Small amount
Pale yellow	Colorless	Yellow	Violet	Ti	Small to moderate amount
Pale yellow	Colorless	Gray	Gray	Pb, Sb, Bi	Large amount
Pale yellow	Colorless	Dirty blue	Fine blue	W	Moderate amount
Pale yellow	Colorless	Brown	Brown	Nb	Large amount
Yellow	Pale greenish yellow	Pale green	Fine green	U	Large amount
Yellowish green	Colorless	Dirty green	Fine green	Mo	Large amount
Yellow to brownish red	Colorless to yellow	Red, yellow or yellow-green	Pale violet to colorless	Fe	Moderate to large amount
Yellow to deep yellow	Yellow	Dirty green	Fine green	V	Small to moderate amount
Red to brown	Yellow to reddish	Red to brown	Yellow to reddish	Ni	Small to moderate amount
Green	Pale blue	Pale yellowish green	Pale blue or ruby red	Cu	Small amount
Dark green	Blue	Brownish green	Opaque red	Cu	Moderate amount
Dirty green	Fine green	Dirty green	Fine green	Cr	Small to moderate amount
Blue	Blue	Blue	Blue	Co	Small to moderate amount
Grayish violet	Violet	Colorless	Colorless	Mn	Moderate amount

Dry reagents

The following are the more important dry reagents used in testing minerals:

Sodium carbonate, Na_2CO_3, or sodium bicarbonate, $NaHCO_3$, is used chiefly as a flux to decompose minerals on charcoal.

Borax, $Na_2B_4O_7 \cdot 10H_2O$, is used chiefly in a loop of platinum wire to make bead tests.

Microcosmic salt or salt of phosphorus, $HNaNH_4PO_4 \cdot 4H_2O$ is also used chiefly in a loop of platinum wire to make bead tests.

Potassium bisulfate is used in fusions to decompose minerals. The same compound with one third as much calcium fluoride is used to test for boron in silicates; it is called Turner's flux.

Potassium iodide with an equal part $KHSO_4$ and two parts of sulfur is used to test for bismuth. It is called von Kobell's flux.

Test papers of litmus or turmeric are used to test for acids or alkalies or for boracic acid and zirconium.

Wet reagents

The following are the more important wet reagents:

Ammonium hydroxide, NH_4OH, is the most useful alkali; it is commonly used diluted with three parts of water.

Ammonium oxalate, $(NH_4)_2C_2O_4$, and ammonium carbonate, $(NH_4)_2CO_3$, are used (dissolved in water) chiefly to precipitate alkaline earths from their solutions.

Ammonium molybdate, $(NH_4)_2MoO_4$, is used to test for phosphates.

Barium chloride, $BaCl_2$, is used to test for sulfuric acid.

Cobalt nitrate, $Co(NO_3)_2$, is used to test for aluminum and zinc.

Dimethylglyoxime, $C_4H_8O_2N_2$, is used to test for nickel.

Disodium acid phosphate, $Na_2HPO_4 \cdot 12H_2O$, is used to test for magnesium.

Hydrochloric acid (or muriatic acid), HCl, is used to dissolve minerals without oxidation.

Hydrogen peroxide, H_2O_2, is used to test for titanium.

Nitric acid, HNO_3, is a strong solvent and oxidizing agent.

Potassium ferricyanide, $K_6Fe_2(CN)_{12}$, and potassium ferrocyanide, $K_4Fe(CN)_6 \cdot 3H_2O$, are used in dilute solutions to test for ferrous and ferric iron respectively.

Silver nitrate, $AgNO_3$, is used to test for chlorine.

Sulfuric acid, H_2SO_4, is commonly used with four parts of water. In diluting it, pour the acid slowly into water; do not pour water into the acid.

Chemical tests for elements

For convenience the chief blowpipe and other chemical tests for the elements are described in the following pages, arranged alphabetically:

Aluminum (Al^{+3}; at. wt. 26.97)

(1) *Color with cobalt nitrate.* Any infusible light-colored mineral containing aluminum becomes decidedly blue if the fine powder is moistened with cobalt nitrate and then intensely heated either on charcoal or in a small loop of a platinum wire. A blue color can be obtained from various fusible minerals which contain no aluminum; the test is not significant unless the mineral is infusible. Zinc silicates give the same blue color and one (hemimorphite) is almost infusible; a flame (or other) test for zinc is decisive.

(2) *Precipitate with ammonia.* Dissolve the mineral in acid; add ammonia in slight excess; if aluminum is present a white gelatinous precipitate of $Al(OH)_3$ is formed. To distinguish this from other similar precipitates obtained in the same way, filter, wash the precipitate, put one part of it in a test tube with H_2O and KOH; $Al(OH)_3$ dissolves easily. The rest of the precipitate, after ignition, will give the preceding test with cobalt nitrate if it contains aluminum.

For aluminum in silicates see Silicon, page 218.

Antimony ($Sb^{+3 \text{ or } +5}$; at. wt. 121.77)

(1) *Sublimate on charcoal.* Antimony, antimonides and antimony sulfides give a dense white sublimate of Sb_2O_3 near the assay when heated on charcoal in the oxidizing flame. Where thin the coating appears bluish. There is no distinct odor, unless arsenic or sulfur is present.

(2) *Sublimate in the open tube.* Most antimony sulfides give a white sublimate of Sb_2O_4 in the open tube; it is not volatile; straw-yellow when hot and white when cooled.

(3) *Flame color.* Antimony volatilizes in the reducing flame and gives a pale greenish color to the flame. Platinum forceps must not be used.

(4) *Oxidation with nitric acid.* Antimony minerals yield a white insoluble residual powder ($HSbO_3$) on heating in HNO_3. This may be tested for its sublimate on charcoal, as directed above.

(5) *Iodide sublimate on plaster.* If an antimony mineral powder is moistened with HI or mixed with potassium iodide and

sulfur and then heated on plaster in the oxidizing flame, an orange-red sublimate is produced, which disappears in strong ammonia fumes.

Arsenic ($As^{+3\ or\ +5}$; at. wt. 74.93)

(1) *Sublimate on charcoal.* Arsenic, arsenides, and sulfides of arsenic, when heated on charcoal, give white fumes with an alliaceous odor and a white sublimate of As_2O_3 far from the assay.

(2) *Sublimate in the open tube.* The same substances yield the same odor and sublimate in the open tube. It is volatile, and easily driven out of the tube.

(3) *Arsenic mirror in the closed tube.* Arsenic and some arsenides (and arsenates, if mixed with powdered charcoal) produce a brilliant black arsenical mirror when heated in the closed tube. By breaking off the closed end of the tube and heating the As mirror, a white sublimate of As_2O_3 and the characteristic alliaceous odor are produced.

(4) *Flame color.* In the reducing flame arsenic volatilizes and gives a violet color to the flame.

(5) *Insoluble arsenic acid.* Arsenic minerals are attacked by hot nitric acid yielding white insoluble arsenic acid (H_3AsO_4), which may be tested by the third method above.

Barium (Ba^{+2}; at. wt. 137.36)

(1) *Flame color.* Barium (except in silicates) produces a greenish yellow flame color, intensified in some cases by moistening the assay with HCl. Boron, phosphorus, and manganese chloride produce similar colors.

(2) *Sulfate precipitate.* If a mineral containing barium can be dissolved in HCl or HNO_3 (silicates require a previous fusion of the finely powdered mineral with three volumes of soda in a loop of platinum wire), the addition of a few drops of dilute H_2SO_4 produces a white precipitate of $BaSO_4$. This precipitate differs from a similar one of calcium by being insoluble in boiling water, but $SrSO_4$ is almost as insoluble as $BaSO_4$. Neither boron nor phosphorus nor manganese, when treated in the same way, produce precipitates.

Bismuth (Bi^{+3}; at. wt. 209.0)

(1) *Sublimate on charcoal.* To test a mineral for bismuth, heat the powder with three volumes of soda on charcoal; if

bismuth is present, brittle metallic globules are formed as well as a yellow sublimate of Bi_2O_3 (white farther from the assay). This coating is much like that produced by lead, but the metal is less malleable, and the following test distinguishes it.

(2) *Sublimate on charcoal or plaster.* Mix the powdered mineral with one part of potassium iodide, two parts of sulfur and one part of potassium bisulfate (or moisten it with HI) and heat it in the oxidizing flame on charcoal. If bismuth is present, the sublimate is yellow near the assay and brilliant red (BI_3) farther away. If the same material is heated on a plaster plate, the sublimate is chocolate brown, but changes to a brilliant red if exposed to strong ammonia fumes.

Boron (B^{+3}; **at. wt. 10.82**)

(1) *Flame color.* Boron produces a siskin-green (somewhat yellowish green) flame color, which should be compared carefully with the flame colors produced by barium (greenish yellow) and by manganese chloride (yellowish green). Some boron minerals produce no boron flame color until mixed with one volume of powdered fluorite (CaF_2) and three volumes of potassium bisulfate ($HKSO_4$). Even then the BF_3 formed may give only a momentary color to the flame. H_2SO_4 may help produce the color.

(2) *Turmeric paper test.* Dissolve the mineral in HCl (after fusion with three parts of soda on a platinum wire loop, if necessary); add water; moisten turmeric paper with the solution and then dry the paper at 100° C. (on the outside of a test tube containing boiling water). If boron is present, the paper becomes reddish brown; on moistening with ammonia it becomes black.

Bromine (Br^{-1}; **at. wt. 79.9**)

(1) *Precipitate as bromide.* If a mineral containing bromine is dissolved in water or dilute nitric acid, the addition of $AgNO_3$ solution produces a white precipitate of AgBr.

Cadmium (Cd^{+2}; **at. wt. 112.4**)

(1) *Sublimate on charcoal or plaster.* If a cadmium mineral is powdered and heated on charcoal with three parts of soda, the cadmium is volatilized and forms a reddish brown sublimate of

CdO, which is yellow at a distance from the assay, and iridescent if only a little is present. On a plaster plate the sublimate is greenish yellow with brown farther away.

Caesium (Cs^{+1}; at. wt. 132.8)

(1) *Chloride precipitate.* If a mineral containing caesium is dissolved in HCl (after fusion with soda, if necessary), addition of hydrochlorplatinic acid (H_2PtCl_6) produces a fine yellow crystalline precipitate of Cs_2PtCl_6.

Calcium (Ca^{+2}; at. wt. 40.07)

(1) *Flame color.* Some calcium minerals give a yellowish red color to the flame (green through green glass), somewhat intensified by moistening with HCl. Strontium and lithium produce more decided red color and sodium produces a strong yellow color.

(2) *Precipitate with H_2SO_4.* If a calcium mineral is dissolved in dilute HCl (after fusion with soda, if necessary), the addition of a little dilute H_2SO_4 produces a white precipitate of $CaSO_4 \cdot 2H_2O$, which (unlike $BaSO_4$ and $SrSO_4$) is soluble in boiling water. There should be no great excess of HCl.

(3) *Precipitate with ammonium oxalate or carbonate.* If a calcium mineral is dissolved in acid (after fusion with soda, if necessary) the addition of ammonium oxalate to the slightly acid solution produces a white precipitate of calcium oxalate. Ammonium carbonate produces a similar precipitate in an alkaline solution.

For tests for calcium in silicates, see Silicon, page 218.

Carbon ($C^{+4 \text{ or } +2 \text{ or } -4}$; at. wt. 12)

(1) *Odor in the closed tube.* Hydrocarbons give the characteristic empyreumatic odor when heated in the closed tube. Anthracite is the only kind of coal which does not give it. Anthracite or graphite burns when a small fragment is heated to redness in the closed tube with abundant pyrolusite.

(2) *Effervescence of carbonates.* Any carbonate when powdered and treated with dilute acid (HCl, HNO_3 or H_2SO_4) will effervesce, because CO_2 is evolved. Heat is necessary in some cases, but should be avoided, to prevent mistaking boiling for

effervescence. By pouring the escaping CO_2 gas into a test tube containing $Ba(OH)_2$ in solution a white precipitate of $BaCO_3$ may be formed.

Chlorine (Cl^{-1}; at. wt. 35.45)

(1) *Flame color with copper.* If a powdered mineral containing chlorine is mixed with Cu filings or CuO powder, moistened with H_2SO_4, dried carefully on charcoal and then ignited, the purple flame color of $CuCl_2$ will appear. The same result may be obtained by saturating a salt of phosphorus bead with CuO and adding a small portion of the mineral. Bromine gives a similar reaction.

(2) *Precipitate with silver.* If a mineral containing chlorine is dissolved (after fusion with soda, if necessary) in dilute nitric acid and a little $AgNO_3$ is added, a white precipitate of AgCl forms. Bromine and iodine give similar reactions.

Chromium ($Cr^{+3 \text{ or } +6}$; at. wt. 52)

(1) *Borax bead test.* A mineral containing chromium when powdered and added to borax gives a bead in the oxidizing flame which is yellow to red when hot and yellowish green when cold; in the reducing flame it is emerald green when hot or cold.

(2) *Salt of phosphorus bead.* When the powdered mineral is added to salt of phosphorus and heated in the oxidizing flame the bead is dirty green when hot and clear green when cold; in the reducing flame the color is the same, but weaker.

Cobalt (Co^{+2}; at. wt. 58.94)

(1) *Borax bead test.* A mineral containing cobalt when powdered and added to borax gives in either oxidizing or reducing flame a beautiful blue bead. If sulfur or arsenic is present, roast the mineral before adding it to the bead. Copper or nickel may interfere; in that case, fuse the bead on charcoal with a granule of tin to give the blue color.

(2) *Salt of phosphorus bead test.* The treatment and results are the same as with borax.

Copper ($Cu^{+2 \text{ or } +1}$; at. wt. 63.57)

(1) *Flame color.* Copper oxide and oxidized sulfides give an emerald green flame color. Copper chloride, obtained by

moistening the powder (previously roasted if a sulfide) with HCl, produces an azure blue flame color. Copper chloride can be obtained also by adding a grain of common salt, NaCl, to a salt of phosphorus bead saturated with the powdered mineral.

(2) *Borax bead test.* A mineral containing copper when powdered and added to borax gives in the reducing flame a bead which is pale red with a little copper and dark red to opaque with much (because of the presence of Cu_2O and Cu). In the oxidizing flame it is green when hot and blue when cold. By adding a little tin it becomes ruby red after *brief* treatment in the reducing flame.

(3) *Salt of phosphorus bead test.* The treatment and results are the same as with borax.

(4) *Color in solution.* Most copper minerals are soluble in nitric acid (also in HCl). The solution may be blue or green, but it is made deep blue by adding ammonia in excess. Nickel minerals give a much paler blue color when treated the same way.

Fluorine (F^{-1}; at. wt. 19)

(1) *HF in closed tube.* Mix the finely powdered mineral with an equal volume of powdered glass and three volumes of $HKSO_4$, and heat gently in the closed tube. If fluorine is present, the HF produced attacks the glass, forming SiF_4, which decomposes to H_2SiF_6 with separation of SiO_2 as a volatile white sublimate. If the bottom of the tube is broken off, the H_2SiF_6 washed out with water, and the tube then dried, the remaining SiO_2 sublimate is not volatile. Such a sublimate can be produced also by mixing the powdered mineral with five volumes of powdered salt of phosphorus beads and heating strongly in the closed tube.

(2) *Etching glass.* The effect of HF in etching glass can be made clear by coating a glass plate with paraffin, scratching off the paraffin with a pointed instrument (thus writing or drawing on the surface) and adding a few drops of H_2SO_4 to the powdered mineral on this surface. After allowing to stand at least five minutes, wash off the acid and powder, warm the glass, wipe off the paraffin and observe the etching.

Gold ($Au^{+1 \text{ or } +3}$; at. wt. 197.2)

(1) *Metal on charcoal.* Minerals containing gold yield the metal when heated on charcoal (with soda, if needed). Gold is

easily recognized by its color, fusibility, malleability, and insolubility in any single acid (when present in visible particles).

Hydrogen (H^{+1}; at. wt. 1)

(1) *Water in closed tube.* Minerals containing hydrogen (as acid H, OH, water of crystallization or zeolite water) lose water (which condenses in the cold part of the tube) when heated sufficiently. Even hygroscopic water will give a slight test. Zeolitic water goes off through a long range of temperature; water of crystallization is lost at one (or more) definite temperature; hydroxyl and acid hydrogen go off at high temperature.

Iodine (I^{-1}; at. wt. 126.9)

(1) *Sublimate with galena.* Minerals containing iodine may be powdered and heated with powdered galena in the closed tube; a sublimate of PbI_2 is formed, which is dark orange-red while hot and lemon-yellow when cold.

Iron ($Fe^{+2 \text{ or } +3}$; at. wt. 55.8)

(1) *Magnetism.* A few iron minerals are magnetic as found in nature; many others become so when heated in the reducing flame (after roasting in the case of sulfides and similar compounds), especially if the powder is fused with a little soda, and allowed to cool. Even pure iron is not magnetic at high temperature.

(2) *Borax bead test.* With very little iron the borax bead after being heated in the oxidizing flame is yellow when hot and nearly colorless when cold; in the reducing flame it is pale green when hot and colorless when cold. With much iron the bead (when heated in the oxidizing flame) is brownish red when hot and yellow when cold; in the reducing flame it is bottle-green when hot and pale green when cold. Sulfides and similar salts must be roasted before being tested in borax.

(3) *Precipitate with ammonia.* If an iron mineral is dissolved in HNO_3 (after fusion with soda, if necessary), the addition of ammonia in excess produces a brownish red precipitate of $Fe(OH)_3$. If the mineral contains ferrous iron, ammonia added to the HCl solution produces a dirty green precipitate of $Fe(OH)_2$, which slowly oxidizes to brown.

For tests for iron in silicates, see Silicon, page 218.

Lead ($Pb^{+2 \text{ or } +4}$; at. wt. 207.22)

(1) *Metal and sublimate on charcoal.* If a lead mineral is powdered, mixed with one part of powdered charcoal and three parts of soda, and fused in the reducing flame on charcoal, globules of the metal form in the assay and also a sublimate of PbO, which is yellow near the assay and bluish white farther away. The globules are malleable and sectile, bright metallic when heated and dull on cooling.

If the original powder is mixed with one part of potassium iodide, two parts of sulfur, and one part of potassium bisulfate, and heated in the oxidizing flame, a sublimate of PbI_2 forms, which is chrome-yellow near the assay and greenish yellow farther away.

(2) *Precipitate from solution.* If a lead mineral is dissolved in dilute HNO_3, addition of H_2SO_4 causes a white precipitate of $PbSO_4$, or addition of HCl causes a similar precipitate of $PbCl_2$.

(3) *Flame color.* Lead produces an azure blue flame color tinged with green.

Lithium (Li^{+1}; at. wt. 6.9)

(1) *Flame color.* If a lithium mineral is powdered and heated on clean platinum wire, it produces a crimson flame color. If it is a silicate, the color is made more distinct by mixing with an equal part of powdered gypsum. The color is easily distinguished from that of calcium, but easily mistaken for strontium. The sulfate precipitate of strontium suffices to separate it from lithium.

Lithium minerals do not produce an alkaline reaction on turmeric paper, even after ignition.

Magnesium (Mg^{+2}; at. wt. 24.3)

(1) *Color with cobalt nitrate.* Infusible light colored magnesium minerals become light pink after moistening with cobalt nitrate and strong ignition.

(2) *Precipitate with sodium phosphate.* If a magnesium mineral is powdered, dissolved in HNO_3 (or HCl with addition of a drop of HNO_3 and boiling), and made strongly alkaline by adding ammonia, iron, alumina, and silica will be precipitated. Add ammonium oxalate to the filtrate to precipitate calcium.

In the clear filtrate a solution of sodium phosphate will precipitate any magnesium as ammonium magnesium phosphate (allow the solution to stand).

For tests for magnesium in silicates, see Silicon, page 218.

Manganese ($Mn^{+2 \text{ or } +3 \text{ or } +4}$; at. wt. 54.9)

(1) *Soda bead reaction.* If a manganese mineral powder is added to a sodium carbonate bead and heated in the oxidizing flame, sodium manganate (Na_2MnO_4) forms, which colors the bead green while hot and bluish green when cold; in the reducing flame the bead is white.

(2) *Borax bead reaction.* If a manganese mineral powder is added to a borax bead and heated in the oxidizing flame, it is opaque while hot and reddish violet when cold (but black if too much of the mineral is used); in the reducing flame it is colorless.

(3) *Flame color.* If a manganese mineral powder is dissolved in HCl, the solution will color the flame yellowish green. Barium and boron give similar colors.

Mercury ($Hg^{+1 \text{ or } +2}$; at. wt. 200.6)

(1) *Sublimate in closed tube.* If the mercury mineral powder is covered with four parts of sodium carbonate (previously dried by heating on metal or porcelain nearly to redness) and heated slowly, pure mercury appears as a gray sublimate (not as good a mirror as that of arsenic) or as globules on the walls of the tube. In the open tube cinnabar gives a black sublimate much like the arsenical mirror. If heated without soda in the closed tube most mercury minerals volatilize without decomposing.

(2) *Mercury coating on copper.* If a mercury mineral powder is dissolved in a weak acid, a clean piece of copper placed in the solution will be coated with metallic mercury so as to look as though it were silver plated.

Molybdenum ($Mo^{+4 \text{ or } +6}$; at. wt. 96)

(1) *Iodide sublimate on plaster.* If a molybdenum mineral powder is moistened with HI or mixed with potassium iodide and sulfur and heated on plaster, the sublimate is deep ultramarine blue.

(2) *Salt of phosphorus bead reaction.* If a little molybdenum mineral powder is added to a salt of phosphorus bead and heated

in the oxidizing flame, the color is yellowish green while hot, paler when cold; in the reducing flame it is dirty green when hot, pure green when cold.

(3) *Flame color.* Molybdenum oxide or sulfide colors the tip of the blue flame a pale yellowish green.

(4) *Color in solution.* If a finely powdered molybdenum mineral is placed in a test tube with a tiny bit of paper (about 1 mm. sq.) and a few drops of water are added and then a few drops of concentrated H_2SO_4, and the tube is heated till the acid fumes, and then allowed to cool before adding slowly a few drops of water, the solution becomes deep blue.

Nickel (Ni^{+2}; at. wt. 58.69)

(1) *Borax bead reaction.* If a nickel mineral powder is added to a borax bead and heated in the oxidizing flame, it becomes violet when hot and reddish brown when cold; in the reducing flame metal with a distinct metallic luster separates and the bead gradually becomes opaque. Even a small amount of cobalt makes the test unsatisfactory.

(2) *Color of solution.* If a nickel mineral is dissolved in HNO_3, the solution is apple green, and becomes pale blue with ammonia. A similar treatment of a copper mineral produces a deep blue color.

(3) *Dimethglyoxime precipitate.* If a nickel mineral is dissolved in weak acid and ammonia is added in slight excess, a few drops of dimethylglyoxime will produce a scarlet precipitate. If iron is also present, add tartaric acid before adding dimethylglyoxime.

Niobium (Columbium) (Nb^{+5}; at. wt. 93.1)

(1) *Color in solution.* If a niobium mineral powder is mixed with five parts of borax, moistened with water and fused to a bead, when two or three such beads are powdered and dissolved in HCl, addition of tin and boiling produces a blue color, changing slowly to brown with continued boiling; the color disappears on dilution with water. If much titanium is present a violet color appears before the blue color of niobium. Tungsten gives a similar reaction, but it may be distinguished by other tests.

Nitrogen ($N^{+3 \text{ or } +5}$; at. wt. 14)

(1) *Deflagration on charcoal.* If a nitrogen mineral is heated on charcoal it deflagrates, that is, it flashes into flame somewhat like gunpowder.

(2) *Fumes in the closed tube.* If a nitrogen mineral powder is heated in the closed tube with $HKSO_4$, NO_2 fumes are given off, whose red color is seen best by looking into the end of the tube.

Phosphorus (P^{+5}; at. wt. 31.02)

(1) *Precipitate with ammonium molybdate.* If a phosphorus mineral powder is dissolved in HNO_3 (after fusion with soda, if necessary) and a few drops of the cold solution are added to a solution of ammonium molybdate slightly acidulated with HNO_3, a yellow precipitate forms slowly. Arsenic minerals give a similar precipitate in a hot solution.

(2) *Phosphine odor.* If a phosphorus mineral powder is heated intensely with a little Mg ribbon in a closed tube and the mineral is then moistened with water, phosphine gas (PH_3) is produced, easily recognized by its offensive odor.

(3) *Flame color.* Phosphorus minerals, especially after moistening with H_2SO_4, produce a pale bluish green flame. Other elements giving a decided flame color may prevent this test from being satisfactory.

Potassium (K^{+1}; at. wt. 39.1)

(1) *Flame color.* A potassium mineral produces a pale violet flame color, easily hidden by even a small amount of sodium; but sodium color can be eliminated by observing the flame through a blue glass filter when the K color is violet or purplish red. Silicates should be powdered, mixed with an equal part of powdered gypsum and heated on a platinum wire previously moistened to make the powder adhere).

(2) *Alkaline reaction.* Some potassium minerals give an alkaline reaction on moist turmeric paper after intense ignition; but this test is also given by sodium, calcium, and some magnesium, strontium, and barium minerals.

For tests for potassium in silicates, see Silicon, page 218.

Selenium ($Se^{+2 \text{ or } +6}$; at. wt. 79.2)

(1) *Odor.* The fumes of an ignited selenium mineral have a horse-radish-like odor which is as distinctive as it is disagreeable.

(2) *Sublimate on charcoal.* If selenium is plentiful in a powdered mineral heated in the oxidizing flame on charcoal, brownish fumes are accompanied by a sublimate of steel gray SeO_2, which may have a border of red Se. Similar sublimates are obtained in the open and closed tubes.

(3) *Flame color.* The sublimate obtained on charcoal is volatile in the reducing flame and produces an azure blue flame color.

(4) *Sublimate on plaster.* A selenium mineral heated on plaster gives a red to crimson sublimate of Se, volatile in the reducing flame.

Silicon (Si^{+4}; at. wt. 28.06)

(1) *Reaction with sodium carbonate.* Quartz and opal, when powdered and mixed with Na_2CO_3, cause the soda bead to effervesce freely because the SiO_2 sets free CO_2.

(2) *Reaction with salt of phosphorus.* If a small fragment of a silicate mineral is heated in a salt of phosphorus bead, the bases dissolve in the bead, leaving a skeleton of undissolved translucent silica.

(3) *Gelatinization.* Some silicates are completely soluble in acids; but when the solution is boiled to supersaturation (at least on cooling) a jelly of H_2SiO_3 separates. Insoluble silicates give the same test if the powder is mixed with five parts of soda, fused, and then dissolved in HCl. It is desirable to make two or three large beads to provide plenty of material for this test, and for tests for bases present (described below).

(4) *Insoluble residue of SiO_2.* As stated above, some silicates are completely soluble in acids, and some are completely insoluble; still others are partly soluble, all the bases going into solution, leaving an insoluble residue of silica in powdery form, which makes the solution translucent if it remains in suspension.

To test for bases in silicates dissolve the powdered silicate mineral in HNO_3, after fusion with soda, if necessary. Evaporate to dryness, moisten with concentrated HCl and heat to boiling, add two parts of water, and boil again. The bases are dissolved and the silica is removed by filtering. Add a little HNO_3 to the filtrate, boil, and then add NH_4OH in slight excess. A light colored precipitate is evidence of alumina with practically no iron. A reddish brown precipitate is due to iron, but alumina may also be present. To test for Al, filter, put the precipitate in a test tube with a little water and a little KOH, and boil. $Al(OH)_3$ is dissolved and $Fe(OH)_3$ remains undissolved. Filter, add HCl, boil, and add NH_4OH in excess to precipitate $Al(OH)_3$. After removing the $Fe(OH)_3$ and $Al(OH)_3$ (if these are present), heat the filtrate to boiling and add ammonium oxalate to precipitate Ca; let stand ten minutes and filter (repeatedly, if necessary). Add to this filtrate a little more ammonium oxalate to make sure all the Ca has been precipitated. If no precipitate forms, add sodium phosphate and strong ammonia to precipitate Mg. Allow to stand for some time as this precipitate forms slowly. Filter; evaporate the filtrate to dryness and then heat to redness to expel ammonia salts; test the residue for K and Na flame colors by heating on a platinum wire.

Silver (Ag^{+1}; at. wt. 107.9)

(1) *Chloride precipitate.* If a silver mineral powder is dissolved in strong HNO_3 and the solution is diluted with water, addition of NaCl or HCl will cause a white precipitate of AgCl, which darkens on exposure to light and is soluble in ammonia. The precipitate may be tested as follows:

(2) *Sublimate on charcoal.* If a silver salt or mineral powder is mixed with three parts of soda and fused on charcoal in the reducing flame, a malleable metal globule of Ag is obtained. If Pb and Sb are also present, the sublimate is brown, red, or lilac.

Sodium (Na^{+1}; at. wt. 23)

(1) *Flame color.* Sodium compounds give a deep yellow flame color; some sodium silicates should be powdered and mixed with an equal volume of powdered gypsum before heating on a platinum wire to get a good test. But the test is so delicate that it is significant only when the color is strong and persistent. A clean platinum wire will give a slight sodium flame after being touched by the hands.

(2) *Alkaline reaction.* Some sodium minerals give an alkaline reaction on moist turmeric paper after ignition; but this test

is also given by potassium, calcium, and some magnesium, strontium, and barium minerals.

For tests for sodium in silicates, see Silicon, page 218.

Strontium (Sr^{+2}; **at. wt. 87.6**)

(1) *Sulfate precipitate.* If a strontium mineral powder is dissolved in strong acid (HNO_3, or not too much HCl), addition of a few drops of H_2SO_4 will produce a white precipitate of $SrSO_4$; the precipitate is soluble in much acid (unlike $BaSO_4$) and insoluble in boiling water (unlike $CaSO_4 \cdot 2H_2O$).

(2) *Flame color.* If a strontium mineral fragment or powder is moistened with HCl it will give a crimson flame color, similar to that of lithium; redder and more persistent than the Ca flame color. Lithium gives no precipitate with H_2SO_4.

(3) *Alkaline reaction.* Some strontium minerals give an alkaline reaction on moist turmeric paper after ignition; but this test is also given by potassium, calcium, and some sodium, magnesium, and barium minerals.

Sulfur ($S^{+2 \text{ or } +6}$; **at. wt. 32.1**)

Sulfides:

(1) *Fumes.* Some finely powdered sulfides give characteristic SO_2 fumes when heated in the oxidizing flame in the open tube or on charcoal. Such fumes give an acid reaction on moist litmus paper. Other sulfides (Fe and Cu) give white fumes of SO_3 and H_2SO_4 in the upper part of the tube.

(2) *Reaction with soda.* If a finely powdered sulfide is mixed with three parts of soda and fused (on charcoal or platinum or a flake of mica) and then placed on clean silver and moistened with water, a black stain of Ag_2S is produced. Or if the fused mass is moistened with HCl, H_2S gas is formed, easily recognized by its offensive odor. But Se or Te obscures this reaction.

(3) *Reaction with $BaCl_2$.* If a finely powdered sulfide is heated in strong HNO_3, red NO_2 fumes are given off and H_2SO_4 is formed. (In some cases free S may form a yellow to black scum on the liquid.) If the solution is diluted and $BaCl_2$ is added, a white precipitate of $BaSO_4$ is formed.

Sulfates:

(1) *Reaction with $BaCl_2$.* If a finely powdered sulfate is dissolved in dilute HCl and $BaCl_2$ is added, a white precipitate

of $BaSO_4$ is formed. A similar precipitate of $CaSO_4 \cdot 2H_2O$ is soluble in boiling water, which does not affect $BaSO_4$.

(2) *Reaction with soda.* If a finely powdered sulfate is mixed with one part of powdered charcoal and two parts of soda and then fused, it gives the same reaction as a sulfide does with soda. See (2) on preceding page.

Tellurium (Te^{+2}; at. wt. 127.5)

(1) *Sublimate on charcoal or in the tube.* If a powdered tellurium mineral is heated in the oxidizing flame on charcoal, a white sublimate of TeO_2 forms near the assay; it is volatile in the reducing flame, giving a pale greenish flame color. There may be a brownish coating farther from the assay. The results in the open tube are similar. In the closed tube metallic globules may form also.

(2) *Color of solution.* If a finely powdered tellurium mineral is heated gently in concentrated H_2SO_4 the solution has a reddish violet color. After the solution is cooled, the addition of water causes a black precipitate of Te, with disappearance of the color (unlike Mn).

Tin (Sn^{+4}; at. wt. 118.7)

(1) *Sublimate on charcoal.* If a finely powdered tin mineral is fused on charcoal with one part of powdered charcoal and two parts of soda, globules of metallic tin form; long continued ignition in the oxidizing flame produces a white sublimate of SnO_2, not easily volatilized.

(2) *Reaction with HNO_3.* If tin or a tin sulfide is heated in concentrated HNO_3, it does not dissolve, but reacts to form white metastannic acid (H_2SnO_3).

(3) *Reaction with HCl and Zn.* If a fragment of cassiterite is heated with Zn in dilute HCl, it becomes coated with dull gray metallic tin, which becomes bright when rubbed between the fingers.

(4) *Borax bead test.* If a finely powdered tin mineral is added to a borax bead made pale blue with Cu, and heated well in the oxidizing flame, it becomes ruby red after slight treatment in the reducing flame.

Titanium ($Ti^{+4 \text{ or } +3}$; at. wt. 47.9)

(1) *Salt of phosphorus bead test.* If a finely powdered titanium mineral is heated in a salt of phosphorus bead with a granule of tin in the oxidizing flame, the bead is yellow while hot, colorless when cold; in the reducing flame it is yellow while hot, and violet when cold. The test is not satisfactory if other elements giving color to the bead are present.

(2) *Reaction with HCl and Sn.* If a finely powdered titanium mineral is fused with borax or soda and boiled with a little Sn in HCl, the solution becomes violet if more than 3 per cent of Ti is present.

(3) *Reaction with H_2O_2.* If a finely powdered titanium mineral is fused with soda, and then boiled in a little concentrated H_2SO_4 and an equal volume of H_2O until clear, the solution becomes yellow to amber upon dilution with H_2O and addition of H_2O_2.

Tungsten (W^{+6}; at. wt. 184)

(1) *Salt of phosphorus bead test.* If a finely powdered tungsten mineral is added to a salt of phosphorus bead, the bead is colorless in the oxidizing flame, but in the reducing flame it is green while hot and distinct blue when cold.

(2) *Reaction with HCl and Zn (or Sn).* If a finely powdered tungsten mineral is decomposed by HCl, a yellow residue of WO_3 remains; if Zn (or Sn) is added and boiling is continued, a blue color appears, changing slowly to brown. If the tungsten mineral is insoluble in HCl, fuse with much soda on a platinum wire, pulverize, and dissolve in water (filter, if solution is incomplete); the solution becomes blue when a little HCl is added and it is boiled with Zn (or Sn).

Uranium ($U^{+6 \text{ or } +4}$; at. wt. 238.14)

(1) *Salt of phosphorus bead test.* If a finely powdered uranium mineral is added to a salt of phosphorus bead and heated in the oxidizing flame, the bead is yellow while hot and yellowish green when cold; in the reducing flame it is a pure green.

Vanadium (V^{+5}; at. wt. 50.96)

(1) *Salt of phosphorus bead test.* If a finely powdered vanadium mineral is heated in the salt of phosphorus bead, the color is yellow to amber in the oxidizing flame and green in the reducing flame. The borax bead colors are nearly the same.

(2) *Reaction with H_2O_2.* If a finely powdered vanadium mineral is dissolved in acid (after fusion with soda, if necessary), the solution becomes reddish brown upon addition of H_2O_2 (and consequent formation of pervanadic acid, HVO_4).

Zinc (Zn^{+2}; at. wt. 65.38)

(1) *Color with cobalt nitrate.* If a powdered infusible light-colored zinc mineral is moistened with cobalt nitrate and intensely heated, it becomes green; but infusible zinc silicate, treated the same way, becomes blue, usually with some green also.

(2) *Flame color.* A large fragment of a zinc mineral produces a vivid pale bluish green flame color in streaks, when heated near the tip of the oxidizing flame.

(3) *Sublimate on charcoal.* If a finely powdered zinc mineral is mixed with half its volume of soda and made into a paste with water (after thorough roasting, if it contains S, As or Sb) and heated intensely in the reducing flame on charcoal, a sublimate forms, which is yellow while hot and white when cold. If the charcoal has been moistened previously with cobalt nitrate, the sublimate is grass green.

Zirconium (Zr^{+4}; at. wt. 90.6)

(1) *Reaction with turmeric paper.* If a finely powdered zirconium mineral is mixed with soda and fused on platinum wire and then dissolved in a little HCl, turmeric paper placed in the solution becomes orange-yellow. For comparison, place another turmeric paper in another tube containing only the acid.

5

Descriptive Mineralogy

In order that a description of minerals may be suitably arranged the minerals must first be classified on some reasonable basis. Many classifications are possible and several are very useful especially for determinative work, but there are two of special importance, namely, the classification based on chemical composition and isomorphous relations, and the economic classification, based on the use of minerals. The first is employed as a basis for the descriptions which follow, and the second one will be illustrated in the chapter on the uses of minerals.

Crystal-Chemical Classification of Minerals

More than a century ago the American mineralogist, James D. Dana, first published his "natural" classification of minerals. In somewhat modified form the same classification is still very generally used, not only in America, but wherever minerals are studied. It begins with minerals of the simplest composition. Within each division minerals are arranged so as to bring out isomorphous relations. Ten divisions may be recognized, as follows:

1. Elements.
2. Sulfides and sulfosalts.
3. Halides.
4. Oxides.
5. Nitrates, carbonates, etc.
6. Sulfates, chromates, tungstates, etc.
7. Borates, aluminates, etc.
8. Phosphates, vanadates, arsenates, etc.
9. Silicates, titanates, etc.
10. Organic compounds.

The description of each mineral will be given in the following order:

Name, crystal system, formula.
Crystallography.
Physical characters.
Chemical composition and relations; varieties.
Occurrence, associations, and localities.
Uses.

1: Elements

Disregarding elements found as gases in the atmosphere, fewer than twenty elements are found uncombined in nature. These can be divided into metals, semimetals, and nonmetals. The metals found as such are: gold, silver, copper, platinum, iron, iridium, palladium, osmium, mercury, lead, and tin. The semimetals are arsenic, antimony, and bismuth; these are very closely related crystallographically. The nonmetals are carbon, sulfur, selenium, and tellurium. The elements of sufficient importance to be described here are:

METALS

Noble Metal (Gold-Silver), Copper, Platinum, *Iron*

SEMIMETALS

Arsenic, Bismuth

NONMETALS

Carbon (Diamond and Graphite), Sulfur

Noble Metal $\begin{cases}\text{Gold}\\ \text{Silver}\end{cases}$ **Isometric** **$\begin{matrix}\text{Au}\\ \text{Ag}\end{matrix}$**

Crystals are rare; they show the octahedron, dodecahedron, etc; more frequently acicular reticulated or arborescent. Also matted in tufts or massive.

No cleavage. H. = 2.5–3. The specific gravity varies (as shown in Fig. 346) from 19.3 for gold to 10.5 for silver. Very malleable and ductile. Metallic luster. Opaque. Properties vary markedly with the composition, and the native mineral not only shows the entire range from (nearly) pure gold to (nearly) pure silver, but also may contain palladium, platinum, iron, copper, antimony, mercury, etc. The color and streak vary from gold yellow (nearly pure Au) to very pale yellow (with about 50% Ag) to silver white (nearly pure Ag), and also to brassy yellow (with some Cu). Noble metal fuses easily, see Fig. 346.

Gold is soluble in aqua regia; silver in nitric acid—HCl produces a white precipitate.

Gold is widely but very sparsely distributed in nature, and only rarely in sufficient abundance to be of economic importance. It is found (1) in veins and other primary deposits and (2) in secondary deposits of stream gravels, called placers. The commonest type of primary deposit is that in quartz veins (called "quartz reefs" in Australia) containing sulfides, especially pyrite, as well illustrated at the Homestake Mine in the Black Hills. The most productive gold mines in the world are those in South Africa, but gold is obtained also in considerable quantities in many other places, including Australia, Mexico, Canada, South America, Siberia, Japan, Philippine Islands. Among the localities in this country where gold is obtained are California, South Dakota, Alaska, Colorado, Arizona, Utah, Nevada, Montana. Gold placer deposits are more accessible than primary deposits and many have been completely exhausted, but this type of deposit is still the source of about a quarter of the gold output of the United States. Such gold is now obtained largely by dredging.

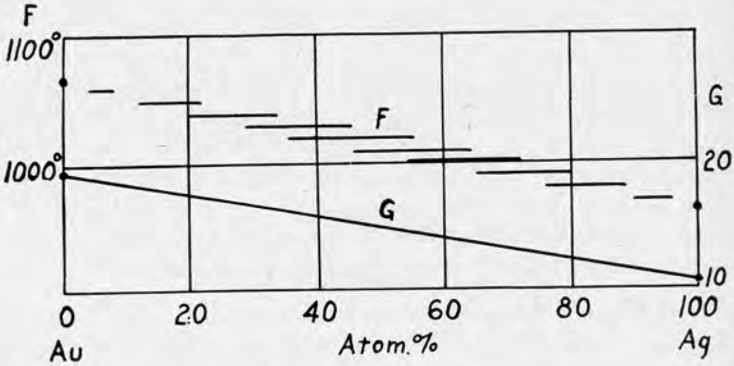


FIG. 346. Noble metal.

The National mine in northern Nevada produced noble metal (valued at several million dollars) which was called "gold" but actually contained about 50 per cent silver—of course, the owners were paid far more for the gold than for the equal quantity of silver produced.

Native silver is much rarer than native copper or even native gold, but it is widely distributed chiefly in the oxide zone as a secondary mineral, associated with calcite, quartz, barite, and fluorite. Crystals and large masses of silver have been found at Kongsberg, Norway. Silver has been obtained also at Freiberg (Saxony), Pribram (Bohemia), Broken Hill (New South Wales). But silver is pre-eminently an American product, being obtained in Chile, Peru, and Bolivia in South America, and notably at Sonora, Durango, and Sinaloa in Mexico. A mass weighing over two tons was obtained from the Keeley Mine at South Lorrain, Ontario. It is also found at Cobalt (Ontario), Butte (Montana), Tonopah (Nevada), Aspen (Colorado), and in the Lake Superior district (with copper), in the Bingham and Tintic districts in Utah, etc.

The chief use of gold is in coinage, but it is also used in some scientific apparatus and in jewelry.

Silver is used for coinage, jewelry, and ornamental purposes, and also in physical, chemical, and surgical apparatus.

Native Copper **Isometric** **Cu**

Crystals of copper have the full symmetry of the normal class of the isometric system, being often tetrahexahedrons or dodecahedrons, often in groups and distorted. More frequently massive and irregular in shape; also filiform or arborescent.

No cleavage. Hackly fracture. H. = 2.5–3. G. = 8.8–8.9. Fuses easily (at 1080°C.). Luster metallic. Color copper red, often modified by alteration. Streak copper red and shining metallic. Opaque. Excellent conductor of heat and electricity.

Native copper usually contains only small amounts of silver, iron, arsenic, bismuth, etc. Soluble in nitric acid; solution gives deep blue color with ammonia.

Some native copper is secondary in origin and found only in the oxide zone of veins containing copper (and iron) sulfides or sulfosalts as primary minerals. Such deposits are found in Arizona and many other regions. But the most important occurrence of native copper is of a different type, which is found abundantly only in northern Michigan. Here the copper is primary and extends to great depths (as far as the ore continues). It occurs (1) as a cement filling the interstices of a conglomerate or even replacing sand grains or pebbles, (2) filling amygdaloidal cavities in a basic igneous rock, and (3) in veins cutting various rocks of the region. It is associated with calcite, datolite, prehnite, quartz, epidote, chlorite, and various zeolites. For some time Michigan produced more copper than any other district in the world; its total output to 1940 exceeded 4,500,000 tons.

Copper is used in large amounts for electrical apparatus, transmission lines, in making copper wire, nails, sheets, valves, etc., as well as in coinage, ammunition, chemical reagents, brass, bronze, etc.

Native Platinum **Isometric** **Pt**

Crystals, small cubes, very rare; usually in scales or grains.

No cleavage. Hackly fracture. Malleable and ductile. H. = 4–5. G. = 14–19 (native); pure melted, 19.7; hammered, 21.2. Infusible. Color and streak whitish steel gray to dark gray; magnetic if the amount of iron is important.

Native platinum is never pure and commonly contains 8–20 per cent of iron, 0.5 to 2.0 per cent each of palladium and copper, and 1 to 3 per cent each of rhodium and iridium. Soluble only in hot concentrated aqua regia.

Platinum was first discovered in placers in Colombia in 1735, associated with gold, zircon, magnetite, etc. Nearly a century later, in 1822, it was found in alluvial deposits of the Ural Mountains. Nearly all the output of platinum comes from placers, but it is known in veins in basic igneous rocks, especially peridotites (from French "peridot" = olivine). It has been found in small amounts in North Carolina, California, and Oregon, but it is obtained chiefly from Russia; recently, however, important deposits have been discovered in South Africa.

Platinum was used in coinage in Russia at one time. It is also used in jewelry, dentistry, surgical instruments, physical, chemical, and electrical apparatus, and as a catalytic agent in the manufacture of acetic, nitric, and sulfuric acids.

Native Iron *Isometric* Fe

Crystals small, rare, cubes or octahedrons. Usually irregular granular.

Distinct cubic cleavage; also a lamellar structure parallel to (111) and (110). Fracture hackly. Malleable. H. = 4–5. G. = 7.3–7.8. Luster metallic. Color steel gray to iron black. Strongly magnetic.

Native iron always contains some nickel; also usually cobalt, copper, etc. It is either terrestrial or meteoric in origin. Meteoric iron usually contains more nickel than terrestrial, but nickel with subordinate iron is also found as a terrestrial product. Terrestrial iron is very rare; found on the coast of Greenland, and very sparsely elsewhere. Meteoric iron forms the whole mass of "iron meteorites," the matrix of "siderolites" and grains or scales in "stony meteorites." Etching a smooth surface with dilute nitric acid commonly discloses a coarse crystalline structure (called Widmanstätten figures) in iron meteorites; it consists of lines or bands crossing at various angles depending upon the crystal direction of the surface. The angle is 60° if the surface is parallel with 111 and 90° if it is parallel with 100.

In spite of its scarcity native iron was of some importance in the development of man in prehistoric times, but it became far more important to him when he learned to make it by reducing oxidized iron ores with charcoal.

Arsenic *Rhombohedral* As

Crystals are rhombohedrons with angles near 90° and therefore closely resembling cubes, but they are very rare. Usually granular or scaly in reniform or botryoidal masses, which may have concentric structure.

Basal cleavage perfect, but not easily recognized. H. = 3–4. G. = 5.6–5.8. Metallic luster. Opaque. Tin-white color on fresh surface, but soon tarnishes to dark gray. Streak gray.

Commonly contains some antimony, and sometimes bismuth; it may contain traces of iron, cobalt, nickel, silver, or gold.

Found chiefly in metalliferous veins associated with silver, cobalt, and nickel ores. It is found at Freiberg and Schneeberg in Saxony, at Andreasberg in the Harz Mountains, at Joachimstal in Bohemia, at Kongsberg in Norway, on Vancouver Island, British Columbia, and rarely in the United States.

Arsenic is used in shot metal and in arsenical copper. But most of the arsenic of commerce is obtained as a by-product in smelting copper and lead ores. It is obtained as "white arsenic," which is arsenic oxide (As_2O_3). It is then converted into calcium arsenate ($CaAs_2O_8 \cdot 3H_2O$), or lead arsenate ($Pb_3As_2O_8$), or paris green (copper aceto-arsenite), etc., which are used as insecticides.

Bismuth *Rhombohedral* Bi

Crystals are rhombohedrons nearly cubic in shape, but they are rare. Elongated rhombohedrons are shown in Fig. 347. Usually reticulated, platy, or compact masses.

Perfect basal cleavage. Sectile. Brittle to malleable, if heated. H. = 2.5. G. = 9.8. Fuses very easily before the blowpipe (271°C.) and volatilizes entirely. Metallic luster. Color silver white with a reddish tinge. Streak lead gray. Tarnishes easily. Opaque.

Usually contains traces of arsenic, sulfur, tellurium, etc. Soluble in nitric acid; addition of water causes a white precipitate.

Found rarely in veins with ores of cobalt, silver, lead, zinc, etc., for example, at Freiberg in Saxony, Joachimstal in Bohemia, Cobalt, Ontario, in Bolivia, Norway, Sweden, Cornwall.

Bismuth is used in making easily fusible alloys, so important for safety plugs for boilers, automatic sprinkler heads, firedoor releases, dental models, etc. It is also used in rifle bullets and thermopiles. But more bismuth is used in making pharmaceutical compounds; salts of bismuth are also used in calico printing and in making highly refractive glass.

Diamond **Isometric** **C**

Crystals are commonly octahedrons or dodecahedrons, but cubes, tetrahedrons and modified forms are also found; faces are often curved (reason unknown) and striated. Twinning common on 111, both of the contact and penetration types; often flattened on 111.

Difficult octahedral and poor dodecahedral cleavage. Conchoidal fracture. H. = 10 (the hardest substance known). G. = 3.2–3.52 (high for a nonmetallic mineral). Adamantine luster. Usually colorless and glassy, but may be yellow, red, green, blue, brown, black; never pleochroic. Transparent to translucent or even opaque. Refringence extremely high:

$N = 2.4135$ Li, 2.4195 Na, 2.4278 Tl. The brilliance of a diamond is due to this very high index of refraction and the "fire" (or color of the refracted and internally reflected light) is due to the strong dispersion—$N_{Tl} - N_{Li} = 0.0143$. Usually isotropic, but may show abnormal birefringence. Transparent to X rays, while lead glass imitations such as *paste* and *strass* are opaque to them. Some diamonds phosphoresce when exposed to electric discharges or to ultraviolet light or even when rubbed; radium emanations may cause a change of color.

Courtesy of Hamilton Watch Co. and U. S. Industrial Diamond Co.

FIG. 347. Photomicrograph between crossed nicols of thick sections of diamonds parallel with 100. ×3.

Diamonds are so hard that it is only by means of other diamonds that they can be scratched, cut, or drilled. Several plates cut from industrial diamonds are shown in Fig. 347.

Colorless diamonds are pure carbon and even black diamond is nearly pure. Infusible, and insoluble in acids and alkalies. If heated out of contact with oxygen (so that combustion cannot occur), it inverts to graphite at about 1885°C. Three varieties of diamond are recognized: (1) Diamond proper, which includes single crystals or fragments and simple aggregates, such as twins. (2) Bort (or bortz or boart), which includes those aggregates which have a confused irregular or fibrous structure. Crystals and fragments of inferior quality are often called bortz. (3) Carbonado or black diamond, which includes aggregates of very fine granular structure. Such aggregates have no cleavage and are therefore extremely useful for diamond drilling, for which diamonds proper are unfit on account of their cleavages. Small black diamonds are more valuable than small diamonds proper, though they are quite unfit for jewels.

In early times India was the chief source of diamonds, although they were occasionally obtained elsewhere. About two hundred years ago Brazil became the leading producer, but for the last sixty years diamonds have been obtained chiefly from the South African mines, which now supply about 95 per cent of the diamonds used for gems. Like gold, diamonds were found first in stream gravels (called "placers" for gold, and "river diggings" for diamonds). Brazilian diamonds have come chiefly from such deposits and the first African stones came from the same source. Some years later the "dry diggings" were discovered. These are the primary sources; near the surface in the South African mines the diamonds were in a highly decomposed material known as the "yellow ground," which occupied roughly circular areas varying from 20 to 800 or more meters in diameter. At depth these areas become less extensive and the rock becomes harder; it is then a basic igneous rock called kimberlite, which is a variety of peridotite. This is called locally the "blueground." Further developments have shown that these diamonds are in volcanic necks. The diamonds were recovered very easily from the decomposed "yellow ground"; they were at first recovered from the "blue ground" by waiting until it altered (upon exposure) to a condition in which it was easily broken up or crushed. This required a variable time—surprisingly short—about a year ordinarily. But later, at most of the large mines, the blue ground was crushed and concentrated immediately. The average tenor of diamonds is less than $\frac{1}{3}$ carat per ton of rock (a carat is one fifth of a gram or 200 milligrams). Recently the output of diamonds from the volcanic rocks of South Africa has declined very considerably and a large production is now coming from placer mines in Southwest Africa and the Belgian Congo.

The largest diamond ever found was the "Cullinan" or "Star of Africa," taken from the Premier Mine in June, 1905.

It measured about 5 × 6.5 × 10 cm. and weighed 3106 carats. Because of flaws in it, it was cut into many (105) smaller stones, the two largest of these cut stones weighing 530 and 317 carats respectively. The Star of Africa was purchased by the Transvaal Assembly for about a million dollars and presented to Edward VII. Some of the other famous cut diamonds include: the Jubilee, 245 carats; Orloff, 195 carats; Regent, 137 carats; Tiffany (yellow), 128 carats; Star of the South, 125 carats; Kohinoor, 106 carats; Hope (blue), 44 carats; and Dresden (green), 40 carats.

In the United States diamonds have been found very sparsely in glacial drift in Ohio, Indiana, Illinois, Wisconsin, etc. In 1906 diamonds were discovered in peridotite in Pike County, Arkansas. Geologically this occurrence is quite similar to the great diamond mines of South Africa, but thus far no great production has been achieved, about 40,000 stones up to 1932 (when production ceased), ten per cent of which were of gem quality.

Diamonds proper are used extensively as gems; inferior stones and powder are used as abrasives especially to polish other stones; as glass cutters, etc. Bortz and carbonado are used in the bits of diamond drills and as diamond dies for drawing wire.

Graphite **Hexagonal** **C**
$c = 1.386$

Crystals have rhombohedral symmetry, showing triangular markings on the basal plane, but the plates have hexagonal appearance. Commonly found in concentric foliated masses.

Perfect basal cleavage giving thin flexible and inelastic laminae. H. = 1–2. G. = 2.25. Greasy feel. Infusible. Luster metallic. Color iron black to steel gray. Streak black (that of molybdenite is greenish especially on unglazed porcelain). Opaque. A good conductor of electricity; transparent to X rays.

Graphite is pure carbon except when it contains some iron. Mechanically held impurities are commoner than with diamond and may amount to considerable percentages, even up to 20%. Not attacked by acids. Deflagrates (burns with violence) with KNO_3. Commercially two varieties are recognized, namely, crystalline and "amorphous." But both types are actually crystalline, though the second is not obviously so.

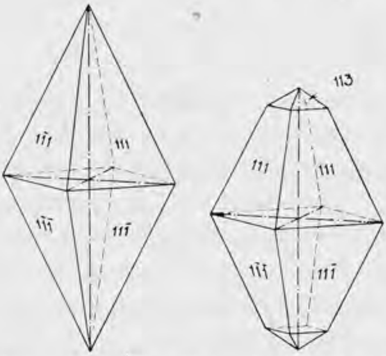
Graphite is found in very small amount in many igneous rocks; also, in greater quantity in rare pegmatities and in some schists and gneisses. It is also found in some contact rocks and in meteorites. In some cases, as in Rhode Island, beds of coal have been partially metamorphosed to graphite. Important production of graphite has been from the Adirondack region of New York, especially near Ticonderoga. The most important foreign sources are in Ceylon and Madagascar. "Crystalline graphite" is the flaky lamellar material; it is used chiefly in the manufacture of crucibles, in pencils (therefore inappropriately called "black lead"), in lubricants, in dynamo brushes, and in electrotyping. "Amorphous graphite" is the massive material, usually impure, which is abundant in nature (usually due to metamorphism of hydrocarbons); it is used chiefly for foundry facings, stove polish, and certain kinds of paint. Artificial graphite is now produced from coal or coke in large quantities in electric furnaces especially at Niagara Falls.

Sulfur **Orthorhombic** **S**

$a : b : c = 0.813 : 1 : 1.903$

Crystals are commonly steep pyramidal; sometimes thick basal tablets. See Figs. 348 and 349. Also massive, granular, earthy, encrusting or powdery.

Cleavages indistinct; conchoidal fracture; brittle. H. = 1.5–2.5. G. = 2–2.1. Resinous luster. Usually translucent. Color yellow, streak white to pale yellow. May be brown, reddish, greenish, or grayish from impurities. Extreme refringence and birefringence with $(+)2V = 69°$ $N_g = 2.240$, $N_m = 2.003$, $N_p = 1.950$, $N_g - N_p = 0.290$. $X = a$, $Y = b$. Poor conductor of heat and electricity; negatively electrified by friction.



Figs. 348–349. Natural crystals of sulfur.

Usually nearly pure, but may contain selenium and impurities of bitumen and clay. Inverts to a monoclinic form at 108°, melts at 119°, and burns at 270°C. with a bluish flame to sulfur dioxide. Several other crystal phases known. Insoluble in water and acids, but dissolves in carbon disulfide.

Sulfur is deposited in nature by several different processes. It is a product of the cooling of gases from igneous sources. Sulfur of this type is found in Sicily, Mexico, Hawaii, Japan, etc. Sulfur is also produced by the reduction of sulfate minerals, especially gypsum. Sulfur of this type is important in Sicily, Louisiana, and Texas. The first type is found around volcanoes. The second type is obtained from regions of salt lake deposits.

The mining of sulfur has been an important industry in Sicily for many years. The Sicilian deposits are found at and near the surface and the sulfur is obtained by ordinary methods of mining. During the last half century the Frasch method of obtaining sulfur from buried deposits has been developed in Louisiana and Texas. When using this method, pipes of three different sizes (the smaller inside the large) are placed in a drill hole from the surface to the deposit, which may be several hundred feet below. Compressed air is forced down the smallest pipe and superheated water (240° F.) down the largest pipe. The water melts the sulfur and the compressed air forces it up the intermediate pipe to the surface. No shafts or tunnels, but only drill holes, are necessary; and the process not only extracts the sulfur but also purifies it.

Sulfur is used as a fertilizer, as an insecticide, in medicines, in bleaching silk, straw and wool, in vulcanizing rubber, in making wood pulp, matches, and gunpowder. It is also used in making sulfuric acid, though sulfides can be used to better advantage for this purpose.

2. Sulfides and Sulfosalts

This division includes some of the most important ore minerals:

Argentite	Ag_2S	Bornite	Cu_5FeS_4
Galena	PbS	Chalcopyrite	$CuFeS_2$
Sphalerite	ZnS	Pyrrhotite	FeS
Pyrite	FeS_2	Cinnabar	HgS
Cobaltite	$CoAsS$	Niccolite	$NiAs$
Smaltite	$(Co,Ni)As_2$	*Greenockite*	CdS
Pentlandite	$(Fe,Ni)S$	*Millerite*	NiS

Molybdenite	MoS_2
Covellite	CuS
Chalcocite	Cu_2S
Stibnite	Sb_2S_3
Bismuthinite	Bi_2S_3
Marcasite	FeS_2
Arsenopyrite	$FeAsS$
Realgar	AsS
Orpiment	As_2S_3
Calaverite	$AuTe_2$
Sylvanite	$(Au,Ag)Te_2$
Gray Copper	
Tetrahedite	$Cu_{10}Zn_2Sb_4S_{13}$
Tennantite	$Cu_{10}Zn_2As_4S_{13}$
Stannite	$Cu_2(Fe,Zn)SnS_4$
Ruby Silver	
Proustite	Ag_3AsS_3
Pyrargyrite	Ag_3SbS_3
Bournonite	$CuPbSbS_3$
Enargite	$Cu_3(As,Sb)S_4$
Jamesonite	$Pb_2Sb_2S_5$

Argentite (Silver Glance) *Isometric* Ag_2S

Crystals often octahedral or cubic. Often in groups or filiform; also massive.

Cleavage only in traces. H. = 2.–2.5. G. = 7.2–7.4. Sectile. Luster metallic but easily tarnishes to dull black. Color and streak lead gray. Opaque.

Fuses on charcoal with intumescence giving sulfurous fumes and a globule of silver. Isometric above 180°C. and orthorhombic (*acanthite*) at ordinary temperatures.

Found in veins often with galena, tetrahedrite, chalcopyrite, bornite, pyrite, etc. Important at Colquechaca (Bolivia), Guanajuato and Zacatecas (Mexico), Aspen (Colorado), Tonopah (Nevada), etc.

Argentite is an important ore of silver.

Galena **Isometric** **PbS**

Crystals usually cubic to octahedral. Twinning on 111. Also massive.

Perfect cubic cleavage. H. = 2.5. G. = 7.3–7.6. Metallic luster. Color lead gray. Streak grayish black.

Galena is rather pure PbS, but nearly always contains traces of silver and may contain small amounts of antimony, iron, zinc, bismuth, or gold. Decomposed by HNO_3.

Galena is very widely distributed both in beds, in contact deposits and in veins in all kinds of rocks, but especially in or near igneous rocks. It is commonly associated with sphalerite, chalcopyrite, pyrite, tetrahedrite, quartz, calcite, fluorite, etc. Important localities include Freiberg (Saxony), Pribram (Bohemia), Müsen (Westphalia), Claustal (Germany), Broken Hill (Australia), San Luis Potosi (Mexico), Sullivan (British Columbia). In the United States galena is important in the Joplin district of Missouri, Oklahoma, and Kansas, in the Platteville district of Wisconsin, Coeur d'Alene region, Idaho, and the Bingham district of Utah.

Galena is the chief source of metallic lead, but it is also a valuable silver ore. Metallic lead is used in storage batteries, cable coverings, building, ammunition, foil, solder, type metal, and bearing metal. Compounds of lead are used as pigments and insecticides (the arsenate).

Sphalerite **Isometric, tetrahedral** **(Zn,Fe)S**

Crystals common and often tetrahedral or dodecahedral or complicated. Twinning on 111, often repeated. Commonly massive cleavable; coarse to fine granular or fibrous and botryoidal.

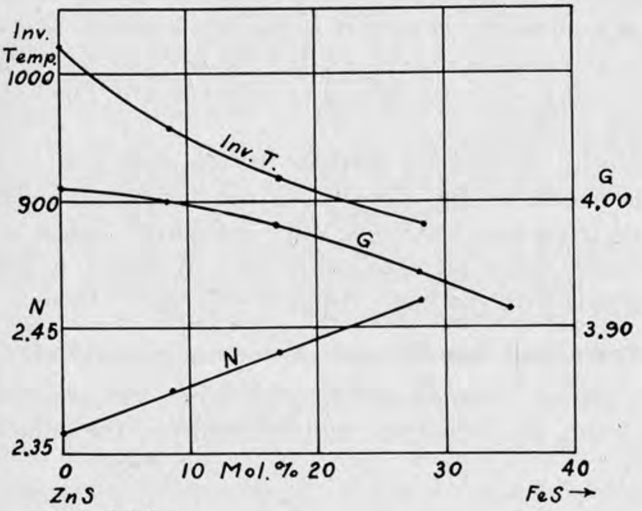


Fig. 350. Sphalerite.

Perfect dodecahedral cleavage (six directions); brittle. H. = 3.5–4. G. = 3.9–4.2. See Fig. 350. Resinous to adamantine luster. Color very variable from white through yellow and brown to black; also green. Streak white to brown. Transparent to translucent. Rarely triboluminescent. Isotropic with extremely high refringence. $N = 2.365$ to 2.47, varying with tenor of iron, as shown in Fig. 350.

Sphalerite usually contains some iron (up to 28% FeS) and may contain manganese, cadmium, mercury as well as traces of iridium, gallium, silver, gold. Infusible or nearly so. Soluble in hot HCl.

It is found in veins and replacements in dolomite and limestone, notably in the Mississippi Valley, especially in Missouri, Kansas, Oklahoma, and Wisconsin. It is also found in metalliferous veins, such as those of Montana, Idaho, Utah; and less commonly in contact deposits of the West. Sphalerite is often closely associated with galena. Important foreign localities include Freiberg (Saxony), Pribram (Bohemia), Binnenthal (Switzerland), Cornwall (England), and Yechigo (Japan).

Sphalerite is the chief ore of zinc. Metallic zinc (called spelter in commerce) is used in brass, white metal, and German silver; in galvanizing iron to prevent rusting and as a precipitant for gold; and in die casting and as rolled zinc. The oxide is an important pigment.

Sphalerite inverts to *wurtzite* at temperatures of 880° to 1020°, as shown in Fig. 350. Both sphalerite and wurtzite are deposited from acid solutions; only sphalerite (below inversion temperature) from alkaline solutions. Wurtzite is hexagonal hemimorphic with distinct prismatic cleavage. Rare.

Pyrite (Fool's Gold, Iron Pyrites) Isometric, pyritohedral FeS_2

Crystals are common and may be large; the common forms are the cube, pyritohedron, and octahedron; the cube is often striated by narrow lines of pyritohedral faces. See Figs. 351 and 352. Twinning by penetration with 110 as the twinning plane; such a twin is called an *iron cross*. Also massive, granular, reniform, etc.

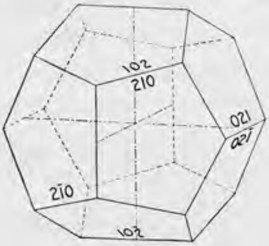


FIG. 351. Pyritohedron of pyrite.

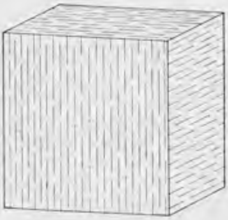


FIG. 352. Striated cube of pyrite.

Very poor cleavage and uneven fracture. H. = 6–6.5. G. = 5.02. Brittle. Metallic luster. Color pale brass yellow. Streak greenish to brownish black. Opaque.

Pyrite is fairly pure FeS_2, but often contains small amounts of cobalt, nickel, copper, arsenic, and gold. Minute amounts of gold make it valuable as a gold ore. Pyrite alters in nature quite readily, especially in the presence of oxygen and water. Alteration products include hematite or limonite and also sulfuric acid, which reacts to produce gypsum and other sulfates. Pseudomorphs of limonite after pyrite are not rare.

Pyrite is one of the most widely distributed of minerals, of course usually rather sparsely so. It is formed under many varying conditions. It is an accessory in many igneous rocks; it is found in many metamorphic rocks in small amount; it is both primary and secondary in origin in various sedimentary rocks; finally it is abundant in some contact deposits and some veins. It forms artificially from alkaline and neutral solutions at moderate temperatures and at higher temperatures under pressure; it also forms from acid solutions.

Notable deposits of pyrite include those at Freiberg (Saxony), Pribram (Bohemia), St. Gotthard (Switzerland), Traversella (Italy), Falun (Sweden), Liskeard (Cornwall), Rio Tinto (Spain), and Hitachi mines (Japan). In this country pyrite is obtained from, among other states, Tennessee, New York, Missouri, Montana, Wisconsin.

Pyrite is used chiefly as a source of sulfuric acid and also of iron sulfate (called *copperas*). It is also a gold ore in some cases. It is only after alteration, usually to limonite (either natural or artificial), that it can be used as an iron ore. Even after alteration it is not considered a desirable iron ore, because even small amounts of sulfur are detrimental to iron and such amounts may still be present.

Other minerals related to pyrite include *hauerite* (MnS_2), *gersdorffite* (NiAsS), *ullmannite* (NiSbS), and *sperrylite* ($PtAs_2$).

Cobaltite **Isometric, tetartohedral** **CoAsS**

Crystals usually cubes or pyritohedrons, like pyrite. Also granular massive. Cube faces often striated, like pyrite.

Good cubic cleavage, uneven fracture. Brittle. H. = 5.5. G. = 6.–6.3. Metallic luster. Color silver white, at times with reddish tinge. Streak grayish black. Opaque.

Cobaltite ($CoAsS$) usually contains some iron, even up to 12 per cent. Soluble in nitric acid. Alters to pink erythrite ($Co_3As_2O_8 \cdot 8H_2O$).

It usually occurs in contact deposits with other cobalt minerals and pyrrhotite, chalcopyrite, pyrite, galena, etc. Localities where it is found include Dashkasan (Russia), Tunaberg (Sweden), Skutterud (Norway), St. Just (Cornwall), Cobalt (Ontario).

It is an ore of cobalt, which is used in "stellite" alloys for high speed steels and "alnico" alloys for permanent magnets. The oxide is used as a coloring agent in pigments and ceramics.

Smaltite **Isometric, pyritohedral** $(Co,Ni,Fe)As_2$

Crystals octahedral or cubic. Usually massive, compact or granular.

Indistinct cleavage; uneven fracture. H. = 5–6. G. = 6.4–6.9. Luster metallic. Color tin white to steel gray. Dull tarnish. Streak grayish black.

In smaltite, nickel may proxy for cobalt in any amount from none to complete substitution ($NiAs_2$, called *chloanthite*). Also iron may come in—a variety with considerable iron has been named *chathamite*. Often contains some sulfur, bismuth, and copper. Alters easily to the pink mineral erythrite ($Co_3As_2O_8 \cdot 8H_2O$).

Usually occurs with other cobalt and nickel and silver ores and with barite, quartz, arsenopyrite, etc. Found at Freiberg (Saxony), Cornwall (England), Tunaberg (Sweden), La Motte Mine (Missouri), Cobalt (Ontario), and elsewhere.

Used as an ore of cobalt and nickel.

Pentlandite **Isometric** $(Fe,Ni)S$

Crystals very rare; usually granular massive.

Octahedral cleavage. H. = 3.5–4. G. = 5±. Luster metallic. Color and streak light bronze yellow. Opaque. Not magnetic.

The tenor of iron and nickel in pentlandite varies widely, notably with the source; for example, it is Fe:Ni = 2:1 at Lillehammer, Norway and about 1:2 at Sudbury, Canada.

Pentlandite is found in veins usually closely associated with pyrrhotite.

It is the chief ore of nickel at Sudbury and therefore the chief source of the world's supply of nickel. Nickel is used in many alloys because it imparts great strength and resistance to corrosion.

Bornite (Peacock Copper) Isometric Cu_5FeS_4

Crystals cubic, often rough, rare. Usually massive, granular or compact.

Cleavage only in traces. Brittle. H. = 3. G. = 4.9–5.2. Metallic luster. Color on fresh surface between bronze and copper red, tarnishing quickly to iridescent peacock colors. Streak gray.

Often contains small amounts of gold and silver. Soluble in nitric acid with separation of sulfur.

Bornite is found with other copper minerals; also with cassiterite, pyrite, siderite, arsenopyrite, quartz, etc. Important at Mt. Lyell, Tasmania, Butte (Montana), in Chile, Peru, Mexico.

An important copper ore.

Chalcopyrite (Copper Pyrites) Tetragonal $CuFeS_2$
$c = 0.985$

Crystals often sphenoidal and pseudotetrahedral. Twinning on (111) or (101) or (110). Commonly massive.

Poor (201) cleavage. Brittle. H. = 3.5–4. G. = 4.15–4.3. Luster metallic. Color brass-yellow. Streak greenish black. Opaque.

Nearly pure $CuFeS_2$, but may contain gold, silver, selenium, thallium, arsenic. Decomposed by nitric acid.

Chalcopyrite is the most widely distributed copper mineral, but not the most important source of the metal, because it is often too sparsely distributed to be of value. Commonly with pyrite, sphalerite, bornite, galena, tetrahedrite, chalcocite, calcite, quartz. Important at Falun (Sweden), Rio Tinto (Spain), Cornwall (England), Ashio mine (Japan), Butte (Montana), Bingham (Utah), Bisbee (Arizona).

An important ore of copper.

Pyrrhotite (Magnetic Pyrites) **Hexagonal** **FeS**
$c = 0.87$

Crystals tabular or pyramidal horizontally striated, but rare. Usually massive and granular.

Basal parting sometimes distinct. Brittle. H. = 3.5–4. G. = 4.58–4.64. Metallic luster. Bronze yellow to copper red in color, tarnishing easily to dark brown. Streak grayish black. Opaque. Variably magnetic.

Pure FeS is a constituent of meteorites called *troïlite*. Terrestrial FeS contains an excess of sulfur, up to 6%, and also a little nickel and cobalt. It inverts to an orthorhombic phase above 138°.

Pyrrhotite is usually a magnetic segregation in basic igneous rocks. It is important at Kongsberg (Norway), Sudbury (Canada), Ducktown (Tennessee), and elsewhere.

Pyrrhotite is mined for nickel, but the nickel is chiefly in admixed pentlandite.

Cinnabar **Hexagonal** **HgS**
$c = 1.145$

Crystals usually rhombohedral only rarely showing trapezohedral faces. May show rhombohedral penetration twins.

Perfect $(10\bar{1}0)$ cleavage. H. = 2–2.5. G. = 8.0–8.2. Somewhat sectile. Luster adamantine. Color cochineal red; streak scarlet. Transparent to opaque. Extreme birefringence and refringence with $N_o = 2.91$, $N_e = 3.27$. Strong circular polarization.

Cinnabar is nearly pure HgS; impurities are enclosed bitumen, clay, iron oxide, etc. Wholly volatile before the blowpipe.

Cinnabar occurs in veins or as impregnations in sedimentary or metamorphic rocks; less frequently in igneous rocks. It is a primary mineral deposited from alkaline solutions and associated with other sulfides and calcite, quartz, fluorite, etc. Important deposits are found at Idria (Italy—formerly in Austria), at Almaden (Spain), Huancavelica (Peru), and in several counties in California.

Cinnabar is the source of most of our mercury. About one third of the production of mercury is used to make mercuric fulminate for explosive caps; it is used in the amalgamation process of recovering gold and silver from their ores; also in scientific and electrical apparatus, and in mercury boilers and many other special equipment. The chloride of mercury is used for medicinal purposes and the sulfide and red oxide as pigments.

Niccolite **Hexagonal** **NiAs**

Crystals rare; usually disseminated or massive.

Fracture uneven. H. = 5.5. G. = 7.3–7.7. Metallic luster. Color light copper red (hence sometimes called *copper nickel*), tarnishing to brown or gray. Streak brownish black.

Niccolite usually contains a little iron and cobalt, as well as sulfur. Moreover there seems to be a complete gradation from NiAs to NiSb (which is called *breithauptite*). Soluble in aqua regia.

It is often associated with smaltite, pyrite, chalcopyrite, etc.

Used as an ore of nickel.

Greenockite *Hexagonal, hemimorphic* CdS

Crystals prismatic hemimorphic; usually in powdery masses. Cleavage prismatic distinct. H. = 3–3.5. G. = 4.9–5.0. Luster adamantine to resinous. Color and streak variable yellow. $N_o = 2.506$, $N_e = 2.529$. Soluble in HCl. Rare in nature; not rare as a furnace product.

Millerite *Rhombohedral* NiS
$c = 0.988$

Crystals very slender to capillary prisms often in radiating groups, or interwoven like a wad of hair.

Perfect cleavage parallel to $(10\bar{1}1)$ and $(01\bar{1}2)$. Brittle. Capillary crystals elastic. H. = 3–3.5. G. = 5.3–5.65. Metallic luster. Color brass to bronze yellow, tarnishing to gray, iridescent. Streak greenish black.

Millerite is nearly pure NiS; it often contains traces of copper and iron.

It usually occurs as tufts in cavities in limestone, dolomite, serpentine, etc. Associated with iron ores, sulfides, etc. Also found in meteorites.

Important localities include Joachimsthal (Bohemia), Müsen (Westphalia), Glamorgan (Wales), Milwaukee (Wisconsin).

Used as an ore of nickel, but too rare to be important.

Molybdenite **Hexagonal** **MoS_2**
$c = 3.816$

Crystals, rare, hexagonal basal tablets; usually in scales or grains, or aggregates.

Perfect basal cleavage. Flexible. Sectile. Greasy feel. H. = 1–1.5. G. = 4.75. Luster metallic. Color lead gray; bluish gray on paper; greenish gray on glazed porcelain. Differs from graphite in density and streak. Opaque.

Molybdenite is almost pure MoS_2, but may contain traces of gold and silver. Infusible before the blowpipe. Decomposed by HNO_3.

Molybdenite is widely but very sparsely distributed in pegmatites, quartz veins, contact deposits, and in limestones and gneiss. It is often associated with tin ores or with wolframite, topaz, epidote, and chalcopyrite. Large crystals found in Renfrew County, Ontario. Important occurrences in Saxony, Bohemia, Cornwall, Queensland. Most of the molybdenum production of the world comes from Climax, Colorado. Recently production has begun in Utah.

Molybdenum is used in very rapidly increasing amounts in making special grades of iron and steel, notably "high-speed" tools. Molybdenite is the chief ore of molybdenum.

Covellite *Hexagonal* CuS
$c = 1.147$

Crystals usually thin hexagonal plates with crystal angles close to those of cinnabar. Often massive.

Perfect basal cleavage; thin laminae are flexible. H. = 1.5–2. G. = 4.6. Luster submetallic to resinous. Color dark indigo blue. Streak lead gray. Nearly opaque, but uniaxial positive with $N_o = 1.45\ Na$. Pleochroic in green.

Covellite is nearly pure CuS. Fuses at 2.5, giving sulfurous fumes.

It is associated with other copper sulfides in zones of secondary enrichment. Also a sublimation product, as at Vesuvius.

Used as an ore of copper.

Chalcocite (Copper Glance) Orthorhombic Cu_2S
$a:b:c = 0.582:1:0.907$

Crystals are tabular to thick prismatic and pseudohexagonal, the prism angle being 119°35′. Pseudohexagonal twinning. Usually massive.

Indistinct (110) cleavage. H. = 2.5–3. G. = 5.5–5.8. Luster metallic, but soon becomes dull. Conchoidal fracture. Color and streak dark lead gray. Opaque.

Chalcocite is (nearly) pure Cu_2S, but may contain a little iron, silver (up to 15% Ag_2S) or excess copper. It inverts[1] at 52°C. from the orthorhombic superstructure to a nonisometric basic structure.

Chalcocite is found in veins often with bornite, chalcopyrite, tetrahedrite, enargite, pyrite, galena, etc. It is important at Butte (Montana), Kennecott (Alaska), Miami (Arizona), and elsewhere.

Chalcocite is the most important ore of copper.

Stibnite Orthorhombic Sb_2S_3
$a:b:c = 0.993:1:1.018$

Crystals prismatic, common, often vertically striated, curved or distorted. Often in aggregates, confused or radiating. Also in bladed, granular or columnar masses.

Perfect 010 cleavage. H. = 2. G. = 4.52–4.62. Metallic luster often splendent. Color and streak lead gray. Opaque, except to red and infrared rays in which $X = c$, $Y = a$, $(-)\ 2V = 26°$, $N_g = 4.303$, $N_m = 4.046$, $N_p = 3.194 \pm$.

Stibnite is quite pure Sb_2S_3, usually, but may contain a little gold or silver. Fuses easily in the candle flame (546°). Soluble in HCl.

Found in veins often with quartz, galena, barite, cinnabar, sphalerite, etc. Localities include Wolfsberg (Germany), Lubilhac (France), Sarawak (Borneo), Hollister (California), Manhattan (Nevada). Wonderfully fine large crystals have been obtained in Japan.

Used as the chief source of antimony, which is now obtained chiefly from China. Antimony is used in storage batteries,

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[1] N. W. Buerger: *Jour. Chem. Phys.* VII, 1067 (1939).

cable coverings, type, babbitt and britannia metals, and in various compounds as pigments, medicinal preparations, etc.

Bismuthinite *Orthorhombic* Bi_2S_3

$a:b:c = 0.968:1:0.985$

Crystals acicular; usually massive.

Perfect 010 cleavage. H. = 2. G. = 6.4–6.8. F. = 1. Luster metallic. Color and streak lead gray. Opaque.

It may contain a little copper and iron; in a rare case it contains antimony (8%). It is comparatively rare, but is nevertheless the chief ore of bismuth. But the entire domestic production is obtained as a by-product in the refining of lead ores.

Marcasite (White Iron Pyrites) Orthorhombic FeS_2

$a:b:c = 0.766:1:1.234$

Crystals usually basal tablets, often elongated and striated parallel to the *a* axis. Twinning on 110 common. Commonly massive, granular, or with radial structure.

Indistinct prismatic (110) cleavage. H. = 6–6.5. G. = 4.8–4.9. Luster metallic. Color pale bronze yellow, deepening on exposure. Lighter yellow than pyrite. Streak gray.

Marcasite is mostly pure FeS_2, but may contain a little arsenic or copper. It alters commonly more easily then pyrite, forming limonite and melanterite. It is formed from acid solutions below 450°C. Powdered marcasite dissolves in concentrated nitric acid with separation of sulfur, while pyrite does not.

Much like pyrite, but has lower specific gravity and slightly different color. Not as common as pyrite. Often found with pyrite, galena, sphalerite, calcite, fluorite. It may occur in replacement deposits in limestone; also in veins; and associated with lignite. Important localities include Freiberg (Saxony), Folkestone (England), Guanojuato (Mexico), Joplin (Missouri), Galena (Illinois), and Mineral Point (Wisconsin).

It has the same uses as pyrite.

Arsenopyrite Monoclinic FeAsS

Crystals prismatic with brachydomes. Pseudo-orthorhombic by twinning on 100 or 001; sometimes cruciform or in trillings due to twinning on (101). Columnar or granular very commonly.

Distinct (110) cleavage. Brittle. H. = 5.5–6. G. = 5.9–6.2. Metallic luster. Color silver-white to steel-gray. Streak black. Opaque.

Usually nearly pure FeAsS, but may contain cobalt (3–9%), antimony, bismuth, gold, silver. *Glaucodot*, (Co,Fe)AsS, is closely related. Decomposed by nitric acid.

Found with tin and tungsten ores, with silver, lead, zinc, copper, nickel, and cobalt ores; for example, at Freiberg (Saxony), Cornwall (England), Tunaberg (Sweden), Binnenthal (Switzerland), Franklin (New Jersey), Leadville (Colorado).

Used very largely as a source of arsenious oxide (As_2O_3), known as "white arsenic" in commerce. Also as a source of metallic arsenic and various arsenates (for insecticides). In rare cases it is an ore of gold or silver.

Realgar **Monoclinic** **AsS**

$a:b:c = 0.720:1:0.459, \beta = 66°15'$

Crystals short prismatic, vertically striated; often in granular masses or incrustations.

Distinct 010 and poor (110) and 001 cleavages. H. = 1.5–2. G. = 3.5. Resinous luster. Color and streak aurora-red to orange-yellow. $X \wedge c = 11°$, $Y = b$. $(-)2V = 40°$, $r > v$ very strong. $N_g = 2.61$, $N_m = 2.59$, $N_p = 2.46$.

Realgar is nearly pure AsS. Soluble in caustic alkalies. Alters to orpiment.

It is a minor constituent of certain ores, notably some silver and lead ores, as at Kapnik in Roumania, Joachimstal in Bohemia, Binnental in Switzerland, in Iron County, Utah, and in Yellowstone Park.

It was formerly used in fireworks to give a brilliant white light (with saltpeter). The artificial compound is now used for this purpose and also as a pigment (but it alters too easily to orpiment to be a good pigment).

Orpiment **Monoclinic** **As_2S_3**

$a:b:c = 0.596:1:0.665, \beta = 89°19'$

Crystals short prismatic, rare. Usually foliated, encrusting.

Perfect 010 cleavage, vertically striated. Sectile. Flexible but not elastic. H. = 1.5–2. G. = 3.4–3.5. Fuses easily (320°C.). Resinous to pearly luster. Color and streak lemon yellow. $X = b$. $Y \wedge c = -1°$ to $-3°$. $(+)2E = 70°, r > v$ strong. $N_g = 3.0+$, $N_m > 2.72\ Li$, $N_p = 2.4\pm$.

Orpiment is quite pure As_2S_3. Soluble in caustic alkalies.

It is found in hot spring, geyser, and volcanic emanation deposits; also in veins and sublimed from burning coal mines. Localities include Felsöbánya (Roumania), Jozankei (Japan), Mercur (Utah), Steamboat Springs (Nevada), and Yellowstone Park.

Orpiment is used in dyeing and tanning and also as a pigment. But the artificial product has replaced almost entirely the natural mineral in these uses.

Calaverite *Monoclinic* $AuTe_2$
$a:b:c = 1.631:1:1.145, \beta = 89°47'$

Crystals are rare; columnar along *b* and complicated by twinning. Usually granular.

No cleavage. H. = 2.5. G. = 9.3. F. = 1. Luster metallic. Color brass yellow to silvery or yellowish. Streak yellowish to greenish gray.

Calaverite usually contains a little silver replacing gold.

It is associated with sylvanite, notably at Cripple Creek, Colorado.

It is an ore of gold.

Sylvanite *Monoclinic* $(Au,Ag)Te_2$
$a:b:c = 1.634:1:1.127, \beta = 89°35'$

Crystals tabular, nearly orthorhombic, often twinned. Also bladed and arborescent (whence the name occasionally used—*graphic tellurium*).

Perfect 010 cleavage. H. = 1.5–2. G. = 7.9–8.3. F. = 1. Luster metallic. Color silver white. Streak gray.

In sylvanite the tenor of gold and silver varies notably, but is near 1:1 as found at Cripple Creek, Colorado.

It is found in veins with pyrite, quartz, fluorite, and carbonates.

It is an important ore of gold and silver.

Gray Copper $\left\{\begin{array}{l}\textbf{Tetrahedrite}\\ \textbf{Tennantite}\end{array}\right.$ **Isometric** $\left\{\begin{array}{l}Cu_{10}Zn_2Sb_4S_{13}\\ Cu_{10}Zn_2As_4S_{13}\end{array}\right.$

Crystals usually tetrahedral, often modified. Twinning on (111). Commonly massive, compact, granular.

No cleavage. H. = 3–4. G. = 4.4 (tennantite)–4.8 (tetrahedrite) and up to 5.4 (with lead and mercury). Metallic luster, often splendent. Color steel gray to iron black, sometimes tarnished. Streak gray to reddish brown. Subtranslucent and red in very thin splinters. $N > 2.72$.

Composition quite variable and formula in doubt. Contains silver (variety *freibergite*), mercury (variety *schwatzite*), lead (variety *malinowskite*), iron, bismuth, manganese, etc.

Widespread in occurrence in veins and in contact deposits. Often with bornite, chalcopyrite, pyrite, galena, sphalerite, etc. Localities where it is important include Freiberg (Saxony), Kapnik (Roumania), and Chile, Peru, Bolivia, Mexico, Bingham (Utah), Butte (Montana).

An important ore of copper, and also of silver.

Stannite *Tetragonal (Pseudo-isometric)* $Cu_2(Fe,Zn)SnS_4$

Nearly always massive and granular; pseudo-isometric twinning.

Indistinct cleavage. H. = 4. G. = 4.3–4.5. F. = 1.5. Luster metallic. Color steel gray to iron black. Streak black.

The tenor of zinc in stannite varies widely and may equal the iron.

Stannite is found in veins with cassiterite, chalcopyrite, pyrite, quartz, etc., for example, in Bolivia and Cornwall.

It is a minor ore of tin.

Ruby Silver $\left\{\begin{array}{l}\textbf{Proustite}\\ \textbf{Pyrargyrite}\end{array}\right.$ **Hexagonal** $\left\{\begin{array}{l}Ag_3AsS_3\\ Ag_3SbS_3\end{array}\right.$

Crystals prismatic to rhombohedral, hemimorphic, small, often modified. Usually massive, compact.

Distinct $(10\bar{1}1)$ cleavage. Brittle. H. = 2.5–3. G. = 5.5 (proustite) to 5.85 (pyrargyrite). Metallic adamantine luster. Color scarlet (proustite) to dark red or lead gray (pyrargyrite). Streak scarlet (proustite) to purple red (pyrargyrite). $N_o =$ 3.087 (proustite), 3.084 (pyrargyrite); $N_e = 2.792$ (proustite), 2.881 (pyrargyrite). See Fig. 353.

Natural crystals are usually nearly pure Ag_3AsS_3 or Ag_3SbS_3, but the two compounds are miscible at fusion temperatures, in all proportions as crystals.[2] Easily fusible. Decomposed by nitric

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[2] Jaeger and Klooster: *Zeit. anorg. Chem.* 78, 245.

acid. (But proustite and pyrargyrite may be two minerals, since they occur together, as if they were not miscible at low temperature.)

Commonly associated with galena, tetrahedrite, sphalerite, etc. as primary minerals in veins and contact deposits. Found at Freiberg (Saxony), Pribram (Bohemia), Guanojuato (Mexico), Chile, Peru, Silver City (Idaho), in Colorado, Nevada, Arizona, Cobalt (Ontario).

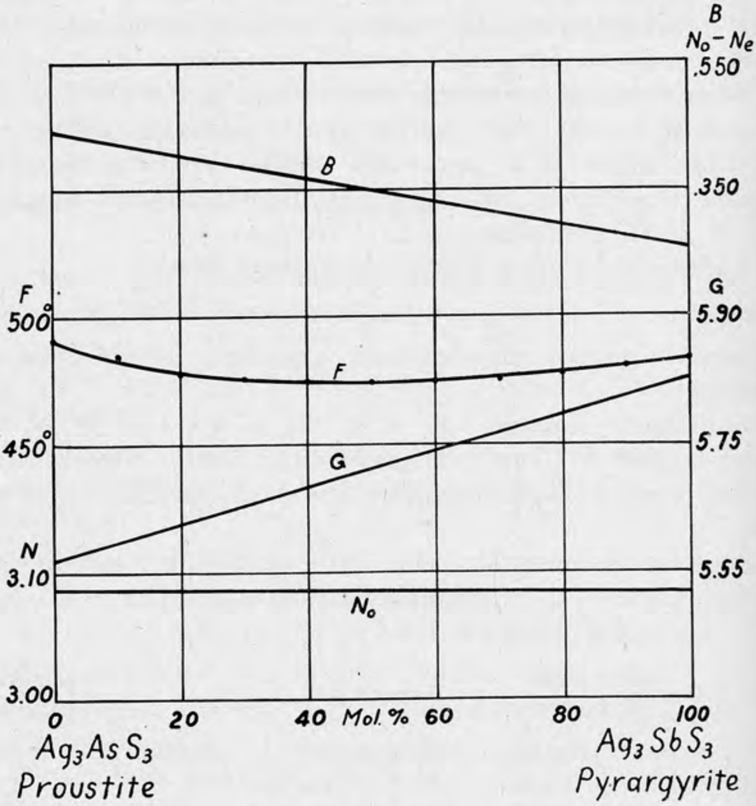

FIG. 353. Proustite-pyrargyrite.

Important silver ore.

Bournonite *Orthorhombic* $CuPbSbS_3$

$a:b:c = 0.938:1:0.867$

Crystals tabular or prismatic, often twinned on (110) producing cruciform or "cogwheel" groups. Also massive.

No good cleavage. H. = 2.5–3. G. = 5.7–5.9. Luster metallic. Color steel gray to iron black. Streak dark gray. Opaque.

$CuPbSbS_3$, but often contains silver, iron, arsenic. Decomposed by nitric acid.

Occurs in veins with galena, tetrahedrite, stibnite, chalcopyrite, sphalerite, etc. Important localities include Freiberg (Saxony), Kapnik (Roumania), Liskeard (Cornwall), and Bolivia, Chile, Mexica, Utah, Arizona.

Used as an ore of copper and lead.

Enargite **Orthorhombic** $\mathbf{Cu_3AsS_4}$
$a:b:c = 0.87:1:0.82$

Crystals prismatic, vertically striated; usually columnar, granular or massive.

Perfect (110) cleavage. Brittle. H. = 3. G. = 4.44. Luster metallic. Color grayish black to iron black. Streak black. Opaque.

Enargite may contain as much as 6 per cent (by weight) of antimony substituting for arsenic; it often contains also some zinc and iron.

Found in veins with chalcopyrite, bornite, tetrahedrite, chalcocite, pyrite, etc. Important localities include Chile, Peru, Bolivia, Mexico, Butte (Montana), and Tintic District (Utah).

An important ore of copper, and a source of arsenic oxide.

Jamesonite (Feather Ore) *Monoclinic* $Pb_2Sb_2S_5$
$a:b:c = 0.832:1:0.426, \beta = 91°24'$

Crystals usually acicular; also fibrous or capillary to compact.

Perfect basal cleavage. H. = 2–3. G. = 5.5–6. F. = 1. Luster metallic. Color and streak steel gray to grayish black.

Jamesonite commonly contains 1–5% Fe and a little Cu and Zn; the formula is doubtful. $Pb_4FeSb_6S_{14}$ has been proposed.

Jamesonite is found in veins associated with galena, sphalerite, stibnite, tetrahedrite, etc., for example, in Cornwall, at Freiberg (Saxony), in Roumania, Bolivia, and Tasmania.

It is a minor ore of lead.

3. Halides

Only a few halides are of importance; the following will be described:

Halite	$NaCl$	Fluorite	CaF_2
Sylvite	KCl	Cryolite	Na_3AlF_6
Cerargyrite	$AgCl$	*Carnallite*	$KMgCl_3 \cdot 6H_2O$

Halite (Common or Rock Salt) Isometric NaCl

Crystals usually cubic, sometimes with the octahedron or with depressions; also skeletal. Usually in granular or cleavable masses.

Perfect cubic cleavage. H. = 2.5. G. = 2.1–2.3. Easily soluble in water. Salty taste. Luster vitreous. Colorless or white; impurities may produce red, blue, gray, yellow, black color, which may be irregular. Transparent to translucent. $N = 1.544$.

Usually very pure NaCl, unless other substances are mechanically enclosed. Gives an intensely yellow flame.

Halite is very widely distributed in sedimentary rocks. Great quantities are in solution in salt waters of the ocean and in some lakes, and saline springs, and wells. Small amounts are found as an efflorescence in arid regions and as a sublimation product about volcanoes. In sedimentary deposits salt is usually closely associated with gypsum, anhydrite, polyhalite, carnallite, etc. Some sedimentary beds are extensive in area and hundreds of feet in thickness. The salt deposits of Stassfurt, Germany, extend over an area of about one hundred square miles. Other important deposits are found at Ipetsk (Russia), in Galicia (Poland), Salzburg (Austria), Alsace (France), in western New York, eastern Michigan, Sevier County (Utah), near Lyons (Kansas), Petite Anse (Louisiana), in Ohio, California, and elsewhere.

Salt is used in large quantities for culinary and preservative purposes, and also in glazing pottery, in various metallurgical processes, and in the manufacture of metallic sodium and its compounds. "Soda ash" or sodium carbonate is used in making glass and also soap. Sodium bicarbonate is used in cooking and in medicine. Sodium cyanide is used in the cyanide process for the extraction of gold from its ores.

Sylvite Isometric KCl

Crystals cubic, often cut by octahedral faces. Also granular massive.

Perfect cubic cleavage. H. = 2. G. = 1.97–1.99. Soluble in water. Bitter salty taste. Luster vitreous. Colorless or white or tinted by inclusions. N = 1.490.

Very pure KCl. Gives a violet flame color.

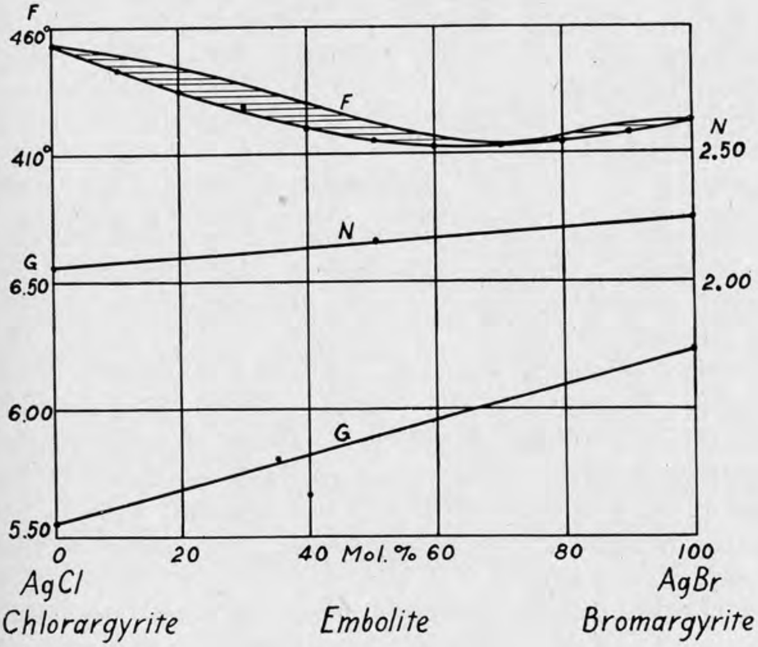

Fig. 354. Cerargyrite.

Sylvite is like halite in its origin and mode of occurrence, but is much rarer. Important localities include Stassfurt (Germany), Galicia (Poland), Carlsbad (New Mexico).

It is used as a source of potash for fertilizers.

Cerargyrite (Horn Silver) **Isometric** **Ag(Cl,Br,I)**

Crystals cubic; usually massive, encrusting.

No cleavage. Highly sectile. Resembles wax or horn. H. = 1–1.5 (chlorargyrite) to 2–3 (bromargyrite). G. = 5.55 (chlorargyrite) to 6.245 (bromargyrite). Luster waxy or resinous. Color pearl gray, yellowish, greenish, white, rarely blue; on exposure to light may turn violet, brown, or black. When rubbed it becomes shiny. Transparent to translucent. N = 2.061 (chlorargyrite) to 2.25 (bromargyrite). See Fig. 354.

Composition variable. May even contain mercury. Varieties include *chlorargyrite*, AgCl, *bromargyrite*, AgBr, *embolite* Ag(Cl,Br), and *iodembolite*, Ag(Cl,Br,I). Soluble in ammonia.

Cerargyrite is a secondary mineral in the oxide zone of ore deposits such as those at Broken Hill (New South Wales), and in Saxony, Norway, Mexico, Peru, Chile, and at Leadville (Colorado), Comstock Lode (Nevada), Silver City (Idaho), Argenta (Montana).

Used as an ore of silver.

Fluorite **Isometric** **CaF_2**

Crystals cubic with or without the tetrahexahedron or hexoctahedron; sometimes twinned on (111), the twins being often of penetration type. Also in granular, fibrous, or cleavable masses.

Perfect octahedral cleavage. H. = 4. G. = 3.18. Luster vitreous. Usually greenish, yellowish, or bluish in color, but may be red, brown, or colorless. Color often in bands or irregularly placed. Color rather easily modified by X rays, radium rays, ultraviolet light, etc. Streak white. Some samples fluoresce or even phosphoresce. Transparent to translucent. $N = 1.434$.

Fluorite is usually remarkably pure CaF_2, but rare varieties contain YF_3 (*Yttrofluorite*) or CeF_3 (*cerfluorite*) or both (*yttrocerite*). With 19% $(Y,Ce)F_3$, G. = 3.536 and $N = 1.454$.

Fluorite is very widespread in occurrence, as it is formed under widely different conditions. It is most common as a vein mineral especially in limestones, but also in sandstones and granites. It is a common gangue mineral of lead, silver, copper and tin ores. It is an accessory constituent of granite, syenite, and pegmatite, as well as of sediments. Excellent crystals have been found in Cornwall, Cumberland, and Derbyshire, England. Fluorite is mined in large quantities in Bavaria and Prussia (Germany), Haute-Loire and Var (France), north part of England, and a district in southern Illinois and adjoining parts of Kentucky.

Fluorite is used extensively in making open hearth steel and iron and steel enamel ware, hydrofluoric acid and derivatives and opalescent glass.

Cryolite **Monoclinic** **Na_3AlF_6**

$a:b:c = 0.966:1:1.388$, $\beta = 84°49'$

Crystals apparently cubic, often grouped in parallel position; chief forms are the prism and base. Inverts to isometric phase at 570°C. Usually compact or cleavable masses.

Good basal and prismatic parting. Brittle. H. = 2.5. G. = 2.95–3.0. Pearly luster on base; elsewhere vitreous to greasy. Colorless, white or tinted reddish. Transparent to translucent. $X = b$; $Z \wedge c = -44°$. (+) $2V = 43°$, $N_g = 1.3396$, $N_m = 1.3389$, $N_p = 1.3385$.

Cryolite is usually nearly pure Na_3AlF_6; it may contain a little Fe_2O_3. Fuses easily. Soluble in sulfuric acid.

Cryolite is very rare and is obtained commercially only from Ivigtut on the coast of Greenland, where it is found in pegmatite in granite associated with siderite, galena, chalcopyrite, fluorite, pyrite, sphalerite, cassiterite, columbite, etc. It is also found in small amounts at Miask, Siberia, and at Pike's Peak, Colorado.

It is used as a flux in the electrolytic process of obtaining aluminum from bauxite; also used in making opalescent glass and enamels, and in white Portland cement.

Carnallite *Orthorhombic* $KMgCl_3.6H_2O$

$a:b:c = 0.594:1:0.691$

Crystals rare, pseudohexagonal pyramids; commonly granular massive.

No good cleavage. H. = 2.5. G. = 1.60. Luster shining, greasy. Color white. $Y = b$, $Z = a$. $(+)2V = 70°$, $N_g = 1.494$, $N_m = 1.475$, $N_p = 1.466$.

Carnallite is nearly pure $KMgCl_3 \cdot 6H_2O$. Soluble in water and has a bitter taste. Deliquescent. Fuses easily.

Found in salt lake deposits associated with halite, sylvite, kieserite, polyhalite, etc. Important at Stassfurt, Germany.

Used as a source of potash for fertilizers.

4. Oxides

Only a few oxides[3] are of such importance that they merit description here; they are:

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[3] Quartz is ordinarily considered an oxide, but crystallographically it is very closely related to the silicates and it may be considered to be a silicate of silicon.

Ice (water)	H_2O	*Braunite*	Mn_2O_3
Cuprite	Cu_2O	Bauxite	$Al_2O_3 \cdot nH_2O$
Zinkite	ZnO	*Diaspore*	$HAlO_2$
Corundum	Al_2O_3	*Gibbsite*	$Al(OH)_3$
Hematite	Fe_2O_3	Limonite (Goethite)	$Fe_2O_3 \cdot H_2O$
Ilmenite	$FeTiO_3$	Manganite	$Mn_2O_3 \cdot H_2O$
Rutile	TiO_2	*Brucite*	$Mg(OH)_2$
Cassiterite	SnO_2	*Uraninite*	UO_2, etc.
Pyrolusite	MnO_2		

Ice (Water) **Hexagonal** **H_2O**

$c = 1.40$

Crystals usually in skeletal form (snow) of hexagonal symmetry, commonly basal plates; also granular massive as in glaciers.

Basal glide plane developed by pressure. H. = 1.5 at −5°C., 4 at −44°C. and 6[4] at −78°C. G. = 0.918 at 0°C. Colorless to white; pale blue in thick solid masses. Transparent to translucent. $N_o = 1.309$, $N_e = 1.313$.

Ice is quite pure H_2O. Melts to *water* at 0°C., which has $N = 1.333$ and G. = 1.00 at 4°C. and 760 mm. pressure. Pure water has no taste. Like ice it is bluish in large quantities.

Under pressure at least four phases of ice are known; one is isometric and isotropic; another is tetragonal.

Ice is very widespread as a filling of pores and cavities in surface rocks in winter; also found occasionally at some depth below the surface. Also formed over lakes and seas as a surface layer composed of large acicular irregularly arranged aggregates or prisms arranged with the vertical axes all normal to the surface of the water. Also in glaciers whose texture is like that of granular limestone. Also in snow in skeletal crystals of great variety. In frost often dendritic, etc. In hail in anhedral crystalline aggregates.

Water is very widely distributed in nature over the whole surface of the earth and also to moderate depths in the rocks. Water, except after distillation, is not as pure as ice; natural water contains air in solution, without which it is unpalatable. Water is a solvent for many minerals and so usually has some salts in solution. Thus, even spring water contains some dissolved mineral matter, and sea water contains about 3.4 per cent

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[4] E. Blackwelder: *Am. Jour. Sci.* 238, 61 (1940).

of such material. Of this amount about one half is common salt (NaCl) and four fifths of the remainder is $MgCl_2$ and $MgSO_4$. Accordingly water is a very important agent in the solution and alteration, as well as in the transportation and formation, of minerals. When water freezes it expands with an increase of volume of nearly 10 per cent and a pressure of about 138 tons per square foot. Therefore freezing water is a powerful agent in disrupting surface rocks and thus extending the zone of activity of percolating water and the air (including oxygen) which it contains.

Cuprite **Isometric** **Cu_2O**

Crystals octahedral or cubic often with the dodecahedron. Also compact, granular or earthy. Capillary aggregates are called *chalcotrichite* or *plush copper*.

Poor (111) cleavage. Brittle. H. = 3.5–4. G. = 5.8–6.15. Luster adamantine to earthy. Color ruby red to nearly black. Streak brownish red. Transparent to opaque. $N = 2.849$.

Usually quite pure Cu_2O. Fuses with emerald green flame color. Soluble in concentrated hydrochloric acid. Alters readily to malachite, azurite, etc.

Cuprite is a secondary mineral found only in the oxide zone. It is rather widespread in occurrence. Important at Chessy (France), Cornwall (England), Broken Hill (New South Wales), Corocoro (Bolivia), Bisbee, Morenci, Jerome, and Clifton (Arizona).

It is an important ore of copper.

Zinkite **Hexagonal** **ZnO**
$c = 1.596$

Crystals rare and hemimorphic; usually in foliated, granular or compact masses.

Perfect basal cleavage. H. = 4–4.5. G. = 5.4–5.7. Luster subadamantine. Color dark red to orange yellow. Streak reddish to orange yellow. Translucent to opaque. $N_o = 2.013$, $N_e = 2.029$.

Zinkite is chiefly ZnO, but often contains 1–8 per cent of MnO and a little iron. Melting point is 1670° with 6.2 MnO, 1550° with more MnO and FeO.

Important at Franklin Furnace, New Jersey, closely associated with franklinite, willemite, rhodonite, etc. Also known in Saxony, Tuscany, Poland, Spain, Tasmania.

Zinkite is an ore of zinc. It has been used in wireless apparatus.

Corundum **Hexagonal** **Al_2O_3**
$c = 1.363$

Crystals rhombohedral, rather common and may be large. Habit may be prismatic, rhombohedral, tabular or apparently pyramidal. Large crystals often rough, rounded or deeply furrowed. Twinning on $(10\bar{1}1)$ common, often of penetration type. Also compact, granular, or lamellar.

Basal and rhombohedral parting. Brittle. H. = 9. G. = 3.9–4.1. Luster vitreous. Commonly gray; also red, brown, blue, yellow, colorless. $N_o = 1.768$, $N_e = 1.760$.

Corundum is nearly pure Al_2O_3, but commonly contains 1–4 per cent of Fe_2O_3 and much less Cr_2O_3, TiO_2, Mn_2O_3, etc. The red color is said to be due to chromium and the blue color to titanium. Infusible, and insoluble in common acids.

Several varieties of corundum are recognized:

1. *Common corundum* includes the kinds with gray or dull colors, not transparent, either in crystals or massive.

2. *Ruby* is transparent and deep red in color.

3. *Sapphire* proper is transparent and fine blue in color, but transparent crystals of other colors (except red) are also known as sapphire; thus, there are *yellow, golden,* and *white sapphires,* and green sapphire is also called *oriental emerald,* violet is called *oriental amethyst,* and yellow may be called *oriental topaz.*

4. *Emery* is really a mineral aggregate, or rock; but is often regarded as a variety of corundum, because that is the chief component. Other minerals may amount to 40 per cent; they are usually magnetite, hematite, quartz, and spinel. Emery is dark gray to black in color and is a finely granular aggregate.

Corundum has been made artificially in several ways. It can be colored red by chromium or blue by cobalt, thus producing true artificial ruby or sapphire, which cost only a small fraction of the price of natural gems, though having all their properties. The presence of microscopic bubbles and curved striae indicate the artificial rather than the natural gems. The artificial abrasive *alundum* is crystallized corundum made by heating bauxite to 5000°–6000°. Alumina has four crystal phases, α, β, γ and δ, the first being stable at high temperature.

Corundum is usually only an accessory constituent of various igneous and metamorphic rocks, often associated with chlorite, tourmaline, spinel, kyanite, magnetite, etc. For example, ruby occurs disseminated in recrystallized limestone in Burma and Asia Minor. Gems are found in dolomite in Switzerland. Opaque crystals are found in mica schist near Antsirabe, Madagascar. Similar crystals are found in peridotite in the Carolinas and Georgia, in nepheline syenite in Ontario, in pegmatite in the Ural Mountains, in a basaltic rock at Yogo Gulch, Montana. Gems are obtained from decomposed surface rocks and placers in some cases.

Ruby and sapphire are important gem stones and are also used as jewels in watches and scientific apparatus. Common corundum (both natural and artificial) is used as a valuable abrasive. Emery is a cheaper abrasive, widely used for that reason.

Hematite **Hexagonal** Fe_2O_3
$c = 1.366$

Crystals often rhombohedral or basal tablets, which may be grouped in rosettes. Basal pinacoid often striated parallel to $(01\bar{1}2)$. Commonly in compact granular, fibrous, or micaceous masses, which may be columnar, oölitic, reniform, botryoidal, etc.

No cleavage, but there may be basal or rhombohedral $(10\bar{1}1)$ parting. H. = 5.5–6.5; earthy varieties very soft. G. = 4.9–5.3. Luster metallic, splendent or dull. Color steel gray in crystals, but fine aggregates are deep red. Streak deep red to reddish brown. Opaque except in very thin flakes. $N_o = 3.22$, $N_e = 2.94$.

Hematite is usually nearly pure Fe_2O_3, but it may contain up to 8 per cent of TiO_2 (as inclusions?) as well as FeO, MgO, MnO. It can be deoxidized to $FeO{\cdot}Fe_2O_3$ without change of crystal structure (then called *maghemite*). Infusible. Slowly soluble in acids. Important varieties of hematite are:

1. *Specular iron ore*, which includes crystals and micaceous and granular masses with a splendent metallic luster and steel gray color.

2. *Red hematite*, which is compact, often fibrous, with iron black to brownish red color and submetallic to dull luster.

3. *Kidney ore*, which occurs in reniform masses, usually with an iron black color and smooth shiny surfaces.

4. *Red ocher*, which includes red earthy masses, soft and dull, often impure, containing clay or sand.

5. *Clay iron-stone* or argillaceous (or clay-like) hematite, is impure containing clay, sand, or jasper; it is hard and compact with brown to red color.

6. *Martite* is hematite (in octahedrons), which is pseudomorphous after magnetite.

Hematite is very widespread in nature, but the ferric iron of magmas goes into magnetite (and other minerals) unless there is a deficiency of FeO. Hematite is produced under oxidizing conditions around volcanoes; it is also produced by the dehydration of the limonite in sedimentary masses such as bog iron ore. It is important in some contact deposits, and it is a conspicuous coloring agent when it occurs as inclusions or in cracks in many rocks and minerals.

The great deposits of hematite are found in pre-Cambrian rocks in Brazil, India, South Africa, and the Lake Superior district. But other very important deposits are located in England, France, Germany, Russia, and Alabama. The chief iron ore districts or "iron ranges" in the Lake Superior region are the Mesabi, Vermilion, and Cuyuna in Minnesota; the Menominee and Gogebic in Michigan and Wisconsin; the Marquette in Michigan, and the Michipicoten in Ontario. This region has produced about two billion tons of iron ore (to 1940) and has about three billion tons of known reserves. It is now producing about 25 per cent of the world's output of iron ore. Other important deposits of hematite in the United States include those in Alabama, New York, Tennessee, Missouri, Pennsylvania, and Wyoming.

Hematite is much the most important ore of iron, supplying more than 90 per cent of the iron of commerce.

Ilmenite **Hexagonal** **$(Fe,Mn,Mg)TiO_3$**

$c = 1.385$

Crystals rhombohedral or thick tabular in habit with trirhombohedral symmetry. Usually massive, compact, or platy.

No cleavage. Conchoidal fracture. H. = 5–6. G. = 4.3–5.5. Infusible. Luster metallic to submetallic. Color iron black. Streak black to brownish red. Opaque; rarely slightly transparent and dark brown in thin plates. Slightly magnetic; much more so after heating.

Ilmenite varies greatly in composition, approaching *crichtonite* ($FeTiO_3$) as one end-member, *geikielite* ($MgTiO_3$) as another, and *pyrophanite* ($MnTiO_3$) as a third. In *senaite* $\{(Fe,Mn,Pb)TiO_3\}$ still another end-member ($PbTiO_3$) is present in notable amount. The Fe_2O_3 in many analyses of ilmenite is due to regular inter-growths of basal plates of ilmenite and hematite, and not to crystal solution. But minor quantities of Fe_2O_3 can probably enter the structure of ilmenite. Ilmenite alters rather easily to a dull white opaque substance called leucoxene, which is usually rutile.

The variations in properties with variations in composition are shown in Fig. 355.

Ilmenite is a common accessory mineral in igneous and metamorphic rocks. It is sometimes more abundant in black sands. It is often associated with magnetite, hematite, apatite, rutile, quartz. It is abundant rarely in veins and pegmatites. Some important localities are Krägero (Norway), Miask (Russia), Binnental (Switzerland), Travancore (India), and Nelson County (Virginia).

Ilmenite is used largely to make titanium pigments and also to make ferro-alloys. It is not used as an iron ore on account of the difficulty in reducing it.

Rutile **Tetragonal** **TiO_2**

$c = 0.644$

Crystals usually short prismatic (to acicular) with pyramid faces. Prism faces often vertically striated. Twinning on 101 common, often geniculated or cyclic. Also compact, granular masses.

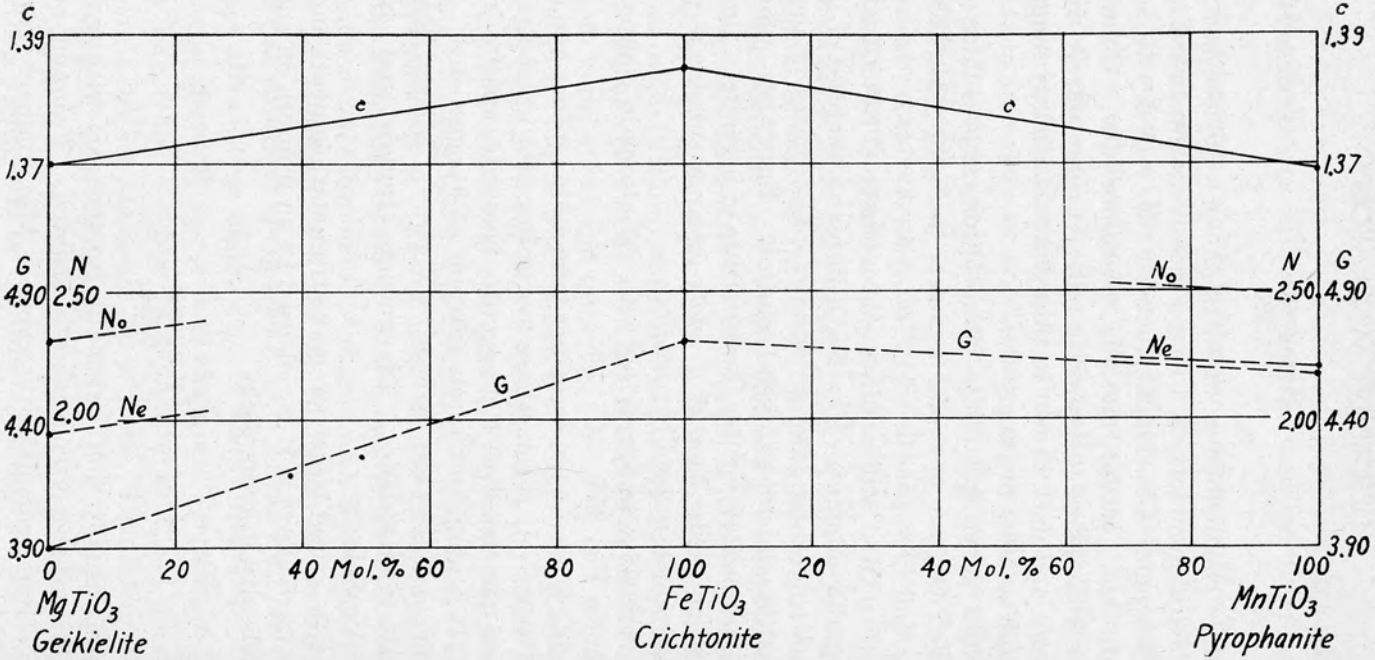


FIG. 355. Ilmenite.

Distinct prismatic cleavage. H. = 6–6.5. G. = 4.18–4.25. {but up to 5.6 with 60% $Fe(Cb,Ta)_2O_6$}. Infusible and insoluble. Adamantine to metallic luster. When artificially freed from iron it is white, but in nature it is dark red to black, rarely brown, or even yellow, violet, or green. Streak yellow to pale brown. $N_o = 2.61$, $N_e = 2.90$.

Rutile is near TiO_2 in composition, but always contains iron (as FeO?), at times up to 10 per cent. This is perhaps due to intergrowths with ilmenite. TiO_2, which may be written as $TiTi_2O_6$, seems to form crystal solutions with $(Fe,Mn)(Ta,Cb)_2O_6$, but these are rare. The relations are shown in Fig. 356.

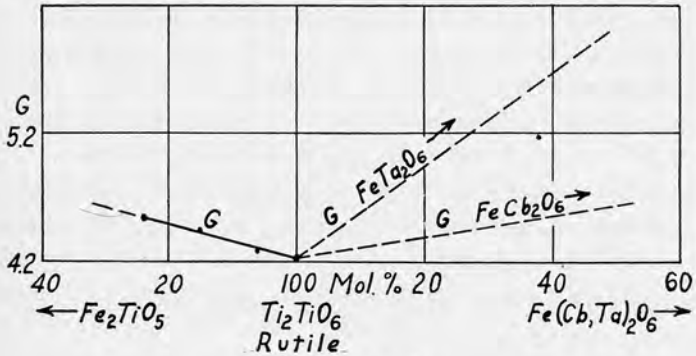


FIG. 356. Rutile.

Nigrine is a variety of rutile containing up to 30 per cent of $FeTiO_3$.

Ilmenorutile is a variety containing considerable $Fe(Ta,Cb)_2O_6$.

Sagenite is the name given to reticulated groups of slender twinned crystals enclosed in quartz.

Brookite and *anastase* (or *octahedrite*) are other crystal phases of TiO_2.

Rutile is a common accessory mineral in igneous rocks, where it is often a product of alteration; in metamorphic and sedimentary rocks, in which the needles can be so tiny that thousands of them may be found in a cubic centimeter and still the tenor of TiO_2 is low. It is very rarely abundant and then usually in veins or pegmatites. Famous localities include Arendal and Krägero in Norway, St. Gotthard and the Binnental in Switzerland, Minas Garaes (Brazil), Chester and Lancaster counties (Pennsylvania), Graves Mountain (Georgia), Magnet Cove (Arkansas), and Nelson County (Virginia).

Rutile is used as a source of titanium, for special grades of steel and copper alloys, and also as a mordant for dyeing leather, as a coloring agent in porcelain and artificial teeth, and in paints, plastics, etc.

Cassiterite **Tetragonal** SnO_2
$c = 0.67$

Crystals low dipyramids or short prisms; rarely acicular; vertically striated. Geniculated or cyclic twinning on (101) common. Granular to fibrous masses may be reniform.

Indistinct (110) cleavage. H. = 6–7. G. = 6.8–7.1. Adamantine luster. Color usually brown, but varies from black through red and yellow to white. Streak white to pale brown. $N_o = 1.997$, $N_e = 2.093$. Rarely pleochroic.

Cassiterite is (nearly) pure SnO_2, but often contains a little iron oxide as well as $(Ta, Cb)_2O_6$, TiO_2, etc. Infusible and insoluble. Varieties include:

Ordinary cassiterite, often called "*tin*," or *tin-stone*, includes crystals and compact masses.

Wood tin is not petrified wood, but resembles it in having radial fibrous structure and concentric bands of color.

Stream tin is the name applied to cassiterite in placer sand and gravel deposits of streams.

Cassiterite is very rare in massive igneous rocks, but is found in pegmatites and veins, and also in altered granitic rocks called *greisen*. It is commonly associated with quartz, tourmaline, fluorite, topaz, etc. It is very resistant to weathering and is therefore found in stream deposits in the regions of primary deposits. Important tin deposits are found in the Malay Peninsula, the Dutch islands of Banka and Billiton, in Siam and China, in Nigeria, and in Bolivia. Deposits in Cornwall have been almost exhausted. Small deposits are known in Saxony, Bohemia, France, Finland, and in the Black Hills of South Dakota, near El Paso, Texas, and in Alaska.

Cassiterite is the only important source of tin which is used extensively as tin plate (sheet iron or steel coated with tin), and in solder, bronze, gun metal, type metal, britannia metal and pewter.

Pyrolusite **Tetragonal** **MnO_2**
$c = 0.66$

Crystals very rare, minute prisms or complex in groups; also encrusting manganite. Commonly fine granular or fibrous aggregates.

Perfect prismatic cleavage. H. = 6–6.5. G. = 4.99. But the common finely granular or fibrous aggregates have H. = 1–2.5, easily blackening fingers, and G. = 4.8. Luster metallic. Color steel gray to black. Streak black. Often pseudomorphous after manganite.

Crystals nearly pure MnO_2, but aggregates contain up to 2 per cent of water, and various other oxides. Infusible. Frees chlorine when treated with HCl.

Pyrolusite is a secondary mineral, usually found with manganite, psilomelane, rhodochrosite, hematite, limonite. It is found in the Harz Mountains and Thuringia in Germany, in Bohemia, France, Brazil, India, Russia, Cuba, and in Virginia, Georgia, Vermont, Arkansas, California.

Pyrolusite is an important ore of manganese, but it is also used in the production of chlorine, and of oxygen. It is a coloring agent in calico printing and dyeing, and in pottery, bricks and paints. It is a decoloring agent for green glass. It is used in dry batteries. Manganese is essential in making steel.

Braunite *Tetragonal* Mn_2O_3
$c = 0.992$

Crystals usually pyramidal, nearly octahedral. Also massive.

Perfect pyramidal (111) cleavage. H. = 6–6.5. G. = 4.7–4.8. Infusible. Luster submetallic. Color brownish black to steel gray.

Braunite only approximates Mn_2O_3; it always contains 3–15 per cent SiO_2 and 1–15 per cent Fe_2O_3; these appear to be in crystal solution, the SiO_2 as $MnSiO_3$. Effects of these on the properties are not known. Soluble in HCl with a residue of SiO_2.

Braunite is commonly secondary; also primary. It is found chiefly in veins. Localities include Ilmenau (Germany), Nagpur (India), Auro Preto (Brazil).

Braunite is a minor source of manganese.

Bauxite **Amorphous** **$Al_2O_3 \cdot nH_2O$**

Commonly in round concretionary grains, pisolitic or oölitic, embedded in clay-like material.

H. = 1–3. G. = 2.4–2.6. Dull to earthy luster. Color white, yellow, brown, or red. $N = 1.56–1.61$.

Bauxite is so impure, often with much SiO_2 and Fe_2O_3, that it is properly considered a rock rather than a mineral; it is included here because it is so important as an aluminum ore. With increase of Fe_2O_3 the specific gravity and index rise and the substance grades into *laterite* and then into limonitic iron ores. X-ray studies show that bauxite is in large part amorphous, but often contains *diaspore* ($Al_2O_3 \cdot H_2O$), *gibbsite* ($Al_2O_3 \cdot 3H_2O$), *quartz* (SiO_2), and *goethite* ($Fe_2O_3 \cdot H_2O$). Bauxite differs from clay in not making a paste with water and in being attacked by alkalies.

Bauxite is a decomposition product produced by weathering of aluminous rocks under tropical or subtropical conditions. It originates evidently as a colloidal precipitate. Bauxite is commonly derived from granites, syenites, or gneisses, but may even form in small quantities in limestones, perhaps as a result of deposition from hot solutions.

Bauxite is obtained in quantity in southeastern France, Algeria, Hungary, Italy, Dutch Guiana, Yugoslavia, British Guiana, Russia, Greece, Dutch East Indies, and in Arkansas, Georgia, and Alabama.

Bauxite is the only important ore of aluminum, but it is also used in making chemicals, abrasives, cements, and refractories.

Diaspore *Orthorhombic* $HAlO_2$

$a:b:c = 0.937:1:0.604$

Crystals prismatic often tabular on 010; also foliated massive.

Perfect 010 cleavage. H. = 6.5–7. G. = 3.3–3.5. F. = 7. Color white, gray, yellowish, greenish. Streak white. $(+)2V = 84°$, $N_g = 1.750$, $N_m = 1.722$, $N_p = 1.702$.

Diaspore may contain some iron and manganese.

It is usually a decomposition product of corundum; also found in volcanic rocks with alunite, and in various schists.

Diaspore (in bauxite) is an important ore of aluminum.

Gibbsite (*Hydrargillite*) *Monoclinic* $Al(OH)_3$

$a:b:c = 1.709:1:1.918, \beta = 85°29'$

Tabular pseudohexagonal basal plates rare; usually in lamellar aggregates or crusts.

Perfect basal cleavage, but rarely seen. H. = 2.5–3.5. G. = 2.3–2.4. F. = 7. Color white, gray, greenish. Streak white. $(+)2V = 0–40°$, $N_g = 1.589$, $N_m = N_p = 1.567$.

Gibbsite may contain a little iron.

It is found with corundum and also often in bauxite deposits.

Gibbsite (in bauxite) is a valuable ore of aluminum.

Limonite (Brown Hematite) $Fe_2O_3 \cdot nH_2O$

Orthorhombic (or amorphous)

Nearly always in compact, porous or earthy masses, often botryoidal or mammillary with fibrous structure and varnish-like surfaces.

Conchoidal to earthy fracture; H. = 1–5.5. G. = 3.4–4.3. Luster often silky; submetallic to earthy. Color yellow to brown. Streak yellowish brown. Often pseudomorphous after pyrite, marcasite, or siderite.

Crystals are nearly pure $Fe_2O_3 \cdot H_2O$, but ordinary limonite contains also more or less silica, alumina, clay, manganese oxide, etc. Soluble in HCl. Important types are:

1. *Goethite*—the crystallized form. Crystals rare, prismatic, with perfect 010 cleavage. H. = 5–5.5. G. = 4.28. $N_g = 2.4$, $N_m = 2.39$, $N_p = 2.26$.
2. *Compact limonite*, which is the common massive material, often fibrous and with smooth surfaces.
3. *Yellow ocher*, which is the yellow to brownish yellow, earthy type, often quite impure with clay, etc.
4. *Bog iron ore*, which forms in marshes and swamps and is generally loose and porous, and may contain organic remains.

Limonite is a product of alteration, especially oxidation and hydration, of various iron minerals. It is widespread in occurrence, being formed not only in swamps, but also generally as a product of weathering of iron minerals. It is important in Lorraine, in Bilboa (Spain), Sweden, Russia, and in Alabama.

Limonite is an important ore of iron in Europe and in Alabama. It is also used as a pigment.

Manganite **Monoclinic** **$Mn_2O_3 \cdot H_2O$**

$a:b:c = 0.844:1:0.545, \beta = 90\pm$

Crystals usually vertically striated prisms, which may be twinned on (011). Also columnar, fibrous, or lamellar.

Perfect 010 and (110) cleavages. H. = 3.5–4. G. = 4.2–4.4. Luster submetallic. Color steel gray to iron black. Streak reddish brown to black. Nearly opaque. $N_g = 2.53$, Li, $N_m = 2.25$, $N_p = 2.25-$.

Manganite is nearly pure $Mn_2O_3 \cdot H_2O$, but often contains a little Fe_2O_3, MgO, etc. Infusible. Soluble in HCl with evolution of chlorine. Alters very easily to pyrolusite without loss of form or luster.

Often associated with other manganese minerals and with hematite, barite, siderite, calcite, etc. Found in metalliferous veins and rarely in sedimentary rocks. Distinguished from other manganese minerals by its crystal form, easy cleavages, frequent fibrous or lamellar state, and streak. Important localities include Ilfeld in the Harz Mountains, Ilmenau in Thuringia, Långban in Sweden, St. Just in Cornwall, Negaunee (Michigan), and Douglas County (Colorado).

Manganite is used with pyrolusite as an ore of manganese and also in the production of chlorine and oxygen.

Brucite *Hexagonal* $Mg(OH)_2$

$c = 1.521$

Crystals basal tablets with rhombohedral symmetry. Also often fibrous or foliated massive; fibers or folia separable and elastic.

Perfect basal cleavage. H. = 2.5. G. = 2.35–2.4. Sectile. Luster pearly to vitreous. Color white or slightly tinted. $N_o = 1.566$, $N_e = 1.585$.

Brucite is fairly pure $Mg(OH)_2$, but commonly contains 1–6 per cent of MnO and FeO. It is miscible (in all proportions?) with $(Mn,Fe)(OH)_2$, the physical properties varying as shown in Fig. 357.

Brucite is abundant in some serpentines and found in some anamorphosed limestones and in slates and schists. It is found, among other places, at Predazzo, Italy, in the Ural Mountains, in Japan, at Brewster (New York), Luning (Nevada), Crestmore (California), in Lancaster County (Pennsylvania).

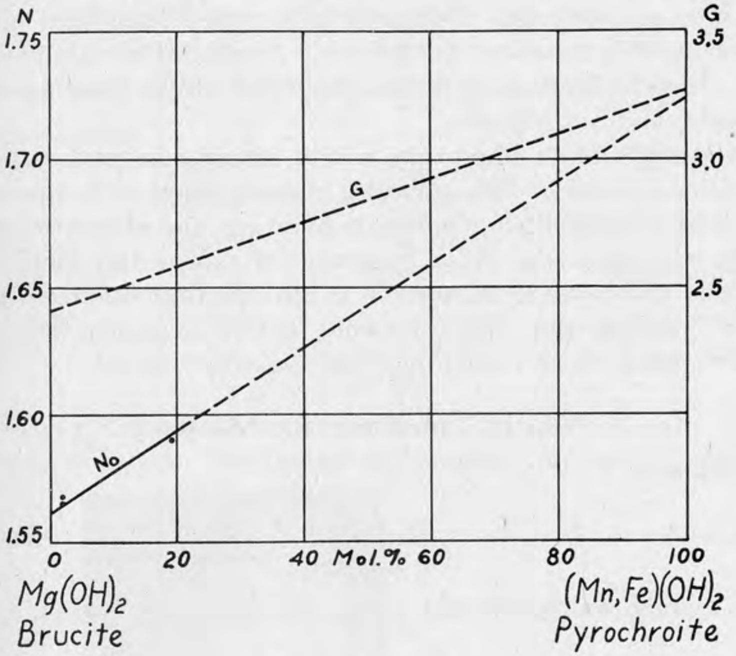


FIG. 357. Brucite.

Brucite is used, like magnesite, to make furnace refractory materials.

Uraninite *Isometric* UO_2, etc.

Crystals octahedral or modified; usually granular compact or lamellar masses, which may be reniform.

Conchoidal to uneven fracture. H. = 5.5 (varies). G. = 9–9.7 in crystals, but 4.8 to 9 in masses. Infusible. Luster submetallic to pitchy on fresh fractures, elsewhere dull. Brown to black in color. Streak brown, black or green. Opaque.

Uraninite is very variable in composition, but the purest crystals were probably originally UO_2 (with isomorphous

ThO_2, CeO_2, etc.), though much of the UO_2 has been altered to UO_3 and some has changed to PbO, Ra, He, etc.

Uraninite is a primary constituent of granite and pegmatite and also a secondary mineral in some ores of silver, lead, copper, etc. Radium was discovered in uraninite from Bohemia. *Cleveite* is a variety from Arendal, Norway, which is rich in yttrium and helium. *Bröggerite* is a type found near Oslo, Norway, with considerable thorium. Uraninite has been found in Cornwall, Roumania, Tanganika, near Great Bear Lake in Canada, and in Colorado.

Uraninite is an important source of uranium and radium. Uranium is used in certain grades of steel; uranium compounds are used as pigments for porcelain painting, and also in coloring glass. Radium is used for treatment of cancer and some skin diseases and as an illuminant; it is also used for discovering by X-ray photography the conditions within a human body, or other opaque object, including steel (to detect flaws).

5. Nitrates, Carbonates, and Manganites

A. Nitrates

Soda Niter *Hexagonal* $NaNO_3$
$c = 0.828$

Crystals are rhombohedral, similar to calcite. Often massive.

Perfect rhombohedral cleavage. H. = 1.5–2. G. = 2.2–2.3. Vitreous luster. Colorless, white, or tinted gray, yellow or red by impurities. $N_o = 1.587$, $N_e = 1.336$.

Soda niter is nearly pure $NaNO_3$, but the yellow color may be due to iodides and the red color to iron. Hygroscopic. Soluble in water and has a cooling and salty taste. Gives an intense yellow flame color.

Found as a surface layer, called *caliche,* in desert regions, notably in northern Chile, intimately mixed with niter (KNO_3), halite (NaCl), gypsum ($CaSO_4{\cdot}2H_2O$), etc. Less extensive deposits are known in Nevada and southern California.

Soda niter is used extensively as a fertilizer (because of its nitrogen) and in the manufacture of nitric acid and potassium nitrate. The *caliche* is also a source of iodine, present as iodides or as *lautarite* (CaI_2O_6). But increasing amounts of nitrogen are now being obtained by electrolytic processes from the air.

Niter *Orthorhombic* KNO_3

$a:b:c = 0.591:0.701$

Crystals equant or acicular with perfect (011) and imperfect 010 and 100 cleavages. H. = 2. G. = 2.1. F. = 1. Soluble in water. Colorless. (−) = 2V = 7°, $N_g = 1.506$, $N_m = 1.505$, $N_p = 1.335$. Found in caves and desert regions.

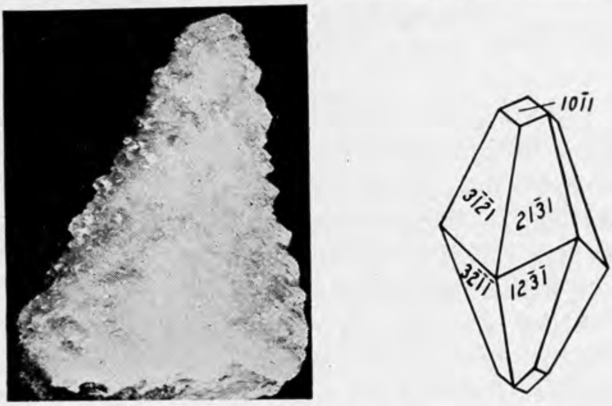
B. Carbonates

Calcite	$CaCO_3$	Aragonite	$CaCO_3$
Dolomite	$Ca(Mg,Fe,Mn)C_2O_6$	Strontianite	$SrCO_3$
Brown Spar		Witherite	$BaCO_3$
Magnesite	$MgCO_3$	Cerussite	$PbCO_3$
Siderite	$FeCO_3$	Malachite	$Cu_2(OH)_2CO_3$
Rhodochrosite	$MnCO_3$	Azurite	$Cu_3(OH)_2(CO_3)_2$
Smithsonite	$ZnCO_3$	*Trona*	$HNa_3(CO_3)_2 \cdot 2H_2O$

Calcite **Hexagonal** $CaCO_3$

$c = 0.854$

Crystals common and remarkably varied in habit, being obtuse or acute rhombohedral, tabular, prismatic, scalenohedral, or complex. See Figs. 358 and 359. Over 300 crystal habits have been observed. Twinning common, on (0001) or (01$\bar{1}$2), etc. Calcite is also common in granular, fibrous, or lamellar masses; sometimes oölitic or stalactitic.



Figs. 358–359. Calcite.

Perfect rhombohedral cleavage making angles of 75° and 105°. H. = 3. G. = 2.72. Infusible. Vitreous to earthy luster. White or colorless. Less commonly yellow, gray or any other color. Streak white or grayish. Transparent to opaque. Some varieties phosphoresce or become luminescent in sunlight or radium emanations. $N_o = 1.6585$. $N_e = 1.4864$.

Calcite is often nearly pure $CaCO_3$, but may contain very little $MgCO_3$ or $FeCO_3$ or more $MnCO_3$ or $PbCO_3$; as these increase the properties vary as shown in Fig. 360. Calcite may also contain a little $SrCO_3$, $BaCO_3$, $ZnCO_3$, or $CoCO_3$. Calcite does not intercrystallize freely with $MgCO_3$ and dolomite is not an evidence of such intercrystallization since it is trirhombohedral (not rhombohedral) in symmetry. $CaCO_3$ crystallizes from solution, at temperatures up to 90°C., to *aragonite* and μ-$CaCO_3$; they invert to calcite in a few days at 100°C. and more rapidly at higher temperatures. Calcite is slowly soluble in surface waters (and this leads to caves in limestone). Easily soluble with effervescence in cold dilute acids. Dolomite effervesces only slowly in cold dilute acids. Calcite, when powdered and boiled in a solution of cobalt nitrate, remains uncolored; aragonite, treated the same way, becomes lilac-red.

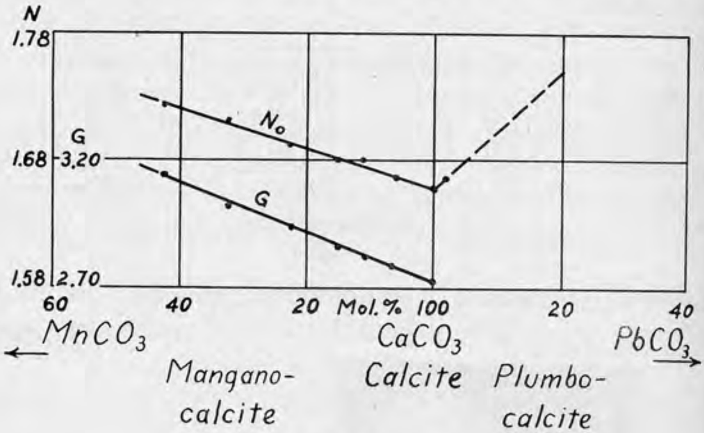


FIG. 360. Calcite.

The important varieties of calcite may be classified as follows: (1) ordinary calcite; (2) spring, stream, and cave deposits; (3) other aggregates.

1. *Ordinary calcite* includes crystals and simple cleavable masses, such as: (a) *dog-tooth spar* = scalenohedral crystals, (b)

nail-head spar = prismatic crystals with obtuse ends, (c) *Iceland spar* = colorless and transparent crystals showing extreme birefringence, (d) *satin spar* = fibrous calcite with a silky luster (but the same name is given to the more common fibrous gypsum).

2. *Spring, stream, and cave deposits* are precipitated from solution of calcium carbonate in water; this may be due to evaporation, as in caves, or to escape of carbon dioxide, causing the soluble bicarbonate of calcium to change to the less soluble normal carbonate, as in caves, spring, and stream deposits, or to the activity of algae in some cases.

(a) *Travertine*, *calcareous sinter*, and *calcareous tufa* are names applied to precipitates of calcite from stream and spring waters. It is abundant along the Anio river near Rome and the Mammoth Hot Springs in Yellowstone Park.

(b) *Stalactites* are deposits of calcite hanging from ceiling or walls of caverns often as cylinders or cones.

(c) *Stalagmites* are similar deposits built up from the floor of caves.

(d) *Onyx marble* (sometimes called *Mexican onyx* or *alabaster*) is a banded deposit of calcite, either stalagmite or travertine, suitable for decorative purposes.

3. *Aggregates* of calcite make up several kinds of rocks, such as:

(a) *Limestone*, which is usually a very finely granular aggregate, of white, yellow, bluish, gray, reddish, or black color. A very even-grained compact type, suitable for making illustrations, is called *lithographic stone*. A limestone containing 10–20 per cent of clay, etc. is called *hydraulic limestone;* it is useful in making cement. A black type giving the odor of bitumen (when pounded), owing to the presence of much organic matter, is called *bituminous limestone*. A coherent mass of shells and shell fragments is called *coquina*. A type consisting of small to larger concretions is called *oölitic* or *pisolitic limestone*. A type consisting largely of earthy masses of foraminifera, etc. is called *chalk*. A mass of fine-grained calcite mixed with clay and sand and rather soft is called *marl;* it is used in making cement.

(b) *Marble* is metamorphosed limestone which has been recrystallized. The process usually produces a coarser grained rock. But commercially any calcareous rock which can be highly polished and thus serve for decorative purposes is called a marble.

Calcite is very widely distributed in nature, but is rare and only an accessory in igneous rocks, in which it is usually secondary in origin. It is found in anygdules, sometimes in large crystals. It is an important cementing material in some sediments. It is the sole or chief constituent of limestone and also of marble. It is an important gangue (that is nonmetalliferous) mineral in many veins. It is abundant around some springs. Only a few of the more important localities may be mentioned here, including Iceland (the chief locality for Iceland spar), Derbyshire, Cumberland, Lancashire, and Durham in England, Freiberg in Saxony, Pribram (Bohemia), Guanajuato (Mexico), Rossie (New York), Bergen Hill (New Jersey), Joplin (Missouri), Gray Cliff (Montana), Bisbee (Arizona), Taos County (New Mexico).

Calcite is used in large quantities and for many purposes. Iceland spar is used in polarizing instruments; chalk is used for whiting, crayons, and as a scouring agent; marl is used in making Portland cement; marble is used for building material and for ornamental and statuary purposes; limestone is used in vast quantities for building material, quicklime, cement, concrete, railroad ballast, and as a flux in metallurgical work; also as a source of carbon dioxide, and as a fertilizer.

Dolomite **Hexagonal** **$Ca(Mg,Fe,Mn,Ca)C_2O_6$**
$c = 0.832$

Crystals commonly rhombohedral in habit with trirhombohedral symmetry. Rhombohedral faces often apparently curved, due to successive small faces not parallel. The curvature may lead to saddle-shaped aggregates. Twinning on (0001) or $(10\bar{1}1)$ or $(02\bar{2}1)$. Also granular, coarse or fine, compact masses.

Perfect rhombohedral cleavage at angles of 74° and 106°. H. = 3.5–4. G. = 2.87 (*magnesiodolomite*) to 3.15 (*ferrodolomite*). Vitreous to pearly luster. White, reddish, greenish, or yellow, brown to black. Streak white or grayish. Transparent to translucent. $N_o = 1.6785$, $N_e = 1.501$ for magnesiodolomite, increasing with Fe or Mn content.

Dolomite $\{Ca(Mg,Fe,Mn,Ca)C_2O_6\}$ has two end-members, namely, the common *magnesiodolomite* ($CaMgC_2O_6$) and *ferrodolomite* ($CaFeC_2O_6$) and it may also contain considerable $CaMnC_2O_6$ and up to 20 per cent of $CaCaC_2O_6$; in rare cases cobalt and zinc enter it. Types between magnesiodolomite and ferrodolomite are known as ankerite.[5] Properties vary with the variations in composition as shown in Fig. 361 and 362.

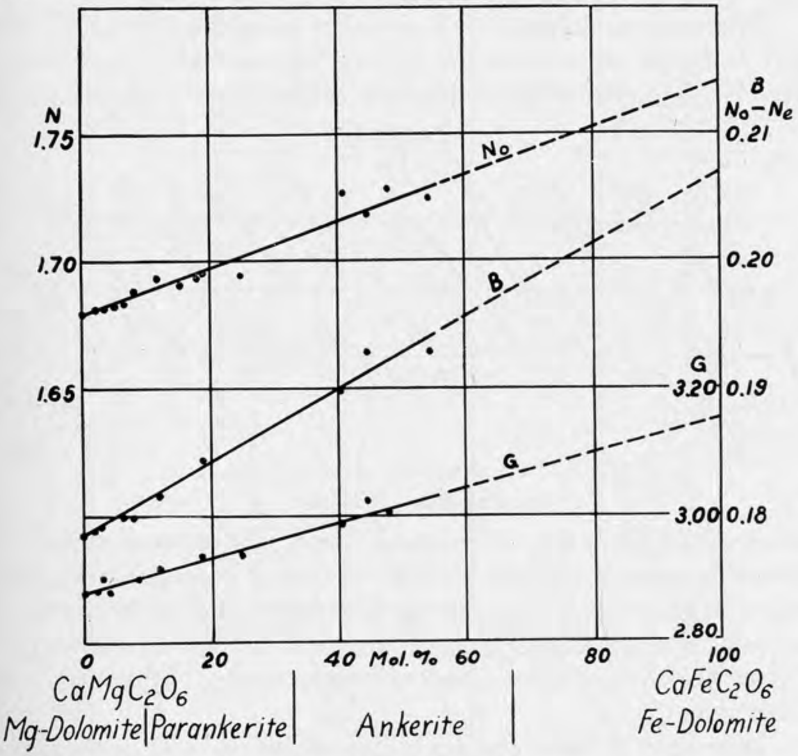


FIG. 361. Dolomite.

Dolomite is only slowly soluble (with effervescence) in cold dilute acid.

Unfortunately massive dolomite has no distinctive name as a rock and dolomite is used as a rock name as well as a mineral name. But many so-called limestones are actually dolomites, as illustrated by many carbonate rocks of the Mississippi Valley. Such rocks are not primary sediments (except, rarely, as detrital

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[5] Ankerite with 8.60% MnO has been called mangananankerite.

products) but probably are produced by reaction between solid calcium carbonate and magnesium salts in solution; for example:

$$2CaCO_3 + MgCl_2 = CaMgC_2O_6 + CaCl_2$$

Recrystallized dolomite is commonly called marble; more accurately it is dolomitic marble.

The mineral dolomite is a common gangue material of veins and is found in cavities in various igneous and other rocks. Massive dolomite is an important sedimentary rock especially in the older terranes. It forms a large part of some mountain ranges in central Europe. Fine crystals of dolomite have been found in mines in Saxony, in the Simplon tunnel in Switzerland, in Cumberland (England), in Guanajuato (Mexico), at Lockport (New York), Hoboken (New Jersey), Joplin (Missouri), and elsewhere.

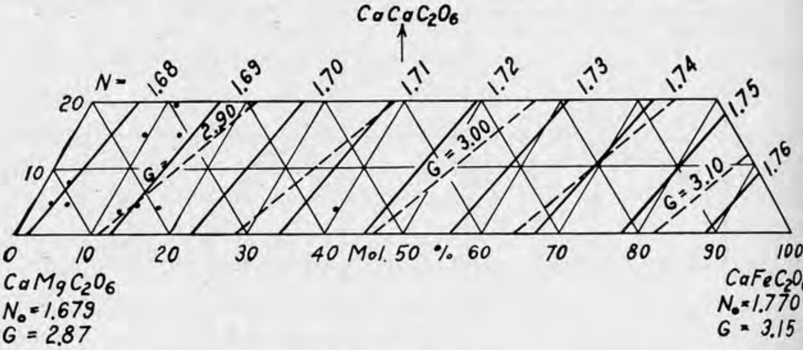


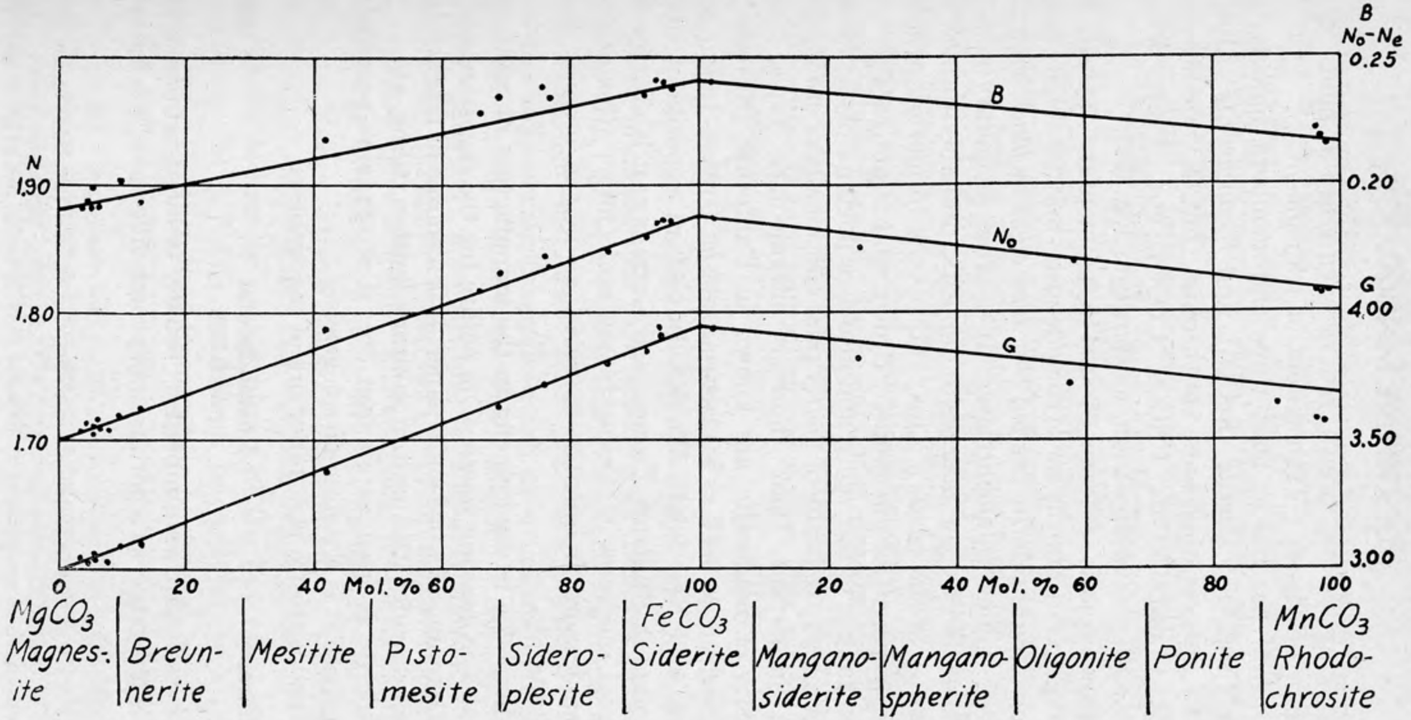
FIG. 362. Dolomite.

Dolomite is used for building, statuary, and ornamental purposes; it is also a source of magnesium compounds and of carbon dioxide; and it is a good refractory material.

Brown Spar	**Magnesite**		**$MgCO_3$**
	Siderite	**Hexagonal**	**$FeCO_3$**
	Rhodochrosite	**$c = 0.811—0.818$**	**$MnCO_3$**

Crystals uncommon, usually rhombohedral in habit; faces often rounded. Usually in masses, either coarse and cleavable, or fine granular compact. At times globular or botryoidal, granular or fibrous; also earthy.

Perfect rhombohedral cleavage. H. = 3.5–4.5. G. = 3.0–3.9. Infusible. Luster vitreous to pearly or earthy. Color


B
$N_o - N_e$
0.25
0.20
G
4.00
3.50
3.00
N
1.90
1.80
1.70
B
N_o
G
0
20
40 Mol. % 60
80
100
20
40 Mol. % 60
80
100
$MgCO_3$
Magnes-ite
Breun-nerite
Mesitite
Pisto-mesite
Sidero-plesite
$FeCO_3$
Siderite
Mangano-siderite
Mangano-spherite
Oligonite
Ponite
$MnCO_3$
Rhodo-chrosite

white, gray, yellow, brown, red, or even green or blue. Streak white or nearly so. Transparent or translucent.

Brown spar has at least three end-members, namely, *magnesite* ($MgCO_3$), *siderite* ($FeCO_3$), and *rhodochrosite* ($MnCO_3$). It may also contain[6] some smithsonite ($ZnCO_3$), *spherocobaltite* ($CoCO_3$) and $CaCO_3$, $CdCO_3$, $CuCO_3$, etc. Properties vary much with the composition, as shown in Fig. 363.

Brown spar is sometimes found in sedimentary deposits, even making up most of the rock; such deposits may be chiefly magnesite or impure siderite (called *clay iron stone* or *black band ores*), or even impure rhodochrosite. It is often secondary in origin, as illustrated by the magnesite deposits, probably formed from dolomite, in the eastern Alps, and by the formation of siderite by replacement of limestone. Brown spar is not rare as a part of the gangue of ore veins, and also as a pneumatolytic mineral. Economically deposits of nearly pure end-members are naturally more important than those of intermediate types. Large deposits of magnesite are known in California, Nevada, and Washington, as well as in Austria, Silesia, Greece, India, South Africa, and New South Wales. Important deposits of siderite are found in England, France, and Germany; it is also found in the coal measures of Pennsylvania and Ohio. Rhodochrosite is found more frequently in veins, as in the ores at Butte, Montana.

Magnesite is used chiefly in the manufacture of refractories and also in making magnesium sulfite for the digestion and for the whitening of wood-pulp paper; it is a source of magnesia and carbon dioxide; it is used in sanitary finishes, tiling, etc.

Siderite is used as an iron ore; if it contains considerable manganese it is a source of spiegeleisen.

Rhodochrosite is a minor ore of manganese.

Smithsonite Rhombohedral $ZnCO_3$

$c = 0.806$

Crystals rare and imperfect; usually in incrustations or compact aggregates; as a porous honeycomb-like mass, it is known as *dry-bone ore*.

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[6] In the $MgCO_3$-$FeCO_3$ series, up to 6% $CaCO_3$ and 10% $MnCO_3$ are known; in the $FeCO_3$-$MnCO_3$ series, up to 3% $CaCO_3$ and 10% $MgCO_3$ are known. Brown spar end-members are apparently miscible only in series, not in all proportions of three compounds.

Perfect rhombohedral cleavage, not easily seen except in crystals. H. = 4.5. G. = 4.1–4.4. F. = 7. Soluble in HCl with effervescence. Luster vitreous. Color usually dirty brown or gray, but may be white, yellow, blue, green, or pink. $N_o = 1.85$, $N_e = 1.62$.

Smithsonite[7] is usually nearly pure $ZnCO_3$, but may contain up to at least 50% $FeCO_3$ (such a type has been called *monheimite*) and some Mn, Co, Mg, Ca, Cd, Cu.

Smithsonite is found in veins and deposits usually associated with sphalerite, galena, and often copper and iron ores. It is usually confined to the oxide zone; it may form pseudomorphs after calcite. Localities where it is found include Laurium in Greece, Moresnet in Belgium, Chessy (France), Matlock (England), and at Mineral Point (Wisconsin), Kelly (New Mexico), Tintic (Utah). In England it is often called *calamine*, but this name is a synonym of heteromorphite in America.

Smithsonite is used as a minor ore of zinc; also, rarely, as an ornamental stone.

Aragonite Orthorhombic $CaCO_3$

$a:b:c = 0.622:1:0.721$

Crystals often acicular to prismatic with domes or pyramids. Twinning on (110) often gives pseudohexagonal groups, which can be distinguished from true hexagonal crystals by the re-entrant angles in the prism zone, and by striations on the base. These features are shown in Figs. 364–366. Also globular, reniform, columnar, or encrusting; then usually fibrous.

Imperfect prismatic (110) and brachypinacoidal cleavage. H. = 3.5–4. G. = 2.9–3.0. Luster greasy on fracture surfaces, but otherwise vitreous. Usually white, colorless, or yellow; also reddish to black. Streak white. Transparent to translucent. $(-)\ 2V = 18°$, $N_g = 1.685$, $N_m = 1.681$, $N_p = 1.530$.

Aragonite is usually nearly pure $CaCO_3$, but may contain up to about 20% $PbCO_3$, or minor amounts of $SrCO_3$(6%), $ZnCO_3$, etc. Distinguished from calcite by crystal form, cleavages, and specific gravity; massive varieties may be easily dis-

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[7] Theoretically it is probable that $ZnCO_3$ can intercrystallize in all proportions with $FeCO_3$ (and is therefore a fourth end-member of the brown spar system), but there is so little evidence of such a series in nature that it seems better for the present to consider that smithsonite is a separate mineral.

tinguished by immersion of the powder in cobalt nitrate (Meigen's reaction) in which aragonite turns lilac, while calcite remains uncolored (or slowly turns blue, if boiled).

Aragonite is only metastable, changing to calcite at about 405°C., or, slowly, at lower temperatures. It is usually deposited from hot solutions, or alone or with calcite from cold solutions. Also it may be formed from cold solutions containing sulfates or carbonates of lead or strontium, or by the action of organisms.

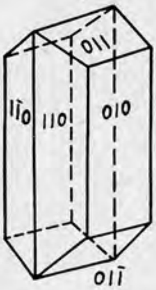

Fig. 364. Aragonite.

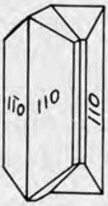

Fig. 365. Aragonite twin.

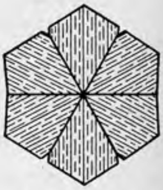

Fig. 366. Cyclic twin of aragonite.

Aragonite is much less common than calcite; it is found in cavities associated with zeolites, in ore deposits especially of iron, in clay often associated with sulfur, gypsum, and celestite, in hot springs and geyser deposits, and in the pearly layer of many shells. Some important localities are Herrengrund in Slovakia, Bilin (Bohemia), Erzberg (Austria), Aragon (Spain), Cumberland (England), Hoboken (New Jersey), Black Hills (South Dakota), Bisbee (Arizona), Fort Collins (Colorado), etc.

Strontianite **Orthorhombic** **$(Sr,Ca)CO_3$**

$a:b:c = \mathbf{0.609:1:0.724}$

Crystals often acicular, arranged radially, or spear shaped; twinning and forms similar to those of aragonite. Also granular compact or fibrous.

Imperfect prismatic (110) cleavage. H. = 3.5–4. G. = 3.71. Vitreous luster—greasy on fracture surfaces. Colorless, white, gray, yellow, or green. Transparent to translucent. $(-)2V = 7°$, $N_g = 1.668$, $N_m = 1.666$, $N_p = 1.520$.

Strontianite nearly always contains 3–13% $CaCO_3$. It inverts (reversibly) to a hexagonal phase at 929°C., which fuses at 1497°C. Soluble in HCl with effervescence.

Strontianite is found in veins both alone and as a part of the gangue in ores. It is commonly associated with celestite, calcite, etc. Important localities include, Strontian, Scotland (whence the name), Freiberg (Saxony), Leogang (Austria), Schoharie (New York), Austin (Texas), and Parlin (Colorado).

Strontianite is used as a source of strontium salts; thus, the oxide and hydroxide are used in precipitating sugar from molasses; the nitrate is used for red flame; the iodide and lactate are used in medicines.

Witherite **Orthorhombic** **$BaCO_3$**

$a:b:c = 0.595:1:0.741$

Crystals pseudohexagonal pyramids by twinning on (110), as in aragonite. Also columnar or granular massive.

Imperfect prismatic (110) cleavage. H. = 3.5. G. = 4.2–4.35. Vitreous luster or somewhat greasy on fractures. Colorless, gray, yellowish. Streak white. Transparent to translucent. $(-)2V = 16°$, $N_g = 1.677$, $N_m = 1.676$, $N_p = 1.529$.

Witherite is (nearly) pure $BaCO_3$. It inverts at 811°C. to a hexagonal form and at 982°C. to an isometric form (which fuses at about 1740°C. under 90 atmospheres pressure of CO_2). Decomposes and fuses easily before the blowpipe.

Witherite is used as a white pigment and also in extracting sugar from beets.

Cerussite **Orthorhombic** **$PbCO_3$**

$a:b:c = 0.610:1:0.723$

Crystals usually tabular, prismatic, or pyramidal in habit, often in clusters; pseudohexagonal twinning common. Also granular or fibrous masses.

Poor prismatic (110) cleavage. H. = 3–3.5. G. = 6.4–6.6. Adamantine luster, sometimes silky. Colorless, white or gray. Streak white. Transparent to subtranslucent. $(-)2V = 8°$, $N_g = 2.078$, $N_m = 2.076$, $N_p = 1.804$.

Cerussite is usually quite pure $PbCO_3$, but may contain a little silver or zinc. It fuses easily, yielding metallic lead in the reducing flame. Soluble in dilute nitric acid with effervescence.

Cerussite is found as a secondary mineral in the oxide zone of lead ore deposits. It is often associated with galena, anglesite, and pyromorphite. It is found at Pribram (Bohemia), Zellerfeld (Germany), Lanark (Scotland), Broken Hill (New South Wales), and at Joplin (Missouri), Leadville (Colorado), Wardner (Idaho), Park City (Utah), and elsewhere.

Malachite **Monoclinic** **$Cu_2(OH)_2CO_3$**
$a:b:c = 0.881:1:0.401$, $\beta = 61°50'$

Crystals acicular in tufts; much commoner in botryoidal masses with fibrous divergent structure, often banded in color; also granular to earthy.

Perfect basal and distinct clinopinacoid cleavages. H. = 3.5–4. G. = 3.9–4.1. Silky, adamantine or dull luster. Color grass green to dark green. Streak paler green. Translucent to opaque. $(-)2V = 43°$, $N_g = 1.909$, $N_m = 1.875$, $N_p = 1.653$.

Malachite is usually nearly pure $Cu_2(OH)_2CO_3$, but apparently the copper may be replaced by zinc to about 20 per cent. Fuses at 2. Soluble in acids with effervescence.

Malachite is common in the oxide zone of copper deposits, especially those in limestone areas. It may be pseudomorphous after cuprite or azurite, and associated with them and with chalcocite, bornite, chalcopyrite, and native copper. Large masses have been obtained from the Ural Mountains; other localities include Chessy (France), Cornwall (England), Katanga (Belgian Congo), Bwana (Rhodesia), and at Bisbee and Globe (Arizona), Park City (Utah), Good Springs (Nevada).

Malachite is an important ore of copper, especially in Arizona. It is also used as an ornamental stone, especially in Russia.

Azurite **Monoclinic** **$Cu_3(OH)_2(CO_3)_2$**
$a:b:c = 0.856:1:0.884$, $\beta = 87°35'$

Crystals very varied in habit, but often short prismatic or tabular, often complex in aggregates. Often in reniform or botryoidal masses with radial fibrous texture. Also in crusts or dull and earthy.

Distinct (021) cleavage. H. = 3.5. G. = 3.7–3.8. Adamantine to vitreous luster. Color light azure to deep blue.

Streak light blue. Transparent to opaque. $(+)2V = 68°$, $N_g = 1.838$, $N_m = 1.758$, $N_p = 1.730$.

Azurite varies in axial ratio so much that variation in composition has been suggested, but analyses are insufficient to determine the point.

Azurite is a secondary mineral found in the oxide zone of copper deposits, nearly always closely associated with malachite. It alters rather easily to malachite, or to cuprite or copper. Much less common than malachite. Excellent crystals found at Chessy, France (whence the synonym *chessylite*), and in the Ural Mountains, and in Chile; also at Bisbee and Morenci, Arizona, and Kelly, New Mexico.

Azurite is used as a copper ore, but is not abundant. A mixture of azurite and malachite, called *azurmalachite*, is used for gem purposes.

Trona (Urao) *Monoclinic* $HNa_3(CO_3)_2 \cdot 2H_2O$

$a:b:c = 2.846:1:2.970$, $\beta = 77°23'$

Crystals usually basal plates or elongated along b; also fibrous to columnar massive.

Perfect orthopinacoid cleavage. H. = 2.5–3. G. = 2.14. Vitreous luster. Color gray to yellowish. Translucent. $(-)2V = 72°$, $N_g = 1.540$, $N_m = 1.492$, $N_p = 1.412$.

Trona is $HNa_3(CO_3)_2 \cdot 2H_2O$. Easily fusible. Soluble in water and has an alkaline taste.

Common in some arid regions as an efflorescence or salt lake deposit. Found near Cairo, Egypt, in the desert of Sahara, and at Borax and Owens Lakes in California.

Artificial trona and natron ($Na_2CO_3 \cdot 10H_2O$) are extensively used in the manufacture of soap and glass.

C. Manganites

Only two manganites merit attention here. They are hausmannite (Mn_2MnO_4) and psilomelane.

Hausmannite *Tetragonal* Mn_2MnO_4

$c = 1.166$

Crystals pyramidal, often cyclic twins; usually granular massive.

Perfect basal cleavage. H. = 5–5.5. G. = 4.7–4.85. Infusible. Greasy to metallic luster. Color brownish black. Streak chestnut brown. $N_o = 2.46$, $N_e = 2.15$.

Hausmannite is usually nearly pure Mn_2MnO_4, but may contain up to 10% ZnO. It is soluble in HCl with evolution of chlorine.

Hausmannite is rare; it is a primary mineral in some veins in acid igneous rocks. Often closely associated with psilomelane, magnetite, hematite, barite. Found at Ilfeld (Germany), Långban (Sweden), and near Batesville, Arkansas.

Psilomelane[8] **Orthorhombic** $\mathbf{H_4(Ba,Mn,Co,Cu,Pb)_2Mn_8O_{20}}$**?**
$a:b:c = \mathbf{0.664:1:0.209}$

Crystals unknown; usually in botryoidal, reniform, or stalactitic masses with smooth surfaces; also earthy.

Earthy masses very soft; others, H. = 5–6. G. = 4.7. Luster submetallic to dull. Dark gray to iron black in color; opaque. Brownish black streak.

Psilomelane is very variable in composition and the formula is in doubt. It is regarded as colloidal MnO_2 with various adsorbed impurities (but X rays prove that it has crystal structure).

Psilomelane is a secondary mineral especially in laterite deposits, often associated with limonite, pyrolusite, calcite, etc. Found at Ilmenau (Germany), Romanèche (France), Cornwall (England), central India, and at Batesville, Arkansas, and Cartersville, Georgia.

Psilomelane is used as an ore of manganese.

6. Sulfates, Chromates, Tungstates, Molybdates, etc.

The important minerals of this division may be listed as follows:

Mirabilite	$Na_2SO_4 \cdot 10H_2O$	Gypsum	$CaSO_4 \cdot 2H_2O$
Glauberite	$Na_2Ca(SO_4)_2$	*Epsomite*	$(Mg,Zn,Fe,Mn)SO_4 \cdot 7H_2O$
Kieserite	$MgSO_4 \cdot H_2O$	*Melanterite* . . .	$(Fe,Cu,Zn)SO_4 \cdot 7H_2O$
Kainite	$MgSO_4 \cdot KCl.3H_2O$	*Chalcanthite* . .	$(Cu,Zn,Fe,Co)SO_4 \cdot 5H_2O$
Anhydrite . . .	$CaSO_4$	*Alunite*	$K_2\{Al(OH)_2\}_6(SO_4)_4$
Barite	$BaSO_4$	Wolframite . .	$(Fe,Mn)WO_4$
Celestite	$SrSO_4$	Scheelite	$CaWO_4$
Anglesite	$PbSO_4$	*Wulfenite*	$PbMoO_4$
Polyhalite	$K_2MgCa_2S_4O_{16} \cdot 2H_2O$	*Crocoite*	$PbCrO_4$

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[8] G. Vaux: *Mineral. Mag.* XXIV, 521 (1937). Crystal system, axial ratio and even the formula based on X-ray study.

Mirabilite *Monoclinic* $Na_2SO_4 \cdot 10H_2O$

$a:b:c = 1.116:1:1.237, \beta = 72°15'$

Crystals resemble pyroxene in habit and angles. Usually in crusts.

Perfect orthopinacoid cleavage. H. = 1.5–2. G. = 1.48. Readily soluble in water with a cool and then feebly saline and bitter taste. Loses its water rapidly in dry air and falls to a powder. Colorless. $(-)2V = 80°$, $N_g = 1.398$, $N_m = 1.396$, $N_p = 1.394$.

Mirabilite or Glauber salt is quite pure $Na_2SO_4 \cdot 10H_2O$.

Mirabilite is found in salt lake deposits associated with halite and gypsum; it occurs thus at Ischl (Austria), Sedlitz (Bohemia), LaRioja (Spain). Obtained in large quantities from the waters of Great Salt Lake, Utah.

Mirabilite (also called Glauber salt) is manufactured from common salt as one step in the manufacture of sodium carbonate.

Glauberite *Monoclinic* $Na_2Ca(SO_4)_2$

$a:b:c = 1.220:1:1.027, \beta = 67°49'$

Crystals basal tablets or prismatic. Also massive.

Perfect basal cleavage. H. = 2.5–3. G. = 2.7–2.85. Luster vitreous. Color pale yellow or gray; rarely red. Streak white. $(-)2E = 0° - 17°$, $N_g = 1.536$, $N_m = 1.532$, $N_p = 1.515$. Optic angle changes rapidly with rise in temperature.

Glauberite is quite pure $Na_2Ca(SO_4)_2$. Fuses easily. Soluble in HCl. Partly soluble in water with a salty bitter taste.

It is found in salt deposits with halite, anhydrite, polyhalite, etc. Found thus at Salzburg (Austria), Stassfurt (Germany), Mayo (India), Iquique (Chile), and at Borax Lake, California.

Kieserite *Monoclinic* $MgSO_4 \cdot H_2O$

$a:b:c = 0.915:1:1.757, \beta = 89°6'$

Crystals pyramidal; but usually granular massive.

Perfect pyramidal cleavages. H. = 3.5. G. = 2.57. Color white or tinted. $(+)2V = 57°$, $N_g = 1.586$, $N_m = 1.535$, $N_p = 1.523$.

Nearly pure $MgSO_4 \cdot H_2O$. Slowly soluble in water. Easily fusible.

Abundant in salt deposits at Stassfurt (Germany), Hallstadt (Austria), Kalusz (Poland), and elsewhere.

Kainite *Monoclinic* $MgSO_4 \cdot KCl \cdot 3H_2O$

$a:b:c = 1.219:1:0.586, \beta = 85°3'$

Crystals 001 tablets or pyramidal. Usually granular massive or in crusts.

Distinct 100 and (110) cleavages; the prismatic cleavage angle is 79°. H. = 3. G. = 2.13. F. = 1.5–2. Soluble in water. Colorless or stained red. $(-)2V = 85°$, $N_g = 1.516$, $N_m = 1.505$, $N_p = 1.494$.

Nearly pure $MgSO_4 \cdot KCl \cdot 3H_2O$, but sodium may proxy for some potassium.

Found with picromerite, halite, sylvite, polyhalite, etc.

Important as a source of potash.

Anhydrite **Orthorhombic** $CaSO_4$

$a:b:c = 0.893:1:1.001$

Crystals uncommon, tabular or elongated along axis *b*. Twinning on (012), or on (101), sometimes lamellar. Usually massive.

Three pinacoidal cleavages, yielding rectangular pseudocubic fragments, but the three cleavages are not equally good, 001 being very perfect and 100 only distinct. H. = 3. G. = 2.93. Luster pearly to vitreous. Colorless or tinted or red. $(+)2V = 42°$, $N_g = 1.614$, $N_m = 1.576$, $N_p = 1.570$.

Quite pure $CaSO_4$. Soluble in HCl. Fusible at 1450° (after inversion at 1193°) with red flame color.

Found often closely associated with gypsum; usually in salt lake deposits; also in veins. Abundant in some sediments, as at Stassfurt (Saxony), Beilberg (Austria), Berchtesgaden (Bavaria), Bex (Switzerland), and in Nova Scotia, New Brunswick, New York, Kansas.

Anhydrite hydrates slowly to gypsum with a large increase of volume, which may cause local disturbances. It is also found occasionally in pseudomorphs after gypsum.

A siliceous variety of anhydrite is sometimes used as an ornamental stone. It is also used as a fertilizer and as a cement retarder.

Orthorhombic

Barite $a:b:c = 0.815:1:1.314$ $BaSO_4$
Celestite $a:b:c = 0.779:1:1.280$ $SrSO_4$

Crystals commonly basal tablets or elongated along *a* or *b*; rarely pyramidal or in diverging groups; also in cleavable, granular, or fibrous masses, or earthy.

Perfect basal and prismatic (110) cleavages. H. = 2.5–3.5. G. varies with composition from 3.95 (celestite) to 4.35 (barite). Vitreous to pearly luster. Colorless, white, yellow, gray, green, blue, red. Celestite is often bluish. Streak white. Optic properties also vary with composition as follows (see Fig. 367):

	Celestite	*Barite*
$(+)2V =$	51°	37°
$N_g =$	1.631	1.648
$N_m =$	1.623	1.637
$N_p =$	1.622	1.636
$N_g - N_p =$	0.011	0.012

Nearly pure end-members are usually found in nature, but types between celestite and barite have been found, as well as up to 30% $PbSO_4$ in barite. It is probable that $BaSO_4$ and $SrSO_4$ are miscible in all proportions. Only a little $CaSO_4$ can be present. Barite fuses at 1580° after inversion at 1149°; celestite fuses at 1605° after inversion at 1152°. Insoluble in acids.

Barite is common in some veins especially with ores of lead, copper, iron, zinc, silver, etc. Also associated with stibnite, fluorite, quartz, calcite, etc. Also found in sandstones, limestones, and marl. Localities include Cornwall, Cumberland, and Derbyshire, England, Roumania, Bohemia, Hungary, and Michigan, New York, Georgia, Missouri, Kentucky.

Barite is used in large quantities to make paint, lithopone, glass, artificial ivory, and insecticides; it is the source of barium hydroxide (used in refining sugar) and other barium compounds.

Celestite is usually found in limestone or sandstone, but it is also associated with sulfur in some volcanic regions, and found in amygdules in igneous rocks. It occurs thus in Italy, Sicily, Switzerland, Egypt, and at Lockport (New York), Nashville (Tennessee), Strontian Island (Lake Erie), El Paso County (Colorado), Death Valley (California), and elsewhere.

Celestite is used in making strontium compounds for refining sugar and for fireworks, etc.

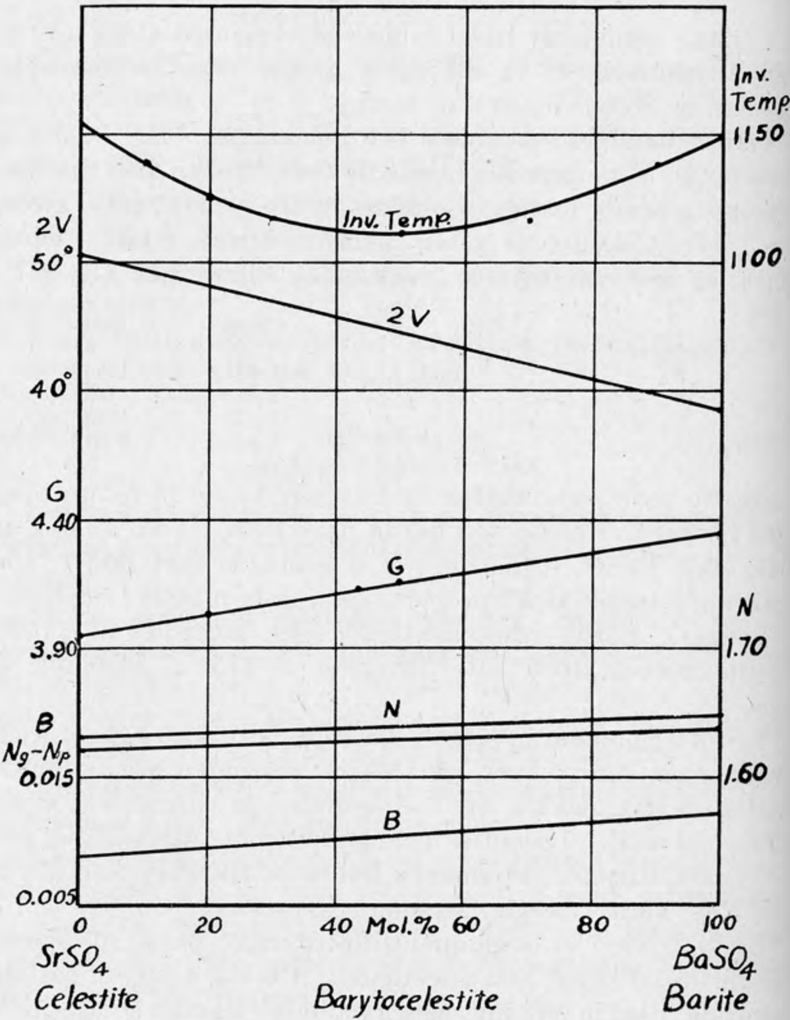

FIG. 367. Celestite-barite.

Anglesite **Orthorhombic** **$PbSO_4$**

$a:b:c = 0.785:1:1.289$

Crystals (001) tablets or columnar along *a*, *b*, or *c*; also pyramidal; often granular massive.

Imperfect basal and prismatic (110) cleavages. H. = 2.75–3. G. = 6.1–6.4. Fuses at 1080° after inversion at 852°. Luster adamantine to resinous. Color white or tinted yellow, gray, green, blue. Streak white. $(+)2V = 75°$, $N_g = 1.895$, $N_m = 1.883$, $N_p = 1.878$.

Anglesite is nearly pure $PbSO_4$.

Anglesite is often formed by oxidation of galena with which it is associated in the upper portions of veins and other deposits of lead ores. Important localities include Leadhills (Scotland), Broken Hill (New South Wales), Lamentos (Mexico), Tintic (Utah), and Coeur d'Alene (Idaho).

Anglesite is a minor ore of lead.

Polyhalite *Triclinic* $K_2MgCa_2S_4O_{16}\cdot 2H_2O$

$a{:}b{:}c = 0.931{:}1{:}0.856$, $\alpha = 92°29'$, $\beta = 123°4'$, $\gamma = 88°21'$

Crystals (010) tablets or fibrous parallel to *b*; usually granular, fibrous, or lamellar masses.

Distinct 100 cleavage. H. = 2.5–3. G. = 2.7–2.8. F. = 1.5. Luster greasy or pearly. Color red or yellow. Streak white, yellow, reddish. $(-)2V = 60$, $N_g = 1.567$, $N_m = 1.562$, $N_p = 1.548$.

Polyhalite is closely associated with halite, sylvite, carnallite, and gypsum in salt deposits, as at Stassfurt, Germany, and Salzburg, Austria.

It is a minor source of potassium.

Gypsum **Monoclinic** $\mathbf{CaSO_4\cdot 2H_2O}$

$\mathbf{a : b : c = 0.690 : 1 : 0.412,\ \beta = 80°42'}$

Crystals usually simple in habit, commonly (010) tablets or prismatic; twinning common on 100 as arrowhead forms or in penetration; also twinned on (101). Often in cleavable, columnar, granular, foliated, or fibrous masses.

Perfect 010 cleavage. H. = 2. G. = 2.32. Fuses at 2.5–3. Vitreous to pearly or silky luster, or even dull. Color white, gray, yellow, blue, or, if impure, brown, red, or black. Streak white. $(+)2V = 58°$, $N_g = 1.530$, $N_m = 1.523$, $N_p = 1.520$.

Gypsum is nearly pure $CaSO_4\cdot 2H_2O$. Soluble in HCl and also in about 400 parts of water. Several varieties of gypsum are recognized:

1. *Selenite* is crystallized or coarsely crystalline cleavable gypsum, usually colorless and transparent.

2. *Satin spar* is fibrous gypsum with a silky luster. Sometimes used in cheap jewelry. But the name is also applied to fibrous calcite.

3. *Alabaster* is a massive fine-granular gypsum, sometimes used for statuary and decorative purposes. But some "alabaster" is a variety of calcite.

4. *Rock gypsum* is a compact scaly or granular variety of dull color and usually impure with clay, silica, etc. It is often ground for use as a fertilizer under the name *land plaster.*

5. *Gypsite* is an impure earthy or sandy variety, abundant in Kansas, Oklahoma, New Mexico and Arizona.

Gypsum is a common mineral and even forms beds of great thickness, which are associated with limestone and shales, and salt deposits. Such beds may be of great economic importance. At ordinary pressure gypsum is formed at temperatures below 90°. It is usually a primary deposit, but may be produced by hydration of anhydrite. In smaller masses it is known as a deposit of hot springs and as a product of volcanic activity and as produced by the action of sulfuric acid (derived from the oxidation of pyrite) on limestone, etc. It is often associated with halite, anhydrite, calcite, dolomite, aragonite, pyrite, sulfur, quartz, etc.

Important localities for gypsum include Laurium, Greece, and Volterra, Italy (for alabaster), Eisleben (Germany), Girgenti (Sicily), Montmartre (France), Matlock (England), Naica (Mexico), and Lockport (New York), Mammoth Cave (Kentucky), Ellsworth (Ohio), Grand Rapids (Michigan), Logan County (Kansas), Fort Dodge (Iowa), Falfurrias (Texas).

Gypsum is ground for use as a fertilizer; it is also used as a flux in glass and porcelain manufacture, as a retarder in making Portland cement, but its greatest use is in making plaster of all kinds. The familiar *plaster of Paris* is so called because it has been made on a large scale at Montmartre, near Paris, for many years. Plaster is made from gypsum by merely heating it until three fourths of the water is driven off; in that condition it is ready for use, because it will take up the water again quickly and "set" to a solid mass.

Epsomite *Orthorhombic* $(Mg,Zn,Fe,Mn)SO_4{\cdot}7H_2O$
$a:b:c = 0.990:1:0.571$

Crystals prismatic (spheroidal); commonly fibrous massive.

Perfect 010 and distinct (011) cleavages. H. = 2–2.5. G. = 1.68. Colorless or white. $(-)2V = 51°$, $N_g = 1.461$, $N_m = 1.455$, $N_p = 1.433$.

Epsomite is usually nearly pure $MgSO_4{\cdot}7H_2O$, but may contain up to about 10% $MnSO_4{\cdot}7H_2O$, about 20% $FeSO_4{\cdot}7H_2O$, about 50% $ZnSO_4{\cdot}7H_2O$ (then[9] $N_g = 1.470$, $N_p = 1.447$).

Soluble in water and has a bitter salty taste.

Epsomite is in solution in some mineral waters, as at Epsom in England. It is common in salt waters and so is found in some salt lake deposits as at Stassfurt, Saxony, where it is associated with carnallite. It is found in crusts on some dry regions such as the alkali plains of Utah and Nevada. It is an efflorescence in some mine galleries and caves, as in Mammoth Cave, Kentucky. It is sometimes an alteration product of serpentine, talc, or magnesite. It is associated with gypsum at Montmartre near Paris, France.

Epsomite is used as a fertilizer, as a coating for cotton cloth, and as a medicine.

Melanterite	*Monoclinic*	$(Fe,Cu,Zn)SO_4{\cdot}7H_2O$
Iron melanterite	$a:b:c = 1.183:1:1.543$, $\beta = 75°44'$	$FeSO_4{\cdot}7H_2O$
Pisanite	$a:b:c = 1.161:1:1.511$, $\beta = 74°38'$	$(Fe,Cu)SO_4{\cdot}7H_2O$
Boothite	$a:b:c = 1.162:1:1.500$, $\beta = 74°24'$	$CuSO_4{\cdot}7H_2O$
Zinc-copper melanterite		$(Zn,Cu,Fe)SO_4{\cdot}7H_2O$

Crystals rare; usually fibrous to earthy masses or crusts.

Perfect 001 and distinct (110) cleavages. H. = 2. G. = 1.89–2.03, varying with composition. Pale green or blue to white. Streak uncolored. $(+)2V$ = large; for iron melanterite: $2V = 86°$, $N_g = 1.486$, $N_m = 1.478$, $N_p = 1.471$. See Fig. 368.

Melanterite varies from the pure iron end member ($FeSO_4{\cdot}7H_2O$) through *pisanite* $\{(FeCu)SO_4{\cdot}7H_2O\}$ to the pure copper end member, *boothite* ($CuSO_4{\cdot}7H_2O$); it may also contain zinc.

Melanterite is commonly a secondary mineral resulting from the alteration of pyrite or marcasite, and the reactions of the

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[9] J. J. Glass: *Econ. Geology:* 33, 756 (1938).

sulfuric acid solutions, thus formed, on various ores. It is easily soluble in water and has a sweetish astringent taste. Loses water easily to $5H_2O$ and becomes *chalcanthite* (in powdery masses).

Melanterite is found in the Harz Mountains, Germany, near Lyons, France, at Falun, Sweden, at the Rio Tinto mines in Spain, and at Ducktown (Tennessee), Bingham Canyon (Utah), Vulcan (Colorado), Alameda County (California), and so on.

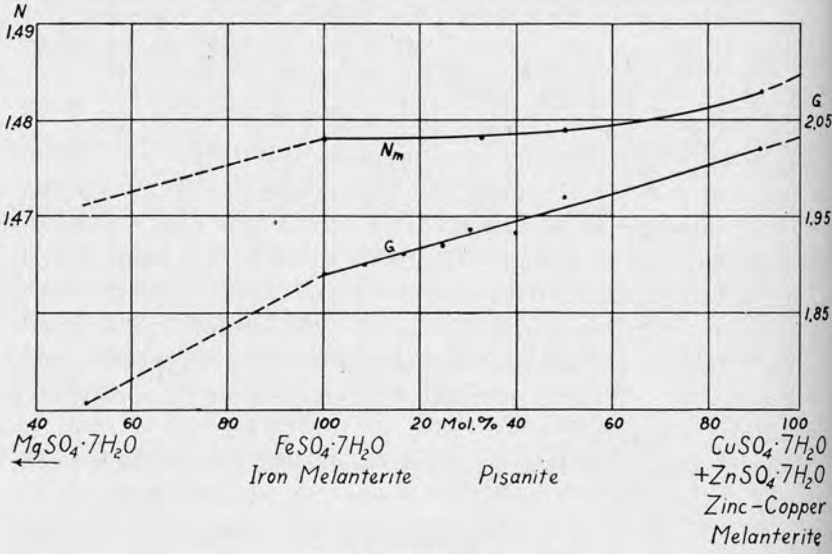

FIG. 368. Melanterite.

Artificial melanterite is used as a mordant in dyeing, as a disinfectant, and in the manufacture of bluing, inks, and pigments.

Chalcanthite	*Triclinic*	$(Cu,Zn,Fe,Co)SO_4 \cdot 5H_2O$
Zinc-copper chalcanthite		$(Zn,Cu)SO_4 \cdot 5H_2O$
(Copper) chalcanthite		$CuSO_4 \cdot 5H_2O$
Iron-copper chalcanthite		$(Fe,Cu)SO_4 \cdot 5H_2O$
Iron chalcanthite or siderotil		$FeSO_4 \cdot 5H_2O$
Cobalt chalcanthite		$CoSO_4 \cdot 5H_2O$

For $CuSO_4 \cdot 5H_2O$ $a:b:c = 0.572:1:0.557$, $\alpha = 97°44'$, $\beta = 107°26'$, $\gamma = 100°40'$

Crystals commonly flattened parallel to 111; also massive, fibrous.

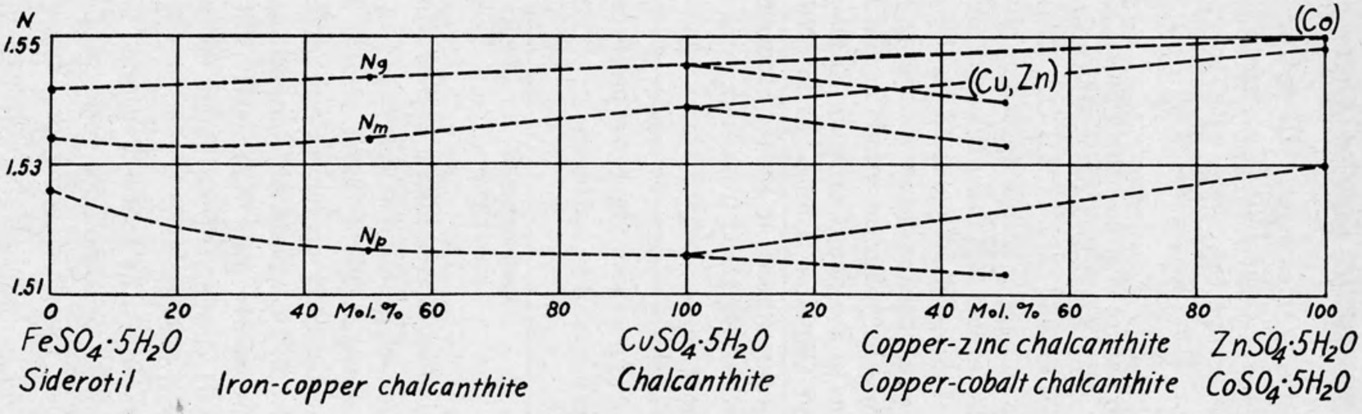

FIG. 369. Chalcanthite.

Imperfect prismatic cleavages. H. = 2.5. G. = 2.2–2.3. Vitreous to dull luster. Color blue (Cu), green (Fe), pink (Co). Streak uncolored. Properties vary with the composition as shown in Fig. 369. For Cu: $(-)2V = 56°$, $N_g = 1.546$, $N_m = 1.539$, $N_p = 1.516$.

Chalcanthite in nature is often nearly pure $CuSO_4 \cdot 5H_2O$, but it seems to vary to $FeSO_4 \cdot 5H_2O$, $CoSO_4 \cdot 5H_2O$, $ZnSO_4 \cdot 5H_2O$ and perhaps $MnSO_4 \cdot 5H_2O$ and $MgSO_4 \cdot 5H_2O$. Readily soluble in water. The artificial copper salt is known as *blue vitriol.*

Chalcanthite is formed by the oxidation and hydration of copper and other sulfides; it is deposited on the walls of mines, but only in dry regions because of its solubility. It is found in the Rio Tinto mines in Spain, in mines in the Harz region in Germany, at Falun in Sweden, Cornwall, England, and also at Chuquicamata and Copiapo (Chile), Reno (Nevada), Clifton (Arizona), and in mine waters at Butte, Montana. Important amounts of copper are recovered from such mine waters by precipitation with scrap iron.

Artificial chalcanthite is used to render water aseptic; and for spraying plants, and as a mordant and preservative of timber, and for copper plating, and in batteries.

Alunite *Rhombohedral* $K_2Al_6(OH)_{12}(SO_4)_4$
$c = 1.252$

Crystals rhombohedral resembling cubes, since the angle is 90°50′. Also fibrous or granular massive.

Distinct basal cleavage. H. = 3.5–4. G. = 2.58–2.84. Infusible. Vitreous to pearly luster. Color and streak white. $N_o = 1.572$, $N_e = 1.592$ (varies with composition).

Alunite may be nearly pure $K_2Al_6(OH)_{12}(SO_4)_4$, but often contains $Na_2Al_6(OH)_{12}(SO_4)_4$ up to about 65 per cent (*natroalunite*). Soluble in H_2SO_4.

Alunite is produced by the action of sulfated vapors or waters on acid volcanic rocks or aluminous rocks, apparently at high temperatures. Also found in some ore deposits. Localities include Tolfa (Italy), Mont Dore (France), and Marysvale (Utah), Death Valley (California), Molokai (Hawaii).

Wolframite **Monoclinic** **$(Fe,Mn)WO_4$**

$a:b:c = 0.826:1:0.866$, $\beta = 89°32'$

Crystals prismatic or (100) tablets; also bladed or lamellar or granular massive.

Perfect 010 cleavage; often 100 and (102) parting. H. = 5–5.5. G. = 7–7.5, varying very little with Fe:Mn ratio. Luster submetallic. Color brownish red to black. Streak brown, gray, black. Indices vary with composition as shown in Fig. 370. Average about: $(+)2V$ = large, $N_g = 2.42$, $N_m = 2.32$, $N_p = 2.26$.

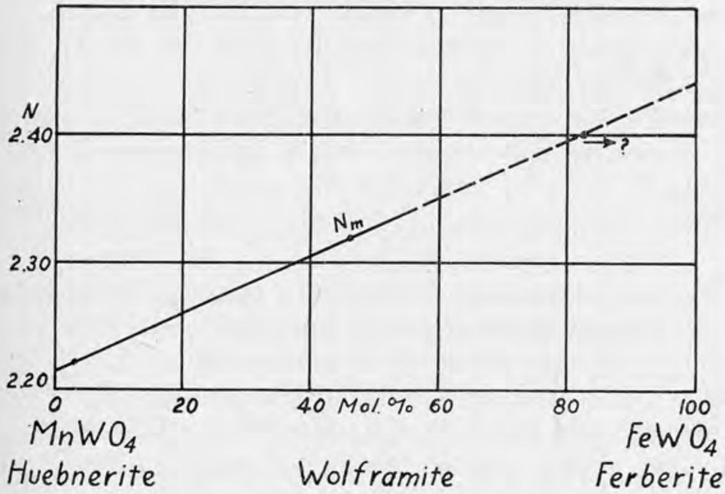

Fig. 370. Wolframite.

Wolframite varies from $FeWO_4$ (*ferberite*), to $MnWO_4$ (*huebnerite*). It fuses easily (F. = 2, ferberite, to 4 huebnerite) to a magnetic globule. Decomposed by aqua regia.

Wolframite is found in pegmatites and veins, often associated with cassiterite; also with sulfides of iron, copper, etc. It has been obtained in Cornwall (England), Bohemia, Roumania, Haute Vienne (France), Burma, Peru, and in the Black Hills (in Colorado), New Mexico, California, and elsewhere.

Wolframite is used as a source of tungsten and its compounds. Tungsten is important in making high-speed tool steel and as a filament for incandescent lamps. Tungstic oxide is used to color glass. Tungsten carbide has found several uses in industry. Other tungsten compounds are used as mordants, in tanning leather, or to render cloth noninflammable.

Scheelite **Tetragonal** **$CaWO_4$**
$c = 1.536$

Crystals pyramidal or tabular, only rarely showing the tripyramidal symmetry. Often as crusts or granular masses.

Distinct pyramidal (111) cleavage. H. = 4.5–5. G. = 5.9–6.2. Vitreous to adamantine luster. Color white, yellow, brownish, or greenish. Streak white. $N_o = 1.918$, $N_e = 1.934$.

Scheelite is usually nearly pure $CaWO_4$, but may contain copper or molybdenum. *Powellite* ($CaMoO_4$) is known to contain up to 9 mol.% $CaWO_4$; then it has: $c = 1.545$, G. = 4.25, $N_o = 1.967$, $N_e = 1.978$.

Scheelite is a notable source of tungsten, which is used especially in electric light filaments and in high-speed tool steel.

Wulfenite *Tetragonal* $PbMoO_4$
$c = 1.577$

Crystals basal tablets or pyramidal or prismatic; also granular. Pyramidal hemimorphic symmetry rarely shown.

Smooth pyramidal (111) cleavage. H. = 3. G. = 6.9. Fuses at 1065°. Luster resinous or adamantine. Color yellow, red, green, rarely gray. Streak white. $N_o = 2.40$, $N_e = 2.30$.

Usually nearly pure $PbMoO_4$, but may contain Ca, V, or Cr; miscible freely with $PbWO_4$ (*stolzite*).

Wulfenite is a secondary mineral found in the oxide zone of lead ore deposits. It is commonly associated with galena, sphalerite, pyromorphite, vanadinite, etc. It occurs at, among other places, Pribram (Bohemia), Bleiberg (Austria), Broken Hill (New South Wales), in the French Congo, in Sonora (Mexico), and in New Mexico, Arizona, Utah, Nevada.

It is used as an ore of molybdenum, which is employed to increase the hardness and strength of steel, and as a part of several alloys.

Crocoite *Monoclinic* $PbCrO_4$
$a:b:c = 0.960:1:0.916$, $\beta = 77°33'$

Crystals prismatic, vertically striated. Also granular.

Imperfect (110) cleavage at 86°. H. = 2.5–3. G. = 5.9–6.1. F. = 1.5. Color bright red. Streak orange yellow. $(+)2V = 57°$. $N_g = 2.66$, $N_m = 2.37$, $N_p = 2.31$.

Usually nearly pure $PbCrO_4$ but may contain some $PbSO_4$.

Crocoite is found in the oxide zone of lead deposits in regions where Cr_2O_3 is present in adjoining rocks. Localities include Dundas (Tasmania), Ural Mountains, Roumania, Vulture district (Arizona).

Crocoite is too rare to be commercially important, but it is a possible ore of lead and of chromium.

7. Borates, Aluminates, and Ferrites

Boracite	$Mg_3ClB_7O_{13}$		Chrysoberyl	$BeAl_2O_4$
Ulexite	$NaCaB_5O_9 \cdot 8H_2O$	Spinel	Spinel	$(Mg,Fe)Al_2O_4$
Kernite	$Na_2B_4O_7 \cdot 4H_2O$		Chromite	$(Fe,Mg)Cr_2O_4$
Borax	$Na_2B_4O_7 \cdot 10H_2O$		Magnetite	$(Fe,Mn,Zn)Fe_2O_4$
Colemanite	$Ca_2B_6O_{11} \cdot 5H_2O$			

Boracite *Pseudocubic-Orthorhombic* $Mg_3ClB_7O_{13}$

Crystals apparently isometric, but with orthorhombic structure below 265°C; inverts to isometric structure at 265°.

Octahedral cleavage very poor. H. = 7. G. = 2.9–3.1. F. = 2 with intumescence. Colorless, white, gray, green. Streak white. $(+)2V = 83°$, $N_g = 1.673$, $N_m = 1.667$, $N_p = 1.662$.

Boracite may contain some iron (which may cause a greenish color and raise the inversion point to 285° and the specific gravity to 3.1).

Boracite is found in beds with halite, gypsum, anhydrite; it is formed by evaporation of salt water, as at Stassfurt.

Boracite is a minor source of borax.

Ulexite **Monoclinic or triclinic** $\mathbf{NaCaB_5O_9 \cdot 8H_2O}$

Usually in finely fibrous "balls."

Color and streak white. Luster silky. H. = 1. G. = 1.7–1.9. F. = 1. Soluble in HCl.

Ulexite seems to vary very little in composition.

It forms from the concentration of brines in playa lakes; it is often associated with borax. It is found in Chile, and in desert regions of Nevada and California.

It is a minor source of borax.

Kernite **Monoclinic** $\mathbf{Na_2B_4O_7 \cdot 4H_2O}$

$a:b:c = 1.523:1:1.699,\ \beta = 71°8'$

Crystals equant or 100 tablets; often massive. Perfect 001 and 100 cleavages. H. = 2.5. G. = 1.91. Colorless or white. $(-)2V = 80°$, $N_g = 1.488$, $N_m = 1.472$, $N_p = 1.454$.

Nearly pure $Na_2B_4O_7 \cdot 4H_2O$; slowly soluble in water, which then yields borax ($Na_2B_4O_7 \cdot 10H_2O$) on evaporation. Fuses to a white glass after swelling.

Found with ulexite and colemanite in thick beds in Kern County, California. It is now an important source of borax.

Borax **Monoclinic** $\mathbf{Na_2B_4O_7 \cdot 10H_2O}$

$a:b:c = 1.0995:1:0.5632,\ \beta = 73°25'$

Crystals prismatic, resembling pyroxene in angles and habit.

Perfect basal and distinct prismatic cleavages. Fuses at 1–1.5 to transparent glass, after enlarging notably. H. = 2–2.5. G. = 1.69–1.72. Luster resinous to vitreous; also earthy. Color white. $(-)2V = 40°$, $N_g = 1.472$, $N_m = 1.469$, $N_p = 1.447$.

Borax is $Na_2B_4O_7 \cdot 10H_2O$, but analyses of the natural mineral are almost unknown. Soluble in water; has a feeble sweetish-alkaline taste. Nearly all borax of commerce has been made artificially from kernite or other borates.

Borax is used chiefly in making enamel ware and glass, but also in washing powders, soaps, soldering, and assaying; it is also a food preservative and antiseptic.

Colemanite **Monoclinic** $\mathbf{Ca_2B_6O_{11} \cdot 5H_2O}$

$a:b:c = 0.775:1:0.541,\ \beta = 69°51'$

Crystals usually prismatic, often highly modified. Also granular or cleavable masses resembling chalk.

Perfect 010 cleavage. H. = 4–4.5. G. = 1.4. Vitreous to dull luster. Colorless to white. $(+)2V = 55°$, $N_g = 1.614$, $N_m = 1.592$, $N_p = 1.586$.

Perhaps $HCaB_3O_9 \cdot 2H_2O$. Soluble in hot HCl; boracic acid separates on cooling. Insoluble in water. Yields borax when treated with sodium carbonate or sulfate.

First found in Death Valley, California, later in neighboring desert regions; usually associated with halite, thenardite, gypsum, etc.

Colemanite was the chief source of borax until the discovery of kernite, and was used as kernite is now used.

Chrysoberyl **Orthorhombic** **$BeAl_2O_4$**

$a:b:c = 0.470:1:0.580$

Crystals 100 tablets or twinned to pseudohexagonal groups; also granular or fragmental.

Distinct brachydome (011) cleavage. H. = 8.5. G. = 3.5–3.8. Infusible. Luster vitreous. Color usually green, pale to dark, or yellow; often red by transmitted light. $(+)2V = 45°$, $N_g = 1.757$, $N_m = 1.748$, $N_p = 1.747$.

Chrysoberyl is usually nearly pure $BeAl_2O_4$, but may contain some iron and chromium. Insoluble. There are three varieties:

1. *Ordinary chrysoberyl,* usually pale green, being colored by iron.
2. *Alexandrite,* emerald green in color, but red in gas or lamp light; less distinctly red in tungsten electric light. Artificial corundum showing these colors is often sold as alexandrite.
3. *Cat's eye* or *cymophane* is an opalescent yellowish green variety from Ceylon.

Chrysoberyl is found in granite, pegmatite, and adjoining schists and gneisses, as well as in placer deposits. It is often associated with beryl, tourmaline, garnet, apatite, and sillimanite. It has been found in the Ural Mountains, Ceylon, Madagascar, Rhodesia, Brazil, and in Maine, Connecticut, New York, and elsewhere.

It is used as a gem stone because of extreme hardness and delicate colors.

Spinel **Isometric** **$(Mg,Fe,Zn,Mn))(Al,Cr)_2O_4$**

Crystals usually octahedral or modified. Twinning on (111) common, hence called spinel twins; also multiple. Often granular.

Imperfect octahedral cleavage. H. = 7.5–8. G. = 3.5–5.0 (see Figs. 371–373). Infusible. Vitreous to metallic luster. Color red, blue, green, brown, or black; rarely yellow to white. Streak white to dark brown. $N = 1.715–2.16$.

Spinel is extremely variable in composition (see Figs. 371–373). Varieties include *spinel proper,* also called *magnesiospinel* or *talcspinel,* $MgAl_2O_4$; *hercynite,* $FeAl_2O_4$; *gahnite,* $ZnAl_2O_4$; *galaxite,* $MnAl_2O_4$; *picrochromite,* $MgCr_2O_4$; and *chromite,* $FeCr_2O_4$. *Ceylonite* and *pleonaste* are types intermediate between spinel and hercynite; *picotite* contains also some chromite. $MgAl_2O_4$ with some $FeFe_2O_4$ is called *chlorospinel;* as in magnetite, the iron may be, in part, Fe_2O_3. Artificial gem spinels may contain as much as 60% Al_2O_3. Varieties of spinel used for gem purposes include:

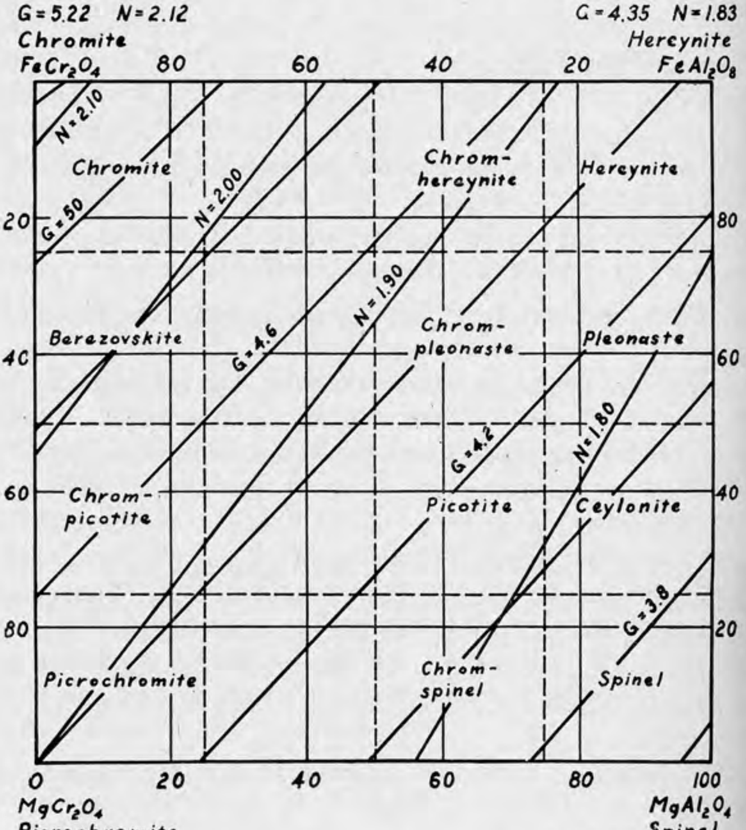

FIG. 371. Spinel, based on data of W. Hugell: Spec. Rep. 26, Iron Steel Institute, 201 (1939).

1. *Ruby spinel*—deep red in color, resembling the true ruby.
2. *Balas ruby*—rose red in color.
3. *Rubicelle*—yellow or orange red.

4. *Blue spinel*—light blue.
5. *Almandine*—bluish red or violet.

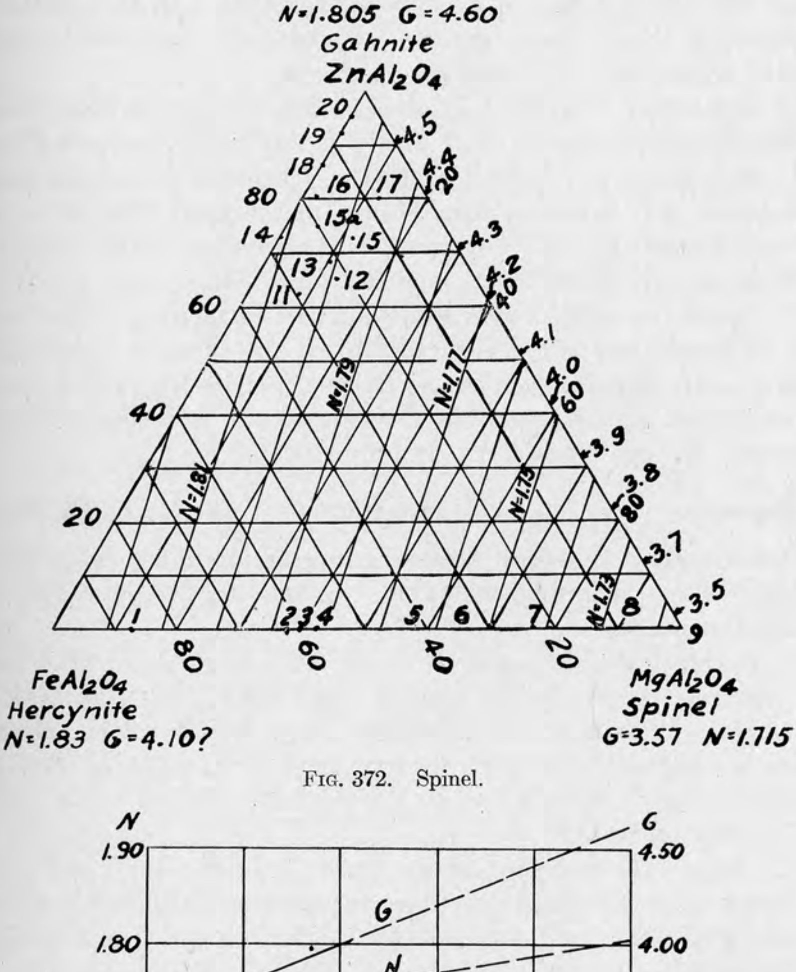

FIG. 372. Spinel.

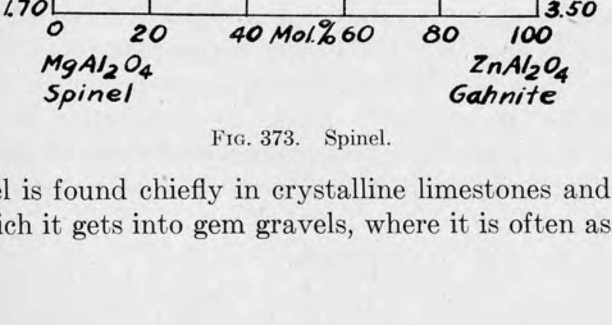

FIG. 373. Spinel.

Spinel is found chiefly in crystalline limestones and schists, from which it gets into gem gravels, where it is often associated with corundum. It is an accessory constituent of various basic igneous rocks, in which the chromite variety is also found, but the two types rarely, if ever, occur together. Gem spinels are obtained chiefly from gravels. Chromite is obtained chiefly from serpentine and basic igneous rocks.

Important localities for spinel include Ceylon, Burma, Siam, Madagascar, Vesuvius, and Amity (New York), Andover (New Jersey), Franklin (North Carolina). Chromite is found in large deposits near Smyrna, Asia Minor, in the Ural Mountains, in New Caledonia, and in crystals at Hoboken (New Jersey), Webster (North Carolina), and in California.

Spinel is used as a gem stone and as a refractory. Chromite is employed in making refractory brick and furnace linings, and as a source of chromium for use in special steels for cutting tools, projectiles, armor plate, stainless steel, and as chromium compounds for pigments, dyes, and mordants.

Magnetite **Isometric** **$(Fe,Mn,Zn,Mg)Fe_2O_4$**

Crystals octahedral, dodecahedral, or modified; cubic faces rare. Rare twinning on (111). Coarse to fine granular or lamellar massive.

Octahedral parting. H. = 5.5–6.5. G. = 5.17 ($FeFe_2O_4$ crystals) to 4.4 (with notable $MgFe_2O_4$). Very difficultly fusible. Metallic to dull luster. Iron black color. Streak black ($FeFe_2O_4$) to dark brown or red $\{(Fe,Mn,Zn)Fe_2O_4\}$. Opaque or very nearly so. $N = 2.42$ ($FeFe_2O_4$) to 2.36 $\{(Fe,Mn,Zn)Fe_2O_4\}$.

Magnetite is often nearly pure $FeFe_2O_4$, but may vary (apparently continuously) to *magnesioferrite* ($MgFe_2O_4$), *jacobsite* ($MnFe_2O_4$), or *franklinite* ($ZnFe_2O_4$), as shown in Fig. 374. (Franklinite in nature contains 30–50% $MnFe_2O_4$). To a limited extent Fe''' may be replaced by Al or Mn'''. Magnetite may be changed partly or completely to Fe_2O_3 by heating to 220° in oxygen, without loss of magnetism or crystal structure; it is then the rare variety *oxymagnite,* which inverts to hematite at about 530°. Ordinary magnetite is strongly attracted by a magnet, but only rare pieces act as magnets themselves. These are called *lodestone.* Magnetite is soluble in HCl.

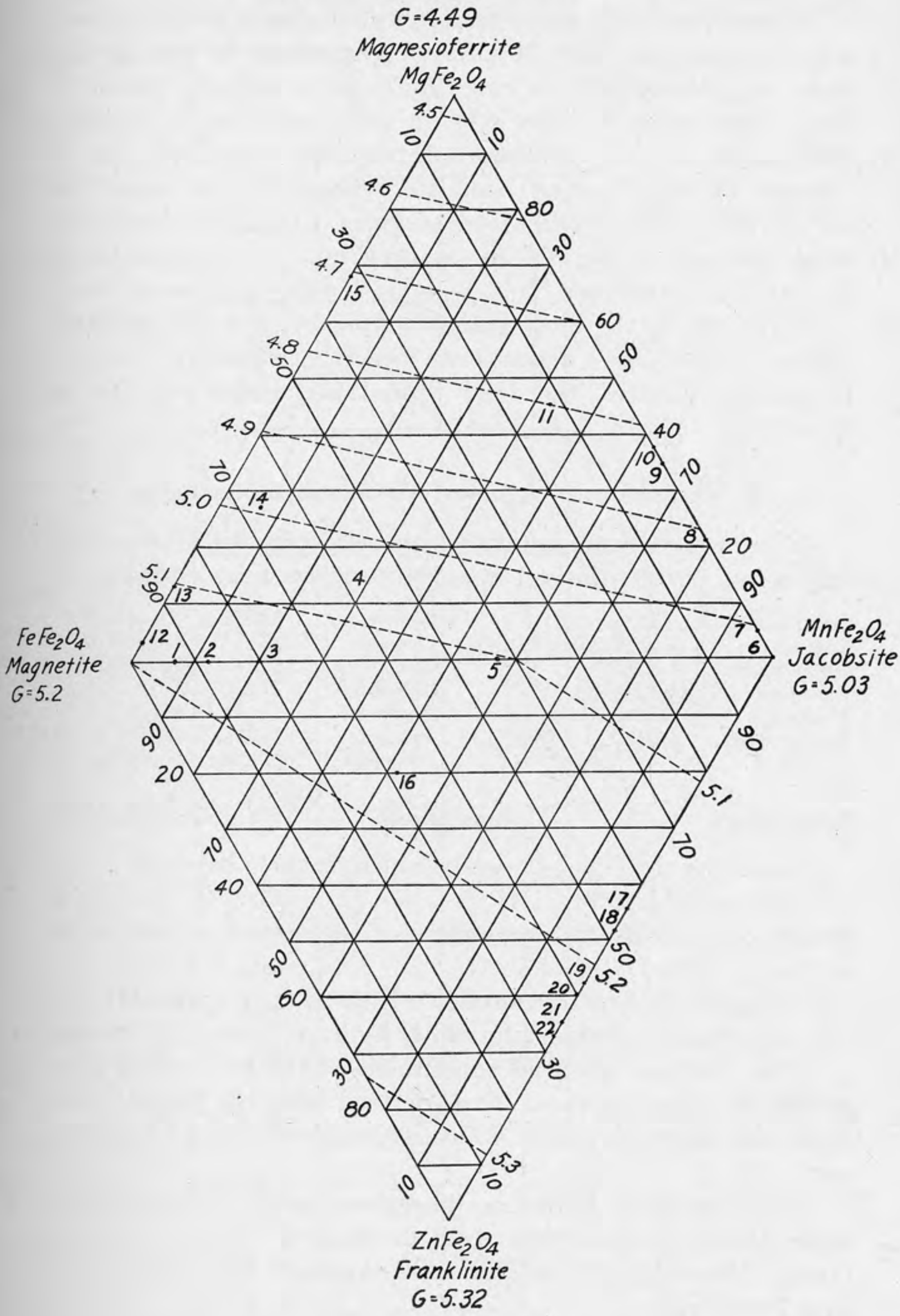

FIG. 374. Magnetite.

Magnetite is very widespread in its occurrence in igneous and metamorphic rocks. It is found only sparingly in acid igneous rocks, but abundantly in basic rocks, even forming masses of great importance as iron ores in rare cases, as in Sweden. Similar masses are sometimes formed by metamorphism of deposits of limonite and hematite. Magnetite is one of the earliest minerals to solidify from magmas. It may be formed by either contact or regional metamorphism. It is concentrated by moving waters into "black sands," which may be of value.

Magnetite is the most valuable iron ore, but not the commonest. The largest deposits are in northern Sweden, Norway, Roumania, Austria, the Ural Mountains; important also in New York.

8. Phosphates, Arsenates, Vanadates, Columbates

Many minerals are known which belong to this division, but only a few are of sufficient importance to be included here:

Collophanite	$Ca_3P_2O_8 \cdot nH_2O$	*Wavellite*	$(AlOH)_3P_2O_8 \cdot 5H_2O$
Apatite	$Ca_5(F,Cl,OH)(PO_4)_3$	*Carnotite*	$K_2(UO_2)_2V_2O_8 \cdot 3H_2O$
Pyromorphite	$Pb_5Cl(PO_4)_3$	*Turquois*	$CuO \cdot 3Al_2O_3 \cdot 2P_2O_5 \cdot 9H_2O$
Vanadinite	$Pb_5Cl(VO_4)_3$	*Scorodite*	$FeAlO_4 \cdot 2H_2O$
Monazite	$(Ca,La,Di)PO_4$	*Erythrite*	$Co_3As_2O_8 \cdot 8H_2O$
Amblygonite	$LiAl(F,OH)PO_4 \cdot \frac{1}{4}H_2O$?	*Vivianite*	$Fe_3As_2O_8 \cdot 8H_2O$
		Columbite	$(Fe,Mn)(Cb,Ta)_2O_6$

Collophanite **Amorphous** **$Ca_3P_2O_8 \cdot nH_2O$**

Usually amorphous, massive, concretionary, banded.

Conchoidal fracture. H. = 2–5. G. = 2.6–2.9. F. = 5–6. Soluble in cold HNO_3, with slight effervescence. Colorless or stained. $N = 1.51–1.63$.

Collophanite usually contains a little calcium carbonate, sulfate, and fluoride, but is dominantly hydrous calcium phosphate.

It is the only essential constituent of the rock called *phosphorite* or *phosphate rock*. It is derived from the bones of animals, and also from guano, which is the excrement of birds, bats, etc.

Collophanite is found (as phosphate rock) in sedimentary deposits on a commercial scale in Belgium, France, Algeria, Tunis, Morocco, and in Florida, Tennessee, Montana, Idaho, and Wyoming.

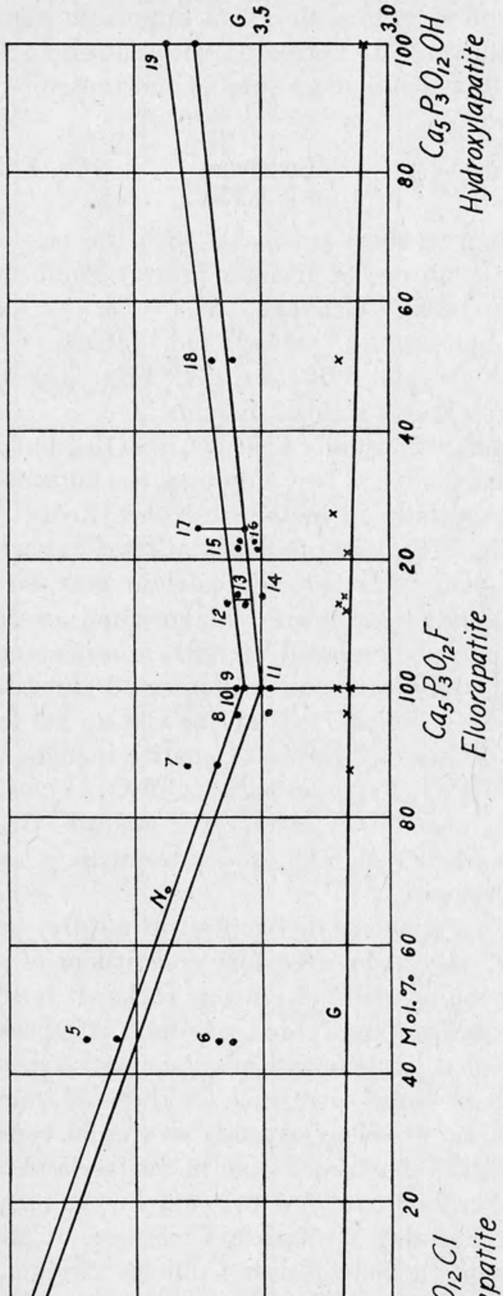

FIG. 375. Apatite.

It is used on a large scale as an important source of phosphorus in fertilizers. It is treated with sulfuric acid to form a superphosphate which is more soluble and therefore more useful to plants.

Apatite **Hexagonal** **$c = 0.735$** **$Ca_5(F,Cl,OH)(PO_4)_3$**

Crystals long to short prismatic with the base or pyramid. Also indistinctly fibrous or granular; rarely reniform.

Indistinct basal cleavage. H. = 5. G. = 3.05–3.20. Color green, blue, white, yellow, red. Streak white. N_o = 1.632–1.655, N_e = 1.63–1.65 (see also Figs. 375–377). Fuses with difficulty. Easily soluble in acids.

Natural apatite is usually near $Ca_5F(PO_4)_3$, but it may vary from this in many ways. Not only may the fluorine be replaced by chlorine (especially in meteorites) or hydroxyl in any proportion (see Fig. 375) but apparently at least in part by oxygen, CO_2, or even SO_3. Further, the calcium may be replaced in part by manganese, strontium, magnesium, or ferrous iron. Also, the PO_4 may be replaced by AsO_4 in any amount (see Fig. 376). Finally, there are more complicated substitutions, such as SiS for PP (see Fig. 377), NaY for CaCa, YO for CaF, YSi for CaP, and others. Varieties of apatite include the common *fluorapatite* ($Ca_5P_3O_{12}F$), *chlorapatite* ($C_5P_3O_{12}Cl$) *hydroxylapatite* ($Ca_5P_3O_{12}OH$), *svabite* ($Ca_5As_3O_{12}OH$), *dahllite* ($C_{10}P_6O_{24}{\cdot}CO_3$), *ellestadite* ($Ca_{10}Si_3S_3O_{24}(OH)_2$), and intermediate types, such as *wilkeite* and *fermorite*.

Apatite is very widely distributed in nature, but is almost always present only as an accessory constituent of rocks. It is found thus in many kinds of igneous rocks; it is slightly more abundant in some metamorphic rocks; and it is present in some sedimentary rocks. It is found in larger crystals in some pegmatites, and also in some ores, such as those of iron and of tin. Localities yielding excellent crystals or special types for study include Salzburg in Austria, Ticino in Switzerland, Gellivare in Sweden, Jumella in Spain, Ashio in Japan, Auburn and Buckfield (Maine), Faraday (Ontario), Crestmore (California). It is associated with rutile in Nelson County, Virginia.

Extensive deposits of phosphates in sedimentary beds are known in Alabama, Florida, Tennessee, Utah, Idaho, and

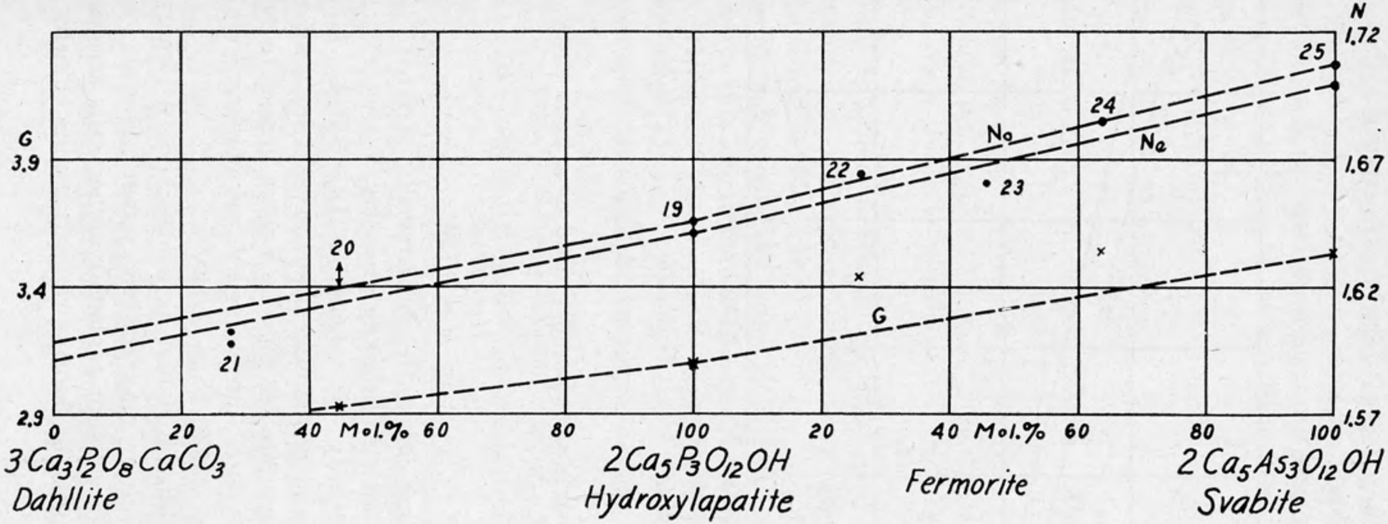

FIG. 376. Apatite.

Wyoming. Such deposits are in part apatite and in part amorphous or colloidal masses related to it. Apatite and such phosphate deposits are used on a large scale as sources of fertilizers. Apatite is occasionally used as a gem stone, but is too soft to be satisfactory.

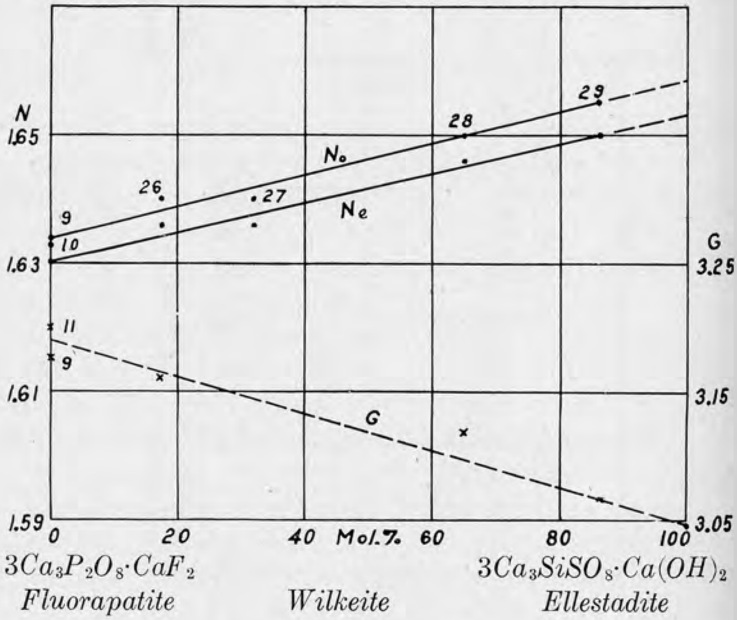

FIG. 377. Apatite.

Pyromorphite *Hexagonal* $Pb_5ClP_3O_{12}$
$c = 0.729$

Crystals are prismatic, horizontally striated. Also often globular, and either fibrous or granular.

Cleavage only in traces. H. = 3.5–4. G. = 6.5–7.1. Fuses easily and on cooling takes crystal form again (whence the name, meaning *fire form*). Luster greasy to adamantine. Color green, yellow, brown, gray, or white. Streak white to yellow. $N_o = 2.060$, $N_e = 2.049$.

Pyromorphite in nature is nearly always remarkably pure $Pb_5ClP_3O_{12}$, but it may contain minor amounts of other elements such as calcium replacing some lead, arsenic replacing some phosphorus, or fluorine replacing some chlorine.

Pyromorphite is a secondary mineral in some lead deposits, but never in large amounts. It has been obtained at, among other places, Berezovsk (Russia), Klaustal (Germany), Huelgoat (France), Leadhills (Scotland), Broken Hill (New South Wales), and Mullan (Idaho).

Pyromorphite is a minor source of lead.

Vanadinite *Hexagonal* $Pb_5ClV_3O_{12}$
$c = 0.712$

Crystals prismatic, sometimes hollow. Also fibrous or globular.

Brittle. H. = 3. G. = 6.7–7.2. Fuses at 990°. Luster resinous. Color red, yellow, brown. Streak yellow to white. $N_o = 2.416$, $N_e = 2.350$. Soluble in HNO_3. Decomposed by HCl.

Vanadinite is usually nearly pure $Pb_5ClV_3O_{12}$, but rare types contain arsenic in variable amount, thus grading through *endlichite* to *mimetite* ($Pb_5ClAs_3O_{12}$).

Vanadinite is a secondary mineral in some lead deposits. Localities where it is found include Berezovsk (Russia), Dumfries (Scotland), Oudjda (Morocco), Zimapan (Mexico), and at Oracle (Arizona), Hillsboro (New Mexico).

It is a source of vanadium and its compounds.

Monazite *Monoclinic* $(Ce,La,Di)PO_4$
$a{:}b{:}c = 0.969{:}1{:}0.915$, $\beta = 76°6'$

Crystals often small 100 tablets or elongated along b; also granular.

Perfect basal and distinct orthopinacoidal cleavages. Twinning on 100. H. = 5. G. = 5.0–5.2. Resinous luster. Color clove brown, yellow, or red. White streak. $(+)2V = 14°$, $N_g = 1.837–1.849$, $N_m = 1.788–1.801$, $N_p = 1.787–1.800$.

Monazite usually contains cerium, lanthanum (either may be in excess), and didymium, with less yttrium, as well as ThO_2 (0–20%) and SiO_2, probably as $ThSiO_4$ in crystal solution.

Monazite is an uncommon accessory mineral in granite, aplite, pegmatite, and gneiss. In rare cases it is more abundant; it may then be further concentrated in derived sediments, resulting in detrital sands containing commercial quantities, as in Travancore (India), Bahia and São Paulo (Brazil), and in

Georgia and North and South Carolina. In granite or pegmatite it is found at Arendal (Norway), Miask (Russia), Valais (Switzerland), Ampangabe (Madagascar), and elsewhere. It is often associated with magnetite, zircon, garnet, chromite, ilmenite, etc.

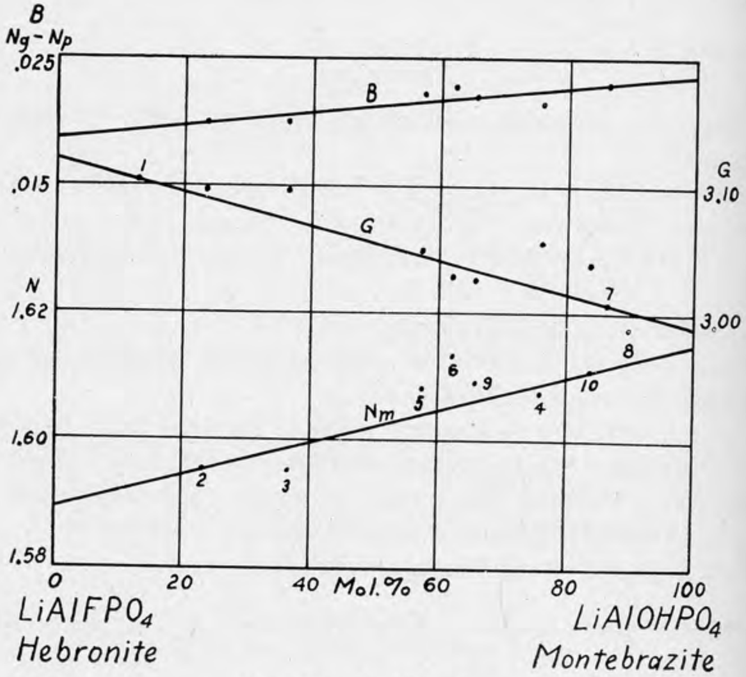

FIG. 378. Amblygonite.

Monazite is the chief source of thorium oxide, which is used in making incandescent gas mantles. It is also a source of cerium oxide. It is obtained largely from Brazil and India.

Amblygonite *Triclinic* $LiAl(F,OH)PO_4 \cdot \frac{1}{4}H_2O$

$a:b:c = 0.733:1:0.763$, $\alpha = 108°31'$, $\beta = 97°48'$, $\gamma = 106°27'$

Crystals large and coarse, not usually well formed. Commonly cleavable to massive, compact.

Perfect basal and good macropinacoid cleavages. H. = 6. G. = 2.9–3.15. Fuses at 2 with intumescence and red flame. Soluble in acids. $(-)2V = 50°$, $N_g = 1.598\text{–}1.63$, $N_m = 1.595\text{–}1.614$, $N_p = 1.578\text{–}1.607$.

Amblygonite varies from $LiAlFPO_4 \cdot \frac{1}{4}H_2O$ to $LiAlOHPO_4 \cdot \frac{1}{4}H_2O$ (called *montebrazite*). The tenor of H_2O is uncertain—perhaps only OH is present. The properties vary, as shown in Fig. 378.

Amblygonite is found in pegmatite, often associated with spodumene, lepidolite, tourmaline, quartz, and so on. Important localities include Penig in Saxony, Montebras in France, Hebron in Maine, Black Hills in South Dakota, Pala in California.

Wavellite *Orthorhombic* $(AlOH)_3P_2O_8 \cdot 5H_2O$

$a:b:c = 0.564:1:0.408$

Crystals rare; usually in crystalline crusts or fibrous aggregates of globular shape.

Good (110), (011) and 010 cleavages. H. = 3.5–4. G. = 2.3–2.34. F. = 7, but swells and gives a blue color with cobalt solution. Vitreous luster. Colorless, gray, yellow, green, blue, or black. $(+)2V = 72°$, $N_g = 1.552$, $N_m = 1.534$, $N_p = 1.525$.

Wavellite is usually $(AlOH)_3P_2O_8 \cdot 5H_2O$, but may contain iron and fluorine (up to 2%). Soluble in HCl, H_2SO_4, or KOH.

Wavellite is usually a secondary mineral; it is found in many kinds of rocks and also in veins and ore beds. Among the places where it is found are Bohemia, Roumania, Saxony, France, England, and Pennsylvania, Arkansas, South Carolina.

It is used rarely as a source of phosphoric acid for fertilizers.

Carnotite *Orthorhombic* $K_2(UO_2)_2V_2O_8 \cdot 3H_2O$

$a:b:c = 0.81:1:?$

Tiny crystal flakes with six sides; also in powder and as incrustations.

Perfect basal cleavage. H. = 1–2. Resinous to dull luster. Color yellow. $(-)2V = 39\text{–}50°$, $N_g = 1.950$, $N_m = 1.925$, $N_p = 1.750$.

Carnotite is a vanadate of uranium and potassium with an uncertain content of water. It contains a little radium.

Found in sandstone in Colorado, Utah, Arizona, and Pennsylvania. It is often associated with quartz, malachite, biotite, magnetite, etc.

Carnotite is used as a source of radium.

Turquois *Triclinic* $CuO·3Al_2O_3·2P_2O_5·9H_2O$
$a:b:c = 0.791:1:0.605, \alpha = 92°48', \beta = 93°30', \gamma = 107°41'$

Crystals very rare; usually amorphous and massive or cryptocrystalline.

Distinct $1\bar{1}0$ cleavage. Uneven fracture. H. = 5–6. G. = 2.6–2.84. Resinous luster. Color sky blue to bluish green. $(+)\ 2V = 40° \pm, N_g = 1.65, N_m = 1.62, N_p = 1.61$.

Turquois usually contains some iron; it is isomorphous with *chalcosiderite* ($CuO·3Fe_2O_3·2P_2O_5·9H_2O$).

Turquois is found in veins in trachyte in Persia; also in New Mexico, Arizona, Nevada.

Turquois is used as a gem stone, but the color is likely to fade.

Scorodite *Orthorhombic* $FeAsO_4·2H_2O$
$a:b:c = 0.866:1:0.954$

Crystals usually pyramidal resembling octahedrons, prismatic, in aggregates; earthy or compact.

No distinct cleavage. H. = 3.5–4. G. = 3.1–3.3. F. = 2–2.5. Luster vitreous to adamantine. Color leek green to brown. Streak white. Translucent. $(+)2V = 54°$, $N_g = 1.814$, $N_m = 1.796$, $N_p = 1.784$, varying considerably with variations of composition; for example, with 4.80 P_2O_5, $N_m = 1.742$.

Scorodite is near $FeAsO_4·2H_2O$, but may contain P_2O_5, Al_2O_3, etc. Soluble in HCl.

Scorodite occurs with arsenopyrite, enargite, limonite, etc. in limestone; it is found also in the oxide zone of some veins; also about geysers. Notable localities include Laurium (Greece), Nassau (Germany), Red Mountain (Colorado), Gold Hill (Utah), Black Pine (Idaho).

Erythrite *Monoclinic* $Co_3As_2O_8·8H_2O$
$a:b:c = 0.763:1:0.709, \beta = 75°59'$

Crystals prismatic, vertically striated, or 010 tablets; also columnar masses of globular shape, or earthy.

Perfect 010 cleavage. Sectile. H. = 1.5–2.5. G. = 2.95–3.18. Pearly luster on 010; on other faces vitreous; also earthy. Color crimson to gray. Streak paler. Dry powder lavender blue. $2V = 89° \pm, N_g = 1.701, N_m = 1.663, N_p = 1.629$.

Erythrite is usually near $Co_3As_2O_8 \cdot 8H_2O$, but Co may be replaced at least in part by Ni, Fe, Cu, or even Ca.

Erythrite is produced by weathering of cobalt minerals and is therefore (and because of its color) appropriately called *cobalt bloom.* It is found at Schneeberg (Saxony), Chalantes (France), Alston Moor (England), Cobalt (Ontario), and at Lovelock (Nevada).

It is a possible ore of cobalt and an indicator of other ores of cobalt.

Vivianite *Monoclinic* $Fe_3P_2O_8 \cdot 8H_2O$

$a:b:c = 0.750:1:0.700,\ \beta = 75°42'$

Crystals prismatic, often in stellate groups; also in fibrous reniform masses or earthy.

Perfect 010 cleavage. Sectile. H. = 1.5–2. G. = 2.6–2.7. F. = 1.5. Colorless (when perfectly fresh) changing slowly to green, blue, and finally brown as the iron oxidizes. When the mineral is powdered it changes almost instantly to blue and then slowly becomes brown. $(+)2V$ = large, $N_g = 1.627$, $N_m = 1.598$, $N_p = 1.580$ (pale green, fresh).

Vivianite is nearly $Fe_3P_2O_8 \cdot 8H_2O$, but often contains Fe_2O_3, as a result of oxidation. Soluble in HCl.

Vivianite is often associated with pyrite, pyrrhotite, and limonite in copper and tin deposits. Crystals have been obtained at Bodenmais (Bavaria), St. Agnes (Cornwall), Llallagua (Bolivia), and at Allentown (New Jersey), Leadville (Colorado), and so on.

Vivianite can be used as a source of phosphoric acid for fertilizers.

Columbite *Orthorhombic* $(Fe,Mn)(Cb,Ta)_2O_6$

$a:b:c = 0.829:1:0.890$

Crystals short prismatic, often 100 tablets; also massive or in groups.

Distinct 100 cleavage. H. = 6. G. = 5.0–8.0. (see Fig. 379). Infusible. Luster submetallic, often brilliant. Color iron-black to brownish black; opaque to translucent (in thin section). Streak black to brown. $2V$ = large. $N_g = 2.2$–$2.6+$, $N_m = 2.17$–$2.5+$, $N_p = 2.15$–$2.3+$.

Columbite includes four types: ferrocolumbite ($FeCb_2O_6$), mangancolumbite ($MnCb_2O_6$), ferrotantalite ($FeTa_2O_6$) and mangantantalite ($MnTa_2O_6$); there are all gradations between these types (see Fig. 379). Also, columbite often contains minor amounts of tin, titanium, uranium, rare earths, and so on. Insoluble.

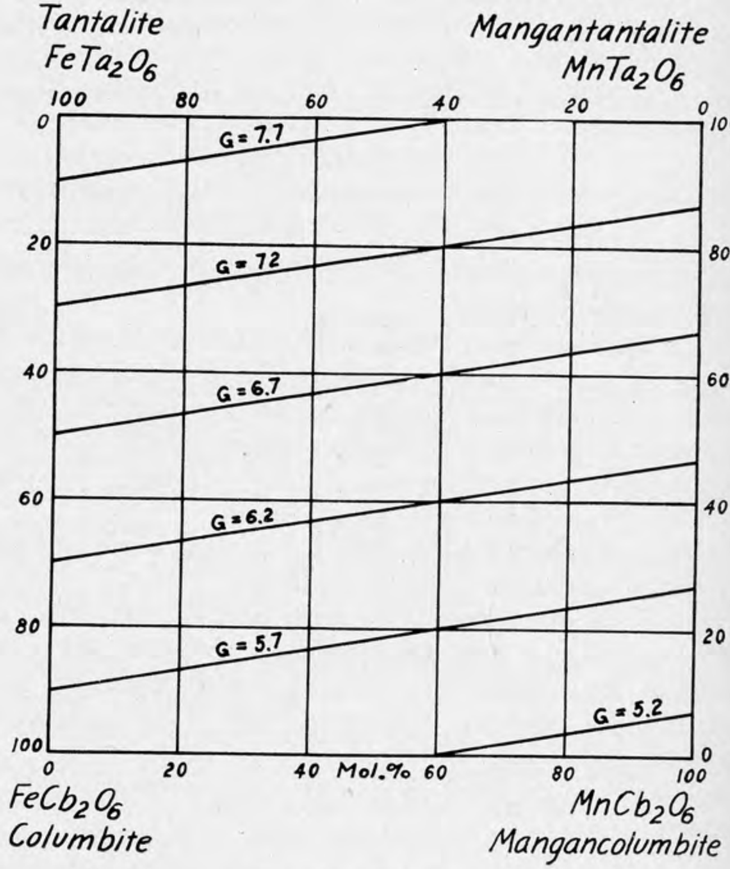

Fig. 379. Columbite.

Columbite is found in pegmatites, often associated with beryl, tourmaline, spodumene, lepidolite, feldspar, quartz, and so on. It is found at Miask (Russia), Broddbo (Sweden), Ivigtut (Greenland), Wodgina (W. Australia), Ampangabe (Madagascar), and at Auburn (Maine), Haddam (Connecticut), Pikes Peak (Colorado), but especially in the Black Hills of South Dakota.

It is an important source of tantalum and columbium; the former is used in some electric lights.

9. Silicates

The silicates are so numerous and abundant that their classification is important. The X-ray studies of W. L. Bragg[10] and many others have developed a classification of all minerals, but it is of special interest for the silicates. It is undesirable to assume that silicates are salts of various hypothetical silicic acids, such as metasilicic acid (H_2SiO_3), polysilicic acid ($H_4Si_3O_8$), and so on: the variable ratio between silicon and oxygen should be explained in a different way.

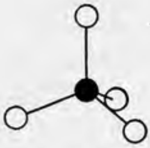

Fig. 380.

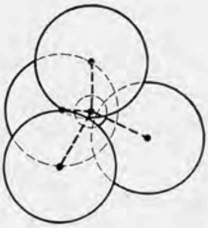

Fig. 381.

Figs. 380–381. A tetrahedral group of oxygen atoms around silicon (SiO_4).

X-ray studies have proved that in silicates each silicon atom is surrounded in all cases by four oxygen atoms arranged at the corners of a tetrahedron, as illustrated in Figs. 380 and 381. In Fig. 380 the silicon and oxygen atoms are assumed to be of the same size, so as to make their relative positions more easily seen. Actually, the oxygen atoms are much larger than the silicon atoms, as shown in Fig. 381. If such tetrahedral groups are not linked directly by sharing one (or more) oxygen atoms, the formula of the substance will include one or more SiO_4 groups, as in zircon, $ZrSiO_4$, and forsterite, Mg_2SiO_4. No silicon tetrahedron is linked to a neighboring tetrahedron by sharing more than one oxygen atom, but one tetrahedron may be thus linked to one, two, three, or four other tetrahedrons. If it is linked to only one other tetrahedron, as shown in Figs.

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[10] *Atomic Structure of Minerals*, Cornell University Press, 1937.

382 and 383, the formula must contain Si_2O_7, as in thortveitite, $Sc_2Si_2O_7$, and åkermanite, $Ca_2MgSi_2O_7$. If it is linked to two other tetrahedrons, it may form a trigonal ring, as in benitoite (Fig. 384), or a hexagonal[11] ring, as in beryl (Fig. 385), or an endless chain, as in pyroxene (Fig. 386). If it is linked to three other tetrahedrons, it forms an endless sheet, as in micas (Fig. 387). Finally, if it is linked to four other tetrahedrons, it forms a continuous three-dimensional framework, as in sodalite (Fig. 388). No other cases are possible except that all tetrahedrons in a single crystal are not necessarily linked to their neighbors

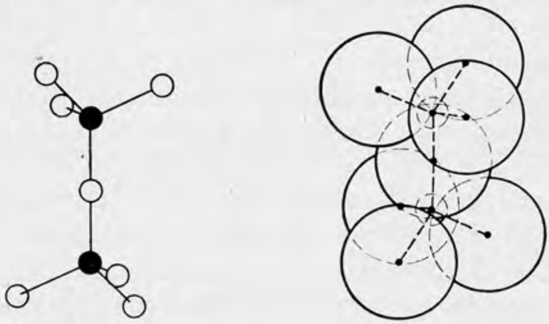

FIG. 382. FIG. 383.

FIGS. 382–383. A double tetrahedral group (Si_2O_7).

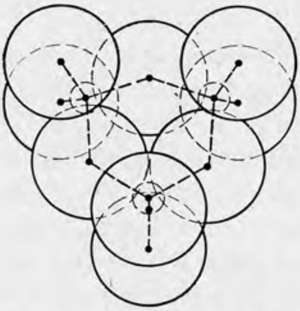

FIG. 384. Three SiO_4 groups forming a trigonal ring (Si_3O_9).

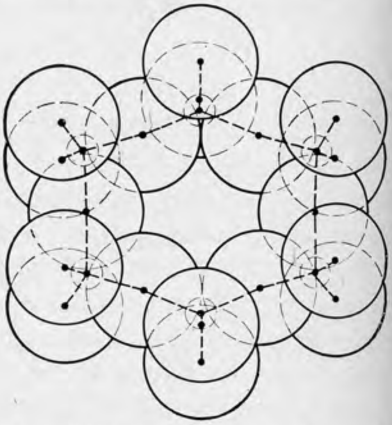

FIG. 385. Six SiO_4 groups forming a hexagonal ring (Si_6O_{18}).

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[11] A tetragonal ring is possible as illustrated (with hexagonal) in analcite.

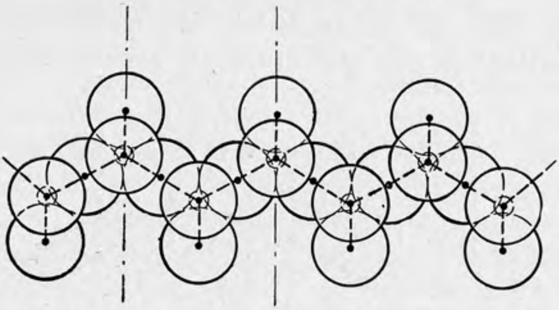

FIG. 386. SiO_4 groups forming a continuous chain (Si_4O_{12}).

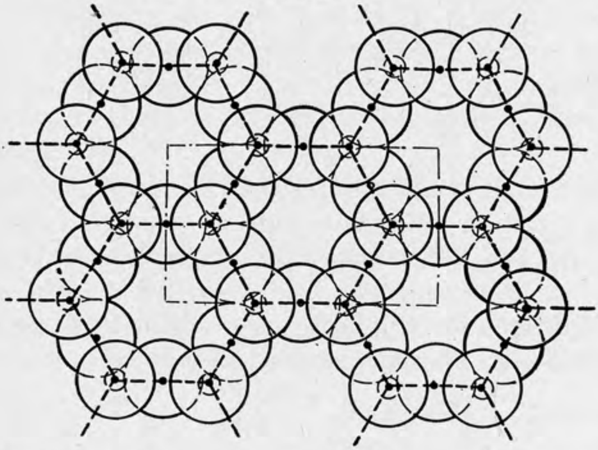

FIG. 387. SiO_4 groups forming a continuous sheet (Si_4O_{10}).

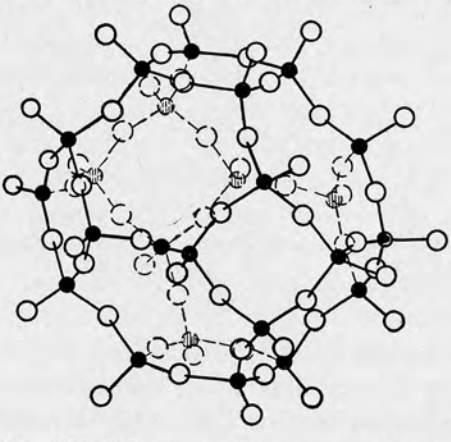

FIG. 388. SiO_4 groups (diagrammatic) forming a continuous three-dimensional network.

in the same way; for example, half the tetrahedrons may be linked to two others and half to three others, forming a double chain, as in tremolite (Fig. 389). On this basis, as suggested by Swartz,[12] silicates may be classified as follows:

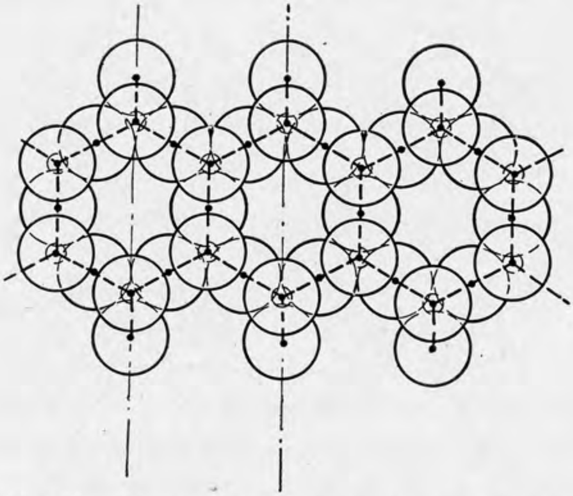

FIG. 389. SiO_4 groups forming a double chain (Si_4O_{11}).

Type	*Class*	*Radical*	*Linkages Between SiO_4 Tetrahedrons*	*Grouping of Radicals*	*Example*	
					Formula	*Mineral*
I	Orthosilicates	SiO_4	0	Single	Mg_2SiO_4	Forsterite
II	Orthodisilicates	Si_2O_7	1	Double	$Ca_2MgSi_2O_7$	Åkermanite
III	Metasilicates	SiO_3	2	Trigonal ring	$BaTiSi_3O_9$	Benitoite
				Hexagonal ring	$Be_3Al_2Si_6O_{18}$	Beryl
				Chain	$MgSiO_3$	Enstatite
IV	Metadisilicates	Si_2O_5	3	Sheets	$Mg_3Si_4O_{10}(OH)_2$	Talc
V	Dioxide type	SiO_2	4	Frameworks	SiO_2	Quartz

One other complication is important; in the silicon-oxygen tetrahedrons of silicates some of the silicon atoms may be replaced by aluminum (or, in some cases, Be) atoms. Of course

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[12] *Am. Mineral.* XXII, 1073, 1161 (1937).

this changes the valence of the acid radical. For example, SiO_2, as such, has zero valence; for convenience it may be written as $Si_{12}O_{24}$; if one quarter of the Si atoms are replaced by Al atoms the radical becomes $Si_9Al_3O_{24}$, with a valence of three; if this valence is satisfied by K the formula is $K_3Al_3Si_9O_{24}$ or $KAlSi_3O_8$, which is orthoclase. If one third of the Si atoms are replaced by Al atoms the radical becomes $Si_8Al_4O_{24}$, with a valence of four; if this valence is satisfied by K the formula is $K_4Al_4Si_8O_{24}$ or $KAlSi_2O_6$, which is leucite. If half of the Si atoms are replaced by Al atoms the radical becomes $Si_6Al_6O_{24}$, with a valence of six; if this valence is satisfied by Na atoms the formula is $Na_6Al_6Si_6O_{24}$ or $NaAlSiO_4$, which is nephelite. Thus the three-dimensional framework illustrated by quartz may become the basis of structures which are classed chemically in various cases as polysilicates or as metasilicates or as orthosilicates.

As already mentioned, some minerals have their silicon tetrahedrons linked to their neighbors in more than one way. In that case a single crystal structure may illustrate two of the preceding cases. For example, vesuvianite contains single tetrahedrons (SiO_4) and also double tetrahedrons (Si_2O_7) in different parts of the same structure. To show this, the formula may be written: $Ca_{10}Al_4\left[\begin{matrix}(SiO_4)_5\\(Si_2O_7)_2\end{matrix}\right]\cdot 2Mg(OH)_2$. Analcite contains tetragonal Si_4O_{12} and also hexagonal Si_3O_{18} rings in its three dimensional framework; therefore it could be referred to group III or to group V. Tourmaline apparently contains two trigonal Si_3O_9 rings and also an $(Si_6Al_{12})O_{36}$ framework in its crystal structure; it seems to be a case in which two-thirds of the silicon atoms are replaced by aluminum atoms. Cordierite, which is pseudohexagonal, probably has slightly distorted $(Si_5Al)O_{18}$ rings in its $(Si_5Al_4)O_{18}$ framework; like analcite it could be referred to group III or to group V. In a few minerals beryllium, like aluminum, may replace silicon in the oxygen tetrahedrons; accordingly beryl may be considered to have a three-dimensional framework with the formula $Al_2(Si_6Be_3)O_{18}$. Finally, in amphiboles some SiO_4 tetrahedrons are linked to two others and some to three others; on the basis of the first of these they should be referred to group III; on the basis of the second to group IV; the generalized formula is $R_6\begin{bmatrix}Si_2O_6\\ Si_2O_5\end{bmatrix}$, which becomes $(Mg,Fe)_7\begin{bmatrix}Si_2O_6\\ Si_2O_5\end{bmatrix}(OH,F)_2$ for anthophyllite.

The important silicates may be classified as follows:

I. Orthosilicates: SiO_4 tetrahedrons not united to each other

Garnet		
Pyralspite	$(Mg,Fe,Mn)_3Al_2Si_3O_{12}$	Isometric
Ugrandite	$Ca_3(Al,Fe,Cr)_2Si_3O_{12}$	Isometric
Zircon	$ZrSiO_4$	Tetragonal
Phenacite	$BeSiO_4$	Hexagonal
Willemite	Zn_2SiO_4	Rhombohedral
Dumortierite	$HBAl_6(Si_3Al_2)O_{20}$	Orthorhombic
Olivine	$(Mg,Fe,Mn)_2SiO_4$	Orthorhombic
Chondrodite	$2Mg_2SiO_4\cdot Mg(OH,F)_2$	Orthorhombic
Staurolite	$2Al_2OSiO_4\cdot Fe(OH)_2$	Orthorhombic
Topaz	$Al_2(F,OH)_2SiO_4$	Orthorhombic
Sillimanite	Al_2OSiO_4	Orthorhombic
Andalusite	Al_2OSiO_4	Orthorhombic
(Kyanite	$Al_2OSiO_4)$	(Triclinic)
Datolite	$CaBOHSiO_4$	Monoclinic
Titanite	$CaTiOSiO_4$	Monoclinic
Axinite	$H(Fe,Mn)Ca_2Al_2B(SiO_4)_4$	Triclinic
Vesuvianite	$Ca_{10}Al_4\begin{bmatrix}(SiO_4)_5\\ (Si_2O_7)_2\end{bmatrix}\cdot 2Mg(OH)_2$	Tetragonal

II. Orthodisilicates: SiO_4 tetrahedrons combined by one solid angle

Melilite	$Ca_2R(Si,Al)_2O_7$	Tetragonal
Hemimorphite	$Zn_4(OH)_2Si_2O_7\cdot H_2O$	Orthorhombic

III. Metasilicates: SiO_4 tetrahedrons combined by two solid angles

A. Rings

Beryl	$Be_3Al_2(SiO_3)_6$	Hexagonal
Tourmaline	$XY_9(Si_6B_3)O_{27}(O,OH,F)_4$ $X = (Ca,Na,K,Mn)$ $Y = (Mg,Fe,Al,Li,Cr,Mn,Ti)$	Trigonal
Cordierite	$(Mg,Fe)_2Al_3(Si_5Al)O_{18}$	Orthorhombic
Wollastonite	$Ca_3(SiO_3)_3$	Monoclinic and triclinic
Rhodonite	$Mn_3(SiO_3)_3$	Monoclinic and triclinic
Pectolite	$HNaCa_2(SiO_3)_3$	Monoclinic and triclinic

B. Chains

Enstenite		
Enstatite	$MgSiO_3$	Orthorhombic
Hypersthene	$(Mg,Fe)SiO_3$	Orthorhombic
Pyroxene proper		
Clinoenstatite	$(Mg,Fe)SiO_3$	Monoclinic
Diopside	$CaMgSi_2O_6$	Monoclinic
Hedenbergite	$CaFeSi_2O_6$	Monoclinic
Spodumene	$LiAlSi_2O_6$	Monoclinic

C. Double chains or bands

Amphibole		
Anthophyllite	$(Mg,Fe)_7\begin{bmatrix}Si_4O_{12}\\ Si_4O_{10}\end{bmatrix}(OH)_2$	Orthorhombic
Hornblende	$X_{2-3}Y_5\begin{bmatrix}Si_4O_{12}\\ Si_4O_{10}\end{bmatrix}(OH,F)_2$	Monoclinic
Glaucophane	$Na_2Mg_3Al_2\begin{bmatrix}Si_4O_{12}\\ Si_4O_{10}\end{bmatrix}(OH)_2$	Monoclinic
Sepiolite	$Mg_8\begin{bmatrix}Si_6O_{18}\\ Si_6O_{15}\end{bmatrix}(OH)_{16}$?	Monoclinic
Serpentine (Chrysotile)	$(MgOH)_6\begin{bmatrix}Si_2O_6\\ Si_2O_5\end{bmatrix}\cdot H_2O$	Monoclinic

IV. Metadisilicates (Sheets): SiO_4 tetrahedrons united at three solid angles

Apophyllite	$4CaSi_2O_5\cdot KF\cdot 8H_2O$	Tetragonal
Prehnite	$Ca_2Al(Si_3Al)O_{10}(OH)_2$	Orthorhombic
Talc	$Mg_3Si_4O_{10}(OH)_2$	Orthorhombic
Kaolinite	$Al_2Si_2O_5(OH)_4$	Monoclinic
Pyrophyllite	$Al_2Si_4O_{10}(OH)_2$	Monoclinic
Mica		
Muscovite	$K_2(Al,Fe)_4(Si_6Al_2)O_{20}(OH)_4$	Monoclinic
Biotite	$K_2(Mg,Fe)_6(Si_6Al_2)O_{20}(OH)_4$	Monoclinic
	$K_2(Mg,Fe)_5Al(Si_5Al_3)O_{20}(OH)_4$	Monoclinic
Lepidolite	$K_2Li_4Al_2Si_8O_{20}F_4$	Monoclinic
	$K_2Li_3Al_3(Si_6Al_2)O_{20}F_4$	Monoclinic
	$K_2LiFe_4Al(Si_6Al_2)O_{20}F_4$	Monoclinic
Chlorite	$(Mg,Fe)_6Si_4O_{10}(OH)_8$	Monoclinic
	$(Mg,Fe)_4Al_2(Si_2Al_2)O_{10}(OH)_8$	Monoclinic
Vermiculite	Hydrated micas and chlorites	Monoclinic
Glauconite	$KFeSi_2O_6\cdot H_2O$?	Monoclinic

V. Dioxide type (Frameworks): SiO_4 tetrahedrons united at four solid angles

A. With little or no water

Leucite	$K(Si_2Al)O_6$	Isometric
Sodalite	$(Na,Ca)_8(Si_6Al_6)O_{24}(Cl_2,SO_4,S_2)$	Isometric
Scapolite	$3Na(Si_3Al)O_8\cdot NaCl$	Tetragonal
	$3Ca(Si_2Al_2)O_8\cdot CaCO_3$	Tetragonal
Nepheline	$Na(SiAl)O_4$	Hexagonal
Cancrinite	$3Na(SiAl)O_4\cdot Ca(CO_3,Cl,SO_4)$	Hexagonal
Quartz	$SiSiO_4$	Hexagonal
Zoisite	$Ca_2(Si_3Al_3)O_{12}(OH)$	Orthorhombic
Epidote	$Ca_2Si_3(Al,Fe)_3O_{12}(OH)$	Monoclinic
Allanite	$(Ca,Ce)_2Si_3(Al,Fe'''Fe'')_3O_{12}(OH)$	Monoclinic
Feldspar		
Orthoclase	$K(Si_3Al)O_8$	Monoclinic
Microcline	$K(Si_3Al)O_8$	Pseudomonoclinic
Plagioclase	$Na(Si_3Al)O_8$	Triclinic
	$Ca(Si_2Al_2)O_8$	Triclinic

B. Hydrous (Zeolites)

Analcite	$Na(Si_2Al)O_6\cdot H_2O$	Isometric
Natrolite	$Na_2Si_3Al_2O_{10}\cdot 2H_2O$	Orthorhombic
Thomsonite	$mNa_3Ca_9(Si_{19}Al_{21})O_{80}\cdot 24\ H_2O +$	Orthorhombic
	$nNa_7Ca_5(Si_{23}Al_{17})O_{80}\cdot 24\ H_2O$	Orthorhombic
Stilbite	$CaAl(Si_2Al)O_6\cdot 6H_2O$	Monoclinic

Chabazite	$\begin{cases} m\mathrm{Ca_7(Si_{26}Al_{14})O_{80}\cdot 40H_2O} + \\ n\mathrm{(Na,K)_4Ca_3(Si_{30}Al_{10})O_{80}\cdot 40\ H_2O} \end{cases}$	Monoclinic (Pseudohexagonal)
Chrysocolla	$CuSiO_3 \cdot nH_2O$?	Amorphous?
Opal	$SiO_2 \cdot nH_2O$	Amorphous

I. Orthosilicates: SiO_4 tetrahedrons having no common oxygen atom

Garnet

Pyralspite	**Isometric**	**$(Mg,Fe,Mn)_3Al_2Si_3O_{12}$**
Ugrandite	**Isometric (metastable)**	**$Ca_3(Al,Fe,Cr)_2Si_3O_{12}$**

Crystals are commonly dodecahedrons, but may be trapezohedrons or combinations, including the hexoctahedron. Pyralspite is stable isometric; ugrandite is usually isotropic in small crystals, but large crystals commonly invert to a lower symmetry, retaining their external form by means of multiple twinning. Often in irregular grains; also granular massive.

Dodecahedral parting not common. Other physical characters vary with the composition as shown below.

Garnets vary greatly in composition; six end-members are commonly recognized, as follows:

	Name	Formula	Colors	Fusibility, etc.	G	*N*
Pyralspite	Pyrope	$Mg_3Al_2Si_3O_{12}$	Red to nearly black	F. = 4 to black nonmagnetic globule	3.51	1.705
	Almandite	$Fe_3Al_2Si_3O_{12}$	Brown, red, black	F. = 3 to dark magnetic globule	4.25	1.830
	Spessartite	$Mn_3Al_2Si_3O_{12}$	Shades of red	F. = 3 to black nonmag. glob. Reacts for manganese	4.18	1.800
Ugrandite	Uvarovite	$Ca_3Cr_2Si_3O_{12}$	Emerald green	F. = 7. Reacts for chromium	3.85	1.86
	Grossularite	$Ca_3Al_2Si_3O_{12}$	Yellow, white brown, red, green	F. = 3 to pale nonmag. globule	3.53	1.735
	Andradite	$Ca_3Fe_2Si_3O_{12}$	Yellow, brown, red, black	F. = 3.5 to black magnetic globule	3.75	1.895

There are still other variations: for example in *schorlomite* titanium replaces part of the silicon (and ferric iron?) of andradite; in other cases Fe_2O_3 or Mn_2O_3 may replace part of the Al_2O_3 in pyralspite, etc. In natural crystals there is a complete gradation from pyrope through almandite to spessartite, and also from andradite to grossularite and probably also to uvarovite. In general, ugrandite and pyralspite intercrystallize only to about 20 or 25 per cent; but grossularite intercrystallizes more freely with spessartite, and this may perhaps connect the two types and thus lead to garnet as one mineral, rather than two. The relations between pyralspite and grandite are shown in Fig. 390. The relations between refractive index, specific gravity, and composition in pyralspite are shown in Fig. 391. The same relations for ugrandite are given in Fig. 392. The relations of both pyralspite and ugrandite are shown in Fig. 393.

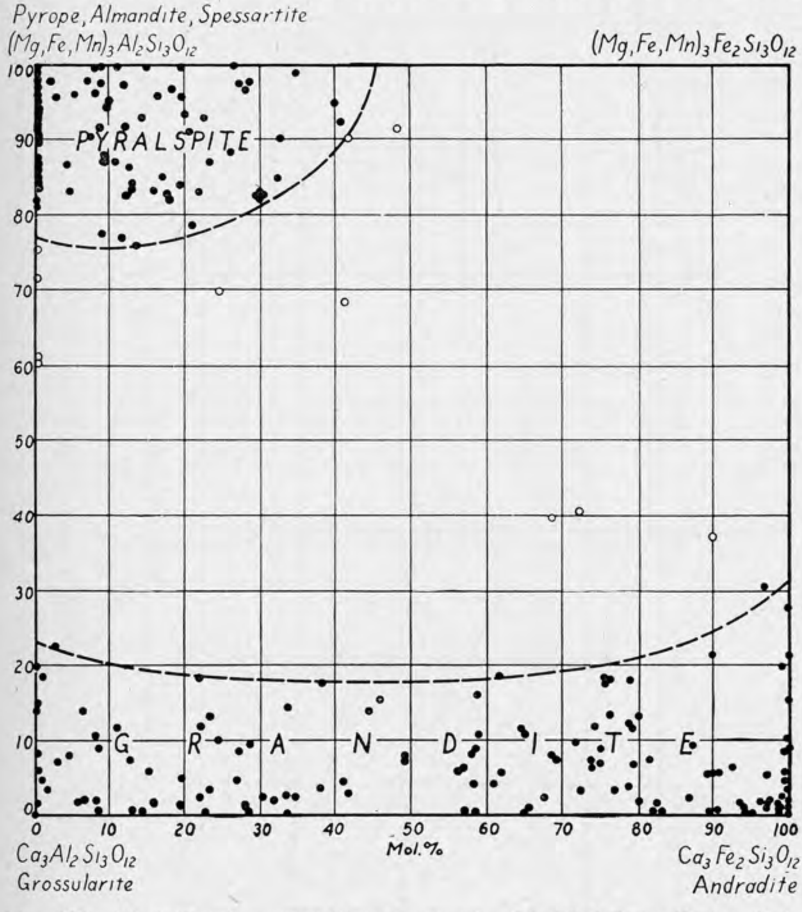

FIG. 390. Variation in composition in garnet. Modified from Boeke, Zeit. Krist. LIII, 149 (1914).

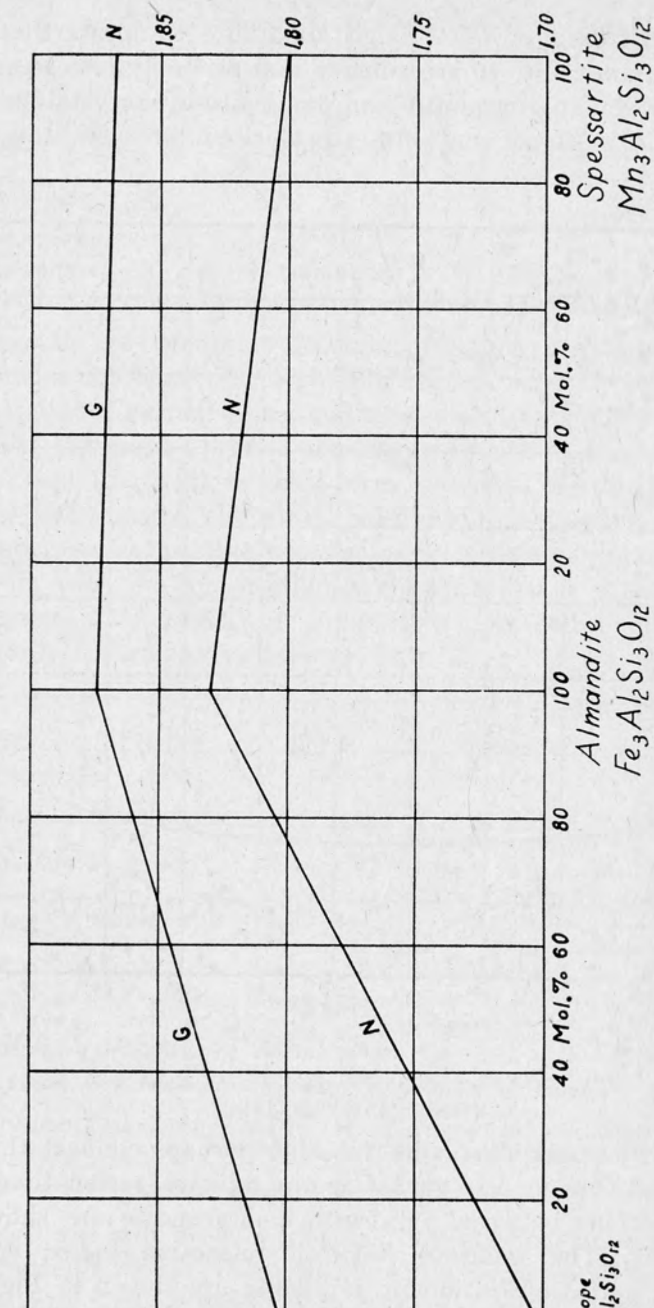

FIG. 391. Pyralspite (garnet).

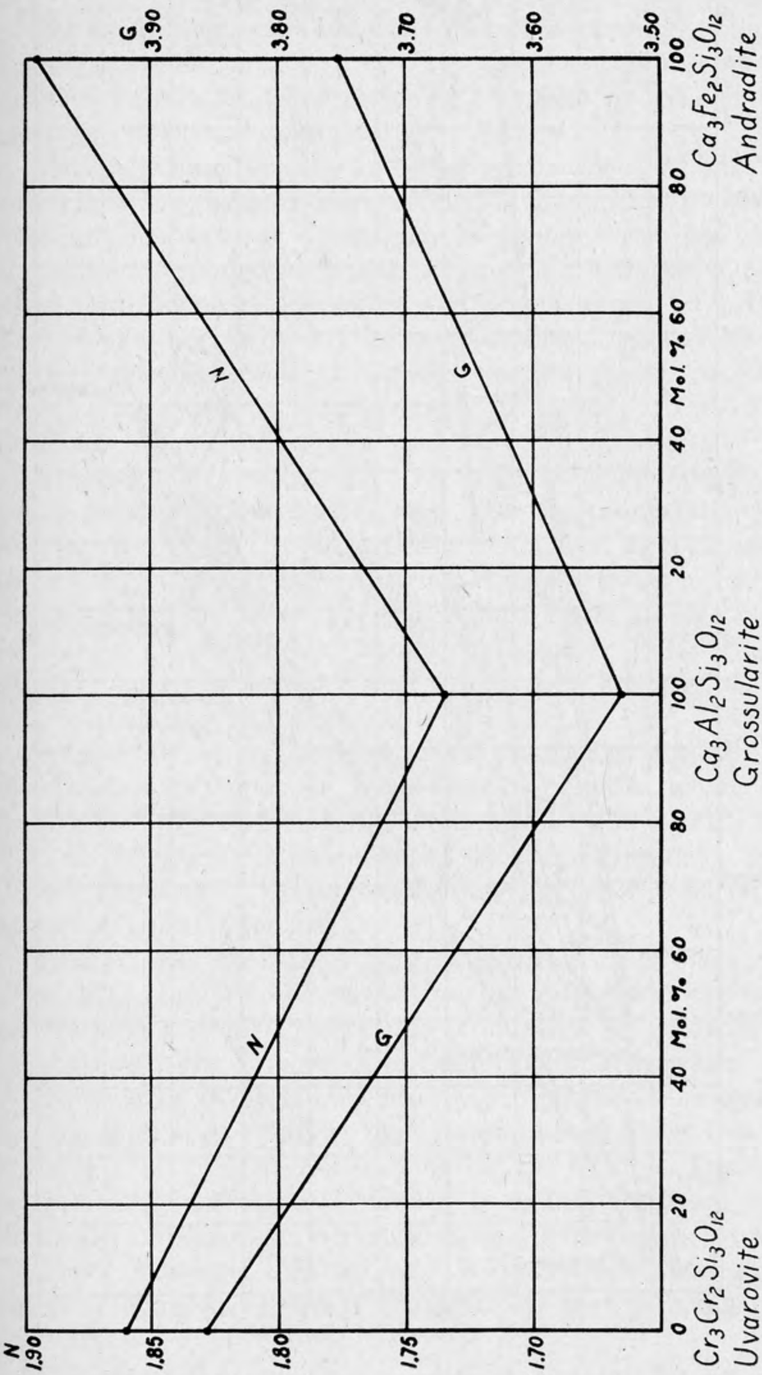

FIG. 392. Ugrandite (garnet).

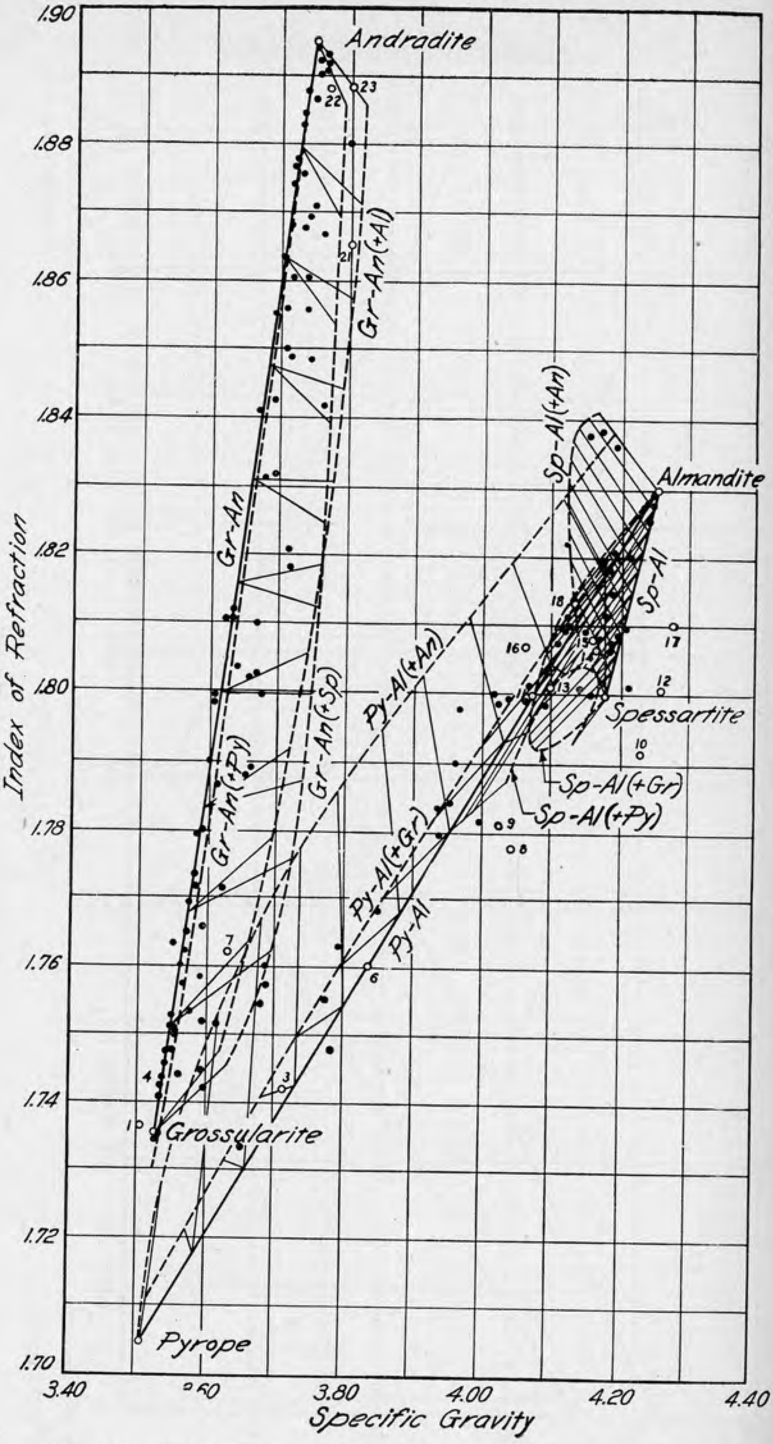

FIG. 393. Variations in refringence and specific gravity in garnet.

Garnet is a common accessory mineral especially in contact and regional metamorphic rocks; in some cases it is an abundant constituent. It is also a common accessory in some igneous rocks and in some detrital sediments.

Pyrope is found usually in basic igneous rocks such as peridotite. It is sometimes associated with diamond. It is rarely found in good crystals, but rather in irregular or rounded grains. It has been obtained at Teplitz (Bohemia), Kimberley (South Africa), in Ceylon, Madagascar, and Brazil, as well as in Utah, New Mexico, and Arizona. Clear transparent samples are used for gem purposes under the name *precious garnet*, or (incorrectly) *Cape ruby* or *Arizona ruby*. Rhodolite (from North Carolina) is two-thirds pyrope and one-third almandite.

Almandite is found in schists associated with kyanite, staurolite, andalusite, tourmaline, etc.; also in pegmatite, as at Yamano, Japan. It is perhaps the commonest kind of garnet, being found in the Tyrol (Austria), Norway, Sweden, Saxony, Bavaria, Scotland, Madagascar, Ceylon, India, Brazil, and at Southbury (Connecticut), Salida (Colorado), Fort Wrangel (Alaska), and elsewhere. Clear red crystals are used as gem stones, sometimes called *carbuncle*.

Spessartite occurs in mica schist, pegmatite, and the like, sometimes with topaz or tourmaline. Localities where it is found include Tyrol, Piedmont, Roumania, Ceylon, Madagascar, and at Haddam (Connecticut), Amelia (Virginia), Salem (North Carolina). Transparent orange crystals from Madagascar are suitable for gems.

Uvarovite is the rarest type of garnet. It is often associated with chromite and serpentine, but is found in cavities in limestone at Oxford, Canada. It is obtained also in the Ural Mountains, in the Transvaal, in California, and elsewhere.

Grossularite is often associated with wollastonite, vesuvianite, diopside, and scapolite, in metamorphosed limestones and in calcareous schists. Some localities are Ceylon, Transvaal (a mottled green massive variety is called *Transvaal jade*), Roumania, Monzoni (Italy), Zermatt (Switzerland), Morelos (Mexico), Rumford (Maine), and Warren (New Hampshire). Yellow, orange, and green grossularites are used as inexpensive gem stones.

Andradite is found in syenite, serpentine, chlorite schists and limestones, often associated with feldspar, nephelite, epidote, etc. It occurs at Dobschau (Czechoslovakia), in the Tyrol, Norway, Russia, and at Franklin (New Jersey), Henderson (North Carolina), Magnet Cove (Arkansas), and so on. *Topazolite* is a yellowish or greenish variety resembling topaz. *Demantoid* is a grass-green variety. *Melanite* is a black andradite. With increase of titanium the refractive index rises from 1.89 to 2.01 (with 19% TiO_2).

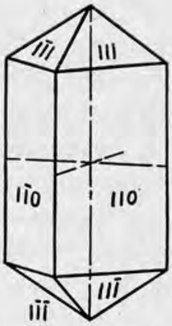

FIG. 394. Crystal of zircon.

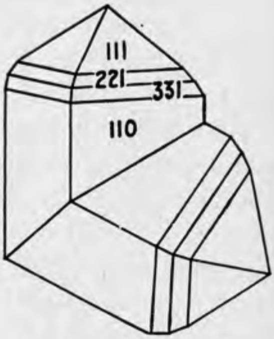

FIG. 395. Geniculated twin of zircon.

All kinds of garnets are used as gems if they are clear and of pleasing color, but pyrope and almandite supply most of the gems. Almandite and andradite are sometimes called common garnets, though grossularite is also common. Small garnets are sometimes used as bearings in (cheap) watches and in some scientific apparatus. Massive compact garnet is used as an abrasive powder and on sand paper.

Zircon (Hyacinth, Malacon) Tetragonal **$ZrSiO_4$**
$c = 0.64$

Crystals usually square prisms with pyramids, such as shown in Figs. 394 and 395. Also in rounded grains in sediments.

Conchoidal fracture. H. = 7.5. G. = 4.0–4.8. Infusible. Luster adamantine. Colorless, yellow, green, brown. Streak colorless. $N_o = 1.80–1.93$. $N_e = 1.80–1.99$. The color of some zircons can be changed by heat treatment.

Zircon is approximately $ZrSiO_4$, but often contains some Fe_2O_3 and sometimes HfO_2, ThO_2, Y_2O_3, SnO_2, U_2O_3, H_2O, etc.

There seem to be three types[13] of zircon: one, called *normal type,* having G. = about 4.7 and N_o = 1.915–1.93, N_e = 1.955–1.99; a second, called *hyacinth,* having G. = about 4.6, N_o = about 1.90, and N_e = about 1.94; the third, called *malacon,* having G. = about 4.1, N_o = 1.80–1.85, and N_e = 1.80–1.86. The chemical differences between these types are unknown.

Zircon is an accessory mineral in many igneous rocks. It is remarkably resistant to attrition and to alteration; therefore it can be traced through more than one cycle of erosion and sedimentation, and is a common accessory in many sediments as well as in schists and gneisses. It is commonly in well-formed crystals in igneous rocks, having crystallized early from the magma. Some localities where it is found are in southern Norway, in the Urals, in Trentino (Italy), in alluvial sands in Ceylon, in Madagascar, Canada, and in Maine, Florida, Texas, Colorado.

Zircon is a source of ZrO_2, which is used in ferroalloys and also as a refractory for lining furnaces. Transparent crystals are used as gems under the names *hyacinth, jacinth, starlite, jargon,* and *matura diamond.* But the unique use of zircon is as a guide to the age and source of the rock containing it.

Phenacite *Hexagonal* Be_2SiO_4
$c = 0.661$

Crystals often rhombohedral in habit; also prismatic or lenticular.

Cleavage rather poor parallel to $(11\bar{2}0)$. H. = 7.5–8. G. = 2.9–3.0. Luster vitreous. Colorless, yellow, pink, or brown. Streak white. N_o = 1.654, N_e = 1.670.

Phenacite is remarkably pure Be_2SiO_4, but may contain a little Ca, Mg, Na, Al.

Phenacite is found in pegmatites as a pneumatolytic mineral and also in mica schist. It is often associated with topaz, quartz, microcline, chrysoberyl, etc.

Phenacite is a possible ore of beryllium.

Willemite *Hexagonal* Zn_2SiO_4
$c = 0.678$

Crystals long to short prisms ended by rhombohedrons, usually small. Also granular to compact massive.

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[13] S. A. Tyler, R. W. Marsden, F. F. Grout and G. A. Thiel: "Studies of the Lake Superior Pre-Cambrian by accessory mineral methods, *Bull.* Geol. Soc. Amer. LI 1429 (1940).

Easy basal cleavage. H. = 5–6. G. = 3.9–4.3. Greasy to vitreous luster. Color yellow, green, brown; rarely blue black or white. $N_o = 1.691$, $N_e = 1.719$.

Willemite is near Zn_2SiO_4, but may vary toward Fe_2SiO_4, as in slags,[14] or toward Mn_2SiO_4, as shown in Fig. 396. With some Mn_2SiO_4 it is called *troostite*.

Willemite is associated with franklinite, zincite, rhodonite, etc. It is found at Altenberg (Belgium), Constantine (Algeria), Mindouli (French Congo), Broken Hill (Rhodesia), Franklin (N. J.), and elsewhere.

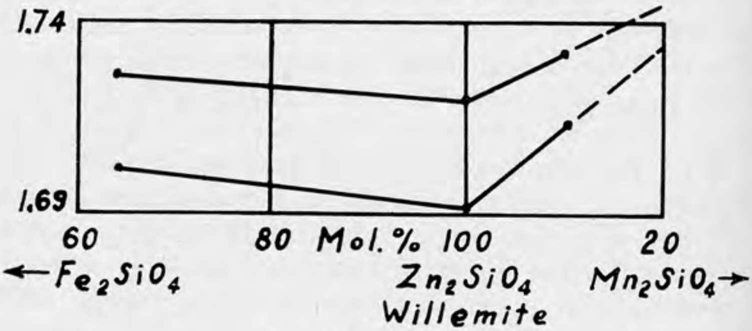

FIG. 396. Willemite.

Willemite is an important ore of zinc at Franklin, New Jersey.

Dumortierite *Orthorhombic* $HBAl_8Si_3O_{20}$

$a:b:c = 0.890:1:0.687$

Usually in fibrous or columnar aggregates, often radiating.

Distinct 100 cleavage and 001 parting. H. = 7. G. = 3.2–3.4. F = 7. Insoluble even in HF. Color blue, violet, pink. Streak white or tinted. $(-)2V = 30° \pm$, $N_g = 1.692$, $N_m = 1.691$, $N_p = 1.670$.

Dumortierite has very variable color and pleochroism probably because of small amounts of titanium and iron (replacing aluminum?) in the formula.

Dumortierite is found in schists and gneisses; less commonly in pegmatites. Localities include Lyons (France), Nacozari

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[14] W. Faber: *Chem. Erde*, X,67 (1935).

(Mexico), Dehesa (California), and the Rochester district in Nevada.

Dumortierite is used in the manufacture of high-grade refractory porcelain.

Olivine	**Orthorhombic**	**$(Mg,Fe,Mn)_2SiO_4$**
Forsterite	**$a:b:c = 0.465:1:0.586$**	**Mg_2SiO_4**
Fayalite	**$a:b:c = 0.458:1:0.579$**	**Fe_2SiO_4**
Tephroite	**$a:b:c = 0.460:1:0.594$**	**Mn_2SiO_4**

Crystals equant or somewhat flattened on 100 or 010 or elongated along *c*, as in Fig. 397. Often granular massive.

Brachypinacoid cleavage poor to rather distinct. H. = 6.5–7. G. = 3.2–4.4. Luster vitreous. Color green (whence the name); rarely brown to red from alteration. Indices: 1.64–1.90 as shown in Fig. 398. Easily decomposed and gelatinizes with acids.

Olivine has at least three end-members; namely Mg_2SiO_4, called *forsterite;* Fe_2SiO_4, called *fayalite;* and Mn_2SiO_4, called *tephroite.* Mg_2SiO_4 forms a complete series of mix crystals with Fe_2SiO_4, with variation of properties as shown in Fig. 398. Fe_2SiO_4 probably forms a similar series with Mn_2SiO_4, but its properties are not fully known. Olivine may contain minor amounts of zinc, titanium, calcium, nickel. Alters easily in nature to serpentine, limonite, magnesite, etc.

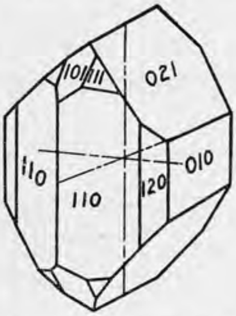

Fig. 397. Crystal of olivine.

Olivine is an essential constituent of some basic igneous rocks, such as basalt, olivine gabbro, and peridotite. It is formed by contact metamorphism of some dolomites, etc. Important localities include Vesuvius, Laacher See (Germany), Snarum (Norway), Mogok (Burma), Minas Geraes (Brazil), Kilauea (Hawaii), Iceland, and Thetford (Vermont), Webster (North Carolina), Buffalo Buttes (Colorado).

Chondrodite *Monoclinic* $Mg_5F_2Si_2O_8$

$a:b:c = 1.086:1:3.145,\ \beta = 90°\pm$

Crystals very nearly orthorhombic ($\beta = 90°\pm$); very small, highly modified. Twinning very common, multiple. Often in granular masses.

Basal cleavage. H. = 6–6.5. G. = 3.1–3.3. Infusible. Vitreous to resinous luster. Color brown, yellow, white, red. Translucent to opaque.

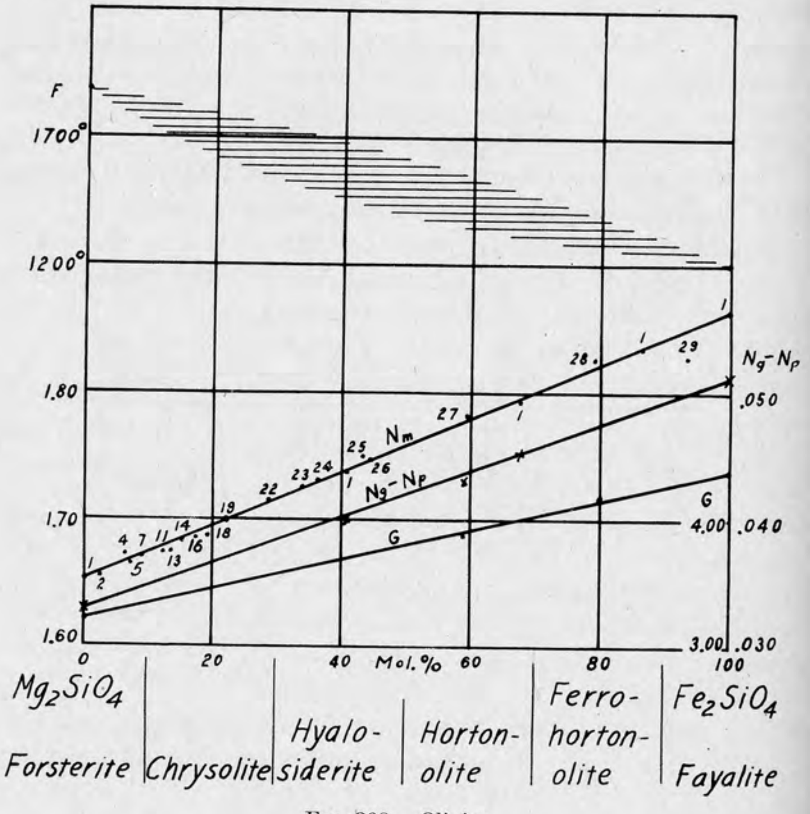

Fig. 398. Olivine.

Chondrodite is, roughly, $Mg_5F_2Si_2O_8$, but hydroxyl often replaces much of the fluorine, and iron may proxy for at least

Mineral	$Mg(F,OH)_2$	Mg_2SiO_4		Mg Atoms	c	System
Forsterite	0	1	$\frac{1}{2}b:a:c =$ 1.072:1:0.6288	2	1 × 0.6288	Orth.
Norbergite	1	1	$a:b:c =$ 1.10:1:1.879	3	3 × 0.6263	Orth.
Chondrodite	1	2	$a:b:c =$ 1.0851:1:3.1394	5	5 × 0.6279	Mono.
Humite	1	3	$a:b:c =$ 1.080:1:4.4033	7	7 × 0.6290	Orth.
Clinohumite	1	4	$a:b:c =$ 1.0803:1:5.6588	9	9 × 0.6288	Mono.

part of the magnesium. The effects on the properties are shown in Fig. 399. Chondrodite belongs to a series of minerals containing different proportions of $Mg(F,OH)_2$ and Mg_2SiO_4, as shown in the table at the bottom of page 332.

X-ray studies of the crystal structures have shown that norbergite consists of alternating layers of Mg_2SiO_4 (with the structure of forsterite) and of $Mg(F,OH)_2$; chondrodite has two layers of Mg_2SiO_4 and then one of $Mg(F,OH)_2$; humite has three such layers (and clinohumite has four such layers) and then one layer of $Mg(F,OH)_2$. The length of the vertical axis varies almost exactly with the number of magnesium atoms, as shown in the table. These minerals (norbergite-clinohumite) are produced under pneumatolytic conditions affecting silica, and magnesia in the presence of fluorine. They are found around volcanoes and ore bodies, especially as an alteration of dolomite. They are known at Vesuvius (sometimes closely associated), at Franklin, New Jersey, and so on.

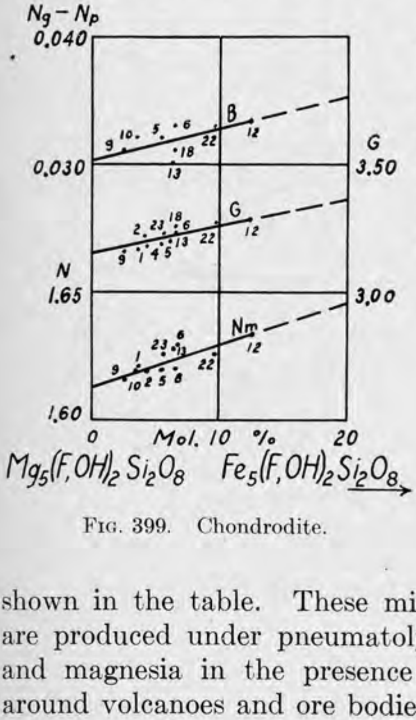

FIG. 399. Chondrodite.

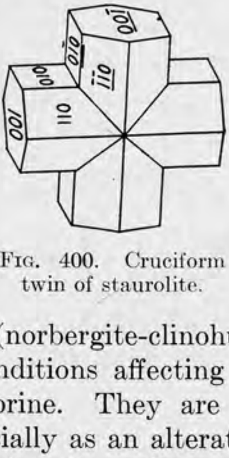

FIG. 400. Cruciform twin of staurolite.

Staurolite **Orthorhombic** $\mathbf{Fe(OH)_2Al_4O_2Si_2O_8}$
$a:b:c = \mathbf{0.473:1:0.683}$

Crystals often well-developed prisms with the base and brachypinacoid. Cruciform twins common, as in Fig. 400.

Distinct 010 cleavage. H. = 7–7.5. G. = 3.4–3.8. Infusible. Vitreous to dull luster. Usually dark brown, or reddish; also light brown or gray. Streak colorless to gray. $N_g = 1.746$, $N_m = 1.741$, $N_p = 1.736$.

Staurolite[15] is nearly $H_2FeAl_4Si_2O_{12}$, but Mg, Mn, Zn, Co may proxy for Fe″ and Fe‴ for Al; properties vary as shown in Fig. 401.

Staurolite is a product of metamorphism, usually found in schists and gneisses, but also in adjoining endomorphosed igneous rocks. It is not rare in the slates and schists of New England; it is found in similar rocks in Virginia, North Carolina, Georgia, and elsewhere.

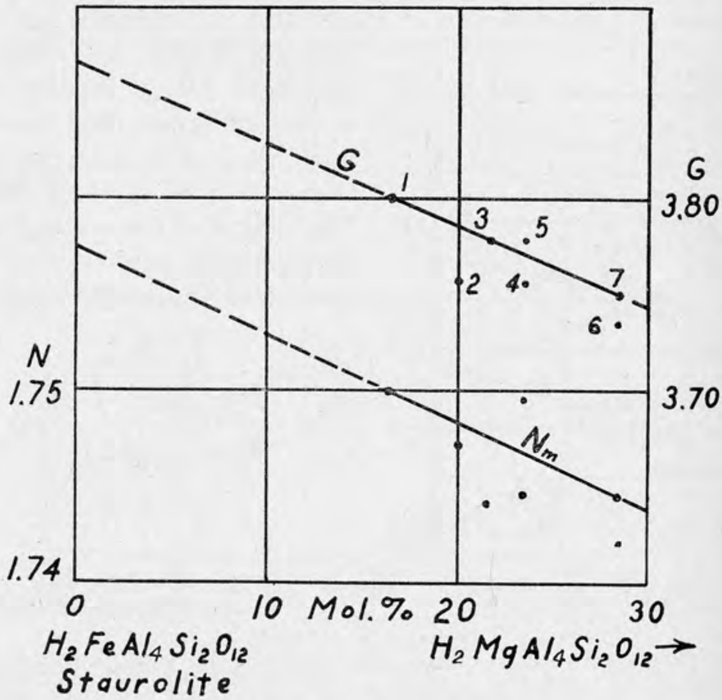

FIG. 401. Staurolite.

Topaz **Orthorhombic** **$Al(F,OH)_2AlSiO_4$**

$a:b:c = 0.528:1:0.954$

Crystals usually prismatic, often vertically striated. Also coarse or fine granular.

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[15] The formula is derived from X-ray studies; analyses rarely show even half as much H_2O as required by this formula and usually show more Al_2O_3, so that the formula is sometimes written $FeAl_5Si_2O_{12}(OH)$.

Perfect basal cleavage. H. = 8. G. = 3.52–3.57. Infusible. Colorless, yellow, gray, green, bluish, reddish. Streak uncolored. $N_g = 1.625$, $N_m = 1.618$, $N_p = 1.616$.

Topaz is $AlFAlSiO_4$, except that hydroxyl may proxy for at least a third of the fluorine. The effects of this are shown in Fig. 402.

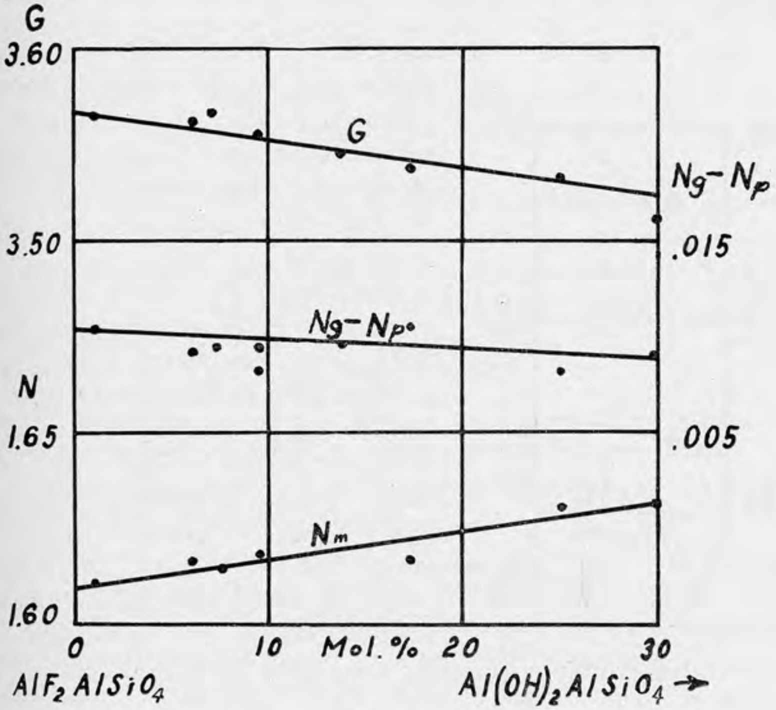

FIG. 402. Topaz.

Topaz is produced by pneumatolytic processes in acid igneous rocks or surrounding schists, gneisses, etc. It is often found in pegmatites, dikes or veins associated with cassiterite, tourmaline, fluorite, quartz, and the like. It alters to mica rather easily. Notable localities for topaz include Nerchinsk in Transbaikalia, Ural region (Russia), Schneckenstein (Saxony), Fossum (Norway), Tasmania, Ceylon, Japan, Brazil, Mexico, and Stoneham (Maine), Pikes Peak and Nathrop (Colorado), Ramona (California).

Clear crystals are used as gems. The yellow variety is often called precious topaz. Quartz having a yellow color (either natural or artificial) is often called topaz and used as an imitation gem.

Andalusite Orthorhombic $AlOAlSiO_4$

$a:b:c = 0.986:1:0.702$

Crystals often large, nearly square, prisms; also columnar, massive.

Good prismatic cleavage. H. = 7–7.5. G. = 3.1–3.2. Vitreous to dull luster. Gray, greenish, reddish or even bluish in color. Uncolored streak. Strongly pleochroic when colored. $(-)2V = 85°$, $N_g = 1.643$, $N_m = 1.638$, $N_p = 1.632$.

Andalusite is (nearly) Al_2SiO_5, but may contain some iron (see Fig. 403). This compound crystallizes as andalusite at low temperature, as *kyanite* (under stress?) and as *sillimanite* at higher temperature. All three change to *mullite* ($3Al_2O_3 \cdot 2SiO_2$) and free silica, kyanite at about 1350°C–1370°C., andalusite at about 1390°, and sillimanite at about 1545°C. All three are infusible and insoluble in acids; they alter to mica, kaolinite, or talc(?).

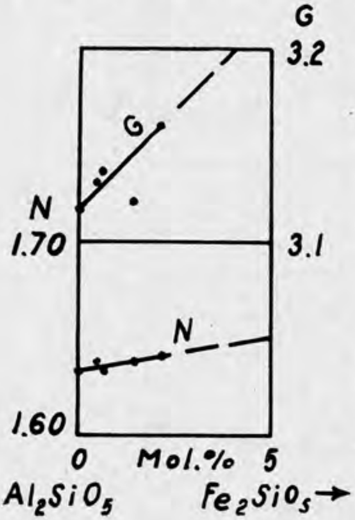

Fig. 403. Andalusite.

Chiastolite is a variety containing abundant carbonaceous inclusions inside a crystal in shapes determined by the enclosing crystal. *Viridine* is a variety (?) containing manganese (and iron and titanium).

Andalusite is found in metamorphic rocks such as schists and slates, which are rather remote from the igneous intrusion producing the change. The mineral was named from its occurrence in Andalusia, Spain. It is also known in the Ural Mountains, Tyrol, France, Ceylon, Brazil, and in Maine, Massachusetts, California, and elsewhere.

Andalusite is used in making spark plugs and special porcelains. Transparent crystals are sometimes used as gems.

Sillimanite **Orthorhombic** **$AlOAlSiO_4$**
$a:b:c = 0.97:1:1.34$

Crystals long prisms, nearly square, vertically striated. Fibrous masses.

Perfect 010 cleavage. H. = 6–7. G. = 3.25. Luster vitreous to silky. Color gray, brown, yellow, or greenish. Streak uncolored. $(+)2V = 25°$, $N_g = 1.677$, $N_m = 1.658$, $N_p = 1.657$.

Sillimanite is near Al_2SiO_5, but may contain a little iron. Changes to mullite and silica at 1545° and to corundum and silica at 1810°.

It is found especially in schists and gneisses; in igneous rocks it results from assimilation of shales, and similar sediments. It may be associated with andalusite, cordierite, corundum, mica. It is known in many places, including Tyrol, Ariège (France), Assam (India), Minas Geraes (Brazil), and in Massachusetts, New York, North Carolina.

Kyanite (Disthene) **Triclinic** **$AlOAlSiO_4$**
$a:b:c = 0.899:1:0.709$, $\alpha = 90°5'$, $\beta = 101°2'$, $\gamma = 105°44'$

Crystals long blades; also fibrous to columnar; crystals may be curved and arranged radially.

Perfect 100 and good 010 cleavage; also 001 parting. H. = 5–7.5, varying greatly on different faces and in different directions on one face. G. = 3.56–3.67. Luster vitreous to pearly. Color blue (hence the name) to white; also gray, green, brown. Color often irregularly distributed or least along the edges. $(-)2V = 82°$, $N_g = 1.728$, $N_m = 1.722$, $N_p = 1.713$.

Kyanite is near Al_2SiO_5, but may contain a little iron. It changes to mullite and silica at 1350°–1370°.

It is found in schists and gneisses, perhaps as a result of shearing stresses. It is often associated with garnet, staurolite or corundum. Some localities are Bohemia, Russia, Serbia, the Tyrol, France, and Massachusetts, Pennsylvania, North Carolina.

Datolite *Monoclinic* $CaBOHSiO_4$
$a:b:c = 0.633:1:0.635$, $\beta = 89°51'$

Crystals short prismatic with the base, or highly modified pyramidal forms. Also columnar or granular massive.

Conchoidal to uneven fracture. H. = 5–5.5. G. = 2.9–3.0. Fuses at 2 with intumescence. Luster vitreous to dull. Color white or greenish, often with yellow to brown spots or streaks. $(-)2V = 74°$, $N_g = 1.670$, $N_m = 1.654$, $N_p = 1.626$.

Datolite is nearly invariant $HCaBSiO_5$.

Datolite is a secondary mineral often associated with zeolite, calcite, danburite, prehnite, etc. It is found in cavities in basic igneous rocks and in veins and beds of iron ore. Some localities include Andreasberg (Germany), Trentino (Italy), Arendal (Norway). It is found also in the diabase of the Connecticut River valley, in trap rocks in New Jersey, and in amygdaloids in northern Michigan.

Titanite (Sphene) **Monoclinic** $\mathbf{CaTiOSiO_4}$

$\mathbf{a:b:c = 0.755:1:0.854,\ \beta = 60°17'}$

Crystals often wedge-shaped (whence the name, *sphene*, for the Greek for *wedge*) with large (001) and (111) faces, but quite varied; at times elongated along *c* or *a*. Compact or lamellar.

Distinct (110) cleavage. H. = 5–5.5. G. = 3.4–3.6. Luster vitreous to adamantine. Color yellow, green, brown, red, or black. $(+)2V = 23°–50°$, $N_g = 1.94–2.05$, $N_m = 1.87–1.92$, $N_p = 1.84–1.91$.

Titanite may be near $CaTiSiO_5$. It often contains Mn, Fe″,Fe‴,Al,Y,Ce in variable amounts so as to reduce the $CaTiSiO_5$ to as low as about 70 per cent, but the effects on physical properties are as yet unknown.

Titanite is a common accessory component of igneous rocks, especially of plutonic rocks such as syenites, diorites, and some hornblende granites. It is also found in schists and gneisses as well as in limestones near igneous instrusions. Titanite is remarkably variable in its crystal habit, but doubly wedge-shaped crystals are rather common. Fine crystals have been found at Rotenkopf in the Tyrol, in Piedmont (Italy), at Grisons (Switzerland), at Isère (France), and at Diana (New York), Franklin (New Jersey), Hot Springs (Arkansas), and elsewhere.

Axinite *Triclinic* $H(Fe,Mn)Ca_2Al_2BSi_4O_{16}$

$a:b:c = 0.602:1:0.827,\ \alpha = 121°32',\ \beta = 44°42',\ \gamma = 140°20'$

Crystals usually wedge-shaped (whence the name, from the Greek for *ax*) of varied habit. Also lamellar to granular aggregates.

Cleavages not easily seen. H. = 6.5–7, G. = 3.25–3.35. F. = 2–3 with intumescence. Insoluble in acid. Luster vitreous. Color clove-brown, gray, dull blue, green, yellow. Distinctly pleochroic in thick plates. Streak white. $(-)2V = 70°–76°$, $N_g = 1.696$, $N_m = 1.692$, $N_p = 1.684$, varying with varying tenor of manganese.

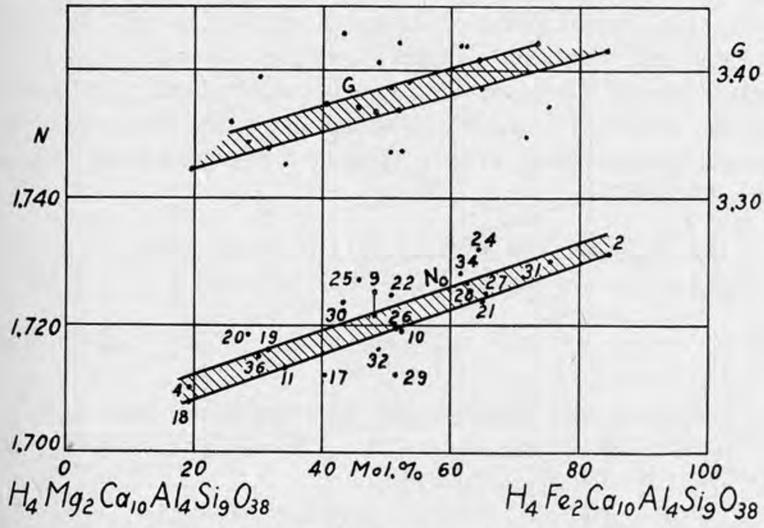

FIG. 404. Vesuvianite.

Axinite has a complicated formula, also written $H(Ca,Mn,Fe)_3Al_2BSi_4O_{16}$. The properties vary with the composition, but data are lacking for a diagram.

Axinite is usually a product of fumarolic action in contact zones; also found in veins. Some localities where it occurs are Isère (France), St. Just (Cornwall), and Franklin (New Jersey), Luning (Nevada).

Vesuvianite (Idocrase) **Tetragonal** $\mathbf{c = 0.537}$ $Ca_{10}Al_4\left[\begin{matrix}(SiO_4)_5\\(Si_2O_7)_2\end{matrix}\right]\cdot 2Mg(OH,F)_2$

Crystals prismatic or pyramidal; also columnar to massive.

Indistinct prismatic cleavage. H. = 6.5. G. = 3.32–3.42. F. = 3. Brown to green; less commonly yellow or blue. Streak white. $N_o = 1.70–1.73$ (see Fig. 404).

Vesuvianite is very variable in composition, but always not very far from grossularite garnet. It may contain iron (ferrous and ferric), titanium, manganese, and rarely, zinc, copper, beryllium, and so on. As iron replaces magnesium the properties change, as shown in Fig. 404.

Vesuvianite was first discovered at Vesuvius in dolomite metamorphosed by volcanic emanations. It is now known in many contact zones, often associated with grossularite, diopside, wollastonite, epidote, and so on. It is not found in igneous rocks. It is found as brown to green crystals in the Ala Valley and also at Vesuvius. Other localities include Vilui River, Siberia (variety *viluite*, optically positive), Orevicza (Roumania), Arendal (Norway), Kuira (Japan), and at Franklin (New Jersey), Amity (New York), Magnet Cove (Arkansas), Crestmore (California).

II. Orthodisilicates: SiO_4 tetrahedrons combined by one solid angle

Melilite *Tetragonal* $Ca_2R(Si,Al)_2O_7$
$c = 0.455$

Crystals usually short prisms; also square tablets.

Distinct basal cleavage. H. = 5. G. = 2.95–3.10. Soluble in HCl. Color white to brown.

Melilite varies much in composition, the chief types being *åkermanite* ($Ca_2MgSi_2O_7$) and *gehlenite* ($Ca_2Al_2SiO_7$). The natural mineral commonly contains iron (which increases the index and density) and may contain sodium, zinc, manganese, etc. The properties of the main series are shown in Fig. 405.

Melilite is common in furnace slags and in Portland cement. It is also found in volcanic rocks very low in silica and rich in lime. It occurs in lava at Vesuvius, in the Hawaiian Islands, in Texas, and elsewhere.

Hemimorphite (Calamine) Orthorhombic $Zn_4(OH)_2Si_2O_7 \cdot H_2O$
$a:b:c = 0.784$

Crystals often 010 tablets or prismatic with 010 faces vertically striated. Hemimorphic. Often in sheaf-like groups or fibrous to granular massive.

Perfect prismatic cleavage. H. = 4.5–5. G. = 3.4–3.5. Color white to pale blue or yellow. $(+)2V = 46°$, $N_g = 1.636$, $N_m = 1.617$, $N_p = 1.614$.

Hemimorphite varies little in composition, but may contain a little iron or lead. Gelatinizes with HCl.

Hemimorphite is an important ore of zinc; it is commonly associated with sphalerite in veins and other zinc ore deposits. It is obtained at, among other places, Nerchinsk (Siberia), Altenberg (Saxony), Iglesias (Sardinia), Moresnet (Belgium), Matlock (England), Santa Eulalia (Mexico), and from Sterling Hill (New Jersey), Granby (Missouri), Elkhorn (Montana), Leadville (Colorado), Organ Mountains (New Mexico).

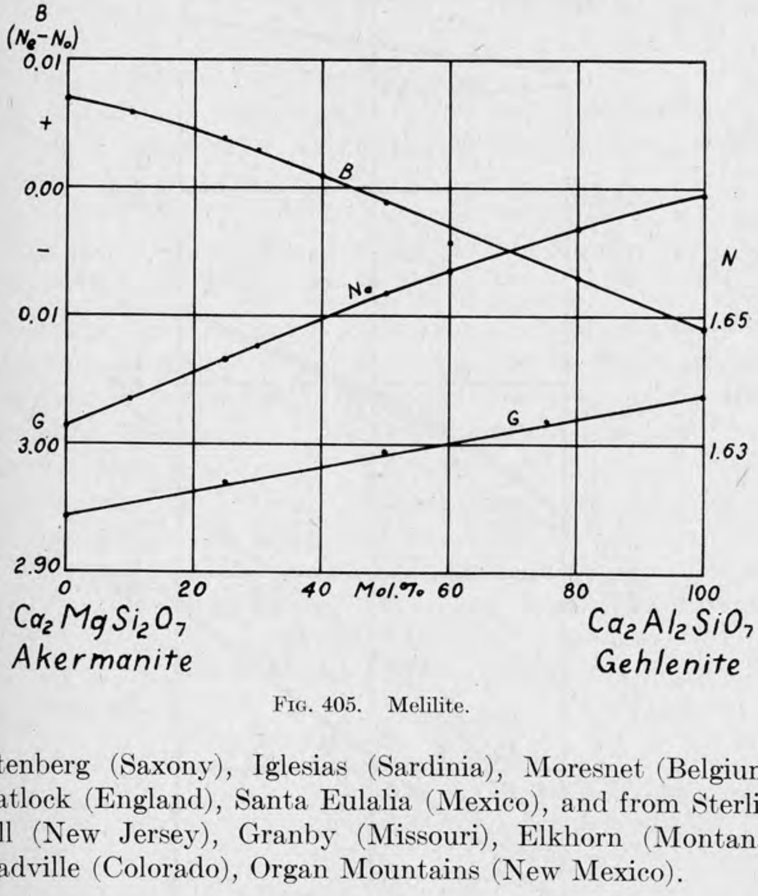

FIG. 405. Melilite.

III. Metasilicates: a. SiO_4 tetrahedrons combined by two solid angles in rings

Beryl **Hexagonal** **$Be_3Al_2Si_6O_{18}$**

$c = 0.499$

Crystals commonly long prismatic and vertically striated; often coarse columnar to granular massive.

No good cleavage. H. = 7.5–8. G. = 2.69–2.85. (See Fig. 406.) Luster vitreous. Color green, blue, yellow, white, pink. N_o = 1.568–1.602; N_e = 1.564–1.595 (See Fig. 406).

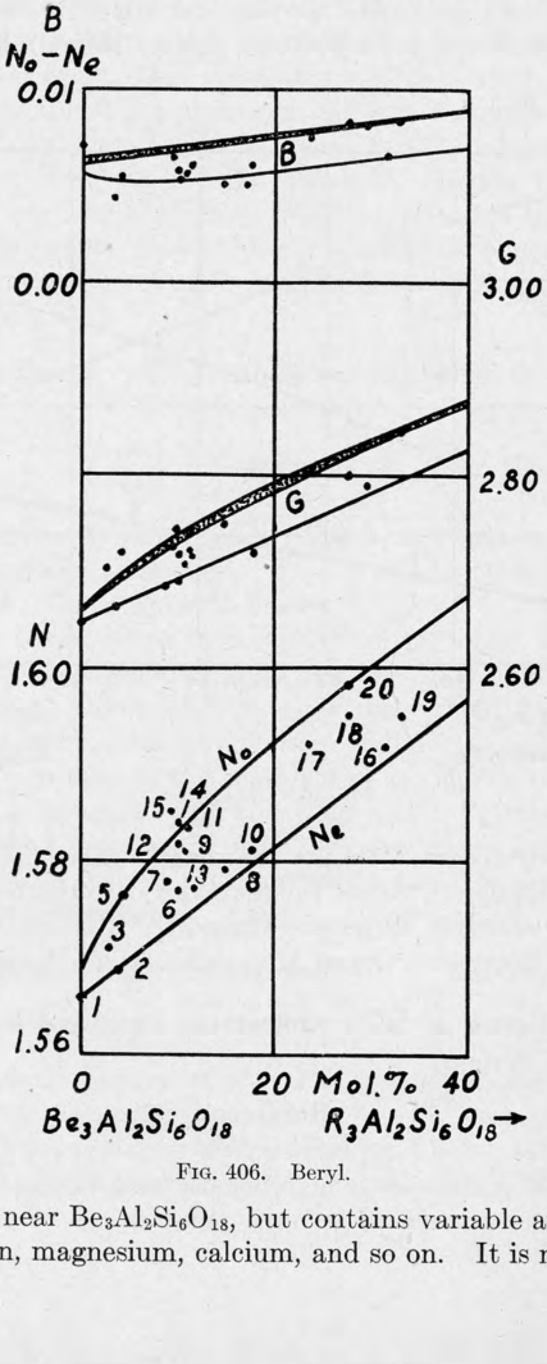

FIG. 406. Beryl.

Beryl is near $Be_3Al_2Si_6O_{18}$, but contains variable amounts of alkalies, iron, magnesium, calcium, and so on. It is not known just how these enter the crystal. In the diagram (Fig. 406) all these elements are assumed to proxy for Be. Water is also present in many cases.

There are five varieties of beryl, as follows:

1. *Common beryl,* which is generally greenish, yellowish, or grayish white in color. Crystals may be extremely large, being measured in feet and weighing tons. It is used as a source of beryllium metal and beryllium alloys.
2. *Morganite* is a pale pink to rose red beryl used as a gem.
3. *Golden beryl* has a beautiful golden yellow color and is an attractive gem stone.
4. *Aquamarine* is a blue to sea green beryl used as a gem.
5. *Emerald* is a beryl with a beautiful deep green color, very highly prized as a gem stone.

Beryl is found in pegmatites and in gneisses, schists, slates and in contact-altered limestones, as well as in placer deposits. It is commonly associated with quartz, feldspar, mica, topaz, tourmaline, cassiterite, chrysoberyl, garnet, and corundum. Emeralds have been found in limestone at Muzo, Colombia, in dolomite near Bom Jesus dos Meiras, Brazil, in the Ural Mountains, in the Tyrol, in Upper Egypt, at Poona, West Australia, etc. Morganite is known in Madagascar and in San Diego County, California. Aquamarine comes from Elba, Ireland, Brazil, Ceylon, India, North Carolina. Common beryl is obtained from New England, the Black Hills, South Dakota, and elsewhere.

Tourmaline	**Hexagonal**	
Dravite	$c = 0.452$	$H_4NaMg_3B_3Al_6Si_6O_{31}$
Schorlite	$c = 0.440$	$H_4NaFe_3B_3Al_6Si_6O_{31}$
Elbaite	$c = ?$	$H_4Na(Li,Al)_3B_3Al_6Si_6O_{31}$

Crystals usually prismatic, vertically elongated and vertically striated. Symmetry rhombohedral-hemimorphic. Crystals often show ternary symmetry distinctly, and are unlike at opposite ends of the vertical axis. Radiating groups common.

Conchoidal to uneven fracture. H. = 7–7.5. G. = 3.–3.2 (see Fig. 407). Fusibility 4–7. Vitreous to resinous luster. Color black, brown, less commonly blue, green, red, pink, colorless. Zonal arrangement of colors not rare; also different colors at opposite ends of vertical axis. Transparent to opaque.

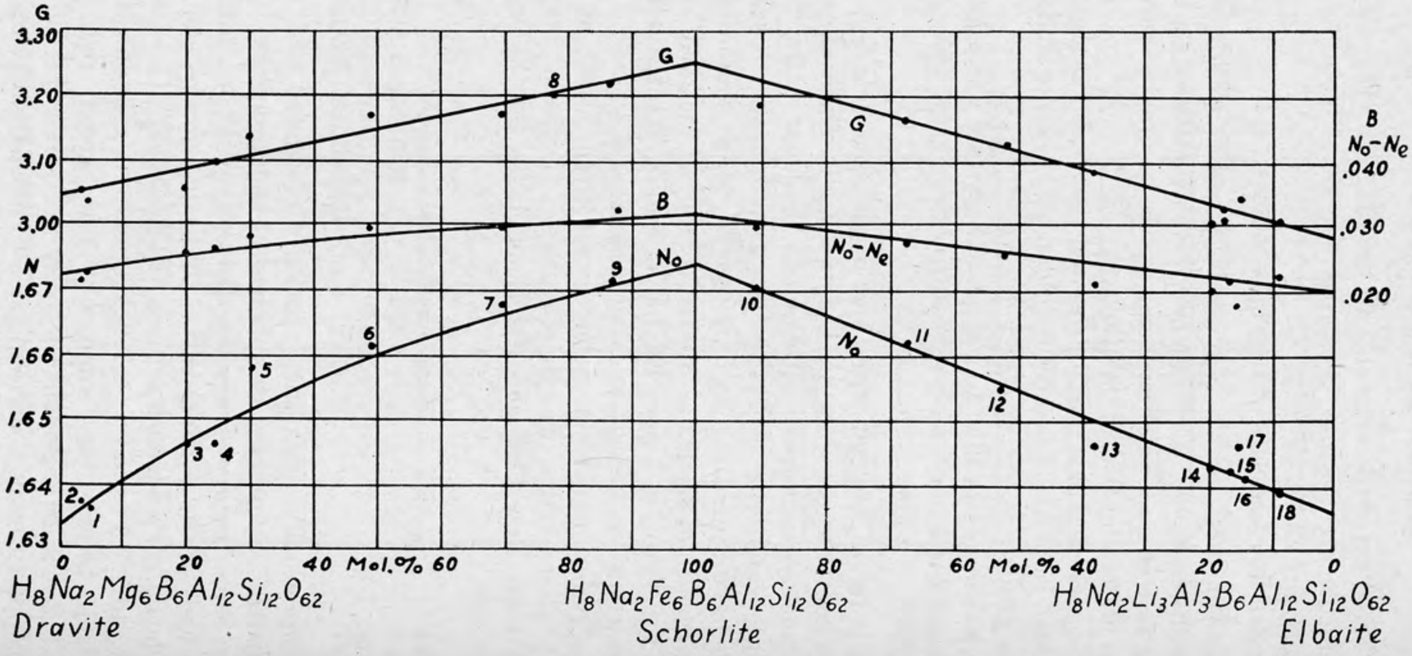

FIG. 407. Tourmaline.

Strongly dichroic with maximum absorption when the elongation is normal to the vibration plane of the light. $N_o = 1.63$–1.69; $N_e = 1.61$–1.66 (see Fig. 407).

Tourmaline varies greatly in composition: in addition to dravite, schorlite, and elbaite, rarer types include a manganese tourmaline, $H_4NaMn_3B_3Al_6Si_6O_{31}$, a calcium-magnesium tourmaline, $H_4CaMg_4B_3Al_5Si_6O_{31}$, a chromium tourmaline, etc. The variations of properties in the two chief series are shown in Fig. 407. These two series can usually be distinguished from each other by the color (brown, or less commonly, blue or green, to black in the dravite-schorlite series and black to delicate tints of green, pink, or yellow in the schorlite-elbaite series) and also by the presence or absence of lithium compounds in the associated minerals.

Tourmaline is important in pegmatites—its content of boron acts as a mineralizer to produce coarse crystallization. It is also found in some igneous rocks, and sparsely distributed in some schists and gneisses. It is a common product of fumarolic action. In detrital sediments it is usually well rounded and flattened. Tourmaline is often associated with quartz, feldspar, beryl, topaz, fluorite, lepidolite, apatite, and muscovite. Fine samples have been found in Ceylon, Madagascar, Ural Mountains, Burma, Brazil, and in Maine, New York, California. Clear crystals may be used as gem stones. Tourmaline can be used to produce light polarized in one plane, because of the strong absorption of one ray. It is also used for frequency control in short-wave radio apparatus.

Cordierite (Iolite) *Orthorhombic* $(Mg,Fe)_2Al_3(Si_5Al)O_{18}$
$a:b:c = 0.487:1:0.559$

Crystals short prismatic with large base; pseudohexagonal twinning rather common, as in aragonite. Often granular, massive.

Distinct 010 cleavage. H. = 7–7.5. G. = 2.55–2.75 (see Fig. 408). Color blue, smoky, greenish, yellow, brown. Streak white. Transparent to translucent. $(-)2V = 40°$–$80°$, $N_g = 1.535$–1.58, $N_m = 1.53$–1.57, $N_p = 1.525$–1.56, $N_g - N_p = 0.005$–0.015.

Cordierite varies much in composition, not only from $Mg_2Al_4Si_5O_{18}$ to $Fe_2Al_4Si_5O_{18}$, but also in containing water and even alkalies. The effects of the first variation on the properties are shown in Fig. 408. Partly decomposed by acids. Alters rather easily to mica, chlorite, etc.

Cordierite often contains inclusions, especially of sillimanite, spinel, staurolite, zircon, or apatite. Cordierite is found in gneiss and schists modified by igneous intrusions, and also in endomorphosed igneous rocks, usually near contacts with rocks rich in alumina and magnesia. It is commonly associated with quartz, orthoclase, albite, tourmaline, andalusite, sillimanite, staurolite, spinel, garnet, enstenite, etc. Samples for detailed study have been obtained from Ceylon, Hitachi and Dosi (Japan), Bodenmais (Bavaria), Träskböle and Attu (Finland),

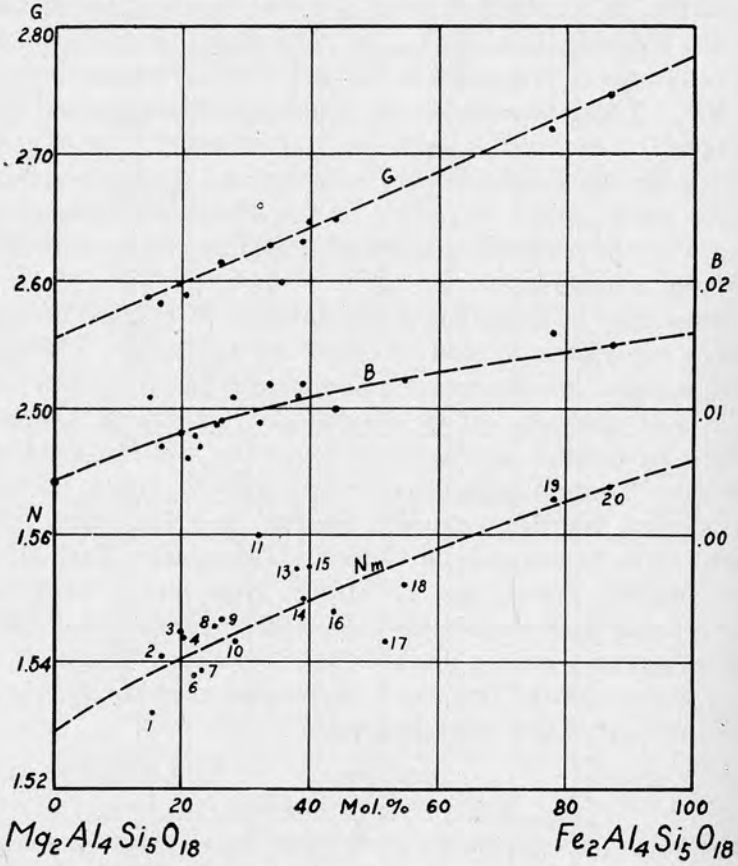

FIG. 408. Cordierite.

Ibity (Madagascar), and from the Amulet mine (Quebec), Haddam and Guilford (Connecticut), Franklin (North Carolina).

Wollastonite *Triclinic* $Ca_3(SiO_3)_3$

$a:b:c = 1.082:1:0.965, \alpha = 90°, \beta = 95°16', \gamma = 103°22'$

Crystals commonly 100 or 001 tablets often elongated along *b*. Usually in cleavable fibrous or granular masses.

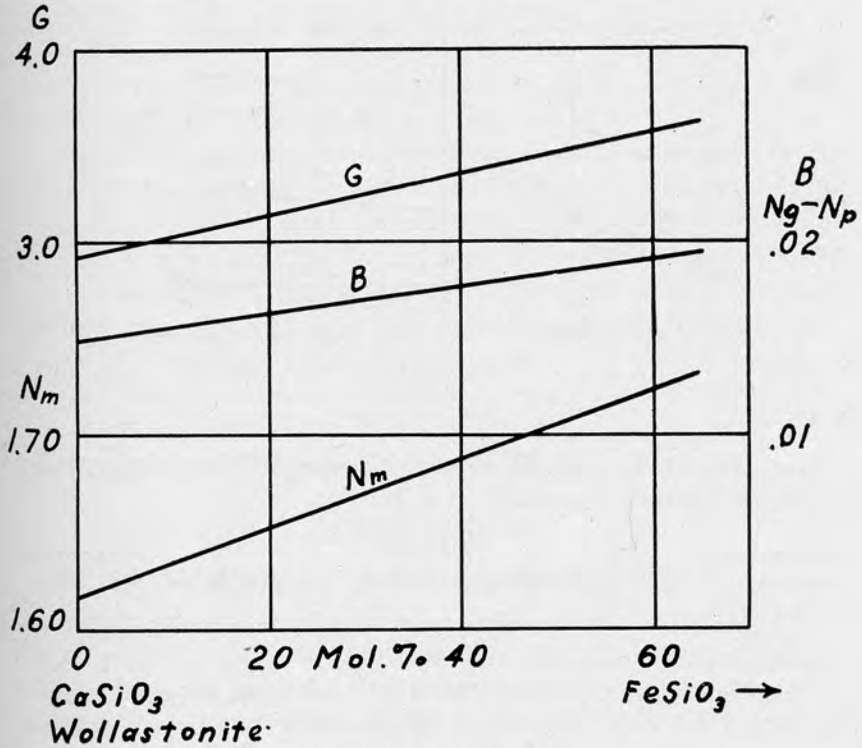

FIG. 409. Wollastonite.

Perfect 100, 001 and $\bar{1}02$ cleavages; also 101 and $\bar{1}01$. Twinning on 100. H. = 4.5–5. G. = 2.915. F. = 1540°. Gelatinizes with HCl. Color white or gray; nearly yellowish. $(-)2V = 39°$, $N_g = 1.634$, $N_m = 1.632$, $N_p = 1.620$.

At low temperature wollastonite is usually nearly pure $CaSiO_3$; at high temperature it may vary far toward $FeSiO_3$, or $SrSiO_3$, less toward $CaMgSi_2O_6$ or $MnSiO_3$. $CaSiO_3$ is triclinic wollastonite or monoclinic parawollastonite at low temperature; it inverts to pseudohexagonal pseudowollastonite at about 1180°. The effects of $FeSiO_3$ on the properties are shown in Fig. 409.

Wollastonite alters easily to calcite. It is found especially in limestones where modified near an igneous intrusion; it is often associated with diopside, garnet, epidote, and calcite. Localities include Elba, Vesuvius, Grenville (Quebec), Franklin (New Jersey), Lewis and Warren Counties (New York), Lake Superior district, Crestmore (California).

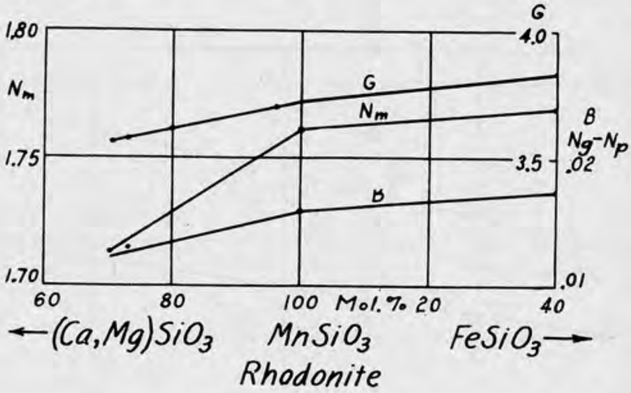

FIG. 410. Rhodonite.

Rhodonite **Triclinic** **$Mn_3(SiO_3)_3$**

$a:b:c = \mathbf{1.073:1:0.721}$, $\alpha = \mathbf{103°18'}$, $\beta = \mathbf{108°44'}$, $\gamma = \mathbf{81°39'}$

Crystals often 001 tablets or prismatic; commonly in granular cleavable or compact masses.

Perfect prismatic (110 and $1\bar{1}0$) and good basal cleavages. H. = 5.5–6.5. G. = 3.4–3.7. Fuses easily to a brown or black glass. Color rose red, pink, gray, or yellowish; brown to black by alteration. $(+)2V = 60°$, $N_g = 1.75$, $N_m = 1.74$, $N_p = 1.735$.

Rhodonite nearly always contains some $FeSiO_3$ or $(Ca,Mg)SiO_3$ (or both). The effects of these on the properties are shown in Fig. 410. Fowlerite is a variety containing some zinc.

Rhodonite is often associated with rhodochrosite, franklinite, willemite, zincite, quartz, calcite, etc. It is found in the Harz Mountains of Germany, in Roumania, Italy, Sweden, Peru, and at Franklin (New Jersey), Butte (Montana), and so on.

It is sometimes used as an ornamental stone. In wartime it is a possible source of manganese.

Pectolite *Triclinic* $HNaCa_2Si_3O_9$
$a:b:c = 1.137:1:0.999$, $\alpha = 90°23'$, $\beta = 95°14'$, $\gamma = 102°42'$

Crystals often elongated along *b*; twinning on 100; generally in fibrous aggregates, radially arranged.

Perfect basal and macropinacoidal cleavages. H. = 4.5–5. G. = 2.74–2.88. F. = 2. Decomposed by HCl. Luster silky to pearly or even vitreous. Colorless or white. $(+)2V = 50°$, $N_g = 1.636$, $N_m = 1.605$, $N_p = 1.600$.

Pectolite is usually near $HNaCa_2Si_3O_9$, but often contains a little iron and potassium; varieties with notable magnesium and manganese exist but their properties are not accurately known.

Pectolite is found in fissures and cavities in basic igneous and metamorphic rocks often associated with zeolites, calcite, datolite, etc. Localities include Fassatal (Tyrol), Thunder Bay (Ontario), Paterson (New Jersey), Isle Royale (Michigan), Magnet Cove (Arkansas), Tehama County (California).

Metasilicates: b. SiO_4 tetrahedrons in chains

Pyroxene Group

The pyroxene group of minerals includes some which are orthorhombic and others which are monoclinic. Even the triclinic wollastonite, rhodonite, and pectolite were formerly included in the group. Pyroxenes are metasilicates of magnesium, iron, calcium, lithium, aluminum, sodium, characterized by a prismatic cleavage angle of about 87° (and 93°). They are important constituents of many igneous and metamorphic rocks. They are usually dark colored: black, brown, green, or blue; but may be yellow, gray, or white. The pyroxenes differ from amphiboles in cleavage angle, in crystal habit (being short rather than long prismatic), in chemical composition (absence of water), in optical properties, and in altering to amphibole (amphibole changes back to pyroxene only through fusion). The pyroxenes to be described are enstenite, pyroxene proper, and spodumene.

Enstenite	**Orthorhombic**	**$MgSiO_3$-$FeSiO_3$**
Enstatite	**$a:b:c = 0.970:1:0.571$**	**$MgSiO_3$**
Hypersthene	**$a:b:c = 0.971:1:0.570$**	**$(Mg,Fe)SiO_3$**

Crystals prismatic, rare; usually in fibrous, lamellar, or compact masses; hypersthene is often in cleavable aggregates.

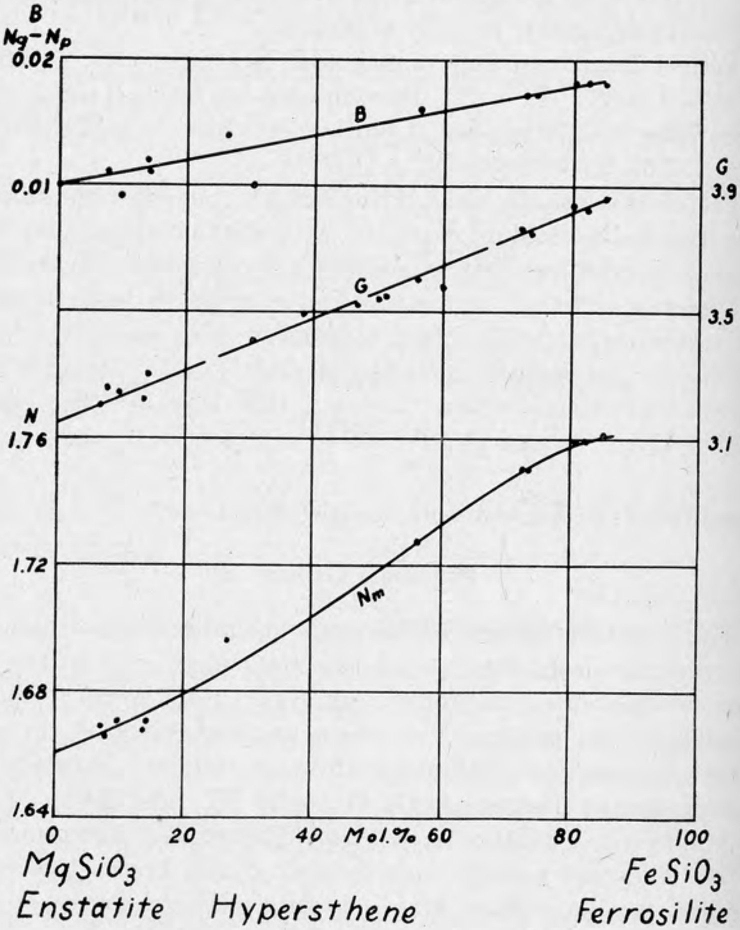

FIG. 411. Enstenite.

Perfect prismatic cleavages at about 88°; parting on 010 or 100. H. = 5.5. G. = 3.18–3.6 (see Fig. 411). Insoluble in HCl. (±)$2V$ over $Z = 60° - 130°$. $N_g = 1.654$–1.77, $N_m = 1.65$–1.76, $N_p = 1.648$–1.75 (see Fig. 411).

Enstenite varies from enstatite ($MgSiO_3$) through hypersthene (with some $FeSiO_3$) to a very rare mineral, *ferrosilite*, which may be nearly pure $FeSiO_3$. It may contain some MnO, Al_2O_3, and Fe_2O_3. A variety with inclusions producing a peculiar bronzy luster is known as *bronzite.* The effects of variation in iron content on the properties are shown in Fig. 411.

Enstenite alters rather easily to a variety of chlorite called *bastite;* also, less frequently, to a variety of hornblende called *uralite*, or to talc.

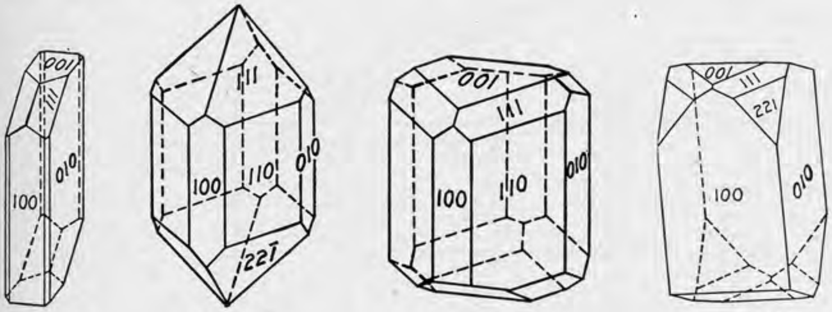

FIG. 412. FIG. 413. FIG. 414. FIG. 415.

FIGS. 412, 413, 414, 415. Crystals of pyroxene.

Enstenite is found in basic igneous rocks, and is characteristic of norite. It is often associated with olivine, spinel, serpentine, labradorite, etc. It is found in Norway, Austria, Bavaria, Prussia, Scotland, Kimberley (South Africa), and in the Adirondack Mountains and Lake Superior district.

Enstenite with an iridescent metalloidal luster is sometimes used as an ornamental stone.

Pyroxene proper	**Monoclinic**	
Clinoenstenite		$(Mg,Fe)SiO_3$
Diopside	$a:b:c = 1.092:1:0.589, \beta = 74°10'$	$CaMgSi_2O_6$
Hedenbergite	$a:b:c = 1.088:1:0.586, \beta = 74°55'$	$CaFeSi_2O_6$

Crystals commonly short prisms with or without 100 and 010, terminated by 111 or 001. See Figs. 412–415. Twinning common on 100 or 001, rare on $\bar{1}22$ or 011. Coarse to fine aggregates, usually cleavable.

Conspicuous prismatic cleavages at 87°. Parting well developed on 100 in the variety called *diallage;* less commonly on 001. H. = 5–6. G. = 3.2–3.6 (see Figs. 416, 417 and 419).

$MgSiO_3$ inverts at 1150°, decomposes at 1557° and fuses at 1577°; $CaMgSi_2O_6$ fuses at 1391°, $FeSiO_3$ decomposes below 800°, but with about 10% $MgSiO_3$ it decomposes at about 960°; $CaFeSi_2O_6$ inverts at 965° and fuses at about 1200°.

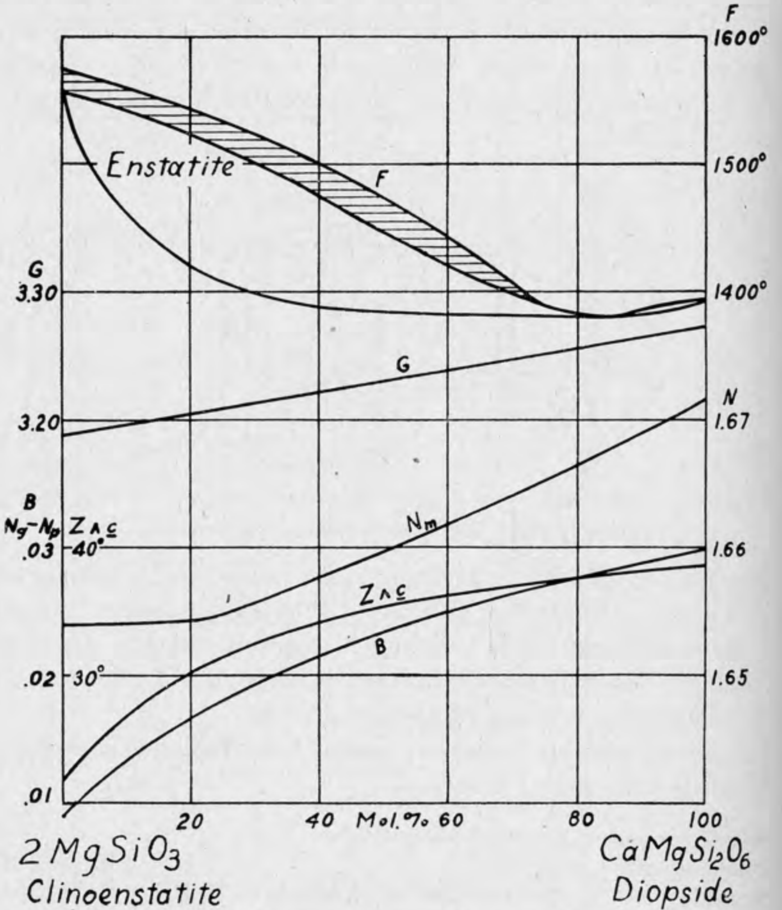

FIG. 416. Clinoenstatite-diopside series of pyroxene.

$(+)2V = 0° - 60°$, $N_g = 1.66–1.79$, $N_m = 1.654–1.76$, $N_p = 1.65–1.76$ (see Figs. 416–419).

Pyroxene proper varies in composition in many ways; it not only has the four end-members $MgSiO_3$ (clinoenstatite), $FeSiO_3$ (clinoferrosilite—not stable in the pure state), $CaMgSi_2O_6$ (diopside), and $CaFeSi_2O_6$ (hedenbergite), but it is usually composed of all four of these in variable proportions (*augite* and *pigeonite*), with or without minor amounts of Al_2O_3, Fe_2O_3, TiO_2, MnO,

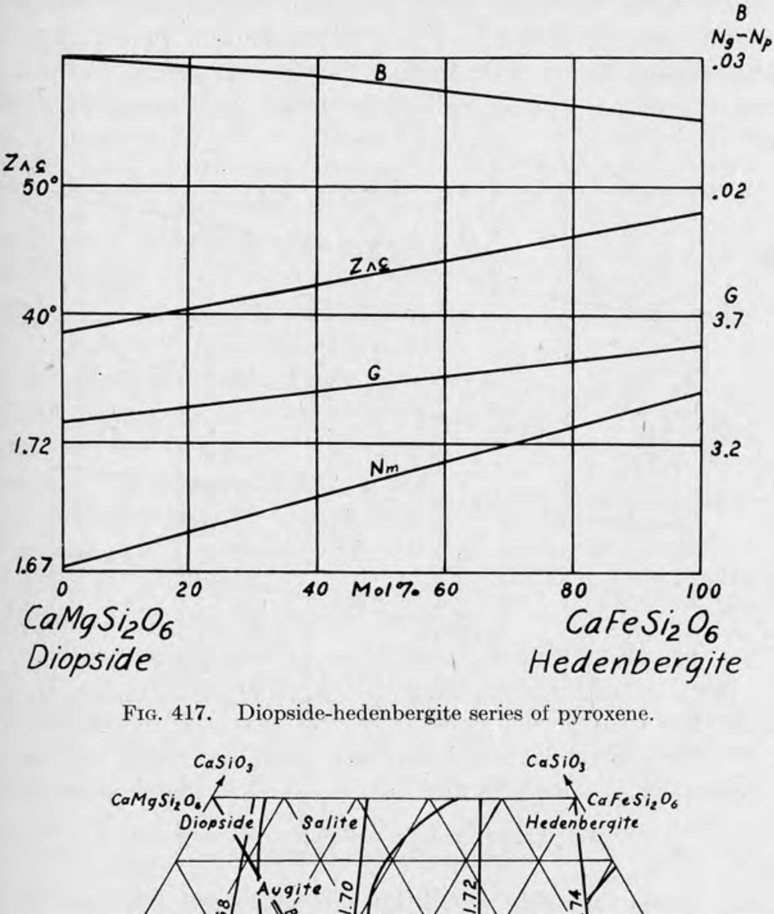

FIG. 417. Diopside-hedenbergite series of pyroxene.

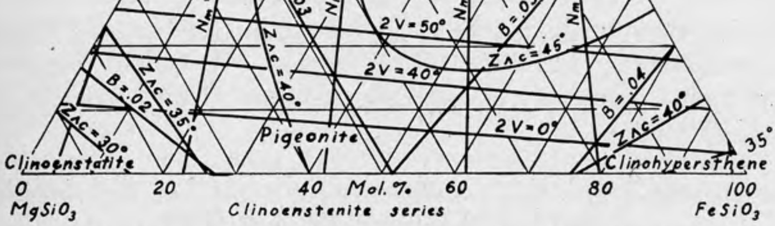

FIG. 418. Diopside-hedenbergite-clinoenstenite system of pyroxene.

ZnO, and so on. The properties vary with the chief variations in composition as shown in Figs. 416–419.

Pyroxene is a common constituent of igneous rocks; in fact it is the most important ferromagnesian mineral in such rocks. It is abundant in basalt, gabbro, and peridotite, and important in many other igneous rocks. It is also common in metamorphic rocks, especially near contacts with igneous rocks, but also in areas of regional metamorphism of shales, limestones, and dolomites. Some notable localities are Fassatal in the Tyrol, Zermatt in Switzerland, Pargas in Finland, Kaiserstuhl in Baden, Arendal in Norway, Tunaberg in Sweden, and Canaan (Connecticut), Franklin (New Jersey), Wakefield (Quebec), Amherst County (Virginia), Lewis County (New York), Haleakala (Hawaii).

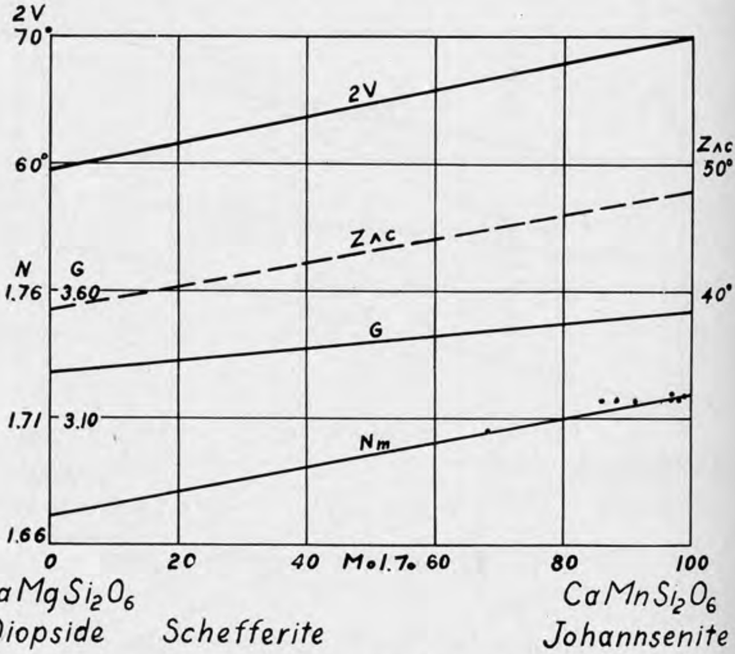

FIG. 419. Diopside-johannsenite series of pyroxene.

Spodumene **Monoclinic** **$LiAlSi_2O_6$**

$a:b:c = 1.124:1:0.636, \beta = 69°40'$

Crystals prismatic, often long columnar; also tabular; may have vertical striations. Single crystals may be 30 to 50 feet long and as much as six feet thick, weighing over 30 tons. More frequently in cleavable masses and broad columnar aggregates.

Prismatic (110) cleavage well developed; also may have 010 parting. H. = 6–7. G. = 3.1–3.2. Fuses easily, giving a deep red flame color. Vitreous to pearly luster. Color white, gray, green, pink, purple. Streak white. $(+)2V$ about 60°, $N_g = 1.675–1.68$, $N_m = 1.66–1.67$, $N_p = 1.65–1.66$.

Spodumene is near $LiAlSi_2O_6$, but usually contains a little sodium, calcium, iron; rarely chromium, etc. Insoluble in acids. By alteration it may lose up to a fifth of the lithium (at the same time one oxygen atom being replaced by OH) without losing its crystal structure. Then the properties change as shown in Fig. 420, and the mineral becomes much softer. A clear yellow to emerald green variety from North Carolina is called *hiddenite;* a clear pink to lilac variety from California is known as *kunzite.*

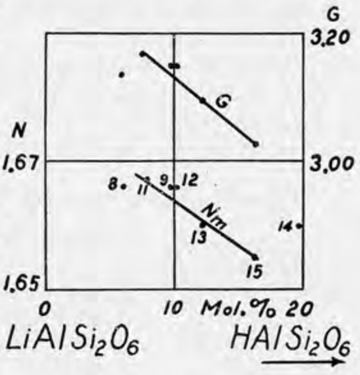

FIG. 420. Spodumene.

Spodumene inverts to a uniaxial mineral with G. = 2.28 and $N_o = 1.52$ at 690°, which fuses at 1380°C.

Spodumene is found in pegmatite, often with tourmaline, beryl, garnet, lepidolite, feldspar, and quartz. Important localities include Utö and Varutrask in Sweden, Killarney in Ireland, Maharitra in Madagascar, and Branchville (Connecticut), Alexander County (North Carolina), Black Hills (South Dakota), San Diego County (California).

Metasilicates: c. SiO_4 tetrahedrons in double chains (or bands)

Amphibole Group

The amphibole group, like the pyroxene group, includes both orthorhombic and monoclinic members. But the formulas are more complex and the minerals are remarkably variable in composition. The amphiboles differ from the pyroxenes as follows:

Amphiboles	*Pyroxenes*
Prismatic cleavages at 124°	Prismatic cleavages at 93°
Crystals long prismatic to fibrous.	Crystals short prismatic.
Specific gravity less	Specific gravity greater.
Contain 2½ (Mg + Fe) for each Ca.	Contain as much Mg + Fe as Ca.
Contain more soda and alumina.	Contain less soda and alumina.
Contain hydrogen.	Contain no hydrogen.
Important in some igneous rocks, but more abundant in metamorphic rocks.	More abundant than amphibole in igneous rocks (especially basic); found also in metamorphic rocks.

The amphiboles to be described are:

Anthophyllite	$(Mg,Fe)_7Si_8O_{22}(OH)_2$	Orthorhombic
Hornblende		
Tremolite	$Ca_2Mg_5Si_8O_{22}(OH)_2$	Monoclinic
Pargasite	$NaCa_2(Mg,Fe)_5AlSiO_7O_{22}(OH)_2$	Monoclinic
Hastingsite	$NaCa_2(Mg,Fe)_4Al_3Si_6O_{22}(OH)_2$, etc.	Monoclinic
Glaucophane	$Na_2Mg_3Al_2Si_8O_{22}(OH)_2$	Monoclinic

Anthophyllite

Orthorhombic $H_2(Mg,Fe)_7Si_8O_{24}$

$a:b:c = 0.514:1:0.294$

Crystals long prismatic to fibrous, rare; commonly fibrous in masses.

Perfect prismatic (110) cleavage at 125°37′; good 010 and 100 cleavages (or parting?). H. = 5.5–6. G. = 2.85–3.2 (see Fig. 421). Luster vitreous. Color brownish gray, brown, green; streak uncolored. $(\pm)2V = 60° - 90°$, $N_g = 1.62–1.71$, $N_m = 1.61–1.68$, $N_p = 1.59–1.67$ (see Fig. 421).

Anthophyllite varies in composition from $H_2Mg_7Si_8O_{24}$ to $H_2Fe_7Si_8O_{24}$ and may also contain alumina (*gedrite*) or soda (*antholite*). The relations between the first kind of variation and the physical characters are shown in Fig. 421. Monoclinic equivalents of anthophyllite are known as *cummingtonite* or (with much iron) as *grunerite*.

Anthophyllite is found in some schists, at times as the chief constituent. It is known at Kongsberg (Norway), Träskböle (Finland), the Caucasus region, and at Edwards (New York), Franklin (North Carolina), Mesabi Range (Minnesota), Trinity County (California), and elsewhere.

A long-fibered variety from South Africa called *amosite* is used as asbestus.

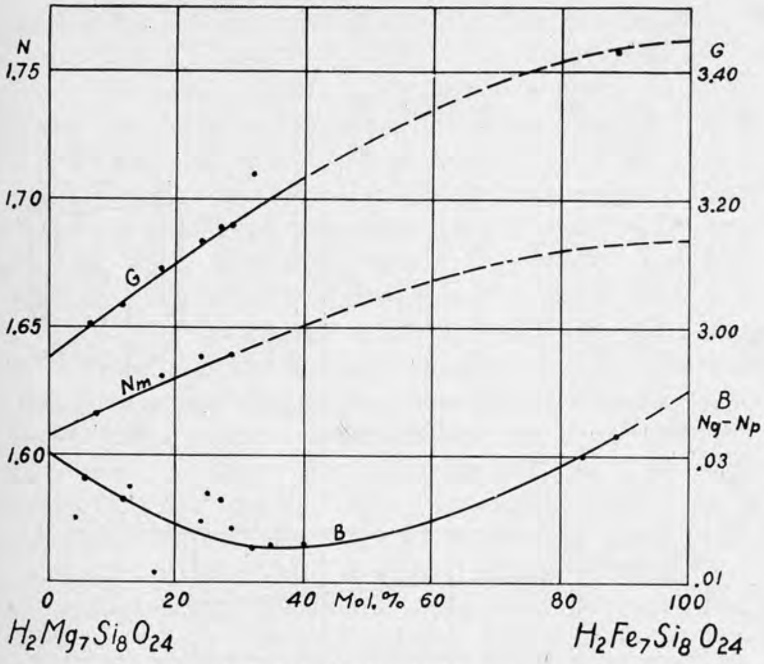

FIG. 421. Anthophyllite series.

Hornblende	**Monoclinic**	
Actinolite	$a:b:c = 0.54:1:0.29$	$Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$
Pargasite	$\beta = 74°$	$NaCa_2(Mg,Fe)_5AlSi_7O_{22}(OH)_2$
Hastingsite		$NaCa_2(Mg,Fe)_4Al_3Si_6O_{22}(OH)_2$

Crystals are long prismatic, often with pseudohexagonal outline made by (110) and 010 and terminated by the clinodome (011), at times with the base, 001. See Figs. 422–424. Also often in columnar to fibrous aggregates.

Perfect prismatic (110) cleavage at an angle of 124°. H. = 5–6. G. = 2.9–3.5. Luster vitreous to silky. Usually dark green, brown, or black in color, but may be gray, yellow, or white. Streak uncolored or lighter than the color in mass. $(\pm)2V$ is about 80°; indices vary widely; see Fig. 425 for the variations in one series.

Hornblende varies greatly in composition and in many ways. The simplest type is perhaps $Ca_2Mg_5Si_8O_{22}(OH)_2$, known as *tremolite;* with some iron $\{Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2\}$ it is called *actinolite.* But hornblende usually contains both alkalies and

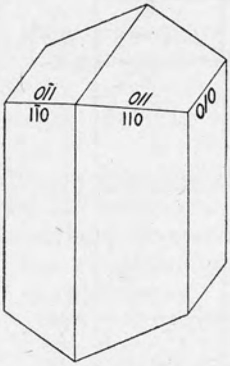

FIG. 422. Crystal of hornblende.

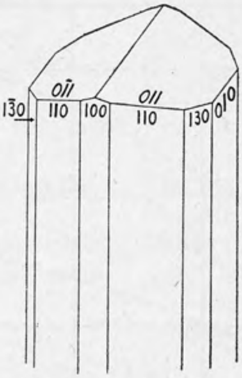

FIG. 423. Crystal habit of hornblende.

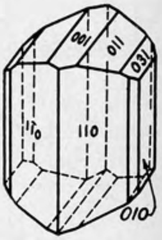

FIG. 424. Crystal of hornblende.

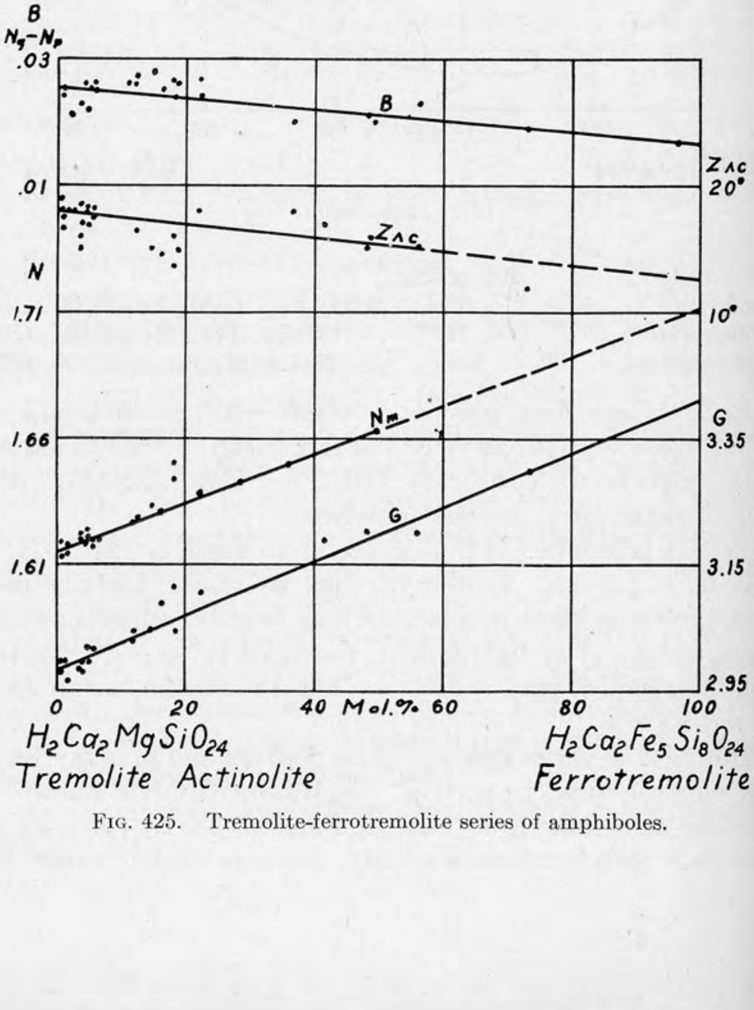

FIG. 425. Tremolite-ferrotremolite series of amphiboles.

alumina in varying amounts as in $NaCa_2(Mg,Fe)_5AlSi_7O_{22}(OH)_2$ and $NaCa_2(Mg,Fe)_4Al_3Si_6O_{22}(OH)_2$. It often contains ferric iron and titanium. *Common hornblende* is green to black in color and has the following properties (approximate): $(-)2V = 84°$, $N_g = 1.68$, $N_m = 1.67$, $N_p = 1.66$, $Z \wedge c = 15°$; *oxyhornblende* (or *basaltic hornblende*) is brown to black in color with more ferric iron and approximately: $(-)2V =$ large, $N_g = 1.71$, $N_m = 1.69$, $N_p = 1.68$, $Z \wedge c =$ near 0°.

Hornblende produced by alteration of augite is called *uralite;* hornblende does not change to augite except through fusion; it alters to chlorite, epidote, calcite, siderite, limonite, and quartz.

Hornblende is an important constituent of many igneous rocks, especially diorite, syenite, and granite, as well as of schists and gneisses. Tremolite and actinolite are found as alteration products in some igneous rocks, but are important in some metamorphic rocks. Some of the more important localities are Mount Vesuvius (Italy), Pargas (Finland), Greiner (Tyrol), Teplitz (Bohemia), Nordmark (Sweden), Renfrew County (Ontario), Chester (Massachusetts), Warwick (New York), Franklin (New Jersey), Pylesville (Maryland).

Glaucophane *Monoclinic* $H_2NaMg_3Al_2Si_8O_{24}$

$a:b:c = 0.53:1:0.29$, $\beta = 75° \pm$

Crystals are prismatic in habit, but usually indistinct; commonly massive, fibrous to columnar.

Perfect prismatic (110) cleavage at 124°. H. = 6–6.5. G. = 3–3.15. Fuses at 3–3.5. Insoluble. Luster vitreous to pearly. Color light to dark blue; rarely gray. Streak grayish blue. $(-)2V =$ small, $N_g = 1.639$, $N_m = 1.638$, $N_p = 1.621$, $Z \wedge c = 5° \pm$.

Glaucophane is near $H_2Na_2Mg_3Al_2Si_8O_{24}$ in composition, but often contains some $Ca_2Mg_3Al_2Si_8O_{24}$ and forms a (continuous?) series with *riebeckite*, $H_2Na_2Fe_3Fe_2Si_8O_{24}$, the properties varying as shown in Fig. 426. Still other variations are known.

Glaucophane is found in schists and contact rocks. Riebeckite is a constituent of certain granites, pegmatites, and syenites. *Crocidolite* is a fibrous variety of riebeckite found in South Africa; it has a blue color and is used as asbestus. Other localities for glaucophane or riebeckite include Zermatt (Switzerland), Krivoi-Rog (Russia), and Berkeley (California), Quincy (Massachusetts).

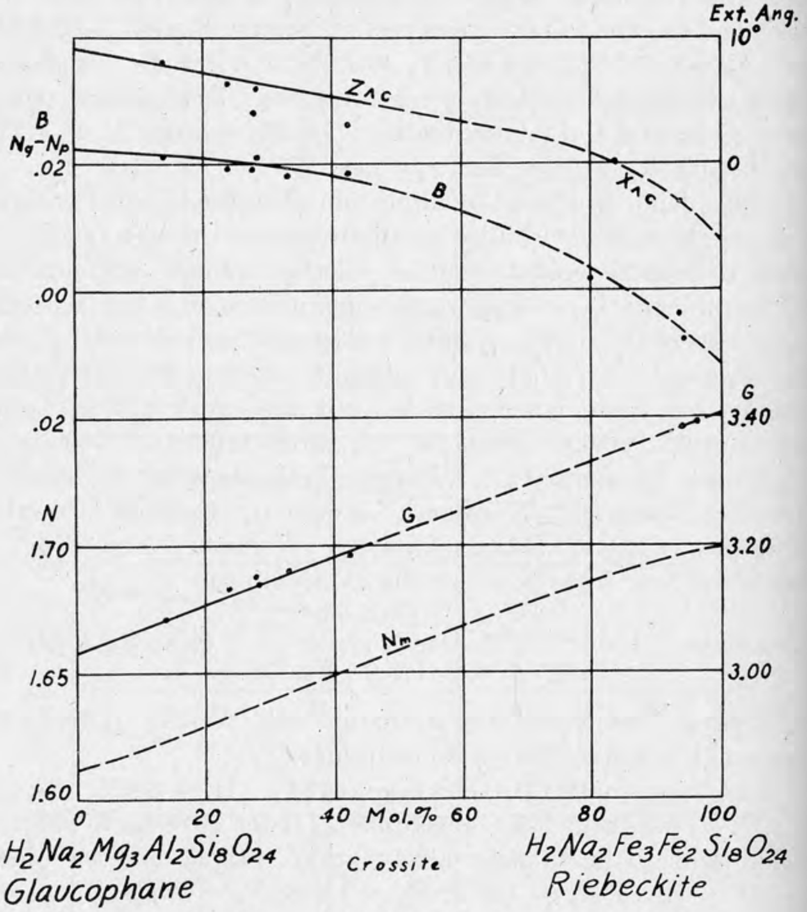

FIG. 426. Glaucophane-riebeckite series of amphiboles.

Sepiolite *Monoclinic* (?) $Mg_8\begin{bmatrix}Si_6O_{18}\\Si_6O_{15}\end{bmatrix}(OH)_7 \cdot 5H_2O$

Found only in compact nodular or earthy masses; finely fibrous to amorphous.

Conchoidal to uneven fracture. H. = 2–2.5. G. = 2. F. = 6 in most cases after turning black, giving a burnt smell. On account of its porosity samples often will float on water. Hygroscopic. $(-)2V$ = small, $N_g = 1.53$, $N_p = 1.52$.

The sepiolite formula is often written $H_4Mg_2Si_3O_{10}$, but the tenor of water is variable and the structure is similar to that of amphibole, so that the complicated formula given above is probable.

Sepiolite is an alteration product of serpentine; it is often associated with magnesite and opal. An impure sepiolite containing also opal, etc., is called *meerschaum;* it is easily carved, takes an excellent polish and is used extensively for pipe bowls and cigar tips. It is used as a building stone in Spain.

Serpentine **Monoclinic** $(\mathbf{MgOH})_6\left[\begin{matrix}\mathrm{Si_2O_6}\\ \mathrm{Si_2O_5}\end{matrix}\right]\cdot \mathbf{H_2O}$

Well-formed crystals are unknown except as pseudomorphs. It is usually in fibrous aggregates.

Conchoidal or splintery fracture. H. = 2.5–4. G. = 2.3–2.65. F. = 6. Luster dull resinous or greasy to earthy. Color green of various shades; less commonly yellow to brown or black. Smooth to greasy feel. $(+)2V = 30°$, $N_g = 1.555$, $N_m = 1.543$, $N_p = 1.542$, but variations in index are known from 1.49 to 1.58 due apparently largely to varying hydration.

Serpentine is near $H_4Mg_3Si_2O_9$ in composition but may contain more MgO and also Al_2O_3, Fe_2O_3, FeO, MnO, NiO, etc. *Garnierite* is a variety with little to much NiO (then $N_g = 1.63$, $N_p = 1.622$). $H_4Mg_3Si_2O_9$ crystallizes also as *antigorite,* which is one kind of chlorite.

The rock called *serpentinite* is composed largely of serpentine or antigorite or both. It is often compact massive and dark colored, often multicolored. *Precious serpentinite* is a variety which takes a good polish and is used as an ornamental stone; usually greenish. *Verd antique* is an impure serpentinite, containing serpentine (or antigorite or both) with calcite, dolomite, magnesite, or talc; it has a mottled or veined appearance, takes a fine polish and is much used as an ornamental stone, sometimes called *serpentine marble.* *Chrysotile* is the serpentine of normal composition and fibrous habit. In some cases it has fine fibers which are separable; such material is called *asbestus,* but asbestus includes fibrous amphibole also. Serpentine asbestus is shorter fibered than amphibole asbestus, but is more suitable for spinning and is used in large quantities to provide heat and electric insulation. Garnierite is a valuable nickel ore.

Serpentine is produced by alteration of olivine or pyroxene or amphibole, usually through the agency of hot siliceous solutions. It is often associated with residual olivine, pyroxene, or amphibole, and also with magnesite, calcite, chromite, talc, pyrope, and the like. It is quarried in Chester County, Pennsylvania, the Thetford district in Quebec, Rhodesia, Cyprus, and elsewhere.

IV. Metadisilicates: SiO_4 tetrahedrons united at three solid angles to form sheets

Apophyllite **Tetragonal** **$4CaSi_2O_5 \cdot KF \cdot 8H_2O$**
$c = 1.25$

Crystals of varied habit, prismatic, pyramidal or tabular, as shown in Figs. 427–429. The prism faces are lustrous and often vertically striated; the base is dull or rough; pyramid faces are likely to be uneven. Also found in lamellar aggregates.

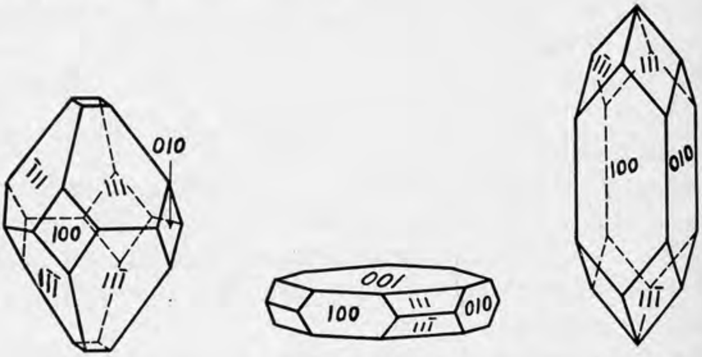

Fig. 427. Fig. 428. Fig. 429.

Figs. 427, 428, 429. Crystal habits of apophyllite.

Perfect basal cleavage parallel with the sheets of SiO_4 tetrahedrons in the structure. H. = 4.5–5. G. = 2.3–2.4. It fuses easily (after exfoliation) to a white enamel. Vitreous to pearly luster with pearly opalescence on the basal pinacoid. Colorless, white or light green, yellow or reddish. $(\pm)2V = 0°$ or small, $N_o = 1.535$–1.543, $N_e = 1.537$–1.543.

Apophyllite is near $4CaSi_2O_5 \cdot KF \cdot 8H_2O$, but sodium may proxy for potassium and hydroxyl for fluorine; rarely, zinc may be present. Apophyllite contains as much water as a zeolite, but it contains no alumina and has a different structure. It is decomposed by HCl with separation of silica. It alters to calcite, pectolite, kaolin, etc.

Apophyllite is found as a secondary mineral in cracks and amygdules in basic igneous rocks; also in granite and gneiss. It is often associated with natrolite, analcite, datolite, prehnite, calcite, pectolite, and the like. It is known at Freiberg (Saxony), in Tyrol, Sweden, Iceland, Nova Scotia, and at Bergen Hill (New Jersey), Table Mountain (Colorado), New Almaden (California).

Prehnite **Orthorhombic (Hemimorphic)** $\mathbf{H_2Ca_2Al_2Si_3O_{12}}$
$a:b:c = 0.840:1:0.555$

Crystals rare, (001) tablets or prismatic or pyramidal. Often reniform, globular or lamellar.

Distinct basal cleavage. H. = 6–6.5. G. = 2.80–2.95. Luster vitreous, slightly pearly on base. Color light green, white, or gray. Streak white. $(+)2V$ varies. $N_g = 1.649$, $N_m = 1.626$, $N_p = 1.616$.

Prehnite is $H_2Ca_2Al_2Si_2O_{12}$, but may contain some ferric iron replacing Al.

Prehnite is associated with zeolites, but contains no water that goes off gradually, as the water in zeolites does. It is found in amygdules in basic igneous rocks as a secondary mineral; also in granite, gneiss, and other metamorphosed rocks.

Talc **Monoclinic** $\mathbf{H_2Mg_3Si_4O_{12}}$
$a:b:c = 0.578:1:2.067, \beta = 80°$

Crystals are rare; they are tabular or scaly and poorly developed. Often foliated massive; rarely fibrous.

Perfect basal cleavage, the laminæ being flexible, but not elastic. H. = 1–2.5. G. = 2.6–2.9. Pearly to greasy luster. Commonly pale green, white or gray; rarely yellowish to brown. $(-)2V = 0\text{–}30°$, $N_g = 1.575\text{–}1.589$, $N_p = 1.538\text{–}1.545$ (see Fig. 430).

Talc is near $H_2Mg_3Si_4O_{12}$, but iron (also Mn, Ni) may proxy for the magnesium and the tenor of water (and even silica) seems to vary. By exception, the increase in iron seems to decrease the specific gravity and birefringence, as shown in Fig. 430, but more data are needed.

Ordinary talc is foliated and has a soapy feel and pale green to white color; laminæ easily separated; H. = 1.

Steatite or *soapstone* is massive talc, usually impure, gray, greenish, or brownish in color; H. = 1–2.5.

Indurated talc may be found along faults; it is impure and harder than ordinary talc.

French chalk is finely granular talc in compact white masses. It marks cloth easily.

Talc is often an alteration product of pyroxene or amphibole, but it may also be formed by anamorphic processes as in some talc schists. It is often associated with serpentine, chlorite, magnetite, as well as residual pyroxene, amphibole, or olivine.

Talc and soapstone have many uses; they may be easily cut into various shapes for wash tubs, mantels, laboratory tables, fire bricks, slate pencils, and so on. Ground talc is used as face powder, in toilet soaps, water proof cement, as an insulator, or a lubricant, and as a "filler" for paint, paper, and roofing material.

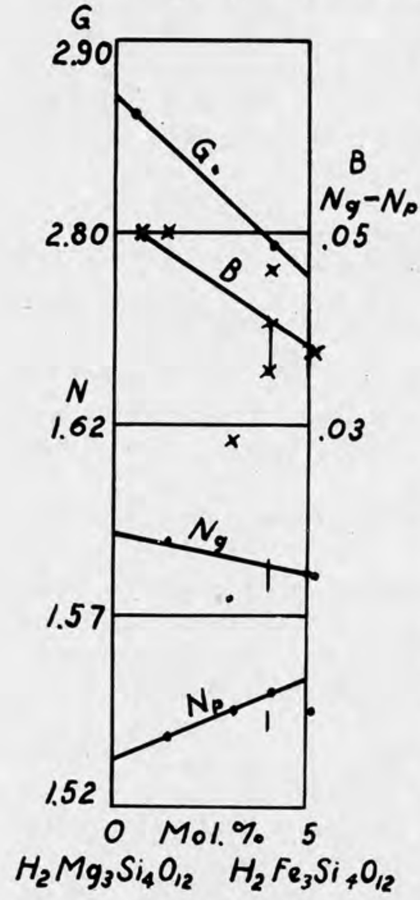

Fig. 430. Talc.

Talc is mined extensively in St. Lawrence County, New York and also in Vermont. Soapstone is obtained chiefly from Nelson and Albemarle Counties, Virginia.

Kaolinite **Monoclinic** **$Al_2Si_2O_5(OH)_4$**

$a:b:c = 0.577:1:1.630, \beta = 79° \pm$

Usually compact massive; rarely in tiny basal plates with six or four sides.

The basal plates have perfect basal cleavage. H. = 1–2.5. G. = 2.5–2.6. F. = 7. Insolube in acids. Greasy to chalk-like feel. Usually adheres to the tongue and becomes plastic when wet. Argillaceous odor. Compact masses have dull luster; scales have pearly luster. Usually white, but may be yellowish, bluish, greenish, or reddish. $(-)2V = 0°–40°$, $N_g = 1.567$, $N_m = 1.566$, $N_p = 1.561$.

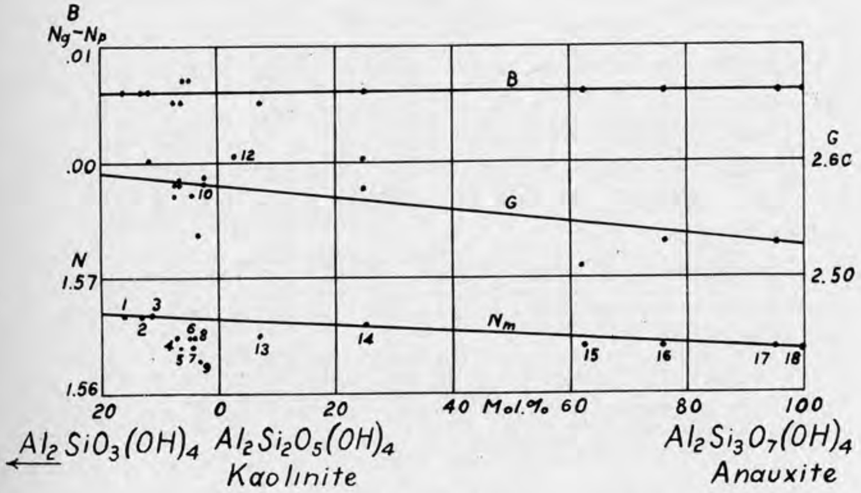

FIG. 431. Kaolinite.

Kaolinite varies from $Al_2Si_2O_5(OH)_4$ in its Al:Si ratio in both ways, but Si increases more than it decreases. The resulting formulas are uncertain, but may be as given in Fig. 431, which shows the slight changes in properties which result. An increase in tenor of water causes a marked decrease in density (even to 2.3) and indices. The compound $Al_2Si_2O_5(OH)_4$ also crystallizes as *nacrite* and *dickite* with different, though somewhat similar, properties.

Kaolinite, nacrite, and dickite are secondary minerals produced by alteration of feldspar, nephelite, topaz, augite, etc. Kaolinite may be produced by weathering, dickite by hydrothermal alteration, and nacrite by pneumatolytic or hydrothermal change. Kaolinite is the chief component of ordinary clay and is therefore found very widely distributed especially in soils.

Kaolinite is used in large quantities in the manufacture of chinaware, porcelain, tile, brick, and refractory materials. China clay is mined especially in Georgia, South Carolina, Pennsylvania. Ball clay (for making pottery, and so on) is obtained largely from Kentucky and Tennessee. Fire clay (for use in refractories) is mined in Pennsylvania, Missouri, Ohio, Kentucky, Illinois, and elsewhere.

Pyrophyllite **Monoclinic** $\mathbf{Al_2Si_4O_{10}(OH)_2}$

$a:b:c = 0.577:1:2.085, \beta = 80°5'$

Usually in foliated masses or somewhat fibrous; plates are flexible.

Perfect basal cleavage. H. = 1–2. G. = 2.8–2.9. Luster pearly to dull. Color white, light green, gray, yellow. $(-)2V = 53\text{–}60°$, $N_g = 1.585\text{–}1.600$, $N_m = 1.58\text{–}1.59$, $N_p = 1.533\text{–}1.552$.

Pyrophyllite is near $Al_2Si_4O_{10}(OH)_2$ in composition, but commonly contains a little iron and is somewhat variable in tenor of water.

Pyrophyllite resembles talc in appearance, properties, and uses. It is used as a talc substitute in some cases; also used for slate pencils. It is mined in North Carolina.

Mica Group

The minerals of the mica group are characterized by an excellent basal cleavage yielding very thin laminæ which are elastic through a very wide angle. This cleavage is a result of a structure based on sheets of $(Si,Al)O_4$ tetrahedrons. Crystals are pseudohexagonal and apparently orthorhombic, but actually monoclinic. Twins are not uncommon. The micas are all basic aluminum silicates of potassium with more or less magnesium, iron, lithium. Sodium may proxy for part of the potassium and fluorine for hydroxyl. The micas to be described are: muscovite $\{K(Al,Fe)_2(Si_3Al)O_{10}(OH)_2\}$, biotite $\{K(Mg,Fe)_3(Si_3Al)O_{10}(OH)_2\}$ and lepidolite $\{K_2Li_3Al_3(Si_6Al_2)O_{20}(OH,F)_4\}$.

Muscovite **Monoclinic** $\mathbf{KAl_2(Si_3Al)O_{10}(OH)_2}$

$a:b:c = 0.577:1:3.313, \beta = 89°54'$

Crystals are usually tabular with hexagonal or rhombic outline. They may be large and rough attaining several feet across; such large crystals may show distinct partings normal to the cleavage similar to the lines which can be produced artificially by a blow (called percussion figure) or by pressure (called pressure figure). The relation of these figures to the crystal outline is shown in Fig. 432.

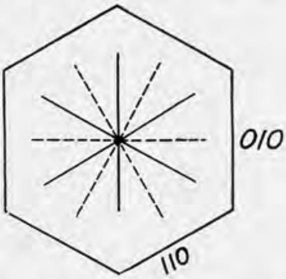

FIG. 432. Percussion (full lines) and pressure figures (dotted lines) in mica.

Very perfect basal cleavage yielding thin elastic laminæ. H. = 2.5–3. G. = 2.76–3. F. = 5.7. Insoluble in acids. Pearly to vitreous luster. Colorless, yellowish, brownish, or reddish. $(-)2V = 47°$, $N_g = 1.588$, $N_m = 1.582$, $N_p = 1.552$, varying with the composition as shown in Fig. 433.

Muscovite is usually near $KAl_2(Si_3Al)O_{10}(OH)_2$, but it may vary toward *ferrimuscovite* $\{KAlFe(Si_3Al)O_{10}(OH)_2\}$ or toward *phengite* $\{K_2(Mg,Fe)Al_2(Si_7Al)O_{20}(OH)_4\}$, or both. Moreover it may contain fluorine proxying for hydroxyl and sodium for potassium, as well as minor amounts of titanium, manganese, etc. A variety with vanadium replacing some aluminum is called *roscoelite.* Fine scaly masses produced by alteration are called *sericite,* and tend to be rich in water.

Muscovite and biotite are the common micas. Muscovite occurs in granite, syenite, and pegmatite, as well as abundantly in some mica schists and gneisses. It is commonly associated with quartz, feldspar, garnet, tourmaline, fluorite, etc. Muscovite is obtained especially from India and Madagascar; in this country it is mined mainly in North Carolina and New Hampshire; South Dakota production has been important at times.

Muscovite is used as "sheet mica" in electrical apparatus and machinery such as dynamos, motors, switchboards, lamp sockets, radio tubes, etc. Clear sheet mica (isinglass) is also used as windows in coal-oil and gas stoves, and as lamp shades and chimneys. "Scrap mica" (too small for sheets, but pure) is ground in large quantities for use in wall paper, electrical insulators, lubricants, roofing papers, coverings for steam pipes, fancy paints, rubber goods, etc. "Mica splittings" are used to produce "built-up mica" with a suitable binder such as shellac; in this way plates are produced usually up to half an inch thick and three feet square, which are used in motors and generators; the built-up mica can be shaped into tubes, tape strips, V-rings, and so on.

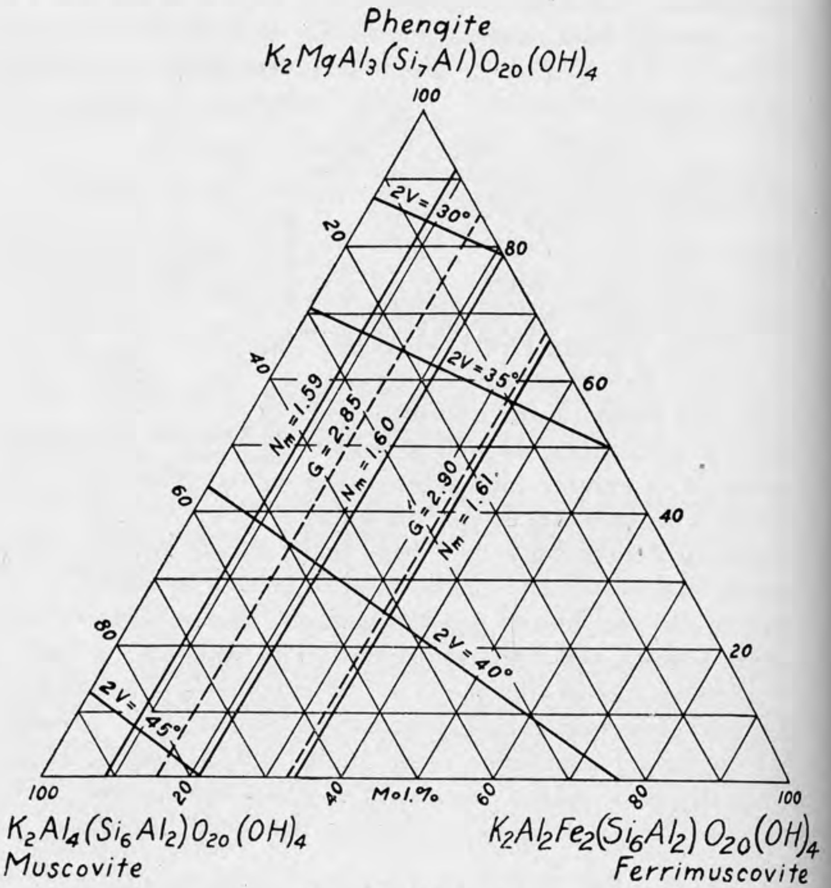

FIG. 433. Muscovite.

Biotite Monoclinic $\mathbf{K_2(Mg,Fe)_6(Si,Al)_8O_{20}(OH)_4}$

$a:b:c = \mathbf{0.577:1:3.274},\ \beta = \mathbf{90° \pm}$

Crystals are commonly tabular with six or four sides, sometimes horizontally striated. Very nearly hexagonal in angles. Generally found in platy or lamellar masses or disseminated scales.

Very perfect basal cleavage. H. = 2.5–3. G. = 2.7–3.4. F. = 5. Decomposed by H_2SO_4 leaving silica in scales. Color usually dark brown to black; also green or light brown or yellow. $(-)2V = 0°$, rarely more. $N_g = 1.57–1.69$, N_m nearly $= N_g$, $N_p = 1.54–1.63$, $N_g - N_p = 0.03–0.06+$ (see Fig. 434).

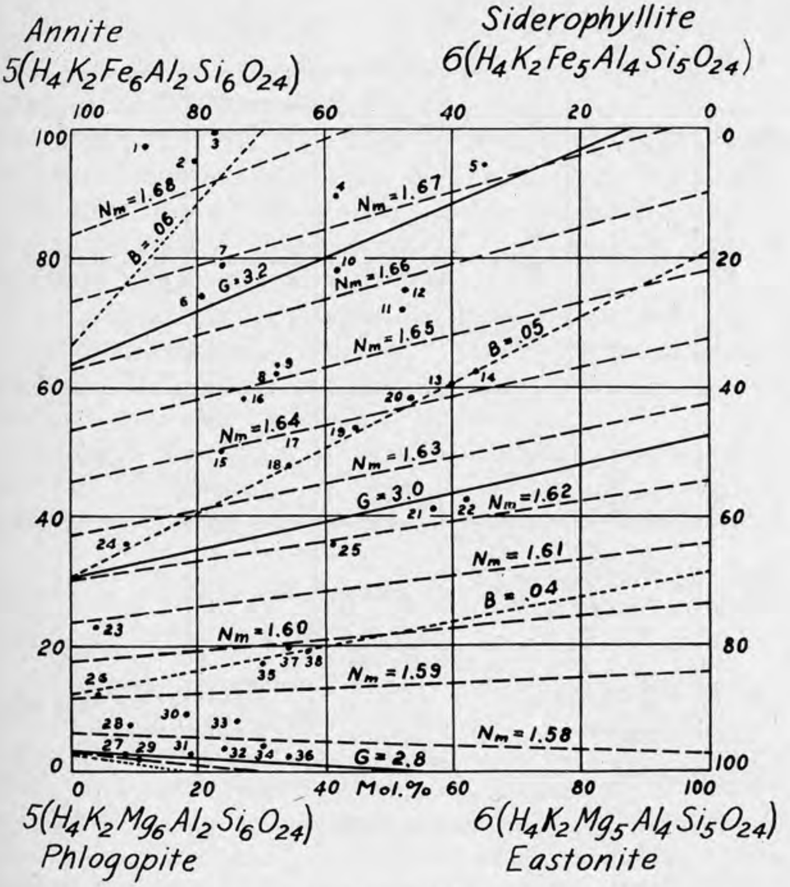

FIG. 434. Biotite.

Biotite varies much in composition; four end-members are *phlogopite* $\{K_2Mg_6(Si_6Al_2)O_{20}(OH)_4\}$, *eastonite* $\{K_2Mg_5Al(Si_5Al_3)O_{20}(OH)_4\}$, *annite* $\{K_2Fe_6(Si_6Al_2)O_{20}(OH)_4\}$, and *siderophyllite* $\{K_2Fe_5Al(Si_5Al_3)O_{20}(OH)_4\}$. *Lepidomelane* is a variety rich in iron oxide. Like muscovite, biotite may contain titanium, sodium, and fluorine; also manganese. The relations between physical properties and variations in composition are shown in Fig. 434.

Biotite alters to chlorite, often with rutile; or to epidote, quartz, and iron oxide. It is very common, being an important constituent of various igneous rocks such as granite, syenite, diorite, and tonalite, as well as of metamorphic rocks such as

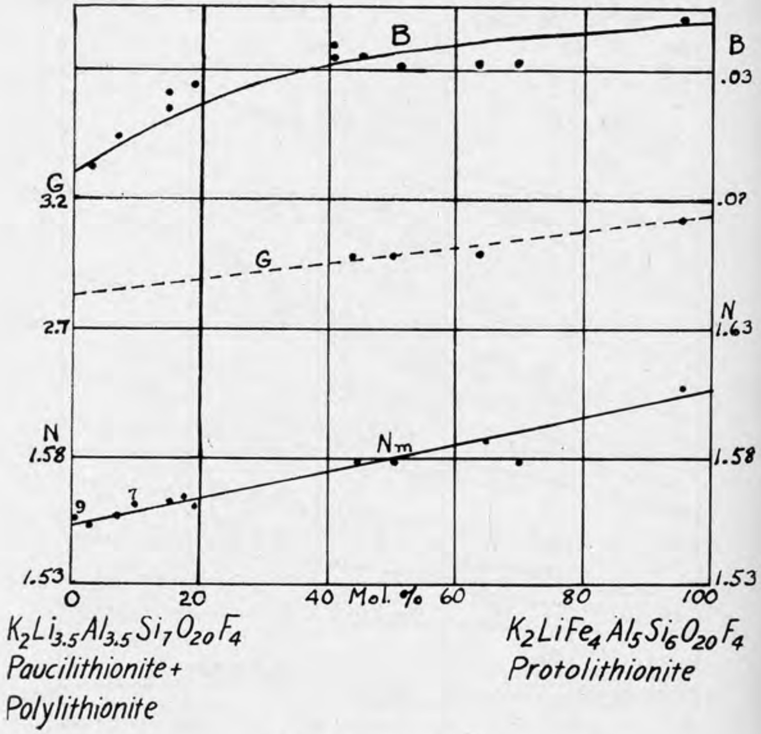

Fig. 435. Lepidolite.

gneiss and mica schist. Phlogopite is found especially in metamorphosed dolomites, and limestones, and also in serpentinites and schists. Phlogopite is used as an insulator in electrical apparatus, being preferred to muscovite for use on commutators because it is nearly as hard as the copper of the commutator segments. It is also used in heater plates, tape, etc. Phlogopite is obtained especially from Madagascar and from Ontario and Quebec.

Lepidolite

Monoclinic $K_2Li_3Al_3(Si_6Al_2)O_{20}(F,OH)_4$

$a:b:c = 0.574:1:2.214,\ \beta = 90° \pm$

Crystals are short prisms, often in aggregates; usually in scaly masses or tabular plates. Often twinned.

Perfect basal cleavage. H. = 2–4. G. = 2.8–3.2. Fuses at about 2. Luster pearly. Color rose red or lilac; also white, gray, greenish or brownish. $(-)2V = 0°–45°$, $N_g = 1.56–1.61$, $N_m = 1.55–1.61$, $N_p = 1.54–1.57$, $N_g - N_p = 0.02–0.04$.

Lepidolite is often near $K_2Li_3Al_3(Si_3Al)_2O_{20}(F,OH)_4$, but varies much. One variety containing considerable iron is called *zinnwaldite*, but *protolithionite* $\{K_4LiFe_4Al(Si_6Al_2)O_{20}(F,OH)_4\}$ contains still more. Another type with maximum lithium is called *polylithionite* ($K_2Li_4Al_2Si_8O_{20}F_4$). Variations in properties in one series are shown in Fig. 435.

Lepidolite is found especially in pegmatites, and also in some granites and gneisses, usually as a product of pneumatolytic processes. It is often associated with tourmaline, spodumene, cassiterite, muscovite, albite, and topaz.

Lepidolite is an important source of lithium compounds. It is used in glass making. Compounds are used in photography and in fireworks. It is mined in California and South Dakota.

Chlorite

Monoclinic $\left\{\begin{array}{l}(\mathbf{Mg,Fe})_4\mathbf{Al}_2(\mathbf{Si}_2\mathbf{Al}_2)\mathbf{O}_{10}(\mathbf{OH})_8\\ +n(\mathbf{Mg,Fe})_6\mathbf{Si}_4\mathbf{O}_{10}(\mathbf{OH})_8\end{array}\right.$

$a:b:c = 0.577:1:2.277,\ \beta = 89°40'$

Crystals are tabular and usually six-sided, resembling mica in habit. Commonly foliated or thin scaly in aggregates.

Perfect basal cleavage yielding thin laminæ, which are flexible but not elastic. Twinning common. H. = 1–2.5. G. = 2.6–3.0. Luster pearly to dull. Color nearly always green (whence the name), but may be white, pink, blue, brown, or black. $(\pm)2V = 0°–90°$, but usually $0° \pm$ (except in antigorite), $N_m = 1.55–1.68$, $N_g - N_p = 0.000–0.015$. See Fig. 436.

Chlorite varies widely in composition, but the chief types seem to be *antigorite* $\{Mg_3Si_2O_5)OH_4\}$, *amesite* $\{Mg_2Al(SiAl)O_5(OH)_4\}$, and the types intermediate between these, *penninite* and *clinochlore*. Such varieties containing little or no iron are sometimes called *orthochlorites*, while those containing more iron $\{$to *daphnite*—$Fe_2Al_2SiO_5(OH)_4\}$ are known as *leptochlorites*, and seem to crystallize less easily. Unusual chlorites contain manganese, nickel, or ferric iron. Relations between composition and properties are shown in Fig. 436.

Chlorite is a secondary mineral due to alteration of biotite, amphibole, pyroxene, garnet, or other ferromagnesian silicate.

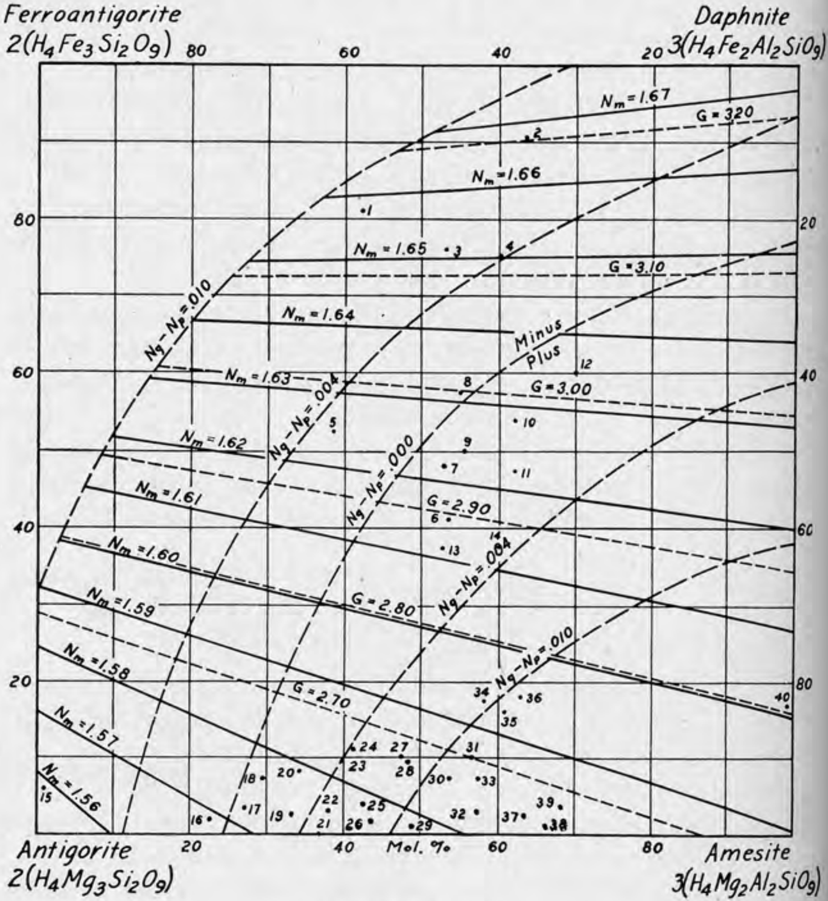

Fig. 436. Chlorite.

It is common especially in serpentinite, and in altered basic igneous rocks and schists. Some important localities for chlorite are: many places in the Alps, Traversella (Italy), Thuringia (Germany), Chester (Massachusetts), Brewster (New York), Lake Superior district. Varieties rich in iron (*chamosite* and *thuringite*) are used as iron ores in Bohemia, Switzerland, Thuringia, and Lorraine.

Vermiculite (*Jefferisite*) *Monoclinic* *Hydrated micas and chlorites*

Lameller; rarely in flaky crystals; flakes are flexible, not elastic.

Perfect basal cleavage. H. = 1–1.5. G. = 2.3–2.8. Luster pearly to dull. Color golden yellow, yellowish brown, brownish red, light to dark green. Streak white.

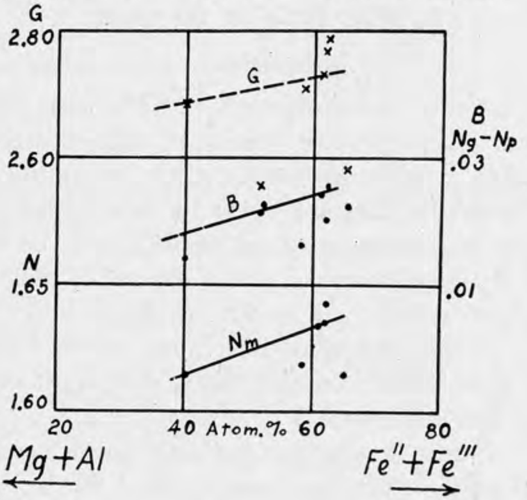

FIG. 437. Glauconite.

Vermiculite is variable in composition; it seems to have layers of mica and chlorite separated by H_2O. When heated, the layers separate, increasing the volume enormously. It is found associated with peridotite, serpentine, talc, chlorite, and micas.

Vermiculite is used as a thermal insulator.

Glauconite *Monoclinic* $H_4K(Mg,Fe)(Fe,Al)_3Si_6O_{20}\cdot 2H_2O$?
$a:b:c = 0.577:1:2.208$, $\beta = 95°$

Crystals only of microscopic size; often colloidal amorphous, resembling earthy chlorite.

Perfect basal cleavage in the microscopic crystals; no cleavage in the colloidal masses. Luster usually dull. Color yellowish, grayish, or blackish green; streak light green to greenish white.

Glauconite varies in composition; the corresponding variation in properties are only crudely known, about as shown in Fig. 437.

It is the main constituent of some greensand beds and occurs also in some marls, sands, clays, and the like.

It has been used as a fertilizer.

V. Dioxide type (frameworks): SiO_4 tetrahedrons united at four solid angles

A. With little or no water

Leucite **Isometric** **$KAlSi_2O_6$**

Crystals usually trapezohedral, often with the cube or dodecahedron. Crystals are stable at high temperature and only metastable at ordinary temperature, retaining their external form (if large) by complex twinning of a tetragonal (?) unit. The twinning disappears at about 625°C. and the crystals fuse at 1686°C. Usually in crystals; also granular.

Conchoidal fracture. H. = 5.5–6. G. = 2.5. Vitreous to greasy luster. Color white or nearly so. $N = 1.508–1.509$.

Leucite varies little from $KAlSi_2O_6$, but sodium may proxy for a little of the potassium.

Leucite is found in alkaline volcanic rocks associated with orthoclase, augite, nepheline, and so on. Material for study has been obtained at Vesuvius, near Rome, in Saxony, Baden, Brazil, and from the Leucite Hills of Wyoming and Magnet Cove, Arkansas.

Leucite is not used commercially.

Sodalite **Isometric** **$3NaAlSiO_4 \cdot Na(Cl,SO_4,S_2)$**

Crystals dodecahedral; generally in compact masses.

Indistinct dodecahedral cleavage. H. = 5–6. G. = 2.2–2.5. Fuses with intumescence to colorless glass. Gelatinizes with HCl. Vitreous to greasy luster. Color usually blue: also white, green, reddish, gray. $N = 1.48–1.51$.

Sodalite varies much in composition, but the variation is chiefly in the second part of the formula (though potassium may proxy for a minor part of the sodium). Sodalite proper is $6NaAlSiO_4 \cdot 2NaCl$; the NaCl is replaced by $CaSO_4$ in *hauynite,* by Na_2SO_4 in *noselite,* and by Na_2S in *lazurite;* and these replacements may be partial. The effects on the physical properties in the sodalite-hauynite series are shown in Fig. 438.

Sodalite is often associated with nephelite, cancrinite, leucite, and feldspar, but not with primary quartz. It is found in alkaline igneous rocks and in contact rocks. It is also an alteration product of nephelite in some cases. Found at, among other places, Miask (Russia), Niedermendig (Germany), on Vesuvius (Italy), at Dungannon (Ontario), and Salem (Massachusetts). Lazurite, chiefly from Persia, Bokhara, and Turkestan, is used as an ornamental stone for costly vases, and so on. It is also ground into *ultramarine* pigment for paints, but this is now produced artificially.

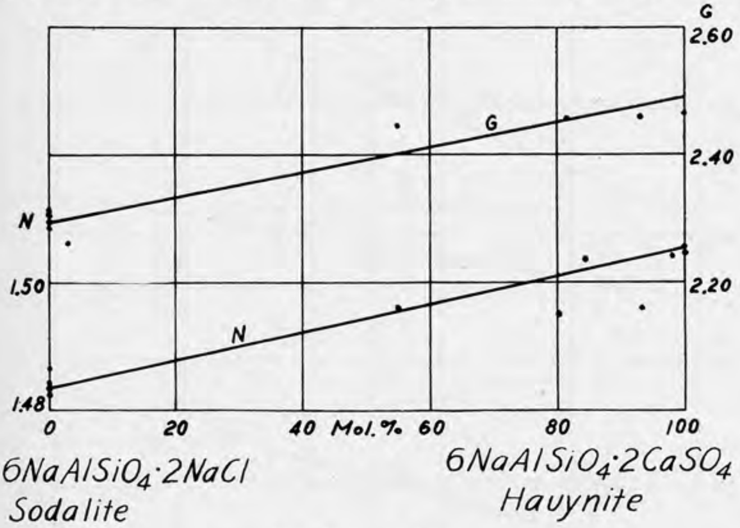

FIG. 438. Sodalite.

Scapolite (Wernerite)	**Tetragonal**	
Marialite	$c = \mathbf{0.44} \pm$	**$3NaAlSi_3O_8 \cdot NaCl$**
Meionite		**$3CaAl_2Si_2O_8 \cdot CaCO_3$**

Crystals short to long prismatic often vertically striated or rough; also fibrous, columnar or granular masses.

Prismatic cleavage. H. = 5–6. G. = 2.6–2.8. Easily fusible with intumescence. Vitreous to greasy luster. Colorless, gray or tinted. $N = 1.55$–1.61. See Fig. 439.

Scapolite varies much in composition; the chief series is from $3NaAlSi_3O_8 \cdot NaCl$ (*marialite*) to $3CaAl_2Si_2O_8 \cdot CaCO_3$

(*meionite*), but K may proxy for Na and SO_4 or F for Cl. The properties of the chief series are shown in Fig. 439.

Scapolite alters rather easily to kaolin, mica, albite, zeolites, etc. It is commonly the result of contact metamorphism, being found especially in metamorphosed limestones near igneous intrusions. It is often associated with pyroxenes, amphiboles, garnet, titanite, etc. It is found at Arendal (Norway), Pargas (Finland), Mount Vesuvius, and in Ontario, Quebec, New York, New Jersey, and elsewhere.

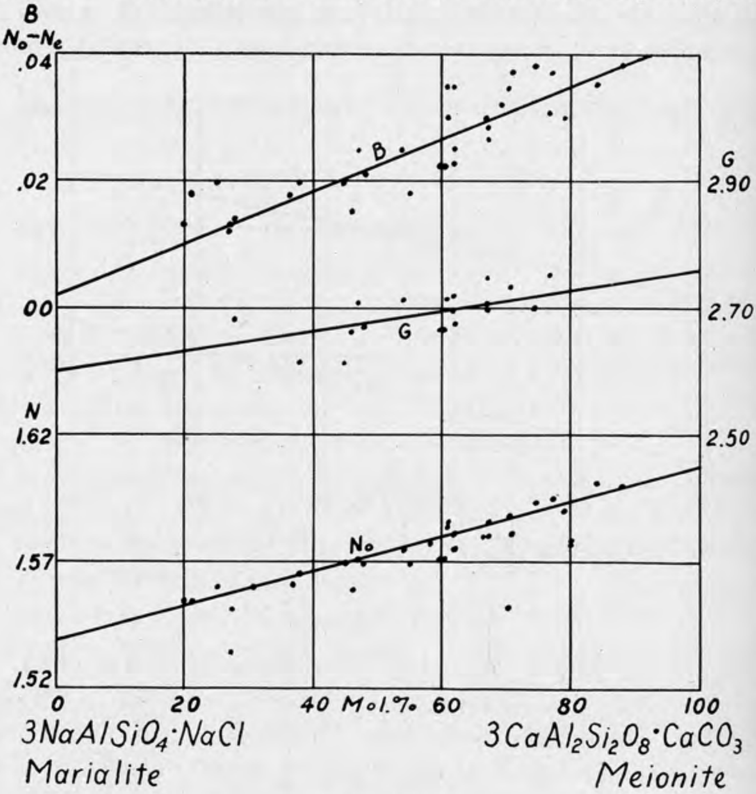

FIG. 439. Scapolite.

It is not important economically, but suitable material is sometimes used for a gem stone.

Nephelite **Hexagonal** **$NaAlSiO_4$**

$c = 0.39$

Crystals often tabular in igneous rocks and prismatic in geodes. Often in compact masses or granular.

Indistinct prismatic and basal cleavages. H. = 5.5–6. G. = 2.55–2.65. F. = 4, but pure $NaAlSiO_4$ fuses at 1526° C., after inversion at 1248°. Gelatinizes with acids. $N_o = 1.536$–1.549, $N_e = 1.532$–1.544.

Light colored glassy nephelite, often showing crystal form, is the type found in alkaline volcanic rocks. *Eleolite* is a massive or coarsely crystalline variety found especially in plutonic rocks, notably syenites; it is often gray to brown, red, green or even blue in color.

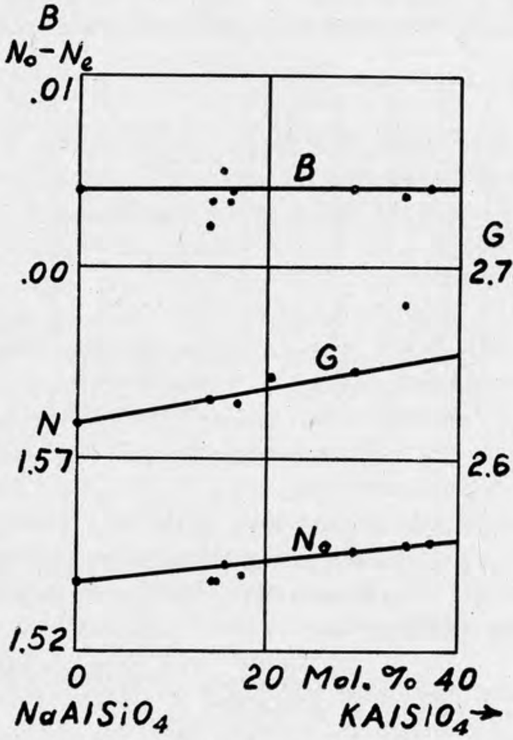

FIG. 440. Nephelite.

Nephelite is variable and complex in composition. Artificially it can be made of $NaAlSiO_4$, but natural crystals contain also more or less $KAlSiO_4$, and also CaO, excess Al_2O_3, SiO_2, etc. (probably as $CaAlAlO_4$, $SiSiO_4$, etc.). The relations between composition and physical characters (as effected by $KAlSiO_4$) are shown in Fig. 440.

Nephelite alters easily to analcite, sodalite, sericite, kaolinite, etc. It is an essential constituent of certain soda-rich igneous rocks, such as nephelite syenite, and phonolite. It is often associated with feldspar, cancrinite, soda pyroxenes and amphiboles, biotite and sodalite, but not with primary quartz. It is obtained at Vesuvius, Larvig (Norway), Honolulu (Hawaii), French River (Ontario), and at Litchfield (Maine), Cripple Creek (Colorado), Magnet Cove (Arkansas), and elsewhere.

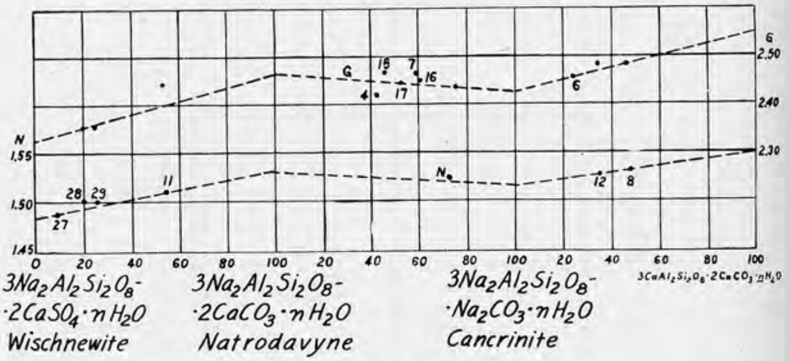

FIG. 441. Cancrinite.

Nephelite as such is used very little, but nephelite syenite from Ontario is used in increasing amounts in making glass and ceramic materials. In Russia nephelite is now concentrated for use as a source of aluminum.

Cancrinite *Hexagonal* $3Na_2Al_2Si_2O_8 \cdot Na_2CO_3 \cdot nH_2O$
$c = 0.422$

Crystals columnar or prismatic, rare. Usually in columnar or disseminated masses.

Perfect prismatic cleavage. H. ≐ 5–6. G. = 2.4–2.5. Fuses at 2. Effervesces with HCl. Luster pearly on cleavages; elsewhere greasy or vitreous. Color yellow, reddish, green, gray or even colorless. Streak uncolored. $N_o = 1.51$–1.53, $N_e = 1.49$–1.535.

Cancrinite varies considerably in composition, but is closely related to both nephelite and sodalite. One suggested formula is $3Na_2Al_2Si_2O_8 \cdot 2CaCO_3 \cdot nH_2O$, but K may proxy for part of the Na and CO_3 may be replaced by SO_4 or Cl_2. Fig. 441 is a first attempt to show relations between composition and properties based on very scanty data.

Commonly associated with nephelite, sodalite, feldspar, biotite, etc. It is in part primary and in part secondary (alteration product of nephelite). Localities include Miask (Russia), Brevig (Norway), Dungannon (Ontario), Litchfield (Connecticut).

Cancrinite is of no importance commercially.

Quartz[16] **Hexagonal** **$SiSiO_4$**

$c = 1.100$

Crystals very common, usually prismatic and terminated by a positive and a negative rhombohedron about equally developed and therefore resembling a hexagonal bipyramid. Prism faces may be absent. If present, they are usually horizontally striated. Twins are common; (1) the twinning axis is c in Dauphiné twins; (2) the twinning plane is $(11\bar{2}0)$ in Brazil twins, which have no twinning axis; other twins are known. Massive quartz may be fine to coarse granular or even fibrous. Ordinary sand is mostly quartz.

No cleavage (except in β-quartz). Fracture conchoidal. Brittle. H. = 7. G. = 2.65. Infusible before the blowpipe. Vitreous luster. Exhibits pyroelectric and piezoelectric properties. Commonly colorless or white, but may be yellow, pink, red, amethystine, green, blue, brown, or black. Color may disappear on heating. Streak white. Transparent to translucent. $N_o = 1.544$, $N_e = 1.553$.

Quartz is very pure SiO_2, but often contains inclusions of rutile, hematite, chlorite, mica, and liquid and gaseous CO_2, etc. Insoluble in common acids, but soluble in hydrofluoric acid.

SiO_2 exists in several crystal phases; the most important are: (1) α-Quartz, stable to 573°C. (2) β-Quartz, stable between 573° and 870°, but does not exist below 573°. (3) *Tridymite,* stable between 870° and 1470° and metastable below 870°; below 117° to 163° another metastable phase appears. (4) *Cristobalite,* stable from 1470° to fusion at 1713° and metastable below 1470°, inverting to another metastable phase between

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[16] Because of its close relation to silicates crystallographically it may be permissible to consider quartz a silicate of silicon.

198° and 275°C. These phases may give important information regarding the temperature of formation of some rocks and ores. α-Quartz is trigonal trapezohedral in symmetry. β-Quartz is hexagonal trapezohedral in symmetry and has distinct $(10\bar{1}1)$ and $(10\bar{1}0)$ cleavages. Tridymite is hexagonal above 163° and orthorhombic below that temperature. Cristobalite is isometric above 200° to 275° and pseudoisometric (tetragonal?) below that temperature.

Many varieties of quartz are recognized; aside from quartz aggregates they are either phenocrystalline or cryptocrystalline.

A. Phenocrystalline or vitreous varieties.

1. *Rock crystal*—colorless quartz, including "Lake George diamonds," "Montana diamonds," drusy quartz, and so on.
2. *Asteriated* or *star quartz* showing asterism, due to regularly arranged inclusions.
3. *Amethyst,* which has a clear purple or bluish violet color, probably due to manganese.
4. *Rose quartz,* which has a pink to rose red color, becoming paler on exposure to light (due to titanium?).
5. *Yellow quartz,* false topaz, or citrine, which has a light yellow color.
6. *Smoky quartz,* which is smoky yellow to dark brown; often called cairngorm stone.
7. *Milky quartz,* which is milky white and nearly opaque, often with a greasy luster.
8. *Aventurine,* containing glistening scales of mica or hematite.
9. *Sagenitic* or *rutilated quartz,* containing fine needles of rutile.
10. *Ferruginous quartz,* colored brown to red by enclosed limonite or hematite.
11. *Cat's-eye,* which exhibits opalescent gray to brown colors due to fibers, which may be of asbestus.
12. *Tiger-eye,* which exhibits chatoyant luster and yellow-brown color, pseudomorphous after crocidolite.

B. Cryptocrystalline varieties.

Cryptocrystalline varieties are compact and may show a crystalline (usually fibrous) texture under the microscope.

More easily attacked by hydrofluoric acid or potassium hydroxide than the phenocrystalline varieties.

1. *Chalcedony,* which is a transparent to translucent variety with a waxy luster. It often contains some opal. G. = 2.6–2.64. Often fibrous microscopically. Varieties are included which seem to be optically distinct from quartz, and chalcedony may be still another phase of silica. White, gray, brown, black in color. *Tripoli* is a (decomposed) fine grained mass of chalcedony (not the same as tripolite).

2. *Carnelian* or *sard* is reddish chalcedony.

3. *Chrysoprase* is apple green chalcedony.

4. *Heliotrope* or *blood stone* is green chalcedony with small spots of red jasper (see below).

5. *Agate* is banded or clouded chalcedony. Moss agate contains visible moss-like inclusions which may be of manganese oxide. The bands are straight or wavy or irregular and vary in color, being often white, brown, or red. The bands are due to successive deposition. They vary in porosity and are easily colored artificially.

6. *Onyx* is an agate with parallel straight bands of white, red, or black colors; it may be used for cameos.

7. *Jasper* is impure opaque colored quartz commonly red, yellow or gray in color.

8. *Flint* is impure fibrous and granular quartz with a gray, smoky brown or brownish black color. Commonly in nodules with a white coating and prominent conchoidal fracture.

9. *Chert* includes impure varieties with a horn-like appearance which are usually impure flints and jaspers.

C. Quartz aggregates.

1. *Sand,* which is (usually) composed of unconsolidated grains of quartz.

2. *Sandstone,* which consists of consolidated sand grains, usually cemented by silica, iron oxide, calcium carbonate, or clay. *Itacolumite* is a flexible sandstone containing some mica.

3. *Quartzite,* which is a recrystallized sandstone in which the cement was silica.

Quartz is one of the most common of all minerals. It is an essential constituent of the acid igneous rocks and of sandstone and quartzite. It is important in many veins and in sand, gravel, conglomerate, many kinds of gneiss, and schist. It is estimated to form more than 10 per cent of the earth's crustal rocks.

Many varieties of quartz are used in jewelry and for ornamental purposes. Agate and chalcedony are used in mortars and pestles; rock crystal is used for optical instruments, vases, chemical and radio apparatus; sand is used for mortar, plaster and glass; ground or crushed quartz and flint are used in wood fillers, pottery, scouring and polishing soaps, and as an abrasive; much crushed quartz is used as a flux in metallurgical work and in making refractory brick, etc. Sandstone and quartzite are used for building material, paving, curbing, and flagging.

Epidote Group[17]

The epidote group includes several basic silicates of aluminum and calcium with or without iron, cerium, and various rare earths. The important types are zoisite and pistacite (or epidote proper).

Zoisite *Orthorhombic* $Ca_2Al_3Si_3O_{12}(OH)$
$a:b:c = 0.620:1:0.343$

Crystals prismatic deeply striated vertically. Also common in masses.

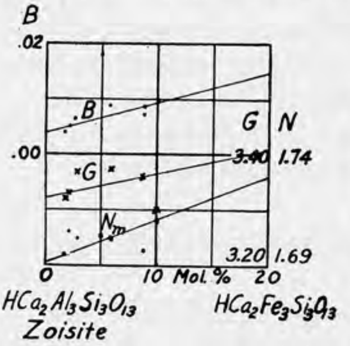

Fig. 442. Zoisite.

Perfect brachypinacoid cleavage. H. = 6. G. = 3.25–3.36. F. = 3 with swelling. Insoluble in acid. Color gray, greenish, brown. $(+)2V = 30\text{–}0\text{–}60°$, $N_g = 1.70\text{–}1.71$, N_m nearly $= N_p = 1.69\text{–}1.70$. See Fig. 442.

Zoisite is produced by alteration of calcic plagioclase under pressure. It is often associated with amphibole in schists. It is found at Gefrees (Bavaria), Loch Garve (Scotland), and at Goshen (Massachusetts), Ducktown (Tennessee), and elsewhere.

Zoisite is not important commercially.

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[17] The classification of the epidote group is doubtful; it may belong with the orthosilicates.

Epidote (Pistacite) **Monoclinic** $Ca_2(Al,Fe)_3Si_3O_{12}(OH)$

$a:b:c = 1.588:1:1.804,\ \beta = 64°37'$

Crystals usually elongated along the *b* axis—even acicular—with striations in the same direction. Also fibrous or granular in masses.

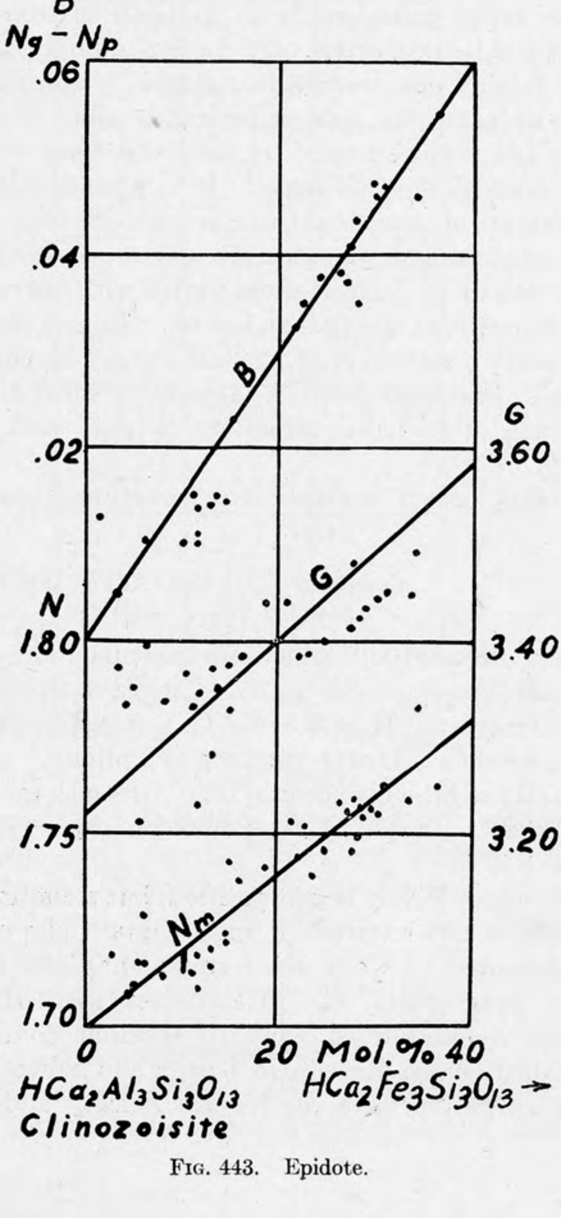

Fig. 443. Epidote.

Perfect basal cleavage. H. = 6–7. G. = 3.3–3.5. Fuses with intumescence at about 3.5. Partly decomposed by HCl. After ignition, gelatinizes with acid. Vitreous to resinous luster. Yellow to dark green in color; also red to gray. $(\pm)2V$ = large, $N_g = 1.71$–1.78, $N_m = 1.70$–1.77, $N_p = 1.70$–1.73. See Fig. 443.

Epidote varies considerably in its tenor of iron (replacing aluminum) and its properties vary correspondingly, as shown in Fig. 443. It may also contain manganese, magnesium, chromium, etc. Epidote with little or no iron is called *clinozoisite.*

Epidote is a typical product of metamorphism, but is locally present in altered igneous rocks. It is abundantly produced both at contacts of igneous intrusions with limestones and dolomites and also in regions of extensive metamorphism in gneisses, schists, and the like. It is often associated with quartz, feldspar, actinolite, chlorite, magnetite, and so on. In rare cases it seems to be a primary constituent of igneous rocks. Important localities include Piedmont (Italy), Arendal (Norway), Haddam (Connecticut), the Lake Superior district, and Riverside (California).

Clear dark green crystals are sometimes used for gem purposes.

Allanite *Monoclinic* $(Ca,Ce)_2(Al,Fe''',Fe'')_3Si_3O_{12}(OH)$
$a:b:c = 1.559:1:1.769,\ \beta = 64°59'$

Crystals often (100) tablets or acicular along *b*. Also granular massive.

Uneven fracture. H. = 5.5–6. G. = 3.2–4.2. Fuses easily with intumescence. Luster submetallic, pitchy. Color pitch black, sometimes brownish or grayish. Greenish gray to brown streak. $(-)2V$ = large, $N_g = 1.66$–1.80, $N_m = 1.65$–$1.78+$, $N_p = 1.64$–$1.77\pm$.

Allanite varies widely in composition, but a continuous series with epidote is not known. It may contain almost any rare earth (represented by Ce in the formula) and also ferrous and ferric iron, magnesium, etc. Gelatinizes with HCl. Many samples are much altered (due to thorium content?) with marked hydration and decrease in density and indices. Samples with little alteration have the highest density and index (see

Fig. 444); hydration reduces the density from 4 ± to 3 ± and the index from 1.75 to as low as 1.64.

Allanite is an accessory constituent in some igneous rocks such as syenite, diorite, granite, and pegmatite. It is also a contact mineral in some limestones and is also found in some schists and gneisses. It is often associated with epidote, magnetite, feldspar, and quartz. Important localities are Miask (Russia), Arendal (Norway), Ytterby (Sweden), Sama (Madagascar) and Monroe (New York), Franklin (New Jersey), Madison (North Carolina).

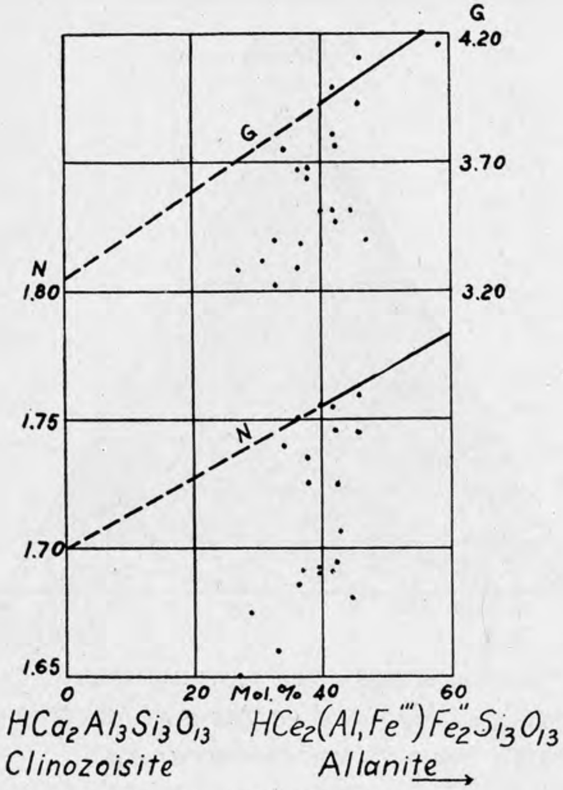

FIG. 444. Allanite.

Allanite is used as a source of cerium.

Feldspar Group

The feldspars are far the most abundant minerals in the earth's crust; they make up about 60 per cent of igneous rocks.

They are silicates of aluminum with potassium, sodium, or calcium (rarely, barium). They crystallize with monoclinic or triclinic symmetry and are very similar in crystal angles and properties. For example, the prism angle varies only from 59° to 61°, the cleavage angle (from the base to the side pinacoid) from 90° to 94°, the angle β (between the crystal axes a and c) from $63\frac{1}{2}$° to 64°, etc. They all have perfect basal and good side pinacoidal cleavage. They have a hardness of 6 to 6.5 and a specific gravity varying between 2.55 and 2.75. Intrinsically they are colorless, but they are often white to gray, and in some cases they are stained red, yellow, or greenish.

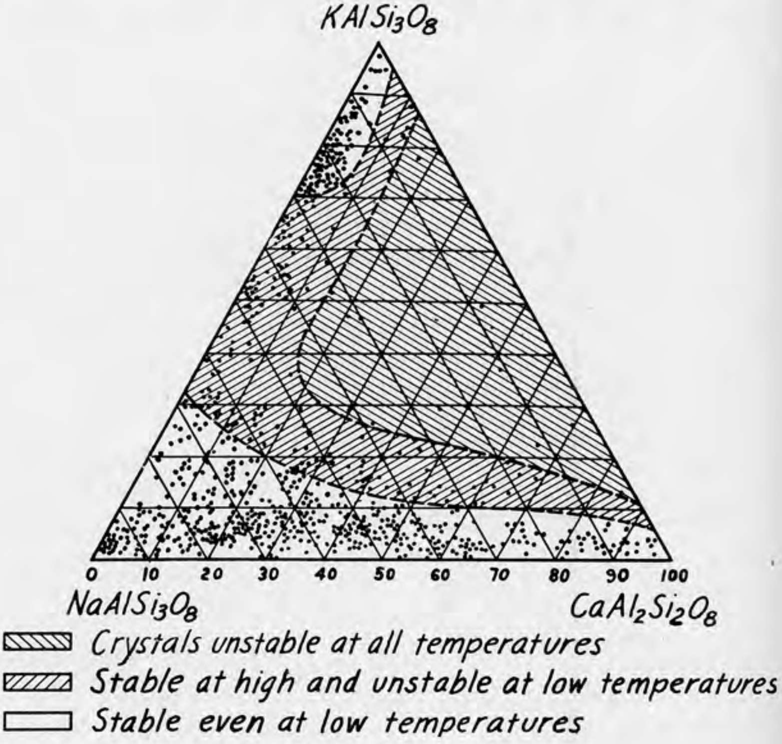

FIG. 445. Stability of feldspars.

Chemically there are three chief types of feldspar, namely $KAlSi_3O_8$, $NaAlSi_3O_8$, and $CaAl_2Si_2O_8$. These intercrystallize more or less freely as shown in Fig. 445.

Orthoclase **Monoclinic** **$KAlSi_3O_8$**

$\mathbf{a:b:c = 0.659:1:0.556,\ \beta = 63°57'}$

Crystals may be short prismatic with the base, orthopinacoid, and orthodome (see Figs. 446 and 447) or tabular parallel to 010 (Fig. 448), or elongated along *a* with the base and side pinacoid well developed (Figs. 449 and 450). Crystals may be large; some are complex. Twinning is common; it is usually one of three types:

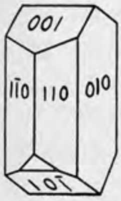

FIG. 446. Crystal of orthoclase.

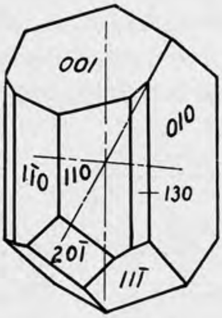

FIG. 447. Crystal of orthoclase.

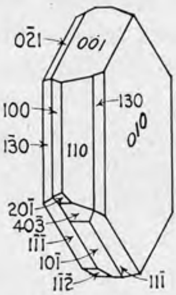

FIG. 448. Crystal of orthoclase.

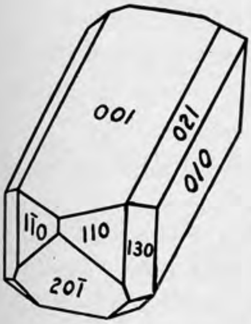

FIG. 449. Crystal of orthoclase.

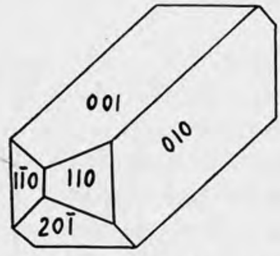

FIG. 450. Crystal of orthoclase.

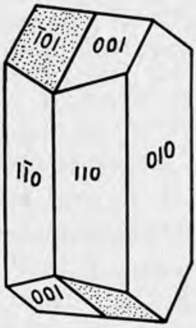

FIG. 451. Carlsbad twin of orthoclase.

1. *Carlsbad* twins have the orthopinacoid as the twinning plane, but the twins interpenetrate more or less or have the clinopinacoid as the contact (or "composition") plane. See Figs. 451 and 452.

2. *Manebach* twins have the basal plane as both the twinning plane and the composition face. See Fig. 453.

3. *Baveno* twins have the clinodome 021 as both twinning plane and composition face. See Fig. 454.

Orthoclase is often found in large cleavable masses as well as in granular aggregates; rarely lamellar or finely granular like flint.

Perfect basal and good clinopinacoid cleavages making an angle of 90°. Uneven fracture. H. = 6. G. = 2.5–2.6. Fuses with difficulty. Insoluble in acids. Vitreous to pearly luster. Usually colorless or white, but may be reddish, yellowish, or even greenish. $(-)2V = 0°\text{–}70°$, $N_g = 1.525$, $N_m = 1.523$, $N_p = 1.519$.

Fig. 452. Partial penetration twin of orthoclase.

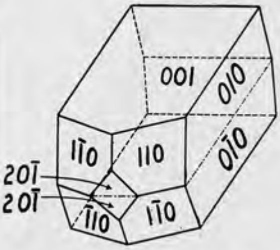

Fig. 453. Manebach twin of orthoclase.

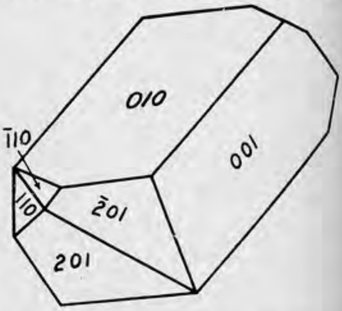

Fig. 454. Baveno twin of orthoclase.

Orthoclase is very rarely *pure* $KAlSi_3O_8$, since it usually contains 10 to 30 per cent of $NaAlSi_3O_8$; it may also contain a little Cs, Rb, Ca, etc. The relations between composition and properties are shown in Fig. 455. At low temperature the stable form is called *adularia;* at high temperature the stable form is *sanidine.* Adularia is often in crystals; it may be transparent, cloudy to opalescent—in the last case it is called *moonstone.* Sanidine is often in glassy, transparent crystals; square or tabular forms are common; it is found especially in volcanic rocks. Orthoclase alters rather easily to sericite and kaolinite.

Orthoclase is abundant in rocks like granite, syenite, rhyolite, trachyte, and pegmatite. It is also common in some schists and gneisses and even in certain sediments—for example, sandstone containing considerable feldspar (often orthoclase) is called *arkose.* Orthoclase is often associated with muscovite, biotite, quartz, other feldspars, hornblende, etc. Orthoclase is widely distributed and is perhaps the most abundant mineral in nature.

Many thousands of tons of "feldspar" are used each year in this country. Much of this is microcline and the rest is orthoclase, with some albite. Commercial "feldspar" is of several grades of purity; much of it contains 5 to 20 per cent of quartz, but it must be nearly free from iron. The purest feldspar commands the highest price; it is used in ceramics and in making artificial teeth; lower grades are used in making glass, enamels, abrasives (alone or in soaps), binders for abrasive wheels, etc.

Feldspar is quarried at Topsham (Maine), Glastonbury (Connecticut), London Grove (Pennsylvania), Mitchell and Yancey Counties (North Carolina), Black Hills (South Dakota), various points in Colorado, and elsewhere. Abroad it is obtained in notable amounts in Sweden, Italy, and Canada.

Microcline **Triclinic** **$KAlSi_3O_8$**

$a:b:c = 0.649:1:0.555$, $\alpha = 90°7'$, $\beta = 115°50'$, $\gamma = 89°55'$

Crystals of microcline are very similar to those of orthoclase, and they show the same types of twinning and also twinning on two other laws:

1. *Albite* twins, which have the brachypinacoid (010) as both twinning plane and composition face. Such twins are nearly always repeated as thin layers parallel with 010.
2. *Microcline* twins, which have the axis b as twinning axis and a plane nearly normal to 010 and to 001 as the composition face. These twins are also multiple in thin layers.

These two types of multiple twinning cross each other nearly at right angles, but they are usually too fine to be seen without a microscope. The resultant cross-hatching or grating as seen with a microscope in basal cleavage plates is a characteristic feature of microcline.

Basal and brachypinacoidal cleavages. Uneven fracture. H. = 6–6.5. G. = 2.55 ±. Vitreous to slightly pearly luster. Color white or tinted by impurities to yellowish, gray, red, or green. Green crystals are called *amazonstone*. $(-)2V$ = large, $N_g = 1.525$, $N_m = 1.522$, $N_p = 1.518$.

Microcline is very rarely *pure* $KAlSi_3O_8$, but usually contains up to about 20 per cent of $NaAlSi_3O_8$; it may also contain a little

Cs, Rb, Ca, etc. The relations between composition and properties are nearly the same as in orthoclase (see Fig. 455). The relations between microcline and orthoclase are still obscure; neither one inverts to the other; but orthoclase changes from adularia to sanidine at about 900°, while microcline shows no inversion at any temperature.

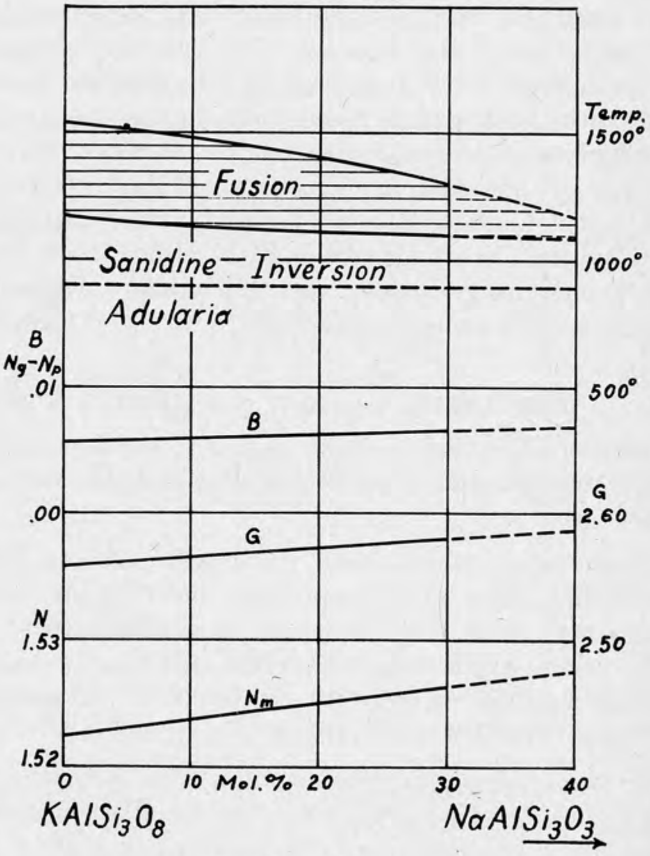

FIG. 455. Orthoclase.

Microcline is rare in volcanic rocks and most abundant in pegmatites. It is commonly closely associated with orthoclase in plutonic rocks; other associated minerals include plagioclase (especially albite), quartz, mica, hornblende, topaz, etc. It is obtained at Arendal (Norway), Baveno (Italy), on the island of

Madagascar, and at Amelia (Virginia), Baringer Hill (Texas), Pike's Peak (Colorado), and elsewhere.

Microcline is used probably even more than orthoclase. Amazonstone is used as a gem. For the uses of feldspar, see orthoclase.

Plagioclase **Triclinic** **$NaAlSi_3O_8$ to $CaAl_2Si_2O_8$**

$$a:b:c = 0.634\pm:1:0.558\text{–}0.550,\ \alpha = 93°13'\text{–}94°3',$$
$$\beta = 116°29'\text{–}115°56',\ \gamma = 88°9'\text{–}91°12'$$

Crystals are usually small and similar to those of orthoclase, but are quite varied in habit: they may be nearly equant, as in Figs. 456 and 457, prismatic as in Fig. 458, tabular along *b* as in Fig. 459, elongated along *a* as in Fig. 460, thin plates as in Fig. 461, lath-shaped as in Fig. 462, or variations from these types.

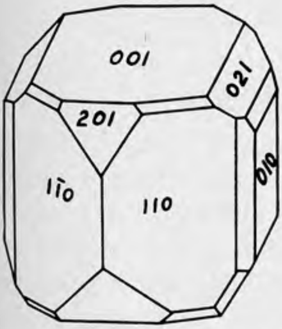

Fig. 456. Crystal of plagioclase.

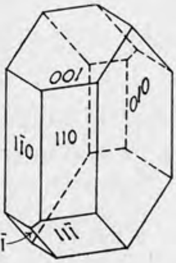

Fig. 457. Crystal of plagioclase.

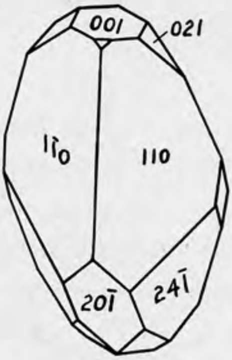

Fig. 458. Crystal of anorthite.

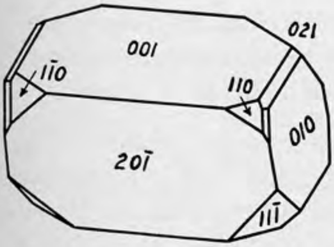

Fig. 459. Crystal of anorthite.

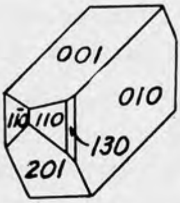

Fig. 460. Crystal of plagioclase.

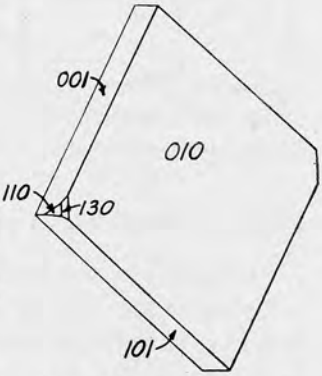

Fig. 461. Microlite of plagioclase.

Twins are so common that single crystals are rather rare. In addition to the twinning laws illustrated in orthoclase (one is shown in Fig. 463) there are two important types of multiple twinning in plagioclase:

FIG. 462. Lath-shaped crystal of feldspar.

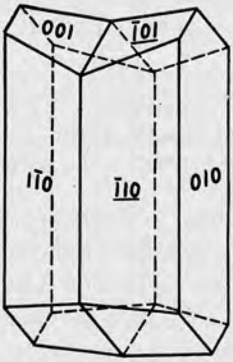

FIG. 463. Contact Carlsbad twin of albite.

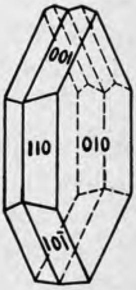

FIG. 464. Simple albite twinning in plagioclase.

1. *Albite* law, (also found in microcline) according to which the brachypinacoid is the twinning plane and also the composition face. Thin plates parallel to 010 result (Fig. 464) which produce striations (because they are nearly always repeated) on the base (001), which are parallel to 010.

2. *Pericline* law. The *b* axis is the twinning axis, but the composition face is parallel with *b* and roughly parallel with 001. A simple pericline twin is shown in Fig. 465; such twins are nearly always multiple, and may produce striations on the brachypinacoid (010).

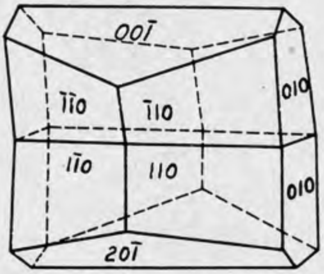

FIG. 465. Simple pericline twin of plagioclase.

Plagioclase also occurs in lamellar or granular masses.

Plagioclase has perfect basal and good brachypinacoidal cleavages, which intersect at an angle varying from 86°24′ in albite to 85°50′ in anorthite. Uneven fracture. H. = 6–6.5. G. = 2.60–2.75. Fusible at 4 to 5. Insoluble in acids, except those rich in lime (bytownite slowly soluble, anorthite more easily). $(\pm)2V$ = large, $N_g = 1.536$–1.588, $N_m = 1.529$–1.583, $N_p = 1.525$–1.576 (see Fig. 466).

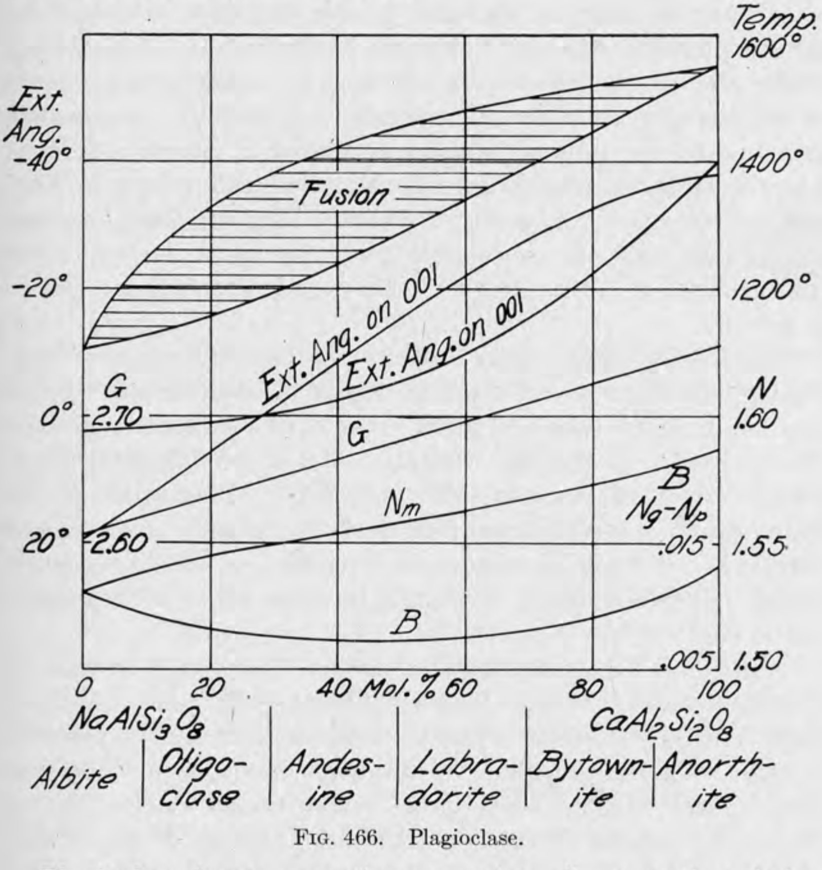

FIG. 466. Plagioclase.

Plagioclase forms a continuous series, all proportions being present in various crystals, from pure $NaAlSi_3O_8$ to pure $CaAl_2Si_2O_8$. This series is so important in igneous rocks that all the parts have been named, as follows:

Albite	contains	100–90%	$NaAlSi_3O_8$	and	0–10%	$CaAl_2Si_2O_8$
Oligoclase	"	90–70%	"	"	10–30%	"
Andesine	"	70–50%	"	"	30–50%	"
Labradorite	"	50–30%	"	"	50–70%	"
Bytownite	"	30–10%	"	"	70–90%	"
Anorthite	"	10–0%	"	"	90–100%	"

As shown in Fig. 445, plagioclase nearly always contains a small amount of $KAlSi_3O_8$; the effects of this on the properties are nearly the same as those of an equal amount of $NaAlSi_3O_8$. Plagioclase may contain very small amounts of still other elements, including iron and strontium.

Aventurine feldspar is a variety with reddish reflections from certain planes (supposed to be due to thin hematite lamellae). Albite also occurs in samples which show a pearly opalescence or delicate play of colors as a result of a perthitic intergrowth with orthoclase; it is then called *moonstone.* Some samples of labradorite show a beautiful play of vivid yellow, green, blue, and red colors on the brachypinacoid. They are used for ornamental purposes sometimes going under the name, *labrador spar.* Intergrowths of albite and orthoclase or microcline are known as *perthite.*

Plagioclase varies in its content of silica so that some kind of plagioclase has about the same tenor of silica as any kind of common magma—accordingly it is the chief component of many igneous rocks; plagioclase contains 43.2 to 68.7% SiO_2, while common magmas contain 45 to 70% SiO_2. Plagioclase is also abundant in some metamorphic rocks, especially gneisses and schists, and is found in some sediments such as arkose and graywacke. It is especially abundant in some kinds of pegmatite and in some veins.

Albite has been quarried (for use as "feldspar") in Chester County (Pennsylvania), Bedford County (Virginia), DeKalb (New York). Moonstone has been obtained in Amelia County, Virginia. Labrador spar is obtained in eastern Labrador. Fine crystals of plagioclase have been obtained at Roc Tourné (France), Arendal (Norway), Shinano, (Japan), Etna (Italy), and Franklin (New Jersey), Amelia (Virginia), Pike's Peak (Colorado), Llano County (Texas), and elsewhere.

B. Hydrous (Zeolites)

Analcite **Isometric** **$NaAlSi_2O_6 \cdot H_2O$**

Crystals are often trapezohedral; also modified cubes; also granular massive.

Conchoidal fracture. H. = 5–5.5. G. = 2.22–2.29. Colorless or slightly tinted. $N = 1.48–1.489$, often weakly anisotropic.

Analcite is near $NaAlSi_2O_6{\cdot}H_2O$, but seems to vary toward $NaAl_2SiO_5OH{\cdot}H_2O$ and may contain a little K and Ca, as well as excess silica.

Analcite occurs commonly with zeolites in cavities in basic igneous rocks; it sometimes replaces nephelite, leucite, sodalite, in the ground mass of such rocks. It is found near Aussig (Bohemia), on Mount Vesuvius, the Cyclopean Islands, at Arendal (Norway), Inverness (Scotland), and at Bergen Hill (New Jersey), Table Mountain (Colorado), in Keweenaw County (Michigan), and elsewhere.

Natrolite *Orthorhombic* $Na_2Al_2Si_3O_{10}{\cdot}2H_2O$
$a{:}b{:}c = 0.978{:}1{:}0.354$

Crystals nearly always prismatic, vertically striated; they are pseudotetragonal, acicular to fibrous. Sometimes arranged in radial or interlacing groups. Also massive.

Perfect prismatic cleavage. H. = 5–5.5. G. = 2.25. F. = 2. Gelatinizes with HCl. Vitreous to silky luster. Colorless or white; also reddish, or greenish. $(+)2V = 63°$, $N_g = 1.493$, $N_m = 1.482$, $N_p = 1.480$.

Natrolite varies only a little from $Na_2Al_2Si_3O_{10}{\cdot}2H_2O$, but may contain minor amounts of potassium and calcium.

Natrolite is found in cavities in basic igneous rocks, often associated with chabazite, analcite, apophyllite, stilbite, calcite, datolite, and so on. It may be an alteration product of nephelite, sodalite, or plagioclase. It is usually one of the latest minerals to form. It has been found at Salesl (Bohemia), Brevik (Norway), Renfrew (Scotland), Kinbane (Ireland), and in Nova Scotia, New Jersey, Arkansas, Michigan, British Columbia, and elsewhere.

Thomsonite **Orthorhombic** $\begin{cases} mNa_3Ca_9Al_{21}Si_{19}O_{80}{\cdot}24H_2O \\ +nNa_7Ca_5Al_{17}Si_{23}O_{80}{\cdot}24H_2O \end{cases}$
$a : b : c = 0.993 : 1 : 1.007$

Crystals rare, prismatic to fibrous and vertically striated. Often lamellar or radiated fibrous.

Perfect brachypinacoid cleavage. H. = 5–5.5. G. = 2.3–2.4. Luster vitreous to pearly. White, or stained green or brown. $(+)2V = 47°–75°$, $N_g = 1.518–1.545$, $N_m = 1.513–1.532$, $N_p = 1.511–1.530$. See Fig. 467.

Thomsonite is decidedly variable in composition, as indicated in the formulas, and also varies easily in its tenor of water. The approximate relations between the former variation in composition and the physical characters are shown in Fig. 467. Thomsonite, like other zeolites, is approximately a hydrated feldspar.

Thomsonite is closely associated with other zeolites and prehnite in its occurrence in cavities in basic igneous rocks.

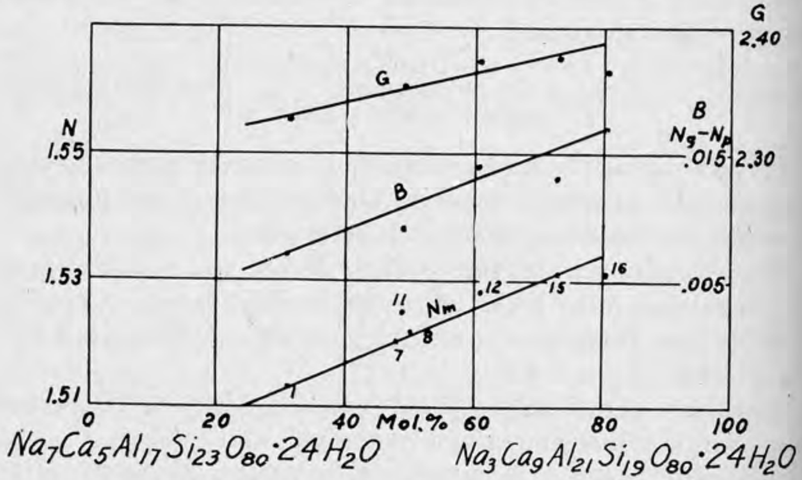

FIG. 467. Thomsonite.

The thomsonite found along the north shore of Lake Superior is occasionally used as an ornamental stone.

Stilbite **Monoclinic** **$CaAl_2Si_2O_6\cdot 6H_2O$**

$a:b:c = 0.463:1:0.381$, $\beta = 89°30'$

Crystals always twinned as crosses to resemble orthorhombic prisms often in sheaf-like aggregates; also radiated or globular.

Perfect clinopinacoidal cleavage. H. = 3.5–4. G. = 2.1–2.2. F. = 3, with exfoliation, to white enamel. Decomposed by HCl. Vitreous to pearly luster. Colorless or white; rarely stained yellow to brown or red.

Stilbite varies from $CaAl_2Si_2O_6\cdot 6H_2O$ in containing very little to about 2% of soda and potassa; some crystals contain less silica and the tenor of alumina also varies. Precise data are lacking.

Stilbite occurs with other zeolites, datolite, and calcite in cavities in basic igneous rocks; also in veins and as an alteration product in granite and gneiss. Interesting samples have been obtained at Giants Causeway, Ireland, on the Faroe Islands, Iceland, Nova Scotia, Bergen Hill (New Jersey), Table Mountain (Colorado), and elsewhere.

Chabazite *Hexagonal* $c = 1.087$ $\left\{\begin{array}{l} m\mathrm{Ca_7Al_{14}Si_{26}O_{80}\cdot 40H_2O} + \\ n\mathrm{Na_4Ca_3Al_{10}Si_{30}O_{80}\cdot 40H_2O} \end{array}\right.$

Crystals are often rhombohedrons, resembling cubes, since the angle is 85°14′; also more complex or basal tablets. Penetration twins on 0001. Microscopically monoclinic and twinned in six sectors.

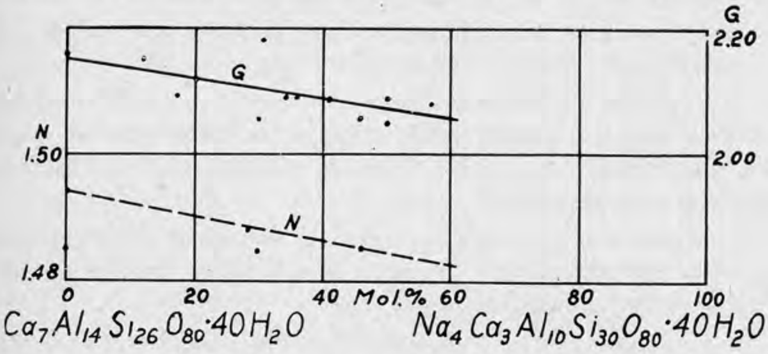

FIG. 468. Chabazite.

Rhombohedral cleavage. H. = 4–5. G. = 2.1–2.2. Fuses with intumescence to a blebby glass. Decomposed by HCl. Vitreous luster. Colorless or stained reddish. $(\pm)2V$ = small, $N_g = 1.48$–1.49, $N_m = 1.48\pm$, $N_p = 1.478$–1.485. See Fig. 468.

Chabazite varies in composition as plagioclase does, but may also have Ca replaced by Na_2 or K_2 and may vary in its tenor of water. The effects of the first kind of variation are shown in Fig. 468.

Chabazite is associated with other zeolites in cavities in basic igneous rocks; it is also found in schists and limestones and as a deposit of certain hot springs. Some localities are at the Giants Causeway (Ireland), Aussig (Bohemia), Iceland, Bergen Hill (New Jersey), Table Mountain (Colorado).

Because of its ready base exchange, chabazite is of possible use as a water softener, but artificial zeolites like "*permutite*" are commonly used for this purpose.

Chrysocolla **Amorphous** **CuO, SiO_2, H_2O**

Chrysocolla is usually amorphous, but may be microscopically crystalline and acicular. Often in compact masses, reniform or earthy; also as incrustations and in veins; it may resemble enamel.

Conchoidal fracture. H. = 2–4. G. = 2.–2.2. Infusible, but decrepitates before the blowpipe. Decomposed by acids. Vitreous, greasy or dull luster. Usually greenish blue, but may be brown to black when impure (then called *copper pitch* ore). N = 1.57–1.63. Also anisotropic.

Chrysocolla, being amorphous, contains CuO, SiO_2 and H_2O in widely varying proportions; it often contains also some iron oxide, alumina, etc. The formula $CuSiO_3 \cdot 2H_2O$ has been suggested for crystals.

Chrysocolla is a secondary mineral found in the oxide zone of many copper deposits. It is often associated with malachite, azurite, native copper, limonite, etc.

It is a minor ore of copper in Cornwall, the Belgian Congo, the Ural Mountains, Butte (Montana), Clifton, Globe and Bisbee (Arizona), Tintic District (Utah), and elsewhere. It is also used for ornamental purposes at times as a substitute for turquois.

Opal **Amorphous** **$SiO \cdot nH_2O$**

Usually compact in irregular masses, sometimes reniform or stalactitic.

Conchoidal fracture. H. = 5.–6. G. = 1.9–2.3; when pure 2.0–2.2. Vitreous to dull luster. Colorless, white, milky, yellow, brown, red, green, blue, black; dark colors due to stain. Streak white. Transparent to translucent. May show a rich play of colors and some samples are opalescent, or even luminescent. N = 1.44–1.46.

Pure opal is $SiO_2 \cdot nH_2O$, the amount of water varying from 1 to 20 per cent, but usually between 3 and 10 per cent. Opal is probably merely hardened gelatinous silica. Yields water in the closed tube. Infusible. Soluble in hydrofluoric acid and in hot caustic alkali.

The chief varieties of opal are:

1. *Common opal,* translucent to nearly opaque of many colors. When milk white to milky yellowish, bluish, or greenish it is *milk opal.* With a resinous luster and waxy or yellowish color it is *resin opal.* Wood petrified to opal is *wood opal.* With a red to brown color due to iron and a resinous luster it is *jasper opal.*

2. *Hyaline* is colorless and transparent opal in irregular masses; it resembles glass.

3. *Precious opal* shows a play of colors—yellowish, gray, bluish. Those with lighter colors are called *white opal* and those with darker colors are called *black opal.*

4. *Fire opal* is a precious opal with red to orange fire-like reflections.

5. *Siliceous sinter* and *geyserite* are deposits of opal made by hot springs and geysers respectively. They may be porous, compact, or fibrous, of white, gray, or brownish color, and may have a pearly luster.

6. *Diatomite* (diatomaceous or infusorial earth, or kieselguhr or tripolite) is a porous, earthy and chalk-like deposit of siliceous remains of diatoms, radiolaria, etc.

Opal is formed only at low temperatures from silica-bearing waters. It is usually a result of decomposition of silicate rocks, and is often found in fissures and cavities in igneous, metamorphic, and sedimentary rocks. It forms the siliceous skeleton of organisms such as diatoms, sponges, etc. Common opal is not found in large quantities, but is rather widely distributed. Precious opal is obtained near Czerwenitz in Roumania, the Barcoo River in Queensland, White Cliffs in New South Wales, in Zimpan, Mexico, in Humboldt County, Nevada, in Latah County, Idaho. Geyserite is abundant in New Zealand, Iceland, and Yellowstone Park. Diatomite is obtained chiefly from California, Oregon, Washington, Idaho, Nevada, and Arizona; also from Virginia, New Jersey, and New Mexico.

Precious (and fire) opal is used widely as a gem, and wood opal for ornamental purposes. Diatomite is used in polishing powders, scouring soaps, metal polishes, dentifrices, and also as insulating material, as an absorbent, as a wood filler, and in filtering and refining sugar.

6

Economic Mineralogy

Minerals may readily be classified on the basis of their uses, but such a classification must vary from time to time and even from place to place, because the uses of minerals vary in both those ways. For example, cryolite was for a short time the chief source of aluminum, but it is now important only as a flux in obtaining aluminum from other minerals, especially bauxite. Again, pyrite is used as an ore of iron in Spain, but in this country only as a source of sulfuric acid. Some minerals are used as sources of some element (often a metal) which they contain; other minerals are used in the condition in which they are found. This distinction is only approximate: some minerals are used in neither way and some are used in both ways. Thus, such common minerals as augite, hornblende, zoisite, leucite, etc., are used in neither way, while pyrolusite is used both as a source of manganese and also as a drier in paints and varnishes, as a coloring agent in glass and pottery, and as an important part of dry batteries. Again, both hematite and limonite are important sources of iron and are also used as pigments.

With some exceptions, silicates are used as such; they are so abundant and important that they may well be grouped by themselves even in an economic classification.

Also, with some exceptions, other minerals are used chiefly as sources of contained elements. Of course these elements are either basic (metals) or acidic. Accordingly, three main divisions may be recognized: (1) basic division; (2) acidic division; (3) silicate division. The subdivisions are arranged in the order of the Periodic classification of elements. For a description of the third (silicate) division it is only necessary to turn to pages 315–399.

1. Basic Division

Gold

The chief minerals containing gold are:

Noble Metal	(Au,Ag)	Isometric
Sylvanite	dominantly $(Au,Ag)Te_2$	Monoclinic
Calaverite	dominantly $AuTe_2$	Monoclinic

For some years now the largest production of gold from any one district has come from the Transvaal in South Africa; indeed it produces about one third of the world's total. The United States (including Alaska and the Philippines) is second in production; other large amounts come from Russia and Canada. About 65 per cent of the gold produced in this country comes from gold "quartz" mines, about 20 per cent from placer mines and about 15 per cent is obtained as a by-product of copper, lead, and zinc ores. The nine leading states (and territories) in order are: California, Philippines, Alaska, South Dakota, Colorado, Nevada, Arizona, Utah, and Montana—together they produce about 75 per cent of the total.

Much gold is reclaimed each year from old jewelry and ornaments, dental scrap, etc. Nearly all of the mined gold is used for coinage; other uses for gold are approximately supplied by gold from scrap. For most of its uses gold is alloyed with minor amounts of other metals (especially silver and copper) to increase its hardness. "White gold" is obtained by combining 14 parts of gold and 10 parts of an alloy consisting of nickel, silver, palladium and zinc.

The world's production of gold in recent years has amounted to thirty to forty million fine ounces, of which the United States has produced three to five million.

Silver

The chief minerals containing silver are:

Noble Metal	(Ag,Au)		Isometric
Argentite	dominantly Ag_2S		Isometric
Ruby Silver dominantly	Ag_3AsS_3	Proustite	Hexagonal
	Ag_3SbS_3	Pyrargyrite	Hexagonal
Cerargyrite dominantly	$AgCl$	Chlorargyrite	Isometric
	$AgBr$	Bromargyrite	Isometric

For many years past 75–85 per cent of the world's production of silver has come from the Americas, and in the western hemisphere the largest production has come from Mexico and the United States. In this country about 80 per cent of the silver is obtained as a by-product from copper, lead, zinc, and gold ores. Only about 20 per cent is obtained from silver ores. The normal domestic production is about 65,000,000 fine ounces, coming chiefly from the following states: Idaho, Utah, Montana, Colorado, Arizona, and Nevada. About one third of this total production is used in industrial arts and two thirds in coinage. Silver used in coins contains 10 per cent copper, while *sterling silver* used in many kinds of table silverware contains 7.5 per cent copper. Silver is also used to electroplate tableware and other articles made of nickel, brass, or brittania metal (tin, antimony, copper, and zinc). *Dental amalgam* is an alloy of silver and tin with small amounts of copper and zinc in a powder form. It is mixed with mercury when used. Silver salts are used in photography and in medicine. Some of the important silver mining regions are at Tintic (Utah), Tonopah (Nevada), Coeur d'Alene district (Idaho), Battle Mountain (Colorado), Butte (Montana), Mogollon (New Mexico), Ajo, Pioneer, and Warren (Arizona).

Copper

The chief minerals containing copper are:

Native Copper	dominantly	Cu	Isometric
Chalcocite	“	Cu_2S	Orthorhombic
Covellite	“	CuS	Hexagonal
Chalcopyrite	“	$CuFeS_2$	Tetragonal
Bornite	“	Cu_5FeS_4	Isometric
Enargite	“	Cu_3AsS_4	Orthorhombic
Tetrahedrite	“	$Cu_{10}Zn_2Sb_4S_{13}$	Isometric
Cuprite	“	Cu_2O	Isometric
Malachite	“	$Cu_2(OH)_2CO_3$	Monoclinic
Azurite	“	$Cu_3(OH)_2(CO_3)_2$	Monoclinic
Chalcanthite	“	$CuSO_4 \cdot 5H_2O$	Triclinic
Chrysocolla	“	CuO, SiO_2, H_2O	Amorphous

Most of the world's production of copper is now coming from the United States, Chile, Canada, Northern Rhodesia, Belgian Congo, Russia, and Japan. The United States produces about one third of the total; in this country the largest production comes from Arizona, Utah, Montana, Nevada, Michigan, and New Mexico. The Bingham District in Utah is now producing far more copper than any other single district, the Butte District in Montana coming next.

Copper is used most extensively in electrical equipment such as generators, motors, transmission and distribution wires, wire cloth, ammunition, automobiles, castings, and alloys. *Brass* consists of copper and zinc; *German silver* of copper, zinc, and nickel; *bronze* usually of copper, tin, and zinc.

Copper sulfate or blue vitriol is used in calico printing, water purification, as a mordant and preservative of timber, in copper plating, etc. Millions of pounds of copper are recovered annually from mine waters by precipitation with scrap iron.

Potassium

The chief minerals containing potassium are:

Sylvite	dominantly	KCl	Isometric
Carnallite	"	$KMgCl_3 \cdot 6H_2O$	Orthorhombic
Kainite	"	$KCl \cdot MgSO_4 \cdot 3H_2O$	Monoclinic
Alunite	"	$K_2\{Al(OH)_2\}_6(SO_4)_4$	Hexagonal

The chief potassium silicates are: orthoclase and microcline ($KAlSi_3O_8$), leucite ($KAlSi_2O_6$), and micas $\{(H_2KAl_3Si_3O_{12}$, etc.)$\}$.

Twenty-five years ago the United States was producing practically no potash. Today this country produces much more than half its consumption and can readily produce all it needs in time of stress. The production comes chiefly from potash deposits in New Mexico and from natural brines in California; domestic potash sold amounted to 370,000 short tons of K_2O in 1939, while exports were nearly equal to imports (in terms of K_2O).

Potassium chloride and various potassium (and KMg) sulfates are important fertilizers. Potassium bitartrate, potassium chlorate, potassium nitrate, and various other compounds are used in chemical industries; caustic potash is used in making soap; the bicarbonate is used in cut glass, optical glass, and incandescent light bulbs; the chlorate is used in matches, the nitrate in black powders, the bichromate in dyeing and tanning, the cyanide in extracting gold from its ores, and so on.

The world's production of potash salts comes largely from Germany, with smaller amounts from Alsace (France), Poland, and Russia.

Sodium

The economically important minerals containing sodium are:

Halite	dominantly	NaCl	Isometric
Cryolite	"	Na_3AlF_6	Monoclinic
Trona	"	$HNa_3(CO_3)_2 \cdot 2H_2O$	Monoclinic
Soda niter	"	$NaNO_3$	Hexagonal
Glauberite	"	$Na_2Ca(SO_4)_2$	Monoclinic
Mirabilite	"	$Na_2SO_4 \cdot 10H_2O$	Monoclinic

Some of the chief sodium silicates are: plagioclase ($NaAlSi_3O_8$-$CaAl_2Si_2O_8$), nephelite ($NaAlSiO_4$), cancrinite ($3NaAlSiO_4 \cdot CaCO_3$), sodalite ($3NaAlSiO_4 \cdot NaCl$), scapolite ($3NaAlSi_3O_8 \cdot NaCl$), analcite ($NaAlSi_2O_6 \cdot H_2O$), natrolite ($Na_2Al_2Si_3O_{10} \cdot 2H_2O$).

Halite or salt is much the most important sodium mineral. Halite obtained by ordinary mining is known as rock salt; large quantities are obtained by evaporation of salt waters—such material is called brine salt. The United States produces all the salt that is needed here and the supply seems inexhaustible. About 9,000,000 tons are produced annually, about 2,000,000 tons being rock salt. The largest production comes from Michigan, New York, Ohio, Kansas, and Louisiana. The evaporation of brine yields not only halite, but also other salts, from which are made soda ash, caustic soda, sodium bicarbonate, sodium acetate, sodium chlorate, sodium phosphate, and even bromine, iodine, and chlorine.

The world's production of salt comes from many countries, but especially from the United States, Russia, China, Germany, England, and India.

Sodium metal is produced from caustic soda; it is used to make tetraethyl lead "antiknock" compounds and synthetic indigo; the production in this country amounts to about 10,000 tons annually.

Lithium

The chief minerals containing lithium are:

Amblygonite	dominantly	$LiAl(F,OH)PO_4 \cdot (\frac{1}{4}H_2O?)$	Triclinic
Spodumene	"	$LiAlSi_2O_6$	Monoclinic
Lepidolite	"	$K_3Li_3Al_3(Si_6Al_2)O_{20}(F,OH)_4$	Monoclinic

By exception lithium is obtained chiefly from silicates, although it is also obtained from phosphates. Lithium is rather widely distributed in nature, but no mineral containing a high percentage of it is available; ordinary lithium ores rarely contain more than 5 or 6 per cent. Lithium is obtained almost exclusively from minerals of pegmatites.

Lithium is the lightest solid substance known, being only half as heavy as water. Lithium metal reacts slowly with air and is therefore useful only in alloys for engineering purposes. Alloys with aluminum, lead, zinc, copper, and magnesium are in use. Lithium chloride is becoming important in air conditioning, but a large part of the lithium consumption is still employed in lithiated waters and medicinal preparations. Lithium hydroxide is used in Edison storage batteries. Lithium minerals have been used in making special glasses and enamels.

Barium

The chief minerals containing barium are:

Witherite	dominantly	$BaCO_3$	Orthorhombic
Barite	"	$BaSO_4$	Orthorhombic

Commercially barite is far more important than witherite. Barite is used chiefly in making pigments, especially *lithopone*, which is an intimate mixture of 70 per cent of barium sulfate, 25–29 per cent of zinc sulfide, and 1–5 per cent of zinc oxide. *Blanc fixé*, or permanent white, is artificially precipitated barium sulfate. Lithopone is used also in making floor coverings, textiles, and rubber goods. Ground barite is used in the same industries and in making artificial ivory, heavy glazed paper, and bristol board. Much is also used in well drilling. Barite bricks are used in X-ray laboratories because they are opaque to X rays. Barium compounds have many uses: barium binoxide is used in making hydrogen peroxide; barium chloride is used as a water softener; barium carbonate is used as an insecticide, in making optical glass, and so on.

Barite is obtained in large quantities in Germany and this country; here it comes chiefly from Missouri, Georgia, Tennessee, California, Illinois, and New Jersey. The annual domestic production amounts to nearly 400,000 tons.

Strontium

The chief minerals containing strontium are:

Strontianite	dominantly	$SrCO_3$	Orthorhombic
Celestite	"	$SrSO_4$	Orthorhombic

Strontianite is more important commercially than celestite, because it is easily converted into the various compounds that are used; but celestite is commoner in nature. The total world consumption of strontium minerals is usually less than 10,000 tons annually. They are obtained chiefly from Great Britain. Much of them is used in making beet sugar in Germany, and another large use, especially in this country, is in pyrotechnics, strontium nitrate signal flares being used commonly on American railways. Some strontium is used in medicines. Attempts have been made to recover strontium salts from brines.

Calcium

The chief minerals containing calcium are:

Fluorite	dominantly	CaF_2	Isometric
Calcite	"	$CaCO_3$	Hexagonal
Aragonite	"	$CaCO_3$	Orthorhombic
Dolomite	"	$CaMgC_2O_6$	Hexagonal
Apatite	"	$Ca_5F(PO_4)_3$	Hexagonal
Colemanite	"	$Ca_2B_6O_{11}\cdot 5H_2O$	Monoclinic
Anhydrite	"	$CaSO_4$	Orthorhombic
Gypsum	"	$CaSO_4\cdot 2H_2O$	Monoclinic
Scheelite	"	$CaWO_4$	Tetragonal

The chief calcium silicates are: plagioclase ($NaAlSi_3O_8$-$CaAl_2Si_2O_8$), wollastonite ($CaSiO_3$), augite $\{Ca(Mg,Fe)Si_2O_6\}$, hornblende $\{H_2Ca_2(Mg,Fe)_5Si_8O_{24}(+Al_2O_3,\ \text{etc.})\}$, scapolite ($Na_4ClAlSi_3O_8$-$Ca_4CO_3Al_2Si_2O_8$), epidote $\{HCa_2(Al,Fe)_3Si_3O_{13}\}$, vesuvianite $\{Ca_{10}Al_4Si_9O_{34}\cdot 2Mg(OH)_2\}$, melilite $\{Ca_2R(Si,Al)_2O_7\}$, datolite ($CaBOHSiO_4$), titanite ($CaTiSiO_5$), ugrandite (garnet) $\{Ca_3(Al,Fe,Cr)_2Si_3O_{12}\}$, pectolite ($HNaCa_2Si_3O_9$), apophyllite ($4CaSi_2O_5\cdot KF\cdot 8H_2O$), stilbite ($CaAl_2Si_2O_6\cdot 6H_2O$), and certain other zeolites.

Calcium is one of the most abundant metals in nature and is an essential constituent of many minerals. But the calcium silicates have no uses which depend upon the calcium in them.

Fluorite, apatite, colemanite, and scheelite have uses depending upon their acidic element. Aragonite and anhydrite are only rarely used for ornamental purposes.

Calcite when found in large transparent clear crystals is quite valuable for making Nicol prisms for optical instruments. But such crystals are rare, whereas aggregates of calcite are very common either as the sedimentary rock called limestone or the metamorphic rock called marble. Limestone proper is composed essentially of calcite; a very similar rock, called dolomite, is composed essentially of the mineral known as dolomite; but "limestone" commercially (and even to some extent in geology) includes both limestone proper and also dolomite. Both limestone and marble are used in large quantities as building and ornamental stones. Limestone is used more extensively than any other building stone in this country, and about 75 per cent of that used comes from Indiana. Limestone is used extensively as a flux in iron and other furnaces; large quantities are also used in making cement and lime. A third large use of limestone is in making lime and Portland and natural cements. The total consumption of limestone for all purposes in this country is about 130,000,000 tons annually, obtained chiefly from Indiana, Michigan, Ohio, Pennsylvania, New York, Illinois, and Iowa.

Dolomite is included to some extent in the statements regarding limestone, but dolomite is used also to make dead-burned dolomite for refractory purposes, and to make basic magnesian carbonate and CO_2 gas.

Gypsum is used in the crude state as a retarder of Portland cement, as a pigment especially in cold water paints, and as a filler for paper and cloth. Calcined gypsum (that is, gypsum heated until three fourths of its water is driven off) is used chiefly to make wall plaster, plaster boards and lath, gypsum blocks and tile, molds for pottery and surgical casts. Gypsum can now be ground and calcined in one operation. About a quarter of the gypsum mined is used in the crude state, and the rest is calcined. The United States produces more gypsum than any other country, followed by France, Great Britain, Canada, and Germany. In this country gypsum is obtained chiefly from New York, Michigan, Iowa, and Texas.

Magnesium

The important minerals containing magnesium are:

Carnallite	dominantly	$KMgCl_3 \cdot 6H_2O$	Orthorhombic
Brucite	"	$Mg(OH)_2$	Hexagonal
Spinel	"	$MgAl_2O_4$	Isometric
Magnesite	"	$MgCO_3$	Hexagonal
Dolomite	"	$CaMgC_2O_6$	Hexagonal
Boracite	"	$Mg_3ClB_7O_{13}$	Pseudocubic (Orth.)
Kieserite	"	$MgSO_4 \cdot H_2O$	Monoclinic
Epsomite	"	$MgSO_4 \cdot 7H_2O$	Orthorhombic
Kainite	"	$MgSO_4 \cdot KCl \cdot 3H_2O$	Monoclinic

The chief magnesium silicates are: pyrope ($Mg_3Al_2Si_3O_{12}$), olivine $\{(Mg,Fe)_2SiO_4\}$, chondrodite $\{Mg_5(OH,F)_2SiO_4\}$, tourmaline $\{H_4Na(Mg,Fe)_3B_3Al_6Si_6O_{31}\}$, cordierite $\{(Mg,Fe)_2Al_4Si_5O_{18}\}$, enstenite $\{(Mg,Fe)SiO_3\}$, augite $\{Ca(Mg,Fe)Si_2O_6\}$, anthophyllite $\{H_2(Mg,Fe)_7Si_8O_{24}\}$ amphibole $\{H_2Ca_2(Mg,Fe)_5Si_8O_{24}(+Al_2O_3, \text{etc.})\}$, glaucophane $\{H_2Na_2Mg_3Al_2Si_8O_{24}\}$, serpentine $\{H_4(Mg,Fe)_3Si_2O_9\}$, sepiolite ($H_4Mg_2Si_3O_{10}$), chlorite $\{H_4(Mg,Fe)_3Si_2O_9\text{-}H_4(Mg,Fe)_2Al_2SiO_9\}$, biotite $\{H_4K_2(Mg,Fe)_6Al_2Si_6O_{24}\text{-}H_4K_2(Mg,Fe)_5Al_4Si_5O_{24}\}$.

Magnesium, like calcium and iron, is one of the most abundant metals in nature and it is an essential constituent of many common minerals. But most of the magnesium silicates have no uses depending on their content of magnesium. Carnallite and boracite have uses depending upon their acidic element. Kainite is more important for its potassium content than for its magnesium. Spinel is used only as a gem stone.

Brucite is used as a source of magnesia and magnesium salts in Nevada; deposits of good quality are known in Ontario and Quebec. It is also a possible ore of magnesium.

Magnesite is at present the chief source of magnesium and its compounds. It is used either as the partially calcined "caustic" or as the "dead-burned" magnesite. The caustic magnesite still contains about 5 per cent of carbon dioxide and is chemically active, combining readily with magnesium chloride to form an oxychloride (*Sorel* cement) used as the basis of various types of flooring. Fillers in this cement may be cork, talc, asbestus, clay, sand, ground marble, etc. Magnesite cement floors are hard and strong; they are easily polished and do not crack. Dead-burned magnesite is chemically inactive; it is used chiefly for refractory purposes, especially as linings of steel and electric furnaces, copper converters, and Portland cement kilns. Magnesite is also used in making magnesium sulfate, magnesium chloride, magnesium bisulfite and basic magnesium carbonate; the sulfate is used in medicine and in textiles; the chloride is used in Sorel cement; the bisulfite is used to disintegrate wood in making wood pulp paper; the basic carbonate (*magnesia alba*) is used in fire-retarding paint and as thermal insulation for steam pipes.

Magnesite is also used as an ore of magnesium; the metal is exceptionally light being about one third lighter than aluminum. Its use in airplane and motor construction is increasing rapidly. It makes good castings, machines well, and is two to four times as strong as aluminum.

Magnesite is produced in large quantities in Russia, Austria, Manchuria, and the United States; in this country it comes chiefly from California and Washington, but deposits are known also in Texas and Vermont.

Dolomite is much more abundant and less expensive than magnesite; it is being used as a substitute in increasing amounts, especially as a source of *magnesia alba* and the bisulfite for use in making paper. Dolomite is also used as a source of carbon dioxide.

Kieserite has been produced chiefly near Stassfurt, Germany, but some can be obtained from natural brines as well as from salt deposits in New Mexico and California. It is used chiefly as a fertilizer. Plans have been made to produce artificial kieserite from olivine at Webster, North Carolina.

Epsomite has been obtained largely from England, but is now produced from brines. It is used in medicine and as a fertilizer in place of gypsum.

Beryllium

The chief minerals containing beryllium are:

Chrysoberyl	dominantly	$BeAl_2O_4$	Orthorhombic
Beryl	"	$Be_3Al_2Si_6O_{18}$	Hexagonal

Beryllium is the only metal (besides lithium) which is obtained chiefly from a silicate. Beryllium minerals occur only rarely and in small amounts, usually in pegmatites. Beryllium is a remarkably light metal but it is still too expensive to be used except in special salts or in alloys with special properties. Beryllium copper alloy is important in cast-setting diamond core bits and reaming shells. A typical bit may contain diamonds so small that they average about twenty-five to a carat.

Beryllium finds its chief market in this country, where the metal is available as well as the oxide, sulfate, nitrate, and fluoride. It is obtained from imported ores and also from South Dakota, California, Colorado, and elsewhere. But the production is still very small.

Zinc

The chief minerals used as zinc ores are:

Sphalerite	dominantly	ZnS	Isometric
Tetrahedrite	"	$Cu_{10}Zn_2Sb_4S_{13}$	Isometric
Zinkite	"	ZnO	Hexagonal
Franklinite	"	$(Fe,Mn,Zn)Fe_2O_4$	Isometric
Smithsonite	"	$ZnCO_3$	Hexagonal
Hemimorphite	"	$H_2Zn_2SiO_5$	Orthorhombic
Willemite	"	Zn_2SiO_4	Hexagonal

The metal zinc (called *spelter* in commerce) was apparently unknown to the Greeks and Romans, though it has been worked in China for many centuries. It is a brittle metal but when heated to the boiling point of water can be rolled into sheets. About 40 per cent of the output in this country is used to coat (or galvanize) iron, about 25 per cent is used to make brass, about 12 per cent is used in pigments, and about 10 per cent is rolled into sheet zinc for roofing and other uses.

The United States produces more zinc than any other country—followed by Germany, Belgium, Canada, and Poland. In this country the production comes chiefly from Oklahoma, New Jersey, Kansas, Idaho, Tennessee, Montana, and Utah.

Sulfuric acid is a by-product of zinc smelting.

Mercury

The chief minerals containing mercury are:

Cinnabar	dominantly	HgS	Hexagonal
Tetrahedrite	"	$(Cu,Hg)_{10}Zn_2(Sb,As)_4S_{13}$?	Isometric

Mercury is obtained almost wholly from cinnabar, but small amounts are found native (in the oxide zone). Native mercury and water are the only substances accepted as minerals which are liquids at ordinary temperature. Mercury is used in making mercuric fulminate for explosive caps, in dental amalgam, in antifouling paints for ship bottoms, in drugs, in scientific apparatus. The oxide is used for ship bottom paints; the salt of sea water converts it to the very poisonous mercuric chloride. The sulfide is a vermilion pigment. The chloride (calomel) is used in medicine. Mercury has been used for generating power in boilers, but this use is not increasing at present. Mercury is also used in vapor lamps, and to float signal lights of lighthouses.

Mercury ores in America are all of low grade—the average recovery is less than 0.5 per cent. The production comes chiefly from California and Oregon. The world production comes chiefly from Italy, Spain, and this country. The Almaden mine in Spain is doubtless the greatest mercury mine now known in the world—its ores average about 6 per cent mercury. It was opened about 400 B. C. and has been producing constantly since about 1500 A. D.

Aluminum

The economically important aluminum minerals are:

Cryolite	dominantly	Na_3AlF_6	Monoclinic
Corundum	"	Al_2O_3	Hexagonal
Bauxite	"	$Al_2O_3 \cdot 2H_2O$	Amorphous
Spinel	"	$MgAl_2O_4$	Isometric
Chrysoberyl	"	$BeAl_2O_4$	Orthorhombic
Alunite	"	$K\{Al(OH)_2\}_6(SO_4)_4$	Hexagonal
Wavellite	"	$(AlOH)_3(PO_4)_2 \cdot 5H_2O$	Orthorhombic
Turquois	"	$H_5CuOH\{Al(OH)_2\}_6PO_4$	Triclinic
Amblygonite	"	$LiAl(F,OH)PO_4(\frac{1}{4}H_2O?)$	Triclinic

There are many aluminum silicates; the most important are: garnet $\{(Ca,Mg,Fe,Mn)_3Al_2Si_3O_{12}\}$, staurolite $\{2Al_2SiO_5Fe(OH)_2\}$, topaz $\{Al_2(F,OH)_2SiO_4\}$, sillimanite (Al_2SiO_5), andalusite (Al_2SiO_5), kyanite (Al_2SiO_5), vesuvianite $\{Ca_{10}Al_4Si_9O_{34} \cdot 2Mg(OH)_2\}$, melilite $\{Ca_2R(Si,Al)_2O_7\}$, analcite $\{NaAlSi_2O_6 \cdot H_2O\}$, beryl $\{Be_3Al_2(SiO_3)_6\}$, tourmaline $\{H_4Na(Mg,Fe)_3B_3Al_6Si_6O_{31}$, etc.$\}$, cordierite $\{(Mg,Fe)_2Al_4Si_5O_{18}\}$, spodumene $(LiAlSi_2O_6)$, hornblende $\{NaCa_2(Mg,Fe)_4Al_3Si_6O_{22}(OH,F)_2$, etc.}, glaucophane {$Na_2(Mg,Fe)_3Al_2Si_8O_{24}$}, kaolinite {$Al_2Si_2O_5(OH)_4$}, pyrophyllite {$Al_2Si_4O_{10}(OH)_2$}, muscovite ($H_4K_2Al_6Si_6O_{24}$, etc.), biotite {$H_4K_2(Mg,Fe)_6Al_2Si_6O_{24}$, etc.}, lepidolite ($K_2Li_3Al_5Si_6O_{20}F_4$, etc.), chlorite {$(Mg,Fe)_2Al_2SiO_5(OH)_4$, etc.}, leucite ($KAlSi_2O_6$), sodalite {$3NaAlSiO_4 \cdot Na(Cl,SO_4,S_2)$}, scapolite ($3NaAlSi_3O_8 \cdot NaCl–3CaAl_2Si_2O_8 \cdot CaCO_3$), nephelite ($NaAlSiO_4$), cancrinite {$3NaAlSiO_4 \cdot Ca(CO_3,Cl,SO_4)$}, zoisite {$Ca_2Al_3Si_3O_{12}(OH)$}, epidote {$Ca_2(Al,Fe)_2Si_3O_{12}(OH)$}, orthoclase ($KAlSi_3O_8$), microcline ($KAlSi_3O_8$), plagioclase ($NaAlSi_3O_8$-$CaAl_2Si_2O_8$), and zeolites, hydrated Na,Ca, Al silicates.

Aluminum is the most abundant metal in the earth's crust, but its use began only about sixty years ago, and the output is still only about one third that of lead or zinc, one fifth that of copper, and less than 0.5 per cent that of iron. The world's production of aluminum is obtained chiefly from Germany, the United States and Canada; it is produced also in France, Russia, Norway, Italy, Switzerland, England, and Japan. The ore in this country is obtained chiefly from Arkansas.

The most important ore of aluminum is bauxite, but cryolite, alunite, kaolinite, andalusite, and dumortierite will be discussed briefly, also.

Aluminum was at first produced from *cryolite* obtained only from Greenland; at present cryolite serves as a flux to dissolve alumina which has been obtained from bauxite by fusion with sodium carbonate followed by leaching and then precipitation by means of carbon dioxide. Aluminum is obtained by electrolysis, the metal collecting in the bottom of the tank. About 160,000 tons of aluminum are produced annually in this country. Aluminum is used in many ways on account of its low specific gravity, toughness, durability, and electrical conductivity; it is used in airplanes (largely in an alloy), motor trucks, window frames, machines, cooking utensils, iron and steel metallurgy, etc. About 30 per cent of the production is used in transportation equipment (air, land and water); about 25 per cent in electrical conductors, appliances and machines, and about 15 per cent in cooking utensils.

Bauxite is used not only as an ore of aluminum but also as a source of several types of abrasives, various aluminum salts (especially aluminum sulfate), refractories, and a specially prepared "activated" material used in the percolation filtration of paraffin-base oils.

Corundum is used as an abrasive and also as gem material, both ruby and sapphire. Artificial corundum is the source of aluminum.

Alunite is used as a source of aluminum sulfate in Italy.

Kyanite, andalusite and *dumortierite* ($HBAl_8Si_3O_{20}$) are used in the production of spark-plug porcelains and refractories. Upon heating they break down to $3Al_2O_3 \cdot 2SiO_2$ (mullite), which has the strength, low thermal expansion, and high dielectric properties needed in such equipment.

Cerium

The chief minerals containing cerium (and other rare earths) are:

Monazite	dominantly	$(Ce,La,Di)PO_4$	Monoclinic
Allanite	"	$(Ca,Ce)_2(Al,Fe''',Fe'')_3Si_3O_{12}(OH)$	Monoclinic

Cerium is used along with any or all of the rare earth elements (57 to 71) to make sparking flints such as used in pocket cigarette lighters. Cerium is also used as a reducing agent in the production of metallic zirconium and thorium. Cerium sulfate is used to remove silver from overdeveloped negatives in photography, as a catalyst in the contact process of making sulfuric acid, and also in making aniline black. Cerium oxide is the compound used in producing sparks. A little cerium is also used, with much thorium, in making incandescent gas mantles. The chief source of both cerium and thorium is monazite, which was formerly obtained in North Carolina, then in Brazil, then in Ceylon and Travancore (India). Thorium has been obtained also from thorianite (a thorium uranate) and thorite ($ThSiO_4$) in Ceylon.

Zirconium

The only important mineral containing zirconium is:

Zircon	dominantly	$ZrSiO_4$	Tetragonal

Zirconium is used in very limited quantities in alloys, in radio tubes and in flashlight mixtures. *Cooperite* is an alloy of zirconium and nickel recommended for use in machine tools because it is self-hardening and no tempering is necessary. The filaments of the Nernst lamp consist of oxides of zirconium, yttrium, erbium, thorium, and cerium. Zirconia is also used as an opacifier in enamel ware, as a refractory and as a permanent white pigment. Zirconium is obtained from zircon and from *baddeleyite* (ZrO_2). Zircon has been obtained in North Carolina and Florida, but is now imported from Brazil, India, Australia, etc.

Titanium

The chief minerals containing titanium are:

Rutile	dominantly TiO_2	Tetragonal
Ilmenite	" $FeTiO_3$	Hexagonal

Titanium is important in one silicate, titanite ($CaTiSiO_5$), and present in some varieties of augite, hornblende, and biotite. Titanium is used in limited quantity in ferrotitanium to deoxidize steel; it is also used to increase the tensile strength of steel. Again, it is used in the alloys, cuprotitanium and titanium-aluminum bronze; the latter is extremely resistant to the action of sea water. Titanium oxide is used as a white pigment and as an opacifier in enamel ware. Kennametal carbide is a new ultra-hard tungsten-titanium carbide used in cutting tools, and so on.

Rutile is the chief source of titanium, but it is also obtained from ilmenite and from *brookite* (TiO_2). Domestic production is chiefly from Virginia, though some is obtained from Arkansas and California. Most of the ilmenite used commercially is imported from India.

Tin

The only important tin mineral is:

Cassiterite	dominantly SnO_2	Tetragonal

Cassiterite is practically the only source of the world's supply of tin although small amounts have been obtained from stannite (Cu_2FeSnS_4). Tin is used in large quantities for coating iron and copper. "Tin" cans are made of iron with a thin coating of tin. Tin alloys with copper to form bronze of various kinds. It is also used extensively as tin foil, but this is usually lead coated with tin. Tin oxide is used in making a paste (putty of tin) for polishing hard stones. Tin chlorides are used in the preparation of dyes; and tin disulfide (called bronze powder) is used to gild articles. Tin is also used in making solder and Babbitt metal and type metal. About 50 per cent of the tin is used in making tin plate in this country. The United States produces very little tin, but uses about 30–40 per cent of the world's output—far more than any other country. The chief production of tin is obtained from the Malay States, the Dutch East Indies, Bolivia, Siam, Nigeria, China, and the Belgian Congo. The tiny production of this country comes chiefly from Alaska; a little also has been obtained in South Dakota.

Lead

The chief minerals used as sources of lead are:

Galena	dominantly	PbS	Isometric
Bournonite	“	$CuPbSbS_3$	Orthorhombic
Cerussite	“	$PbCO_3$	Orthorhombic
Anglesite	“	$PbSO_4$	Orthorhombic
Crocoite	“	$PbCrO_4$	Monoclinic
Wulfenite	“	$PbMoO_4$	Tetragonal
Pyromorphite	“	$Pb_5Cl(PO_4)_3$	Hexagonal
Vanadinite	“	$Pb_5Cl(VO_4)_3$	Hexagonal

The lead of commerce is derived very largely from galena; next in importance is cerussite; anglesite is important in a few localities; pyromorphite is rarely important. In a few mines ores containing all the last three minerals are used.

The chief use of lead is in storage batteries, which take about 30 per cent of the output. Second only to this is the use of lead in making pigments, including white lead (basic carbonate), sublimed white lead (lead sulfate 75 per cent, lead oxide 20 per cent, zinc oxide 5 per cent), sublimed blue lead (lead sulfate about 50 per cent, lead oxide about 40 per cent and a little lead sulfide, lead sulfite, and zinc oxide), red lead (Pb_3O_4), and litharge (PbO). The sublimed lead pigments are made directly from ores; the others are made from pig lead. Large amounts of red lead and litharge are used in storage batteries.

The United States produces about 25 per cent of the world supply of lead. Other large producers are Australia, Mexico, Canada, and Germany. In this country the largest production comes from Missouri, Idaho, and Utah. The amount of lead produced in this country annually from domestic ores has varied greatly during the last twenty years, from an all-time maximum of 680,000 tons in 1926 to a minimum of 250,000 in 1932.

Manganese

The important manganese minerals are:

Pyrolusite	dominantly	MnO_2	Tetragonal
Braunite	"	Mn_2O_3	Tetragonal
Manganite	"	$Mn_2O_3 \cdot H_2O$	Monoclinic
Rhodochrosite	"	$MnCO_3$	Hexagonal
Hausmannite	"	Mn_3O_4	Tetragonal
Psilomelane	"	$H_4(Ba,Mn,Ca,Cu,Pb)_2$ Mn_8O_{20}?	Orthorhombic
Wolframite	"	$(Fe,Mn)WO_4$	Monoclinic
Franklinite	"	$(Fe,Mn,Zn)Fe_2O_4$	Isometric
Columbite	"	$(Fe,Mn)(Nb,Ta)_2O_6$	Orthorhombic

The most important manganese silicates are rhodonite ($MnSiO_3$), tephroite (Mn_2SiO_4), and spessartite ($Mn_3Al_2Si_3O_{12}$).

The chief ores of manganese are the various oxides and the carbonate.

Manganese is a strategic war mineral of the first importance in the United States, because this country uses about one third of the world's output and produces very little, and also because the use of manganese is so important in the production of steel. There is no satisfactory substitute known for the fourteen pounds of manganese used in making each ton of steel. For such use manganese is actually employed in an alloy, either *spiegeleisen* or *ferro-manganese;* the former contains about 20 per cent manganese, and the latter about 80 per cent manganese (each with iron). Spiegeleisen is used in the Bessemer process and ferromanganese in the open-hearth process of steel making. Manganese is used to deoxidize and desulfurize the iron and improve the rolling and forging qualities and the hardness of the steel.

The three sources of manganese (aside from scrap) are: manganese ores proper, which contain 35 to 50+ per cent of manganese; manganiferous iron ores, which contain 5–35 per cent of manganese; and manganiferous zinc residues, which are smelted to spiegeleisen.

About half of the world's supply of manganese comes from the Caucasus region of Russia, but imports into this country come not only from Russia, but from the Gold Coast, Cuba, India, and elsewhere.

Manganese ores are obtained in this country in Tennessee, Arkansas, Montana, Georgia, and Virginia; manganiferous iron ores come chiefly from Minnesota, and manganiferous zinc residues chiefly from New Jersey.

Iron

The chief minerals containing iron are:

Native iron	dominantly	Fe	Isometric
Pyrrhotite	"	FeS	Hexagonal
Pentlandite	"	(Fe,Ni)S	Isometric
Pyrite	"	FeS_2	Isometric
Marcasite	"	FeS_2	Orthorhombic
Arsenopyrite	"	FeAsS	Monoclinic
Chalcopyrite	"	$CuFeS_2$	Tetragonal
Bornite	"	Cu_5FeS_4	Isometric
Hematite	"	Fe_2O_3	Hexagonal
Ilmenite	"	$FeTiO_3$	Hexagonal
Limonite	"	$Fe_2O_3 \cdot H_2O$	Orthorhombic
Siderite	"	$FeCO_3$	Hexagonal
Wolframite	"	$(Fe,Mn)WO_4$	Monoclinic
Melanterite	"	$FeSO_4 \cdot 7H_2O$	Monoclinic
Magnetite	"	$FeFe_2O_4$	Isometric
Spinel	"	$(Fe,Mg)(Al,Cr)_2O_4$	Isometric
Columbite	"	$(Fe,Mn)(Nb,Ta)_2O_6$	Orthorhombic

The most important iron silicates are garnet $\{(Mg,Fe,Mn)_3(Al,Fe)_2Si_3O_{12}\}$, olivine $\{(Mg,Fe,Mn)_2SiO_4\}$, staurolite $\{2Al_2SiO_5 \cdot 2Fe(OH)_2\}$, tourmaline $\{H_4Na(Mg,Fe)_3B_3Al_6Si_6O_{31}\}$, cordierite $\{(Mg,Fe)_2Al_4Si_5O_{18}\}$, enstenite $\{(Mg,Fe)SiO_3\}$, pyroxene $\{Ca(Mg,Fe)Si_2O_6$, etc.$\}$, anthophyllite $\{H_2(Mg,Fe)_7Si_8O_{24}\}$, hornblende $\{H_2NaCa_2(Mg,Fe)_4Al_3Si_6O_{24}$, etc.), biotite $\{H_4K_2(Mg,Fe)_6Al_2Si_6O_{24}$, etc.$\}$, chlorite $\{H_4(Mg,Fe)_2Al_2SiO_9$, etc.$\}$, epidote $\{HCa_2(Al,Fe)_3Si_3O_{13}\}$, and allanite $\{H(Ca,Ce)_2(Al,Fe''',Fe'')_3Si_3O_{13}\}$.

Iron and coal are the very foundation of modern industrial civilization. Practically all machines are made largely or wholly of iron, and coal is the chief source of power to operate the machines.

The output of iron is about fifty times as great (by weight) as that of copper and seventy times as great as that of lead or zinc. In value it is more than three times as great as the gold output, four times the copper, nine times the aluminum, twelve times the zinc, and fifteen times the lead output.

In this country iron is obtained only from hematite, limonite, magnetite, and siderite; in Europe it is obtained, in part, from *chamosite* (a variety of chlorite) and from pyrite.

About sixty per cent of the domestic production comes from Minnesota; other large producers are Michigan, Alabama, New York, Wisconsin, Wyoming, and New Jersey.

The United States leads the world in the production of iron and steel, followed by France, Russia, Sweden, England, and Germany.

Cobalt

The chief minerals containing cobalt are:

Smaltite	dominantly	$CoAs_2$	Isometric
Cobaltite	"	$CoAsS$	Isometric

Cobalt is a metal of limited use at present; it is employed in making high speed tools, as a catalyst, and in electroplating. Cobalt oxide is used in ceramics and cobalt salts in various paints and varnishes. Stellite is an alloy of cobalt, chromium, and tungsten.

Cobalt is not produced in this country; small amounts of ore come from French Morocco, Burma, Belgian Congo, and Canada.

Nickel

The important nickel minerals are:

Millerite	dominantly	NiS	Hexagonal
Pentlandite	"	$(Ni,Fe)S$	Isometric
Niccolite	"	$NiAs$	Hexagonal
Chloanthite	"	$NiAs_2$	Isometric
Garnierite	"	$H_4(Mg,Ni)_3Si_2O_9$	Monoclinic

Nickel is used chiefly in various alloys; for example, *German silver* is an alloy of copper, nickel, and zinc containing about

20–30 per cent of nickel; *Monel* consists of 67 per cent nickel, 28 per cent copper, and 5 per cent other metals; and our copper coinage is 25 per cent nickel. Nickel steel containing 2 to 3.5 per cent nickel has increased elasticity and tensile strength. *Invar* (iron with 36 per cent nickel) is not affected by temperature changes and is therefore used for precision instruments, pendulums, and steel tapes; *nichrome* (an alloy of nickel and chromium) is used in electrical resistance apparatus, crucible triangles, etc.; permalloy (80 per cent iron and 20 per cent nickel) is used in cables for transmitting messages under the sea.

There are no nickel mines in the United States, but the equivalent of about 300 tons of nickel are obtained annually as a by-product of copper refining. Ninety per cent of the world's supply of nickel is obtained from the Sudbury district in Canada, and the remainder comes from New Caledonia.

Platinum

The only important platinum mineral is:

Native platinum	dominantly Pt	Isometric

Platinum was at one time used for coinage in Russia. It is now used in jewelry as a setting for diamonds and other precious stones, as a catalyst in the production of sulfuric acid, as a lining for processing and reaction vessels, in the hydrogenation of organic compounds, in making laboratory equipment of many kinds, in dental work, in thermo-couples, spark-plug electrodes, etc. In some of these platinum is used in an alloy with iridium (also palladium in some cases).

Platinum metals are obtained in large quantities as by-products of the refining of nickel-copper and other mattes in Canada. Large quantities are also obtained from placers in Russia and South Africa. The production in this country is increasing, but is still quite inadequate.

Acidic Division

Fluorine

The important fluorine minerals are:

Fluorite	dominantly	CaF_2	Isometric
Cryolite	"	Na_3AlF_6	Monoclinic
Apatite	"	$Ca_5FP_3O_{12}$	Hexagonal

The most important silicates containing fluorine are: topaz $\{Al_2(F,OH)_2SiO_4\}$, chondrodite $\{Mg_4(F,OH)_2Si_2O_8\}$, apophyllite $(4CaSi_2O_5 \cdot KF \cdot 8H_2O)$, and lepidolite $(K_2Li_3Al_5Si_6O_{20}F_4)$.

Fluorite is an important flux for iron ores and about 65 per cent of the consumption in this country is used in making basic open-hearth steel. It is also used in making hydrofluoric acid and derivatives, in making glass, enamel, ferroalloys, and so on. The domestic production of about 150,000 short tons is obtained chiefly from Illinois and Kentucky. About 60 per cent of the world production comes from the United States and Germany, with Russia, England, and France supplying about 30 per cent.

Chlorine

The chief chlorine minerals are:

Halite	dominantly	$NaCl$	Isometric
Sylvite	"	KCl	Isometric
Cerargyrite	"	$AgCl$	Isometric
Carnallite	"	$KMgCl_3 \cdot 6H_2O$	Orthorhombic
Apatite	"	$Ca_5ClP_3O_{12}$	Hexagonal
Pyromorphite	"	$Pb_5ClP_3O_{12}$	Hexagonal
Vanadinite	"	$Pb_5ClV_3O_{12}$	Hexagonal

The most important silicates containing chlorine are: sodalite $(3NaAlSiO_4 \cdot NaCl)$, scapolite $(3NaAlSi_3O_8 \cdot NaCl)$.

Halite is obtained commercially from "rock salt" beds or from the evaporation of brines. Rock salt beds are widely distributed in this country and are furnishing important amounts of halite, especially in New York, Texas, Illinois, Kansas, and New Jersey. Large amounts of salt are used in brine (without extraction)—indeed about half the total domestic output is used in this way. There are hundreds of uses of salt and many of them are in the making of chemicals. Chlorine derived from salt is used in large quantities; for example, 145,000 tons in pulp and paper, 80,000 tons in dyes and organic chemicals, and 45,000 tons in heavy chemicals.

The United States produces more salt than any other country; other large producers are Russia, China, Germany, Great Britain, British India, France, and Italy.

Sulfur

The important sulfur minerals are:

Native sulfur	dominantly	S	Orthorhombic
Pyrite	"	FeS_2	Isometric
Marcasite	"	FeS_2	Orthorhombic

Sulfur is an essential constituent of all sulfides, sulfosalts, and sulfates; indeed an important portion of the annual output of sulfuric acid is a by-product from zinc and copper ores. Lazurite, a variety of sodalite, is a silicate containing some sulfur.

Nearly three fourths of the sulfur produced in this country is used to make sulfuric acid, and about 60 per cent of the acid produced comes from native sulfur, the remainder being obtained as a by-product of the treatment of copper and zinc ores or from the roasting of pyrite. About a quarter of the sulfuric acid produced is used in fertilizers, about a seventh in petroleum refining, another seventh in iron and other metallurgy, and about a ninth in making various chemicals, and the rest in coal products, paints and pigments, rayon and cellulose, explosives, textiles.

Sulfur not used in making acid goes into the making of paper, insecticides, food preservatives, rubber, and so on. Sulfur is a prominent constituent of several new rubber compounds; one of these is easily dissolved in acid and reprecipitated without losing its rubberlike properties—this provides an easy way to rubberize cloth.

The United States produces about 70 per cent of the world output of native sulfur, much of the remainder coming from Sicily. The domestic production comes chiefly from Texas and Louisiana. Norway leads the world in the production of pyrite, followed by Italy, Portugal, the United States, Cyprus, and Germany. By-product sulfur and sulfuric acid are produced in large quantities in Germany and the United States.

Chromium

The important chromium minerals are:

Chromite	dominantly	$FeCr_2O_4$	Isometric
Crocoite	"	$PbCrO_4$	Monoclinic

Some chromium is to be found in varieties of a few silicates, including tourmaline $\{H_4Na(Mg,Fe)_3B_3(Al,Cr)_6Si_6O_{31}\}$, chrome diopside, and so on.

About 85 per cent of the output of chromium goes into the steel industry as refractory material, plating, or cement, or as ferro-chrome to make rust- and heat-resisting alloys. Chrome steel is used in the manufacture of armor plate, armor piercing projectiles, and high-speed steel tools. Nichrome is an alloy containing 60 per cent nickel and 14 per cent chromium; stellite contains cobalt, chromium, and tungsten or molybdenum. Considerable chromite is also used to make chemicals employed in dyeing, tanning, and pigment industries. The world supply of chromite comes chiefly from Russia, Turkey, Rhodesia, South Africa, and the Philippines. The United States uses about one third of the world output and produces about one tenth as much as it uses.

Molybdenum

The important molybdenum minerals are:

Molybdenite	dominantly	MoS_2	Hexagonal
Wulfenite	"	$PbMoO_4$	Tetragonal

Molybdenum is obtained almost entirely from molybdenite. The United States produces more than 90 per cent of the world output of molybdenum; it is obtained chiefly in Colorado and New Mexico. The chief use of molybdenum is in special grades of steel of high tensile strength and superior ability to retain temper at high temperature. Manganese-molybdenum steels are coming into wider usage, for example in pump power gears and expansion joints for pipe lines.

Tungsten

The chief tungsten minerals are:

Scheelite	dominantly	$CaWO_4$	Tetragonal
Wolframite	"	$(Fe,Mn)WO_4$	Monoclinic

Scheelite is the chief ore of tungsten at present mined in this country; wolframite is the chief ore in most other countries. The world output of tungsten comes chiefly from China (nearly half), United States, Portugal, and Bolivia. In this country the largest production comes from Nevada and California. Tungsten is used chiefly in making high-speed tool steels, which keep their temper even when heated. Such steels contain about 18 per cent tungsten, 4.5 per cent chromium, and 0.6 per cent vanadium. Tungsten is also used to make cemented carbides and electric light and radio-tube filaments. Tungsten salts are used in chemical, pigment, and tanning industries.

Uranium

The important uranium minerals are:

Uraninite	dominantly	U_3O_4?	Isometric
Carnotite	"	$K_2O \cdot 2UO_3 \cdot V_2O_5 \cdot 3H_2O$	Orthorhombic

The chief use of uranium is in the ceramic industry, in which it is used to produce yellow, brown, gray, and orange colors. Alloys of uranium with iron and aluminum have very limited uses. In special steels a small amount of uranium may take the place of tungsten. But the most unusual use of uranium is as an illuminant; it is then mixed with artificial zinc sulfide and some cementing material such as amyl acetate. The radium which is derived from uranium gives off alpha rays, which cause the particles of zinc sulfide to glow. Attempts are being made to obtain an enormous source of energy by concentrating isotope 235 (1 per cent of uranium) and then splitting its atoms.

The world output of uranium comes chiefly from the Belgian Congo and Canada; moderate amounts are obtained also in Czechoslovakia, Portugal, and the United States. In this country the output is chiefly from Colorado.

Nitrogen

The only important nitrogen mineral is:

Soda niter	dominantly	$NaNO_3$	Hexagonal

Nitrogen is an essential constituent of all nitrates, but it is obtained only from soda niter and from the atmosphere. Soda niter is obtained in small quantities associated with guano in caves, but the only source of commercial quantities is in the arid regions of northern Chile. Imports of soda niter (or Chile saltpeter) reach 800,000 tons annually. It is used principally as a fertilizer and also in the manufacture of nitric and sulfuric acids. Commerce obtains about ten times as much nitrogen from the atmosphere as is derived from soda niter. This nitrogen is made available for use by causing it to unite with oxygen in the flaming electric arc; the nitric acid thus obtained is changed to calcium nitrate by reaction with limestone. By another process nitrogen is united with calcium carbide to produce calcium cyanamide, also for use as a fertilizer.

Phosphorus

The chief phosphorus minerals are:

Collophanite	dominantly	$Ca_3P_2O_8 \cdot nH_2O$	Amorphous
Apatite	"	$Ca_5(F,Cl,OH)P_3O_{12}$	Hexagonal
Pyromorphite	"	$Pb_5ClP_3O_{12}$	Hexagonal
Monazite	"	$(Ce,La,Di)PO_4$	Monoclinic
Amblygonite	"	$LiAl(F,OH)PO_4 \cdot (\frac{1}{4}H_2O?)$	Triclinic
Wavellite	"	$(AlOH)_3P_2O_8 \cdot 5H_2O$	Orthorhombic
Turquois	"	$CuO \cdot 3Al_2O_3 \cdot 2P_2O_5 \cdot 9H_2O$	Triclinic

Phosphorus is an essential constituent of all phosphates, but it is obtained only from apatite and closely related calcium phosphates.

Phosphorus (in phosphates) is decidedly the most important mineral fertilizer, plant life requiring soluble phosphates, and the quantity in ordinary soil being insufficient for most crops. The fertilizer is obtained chiefly from "phosphate rock," which contains one or more calcium phosphates. By treating the ground phosphate rock with sulfuric acid a superphosphate is produced, which is readily used by plants. The world output of phosphate rock comes chiefly from French Africa (Tunis, Algiers, and Morocco), the United States, Russia, Ocean and Nauru Islands, and Egypt. The domestic supply comes chiefly from Florida and Tennessee. Vast quantities are available in Idaho, Montana and Utah, but production from this region is small because it is far from the markets.

Vanadium

The important vanadium minerals are:

Patronite	dominantly	V_2S_5	?
Vanadinite	"	$Pb_5ClV_3O_{12}$	Hexagonal
Carnotite	"	$K_2O \cdot 2UO_3 \cdot V_2O_5 \cdot 3H_2O$	Orthorhombic
Roscoelite	"	$H_4K_2(Mg,Fe)(Al,V)_4Si_7O_{24}$	Monoclinic

Patronite is a sulfide of vanadium of uncertain formula, obtained in Peru, which was once the chief source of the element. It is now a source of vanadium in Rhodesia. But most of the world output is obtained from other minerals, including hydrous calcium vanadates, and a hydrous sulfate. In this country the chief supply comes from roscoelite and carnotite.

The most important use of vanadium is in making special steel and iron alloys. It is used in making high speed tool steels and constructional steel of many kinds in both wrought and cast forms. For these purposes vanadium is used with iron as high-carbon and low-carbon ferroalloys. Vanadium is also used to refine the grain of certain types of cast and heat-treated aluminum alloys. In the chemical industry vanadium pentoxide is used as a catalyst to stimulate oxidation and dehydrogenation.

The world output of vanadium comes chiefly from Peru, the United States, South West Africa, Rhodesia, and Mexico. In this country it is obtained chiefly in Colorado, Arizona, and Utah.

Niobium (columbium) and tantalum

The only important mineral containing niobium (and tantalum) is:

Columbite	dominantly $(Fe,Mn)(Nb,Ta)_2O_6$	Orthorhombic

Niobium (columbium) reduces intergranular corrosion of high chromium steels and is therefore used in making weldable high-speed steels; for this use ferrocolumbium is employed. Columbium metal is used in electronic tubes.

Tantalum was used for a few years, 1903 to 1911, for incandescent electric-light bulb filaments; tungsten is now used for that purpose. Tantalum is remarkably resistant to acid corrosion and is used in chemical process equipment; it is also used for anodes or plates in electronic tubes, and also as support rods and grids. Owing to its hardness and high melting point tantalum carbide is a constituent of hard cutting tool mixtures.

Columbite is obtained from Nigeria and the Pilbarra district of Australia. Small amounts have been obtained also in the Black Hills of South Dakota.

Arsenic

The important arsenic minerals are:

Native arsenic	dominantly	As	Hexagonal
Realgar	"	AsS	Monoclinic
Orpiment	"	As_2S_3	Monoclinic
Niccolite	"	NiAs	Hexagonal
Cobaltite	"	CoAsS	Isometric
Smaltite	"	$(Co,Ni)As_2$	Isometric
Arsenopyrite	"	FeAsS	Monoclinic
Proustite	"	Ag_3AsS_3	Hexagonal
Enargite	"	Cu_3AsS_4	Orthorhombic
Tennantite	"	$Cu_{10}Zn_2As_4S_{13}$?	Isometric

As an element arsenic has very limited uses, the chief one being as a hardener of lead in the manufacture of shot. It may be used also in making bearing metal alloys and wiping solder.

The "arsenic" of commerce is arsenious oxide, As_2O_3, often called white arsenic. This is used chiefly as an insecticide, as a weed killer (by railroads), as a wood preservative, in making glass, and in chemicals.

Most of the white arsenic used in commerce is obtained as a by-product of the treatment of copper, gold, silver, and lead ores. The arsenic is recovered from flue, baghouse, and Cottrell dusts, etc. The United States leads the world in the production of white arsenic, followed by Mexico, Germany, and Sweden.

Antimony

The chief antimony minerals are:

Stibnite	dominantly	Sb_2S_3	Orthorhombic
Pyrargyrite	"	Ag_3SbS_3	Hexagonal
Bournonite	"	$CuPbSbS_3$	Orthorhombic
Tetrahedrite	"	$Cu_{10}Zn_2Sb_4S_{13}$	Isometric

Stibnite is the most important antimony mineral. Considerable antimony is obtained from by-product antimonial drosses obtained in lead refining. One of the principal uses of antimony is in making storage batteries; another important use is in babbitt metal (used for bearings), which commonly consists of antimony, tin, and copper. Type metal consists of lead, antimony, tin, and copper. Antimony oxide is used in making white enamel and similar wares. Antimony sulfide is employed in vulcanizing rubber and as a pigment. Some antimony salts are used in medicines and in dyeing.

The United States uses much more antimony than it produces; the world output comes largely from China, Mexico, Bolivia, and Czechoslovakia.

Bismuth

The chief bismuth minerals are:

Native bismuth	dominantly	Bi	Hexagonal
Bismuthinite	"	Bi_2S_3	Orthorhombic

Bismuth is used chiefly in various alloys; its function in some of these is to lower the melting point, and also, in some cases, to prevent change of volume on solidifying. This depends on the fact that pure bismuth expands 3.32 per cent when it solidifies, while metals generally contract. The melting point of some bismuth alloys is as low as 150°F. Low melting point and nonshrinking bismuth alloys have numerous uses, for example, in boiler plugs and automatic sprinklers for fire protection, in solders, dental models, duplicating patterns, and so on. Bismuth salts are opaque to Roentgen rays and are therefore useful in X-ray examination of the alimentary tract. They are also used in dressing wounds, in calico printing, and in making highly refractive glass.

No mines are worked primarily for bismuth; the entire supply is obtained as a by-product of the electrolytic refining of lead and copper ores, the bismuth being recovered from the anode slimes. Consumption in this country amounts to about 500,000 pounds annually. It is obtained chiefly in the United States, Peru, Canada, and Mexico.

Carbon

The chief carbon minerals are:

Diamond	dominantly	C	Isometric
Graphite	"	C	Hexagonal
Calcite	"	$CaCO_3$	Hexagonal
Dolomite	"	$CaMgC_2O_6$	Hexagonal

Of course carbon is an essential constituent of all carbonates, but only calcite and dolomite are used as sources of carbon dioxide.

About 65 per cent of the world output of diamonds (gems and industrial) is now obtained from the Belgian Congo, but South Africa produces most of the gems. This country buys about a third of the world output of diamond gems, the domestic production being negligible.

Flake graphite is obtained chiefly from Ceylon and Madagascar. So-called "amorphous" graphite is obtained in large quantities in Russia, Germany, Chosen, and Mexico. Small amounts of both kinds are mined in this country, especially in New York, Rhode Island, and Nevada. The world output amounts to about 200,000 tons annually.

Carbon dioxide is obtained from wells and as a by-product gas from the treatment of calcite or dolomite to produce lime or cement. In commerce solid carbon dioxide is known as "dry ice"; it is used chiefly in the ice-cream industry, but also in treating and making frozen foods, and in medicine.

Certain other substances are not minerals, in the strict sense of the word; in the broader sense they are always included, as in the phrase "mineral resources." The most important substances of this kind belong to two series, namely, natural gas-asphalt and peat-anthracite. Both of these series are probably derived from the decay of organic material.

Natural gas varies widely in composition as obtained in different sections of the country and at different horizons in the same region. All commercial natural gas is composed largely of hydrocarbons. Of these methane, or marsh gas, is usually by far the most abundant; others often present include ethane, propane, butane, hexane, and heptane. These increase the luminosity of the burning gas. Natural gas containing pentane, hexane, and heptane is fit to yield natural gasoline. Certain Kansas natural gases contain 25 or even 55 per cent of nitrogen, but most natural gases contain at least 90 per cent of hydrocarbons. Natural gas from Petrolia, Texas, contains about 1 per cent helium. More than 2.4 million million cubic feet of gas were produced and used in this country in 1939, chiefly from Texas, California, Louisiana, and Oklahoma. This country leads the world in production of natural gas. It is used for light, heat, and fuel for power purposes.

Petroleum, like natural gas, is composed largely of hydrocarbons, especially methane; other types of hydrocarbons are also present such as ethylene or benzene. Petroleum usually contains minor amounts of sulfur, oxygen, nitrogen, etc. Petroleum occurs in rocks of nearly all geological ages from the Silurian to the present. Like natural gas, it accumulates only in porous rocks which are covered by nonporous rocks; the porous rocks must also be above a source of hydrocarbons, such as a bituminous shale. Petroleum is used for light, heat, and fuel for power, and also as a source, by distillation, of many refined products.

The United States produces about 60 per cent of the world output of petroleum; other large producers are Russia and Venezuela. In this country the production comes largely from Texas, California, and Oklahoma.

Asphalt or mineral pitch is an indefinite mixture of various hydrocarbons, some partly oxygenated. It also commonly contains sulfur and variable amounts of mineral matter, such as sand and clay. Asphalt has a pitch-like color and luster and a bituminous odor. It melts ordinarily at 90°–100° and burns with a bright flame. It is soluble partly or wholly in turpentine, ether, carbon disulfide, or even alcohol. There is a complete gradation from petroleum to asphalt. Asphalt is found usually at or near the earth's surface, but related substances such as elaterite, manjak, gilsonite, etc., are found in veins at some depth. The most famous occurrence of asphalt is on the island of Trinidad, where it forms a "lake" about 1.5 miles in circumference. This is the chief source of native asphalt. Much asphalt is obtained as a residue from the distillation of asphaltic oils; from this source the United States produces about 60 per cent of the world output of asphalt. It is used chiefly in paving and roofing.

Coal is produced through the accumulation and decomposition of plant debris out of reach of the oxidizing effects of the air, probably at least in part under cold damp swamp conditions.

Peat is the first product of the process and in peat plant fibers are easily recognized. Peat is forming today in many places in the temperate and frigid zones, including parts of the Lake Superior region, Ireland, Alaska, etc. Peat is generally less homogeneous than coal. It is used in large quantities as a fuel where other fuels are expensive, as in some parts of Europe. It is also used as a fertilizer in this country; about 50,000 tons are used annually in this way. The reserves available in this country total more than 13,000 million tons, largely in Minnesota, Wisconsin, and Michigan. Millions of tons of peat are used annually in Russia.

Lignite or brown coal is the next step in the production of coal from plants. It usually contains 10–25 per cent moisture, 35–45 volatile matter, 35–45 fixed carbon, and 5–15 ash. The color is brown to black. *Jet* is a black compact variety taking a good polish and used in cheap jewelry. Lignite is abundant in North and South Dakota, Montana, and Texas; it is found also in Alabama, Mississippi, Louisiana, and Arkansas. But the most important lignite deposits in the world, because the most used, are in Germany, where about three fourths of the world output is utilized. Lignite is used like other kinds of coal for fuel and power; it is especially valuable as a source of gas.

Bituminous coal commonly contains 40–80 per cent fixed carbon, 15–40 per cent volatile matter, 2–10 per cent moisture, and 3–10 per cent ash. It has a black color, greasy luster, and compact texture. It burns with a yellow flame and gives hydrocarbons on distillation. There are two main types of bituminous coal, namely cannel coal and boghead coal, but there are all gradations between them. Cannel coal is derived chiefly from spores, pollen, and similar material. Boghead coal is derived chiefly from leaves, stems, roots, and bark (collectively known as lignin). Cannel coal has high total carbon, but low fixed carbon. Coking coal is of any composition that will yield coke on heating, the volatile gases escaping and the remainder becoming strongly coherent.

Bituminous coal is found in rocks of all ages from the Carboniferous to the Tertiary. It is abundant in Pennsylvania, West Virginia, Ohio, Indiana, Illinois, Alabama, Kentucky, Iowa, Colorado, Wyoming, and elsewhere. This country produces about a third of the world output; other large producers are England and Germany. The largest production in this country comes from West Virginia, Pennsylvania, Kentucky, and Illinois. Bituminous coal is used in great quantities for heat and power.

Anthracite contains more than 93 per cent fixed carbon; ("semianthracite" is the name applied to coal intermediate between bituminous and anthracite, that is, having 80–93 per cent fixed carbon). Anthracite is black with a bright iron black submetallic luster; it burns with a blue flame. It is abundant in only one region in America and that is in eastern Pennsylvania. The domestic production is more than 40 per cent of the world output. It is also obtained in Russia, France, England, Belgium, and Germany. Anthracite is used chiefly for fuel, but also for purification of water. Anthracite ash is finding use in building materials and as a soil conditioner.

Boron

The chief boron minerals are:

Boracite	dominantly	$Mg_2ClB_7O_{13}$	Orthorhombic
Ulexite	"	$NaCaB_5O_9 \cdot 8H_2O$	Monoclinic
Kernite	"	$Na_2B_4O_7 \cdot 4H_2O$	Monoclinic
Borax	"	$Na_2B_4O_7 \cdot 10H_2O$	Monoclinic
Colemanite	"	$Ca_2B_6O_{11} \cdot 5H_2O$	Monoclinic
Datolite	"	$HCaBSiO_5$	Monoclinic
Tourmaline	"	$H_4Na(Mg,Fe)_3B_3Al_6Si_6O_{31}$, etc.	Hexagonal

Borax is the most important compound of boron in commerce, but it is not the most abundant in nature; most of the borax of commerce has been made from kernite, colemanite, ulexite or other borates. Borax is an excellent preservative and also a very good cleansing material. It is also used in blowpipe work, in soldering, in welding, in assaying, etc. But much more is now used in making glassware and enamels for pottery. It is a constituent of strass or paste used in making artificial gems. It is used in calico printing and in tanning and preparing furs. Boron is an element which stimulates plant growth; so small amounts are now used in fertilizers.

More than 90 per cent of the world output of borax comes from this country—that is, from California and Nevada. Small amounts are obtained in Argentina, Italy, and Turkey. In Italy volcanic gases yield boric acid, and also ammonia, and carbon dioxide.

7

Determinative Mineralogy

Minerals can be identified by means of their chemical and physical characteristics. Chemical tests alone are not sufficient to identify all minerals because a single chemical substance, or compound, may exist as two or three or more minerals. For example, carbon exists in nature as the mineral known as diamond and also as the mineral called graphite; these are two minerals exactly alike chemically, but very different in their physical characters and uses. Again, titanium dioxide (one compound) is the sole component of *three* different minerals; rutile, anatase, and brookite; and silicon dioxide is the sole component of several minerals, including α-quartz, β-quartz, α-tridymite, β-tridymite, α-cristobalite, β-cristobalite, and perhaps other phases.

Physical tests alone are also often insufficient to identify minerals. Thus, many different minerals are red (or any other color); many have practically the same specific gravity; many have the same crystal habit and cleavage, etc. Even by using several of these physical characters it is sometimes not possible or at least not easy to determine the nature of an unknown mineral without making some chemical tests. In general, physical tests can be made more quickly than chemical, and therefore tables based primarily upon physical characters are now more useful than those based upon chemical tests. However the student should plan in many cases to use both kinds of tests.

Many minerals vary a great deal in composition and therefore vary in both chemical and physical characters. That which is most nearly invariant for any single mineral is its crystal structure; even that may vary a little. For any given conditions of temperature and pressure there are definite limits to the possible variations of composition and characters for each mineral. In this book a mineral is defined so as to include the entire range of these variations for ordinary temperatures and pressures.

Streak and Specific Gravity

Properties of minerals can be determined accurately only from pure homogeneous material, and such material is rarely available except as crystals, or, at least as crystalline pieces. Even a tiny fragment of pure material is more useful than a large mass of impure substance. If no pure material can be obtained, the next best thing is to know the nature (and per cent, if possible) of the impurity and make proper allowance for it in connection with all tests. For example, pure talc has a hardness of 1, but talc with some kaolinite or sepiolite has a hardness of about 2, and, with a little quartz or opal of 3 to 4; these impurities have only a small effect upon the specific gravity, and still less on the color. On the other hand siderite has a hardness of 3.5–4 and specific gravity of 3.8–3.9; the pure mineral has a gray color; it alters easily, especially on the surface, to limonite, a very small amount of which changes the color to yellow, brown or black, though having very little effect on the hardness or specific gravity.

Minerals in a finely fibrous or minutely granular (powdery or earthy) condition seem to be softer and lighter than they really are. They appear lighter than they are because they are porous; their specific gravity cannot be measured correctly with a Jolly balance; a pycnometer gives good results if the air is carefully removed from the pores by an air pump.

A few minerals have definite colors, but most minerals vary widely in color, even when pure; for example, pure pyroxene and pure amphibole may be colorless, green, yellow, brown or black. All minerals are subject to variations in color owing to the presence of impurities; thus, pure quartz is colorless or white, but quartz is often stained so as to be yellow, brown, pink, purple, red, green, or smoky on account of impurities, so scanty in many cases that their nature is uncertain and their effects on hardness and specific gravity cannot be measured. Therefore color is not a good basis on which to identify minerals.

But the streak, or color of the fine powder, of a mineral is remarkably constant for most minerals, no matter what the color of the mass may be. Minerals with an iron-black, steel-gray or silver-white streak have a metallic luster and are opaque even in thin splinters. These facts make it easy in most cases to distinguish them from all other minerals. Only a few minerals illustrate the fact that there is a gradation even in this property (from opaque to translucent, and from iron-black to brownish black, etc.).

Accordingly, the first table is based on the streak of minerals. Secondarily, it is based on their specific gravity, methods of measuring which are described on pages 126–130.

Outline of Table I

MINERALS WITH IRON-BLACK, STEEL-GRAY, OR SILVER-WHITE STREAK

1. Specific gravity 1.9–4.7
2. Specific gravity 4.7–5.5
3. Specific gravity 5.6–6.3
4. Specific gravity 6.4–7.7
5. Specific gravity 7.8–19.0

MINERALS WITH BLUE OR GREEN STREAK

1. Specific gravity 2.0–2.5
2. Specific gravity 2.5–3.0
3. Specific gravity 3.0–4.0
4. Specific gravity 9.0–10.0

MINERALS WITH YELLOW, BROWN, OR RED STREAK

1. Specific gravity 2.0–3.0
2. Specific gravity 3.0–3.6
3. Specific gravity 3.6–4.7
4. Specific gravity 4.7–5.7
5. Specific gravity 5.7–7.2
6. Specific gravity 7.2–19.3

MINERALS WITH COLORLESS, WHITE (OR VERY PALE) STREAK

1. Specific gravity 0.9–2.0
2. Specific gravity 2.0–2.2
3. Specific gravity 2.2–2.3
4. Specific gravity 2.3–2.4
5. Specific gravity 2.4–2.5
6. Specific gravity 2.5–2.6
7. Specific gravity 2.6–2.7
8. Specific gravity 2.7–2.8
9. Specific gravity 2.8–2.9
10. Specific gravity 2.9–3.0
11. Specific gravity 3.0–3.1
12. Specific gravity 3.1–3.2
13. Specific gravity 3.2–3.3
14. Specific gravity 3.3–3.4
15. Specific gravity 3.4–3.5
16. Specific gravity 3.5–3.6
17. Specific gravity 3.6–3.9
18. Specific gravity 3.9–4.3
19. Specific gravity 4.3–5.7
20. Specific gravity 5.7–7.2

Table I. Streak and Specific Gravity

TABLE I. STREAK AND SPECIFIC GRAVITY

1. MINERALS WITH IRON-BLACK, STEEL-GRAY, OR SILVER-WHITE STREAK

G.	H.	Name	Composition	System	Cleavage	Color	Streak	Page
1.9–4.7								
1.9–2.3	1–2	Graphite (Black lead, Plumbago)	C, often with Fe, clay	Hex.	Basal perfect	Steel-gray to iron-black	Grayish black	233
3.7–4.7	5–6	Psilomelane	MnO_2, H_2O, BaO, K_2O, etc.	Amor.	None	Iron-black to steel-gray	Black, brownish black	284
4.0–4.5	5–6	Ilmenite (Titanic Iron Ore)	$FeTiO_3$, often with Mg, Fe'''	Rhom.	None	Iron-black	Iron-black	261
4.1–4.3	3.5	Chalcopyrite (Copper Pyrites)	$CuFeS_2$	Tetr.	(201), poor	Brass-yellow	Greenish black	241
4.2–4.4	4	Manganite	$MnO{\cdot}OH$	Orth.	010, (110)	Steel-gray	Reddish brown to black	268
4.3–4.5	4	Stannite	Cu_2FeSnS_4	Tetr.	Indistinct	Steel-gray	Black	249
4.4–4.5	3	Enargite	Cu_3AsS_4, often with Sb	Orth.	(110) prismatic perfect at 82°	Grayish to iron-black	Grayish to iron-black	251
4.4–5.1	3–4	Gray Copper (Tetrahedrite, Tennantite)	$Cu_{10}(Zn,Fe)_2(Sb,As)_4S_{13}$ often with Ag, Hg, Pb	Isom. Tetrah.	None	Steel-gray to iron-black	Steel-gray to iron-black	248
4.4–5.2	5.5–6.5	Magnetite	$(Fe,Mg,Zn,Mn)Fe_2O_4$	Isom.	(111) parting	Iron black	Black, brown	302
4.5–4.6	2	Stibaite (Antimony Glance)	Sb_2S_3	Orth.	010 pinacoidal perfect	Lead gray	Lead-gray	245
4.5–4.6	1.5–2	Covellite	CuS	Hex.	Basal perfect	Indigo blue	Lead-gray	244
4.5–4.65	3.5–4.5	Pyrrhotite (Magnetic Pyrites)	FeS (with up to 3.5% excess S)	Hex.	Basal indistinct	Bronze-yellow to bronze-red	Grayish black	242

4.7–5.5								
4.4–5.1	3–4	Gray Copper (Tetrahedrite, Tennantite)	$Cu_{10}(Zn,Fe)_2(Sb,As)_4S_{13}$	Isom. Tetrah.	None	Steel-gray to iron-black	Steel-gray to iron-black	248
4.4–5.2	5.5–6.5	Magnetite	$(Fe,Mg,Zn,Mn)Fe_2O_4$	Isom.	(111) parting	Iron-black	Black, brown	302
4.7–4.8	6	Braunite	$3Mn_2O_3 \cdot MnSiO_3$	Tetr.	(111) pyramidal perfect at 70° and 110°	Brownish black to steel-gray	Black or brownish black	265
4.7–4.8	1	Molybdenite	MoS_2	Hex.	Basal perfect	Lead-gray	Greenish lead-gray on paper or porcelain	244
4.7–4.86	2–2.5	Pyrolusite	MnO_2, often $+H_2O$, etc.	Pseudomor. Orth.	None	Black to steel-gray	Black to bluish black	265
4.8–4.9	6	Marcasite	FeS_2	Orth.	(110) prism poor	Pale brass-yellow	Grayish or brownish black	246
4.9–5.2	6–7	Pyrite	FeS_2	Isom.	None	Brass-yellow	Greenish black	238
4.9–5.4	3	Bornite (Peacock, or Horseflesh Ore)	Cu_5FeS_4	Isom.	None	Copper-red to bronze-brown	Grayish black	241
5.3–5.7	3	Millerite (Nickel Pyrites)	NiS	Hex.	$(10\bar{1}1)$ and $(01\bar{1}2)$ rhombohedral Rarely seen	Brass- to bronze-yellow	Greenish black	243
5.3–7.3	6	Columbite (Tantalite)	$(Fe,Mn)(Cb,Ta)_2O_6$	Orth.	100 pinacoidal poor	Iron-black, grayish black, brownish black	Dark red to black	313
5.5–6.3								
5.3–5.7	3	Millerite (Nickel Pyrites)	NiS	Hex.	$(10\bar{1}1)$ and $(01\bar{1}2)$ rhombohedral Rarely seen	Brass- to bronze-yellow	Greenish black	243

TABLE I. STREAK AND SPECIFIC GRAVITY (*Continued*)

1. MINERALS WITH IRON-BLACK, STEEL-GRAY, OR SILVER-WHITE STREAK (*cont.*)

G.	H.	Name	Composition	System	Cleavage	Color	Streak	Page
5.5–6.3 *cont.*								
5.3–7.3	6	Columbite (Tantalite)	(Fe,Mn) (Cb,Ta)$_2$O$_6$	Orth.	100 pinacoidal poor	Iron-black, grayish black, brownish black	Dark red to black	313
5.5–5.8	2.5–3	Chalcocite (Copper Glance)	Cu$_2$S	Orth.	(110) prism poor	Dark lead-gray	Dark gray to black	245
5.5–6.0	2–3	Jamesonite	Pb$_2$Sb$_2$S$_5$	Orth.	001 distinct	Steel-gray	Grayish black	251
5.6–5.8	3–4	Arsenic	As	Rhom.	0001 perfect	Tin-white	Gray	229
5.7–5.9	2.5–3	Bournonite (Cogwheel Ore)	CuPbSbS$_3$	Orth.	Indistinct	Steel-gray to iron-black	Dark gray to black	250
5.9–6.2	5.5–6	Arsenopyrite (Mispickel)	FeAsS	Mono.	(110) prismatic poor at 68°	Silver-white to steel-gray	Grayish black	246
6.0–6.3	5.5	Cobaltite	CoAsS	Isom.	(100) cubic poor	Silver-white to gray (reddish)	Grayish black	239
6.4–7.7								
5.3–7.3	6	Columbite (Tantalite)	(Fe,Mn) (Cb,Ta)$_2$O$_6$	Orth.	100 pinacoidal poor	Iron-black, grayish black, brownish black	Dark red to black	313
6.4–6.5	2	Bismuthinite	Bi$_2$S$_3$	Orth.	010 perfect	Lead-gray	Lead-gray	246
6.4–6.6	5.5–6	Smaltite (Chloanthite)	(Co,Ni)As$_2$ with Fe, S, etc.	Isom. Pyritoh.	(111) octahedral poor at 70½°	Tin-white to steel-gray	Grayish black	240
7.0–7.5	5–5.5	Wolframite	(Fe,Mn)WO$_4$	Mono.	010 clinopinacoidal perfect	Dark gray, brown, black	Black or brownish black	295
7.2–7.4	2–2.5	Argentite (Silver Glance)	Ag$_2$S	Isom.	(100) cubic in traces	Lead-gray to black	Dark lead-gray shining	236

7.3–7.7	5–5.5	Niccolite	NiAs	Hex.	None	Light copper-red	Brownish black	243
7.3–7.8	4–5	Iron	Fe	Isom.	(100) perfect	Steel-gray	Steel-gray	228
7.4–7.6	2.5	Galena (Galenite, Lead Glance)	PbS	Isom.	(100) cubic, perfect	Dark lead-gray	Dark lead-gray	236
7.8–19								
7.9–8.3	1.5–2	Sylvanite	$AuAgTe_4$	Mono.	010 clinopinacoidal distinct	Silver-white (brassy tinge)	Pale steel-gray	248
9.0	2.5	Calaverite	$(Au,Ag)Te_2$	Mono.	None	Bronze-yellow	Yellow-gray	248
9.0–9.7	5.5	Uraninite (Pitchblende)	UO_3, UO_2, Pb, Th, Zr, La, Y, He, Ra, etc.	Isom.	None	Greenish black, brownish black, pitch black	Brownish black, grayish black, olive-green	269
9.8	2.5	Bismuth	Bi	Rhom.	0001 perfect	Silver white	Gray	230
10–12	2.5–3	Silver (Native Silver)	Ag, often with Au, Cu	Isom.	None	Silver-white	Silver-white to lead-gray	225
14–19	4–4.5	Platinum (Native Platinum)	Pt, often with Fe, Pd, Rh, Ir, Os	Isom.	None	Tin-white	Steel-gray shining	228

2. MINERALS WITH BLUE OR GREEN STREAK

2.0–2.5								
2.0–2.2	2–3	Chrysocolla	$CuSiO_3 \cdot 2H_2O$ variable	Amor.	None	Green to blue, brown to black when impure	White to pale blue or green	398
2.2–2.4	1–2	Glauconite (Greensand)	$KFeSi_2O_6 \cdot H_2O$, often with Al, Mg. Varies	Amor. or Mono.	None	Yellowish to dark green	Light green to greenish white	373

TABLE I. STREAK AND SPECIFIC GRAVITY (*Continued*)

2. MINERALS WITH BLUE OR GREEN STREAK (*cont.*)

G.	H.	Name	Composition	System	Cleavage	Color	Streak	Page
2.0–2.5 *cont.*								
2.3–2.8	1–4	Garnierite	$H_4(Mg,Ni)_3Si_2O_9$	Amor.	None	Dark green to yellow-green	White to greenish	361
2.4–2.5	5–5.5	Lazurite	$3NaAlSiO_4 \cdot Na_2S$ (S varies)	Isom.	(110) dodecahedral poor	Azure blue, violet, green-blue	Pale blue	374
2.5–3.0								
2.6–2.7	1.5–2	Vivianite (Blue Iron Earth)	$Fe_3P_2O_8 \cdot 8H_2O$	Mono.	010 clinopinacoidal distinct	Blue, green to greenish black	White, blue, greenish blue	313
2.6–2.8	5.5–6	Turquois	$CuAl_6P_4O_{20} \cdot 9H_2O$	Amor. Tric.	None	Sky-blue to apple-green	White or pale green	312
2.6–3.0	1–2.5	Chlorite	$H_4(Mg,Fe)_3Si_2O_9 + nH_4(Mg,Fe)_2Al_2SiO_9$	Mono. nearly rhomb.	Basal perfect	Light to dark green	White, gray, greenish white	371
2.3–2.8	1–4	Garnierite	$H_4(Mg,Ni)_3Si_2O_9$	Amor.	None	Dark green to yellow-green	White to greenish	361
2.9–3.4	5–6	Hornblende (Tremolite, Actinolite)	SiO_2, MgO, FeO, Fe_2O_3, Al_2O_3, Na_2O, H_2O, etc.	Mono.	(110) prismatic perfect at 56°	Green, brown black, gray	Green, brown, yellow, gray, white	357
3.0–4.0								
2.9–3.4	5–6	Hornblende (Tremolite, Actinolite)	SiO_2, MgO, FeO, Fe_2O_3, H_2O Al_2O_3, Na_2O	Mono.	(110) prismatic perfect at 56°	Green, brown black, gray	Green, brown yellow, gray, white	357
3.0–3.2	6–6.5	Glaucophane	$H_2Na_2Mg_3Al_2Si_8O_{24}$	Mono.	(110) perfect 56°	Blue, gray	Gray blue	359

3.2–3.3	4	Crocidolite (Blue Asbestus)	$NaFe''Fe'''Si_3O_9$ varies	Mono.	(110) prismatic perfect at 56°	Lavender blue to leek green	Pale blue to green	359
3.2–3.6	5–6	Pyroxene (Diopside, Augite, Hedenbergite)	$Ca(Mg,Fe)\ Si_2O_6$ with Al_2O_3, Fe_2O_3, etc.	Mono.	(110) prismatic perfect at 87°	Green, black, brown	Greenish, brownish, grayish	351
3.7–3.8	3.5–4	Azurite (Blue Copper Carbonate)	$Cu_2(OH)_2(CO_3)_2$	Mono.	(021) domatic, perfect at 59°	Azure to dark blue	Blue	282
3.9–4.0	3.5–4	Malachite (Green Copper Carbonate)	$Cu_2(OH)_2CO_3$	Mono.	Basal perfect	Grass- to dark green	Light green	282
9.0–10								
9.0–9.7	5.5	Uraninite	UO_3, UO_2, Pb, Th, Zr, La, Y, He, Ra, etc.	Isom.	None	Greenish black, brownish black, pitch black	Brownish black, grayish black, olive green	269

3. MINERALS WITH YELLOW, BROWN, OR RED STREAK

2.0–3.0								
2.0–2.1	1.5–2.5	Sulfur	S (Traces of Te, Se, As)	Orth.	Indistinct	Yellow, brown	White, yellow	234
2.7–2.8	2.5–3	Polyhalite	$K_2MgCa_2S_4O_{16}\cdot 2H_2O$	Tric.	100 distinct	Pink, red	Red, white	289
2.9–3.2	1.5–2.5	Erythrite	$Co_3As_2O_8\cdot 8H_2O$	Mono.	010 perfect	Crimson to gray	Pink to gray	312
2.9–3.4	5–6	Hornblende (Tremolite, Actinolite)	SiO_2, MgO, FeO, CaO, Al_2O_3, Na_2O, etc.	Mono.	(110) prismatic perfect at 56°	Green, brown black, gray	Green, brown, yellow, gray	357

TABLE I. STREAK AND SPECIFIC GRAVITY (*Continued*)
3. MINERALS WITH YELLOW, BROWN, OR RED STREAK (*cont.*)

G.	H.	Name	Composition	System	Cleavage	Color	Streak	Page
3.0–3.6								
?	0.5–1	Carnotite	K_2O, U_2O_3, U_2O_5, CaO, H_2O, etc.	Orth.	001 basal distinct	Yellow	Yellowish	311
3.2–3.6	5–6	Pyroxene (Diopside, Augite, Hedenbergite)	$Ca(Mg,Fe)\ Si_2O_6$ with Al_2O_3, Fe_2O_3 etc.	Mono.	(110) prismatic perfect at 87°	Green, black, brown	Greenish, brownish, grayish	351
3.3–3.5	5–6	Hypersthene	$(Mg,Fe)\ SiO_3$	Orth.	(110) prismatic perfect at 88°	Grayish, greenish, brownish black to bronze	Brownish gray, grayish white	350
3.4–3.5	1.5–2	Orpiment	As_2S_3	Mono.	010 clinopinacoidal perfect	Lemon-yellow	Pale yellow	247
3.5–3.6	1.5–2	Realgar	AsS	Mono.	010 clinopinacoidal distinct	Deep red to orange	Orange-yellow	247
3.6–4.7								
3.6–4.0	5–5.5	Limonite (Bog Iron Ore, Brown Hematite)	$FeO{\cdot}OH$	Amor.	None	Yellow, brown, black	Yellowish brown	267
3.7–4.7	5–6	Psilomelane	MnO_2, BaO, H_2O, K_2O, etc.	Amor.	None	Iron-black, bluish black, steel-gray	Black, brownish black	284
3.8–3.9	3.5–4	Siderite (Spathic Iron, Chalybite)	$FeCO_3$, often with Mg, Mn	Rhomb.	$(10\bar{1}1)$ rhombohedral perfect at 73°	Gray, yellow brown, black	White, pale yellow	276
3.9–4.1	3.5–4	Sphalerite (Blende, Zinc Blende, Black Jack)	ZnS, with Fe	Isom.	(110) dodecahedral good at 60°	Yellow, brown, red, green, black	White, light to dark brown	237

4.0–4.4		Goethite	FeO·OH	Orth.	010 pinacoidal perfect	Yellow, brown, black	Yellow, yellowish brown	267
4.1–4.3	6–7	Rutile	TiO_2, often with Fe	Tetr.	(100), (110) poor at 45°	Red, reddish brown, black	Pale brown, gray white	261
4.2–4.4	3.5–4	Manganite	MnO·OH	Orth.	010 pinacoidal perfect	Steel-gray to iron-black	Reddish brown to black	268
4.3–4.6	5.5	Chromite (Chrome Iron Ore)	$FeCr_2O_4$, with Mg, Al	Isom.	None	Iron-black, brownish black	Dark brown	300
4.4–5.1	3–4	Tetrahedrite (Gray Copper)	Cu_{10} $(Zn,Fe)_2$ Sb_4 S_{13}, with Ag, Hg, Pb, As, etc.	Isom. Tetrah.	None	Steel-gray to iron-black	Steel-gray to iron-black	248
4.5–5.0	5–6	Ilmenite (Titanic Iron Ore)	$FeTiO_3$, often with Mg, Fe'''	Rhomb.	None	Iron-black, brownish black	Iron-black, brownish black	261
4.7–5.7								
4.4–5.1	3–4	Tetrahedrite (Gray Copper)	Cu_{10} $(Zn,Fe)_2$ Sb_4 S_{13}, with Ag, Hg, Pb, As, etc.	Isom. Tetrah.	None	Steel-gray to iron-black	Steel-gray to iron-black	248
4.5–5.0	5–6	Ilmenite (Titanic Iron Ore)	$FeTiO_3$, often with Mg, Fe'''	Rhomb.	None	Iron-black, brownish black	Iron-black, brownish black	261
4.7–4.8	6–6.5	Braunite	$3Mn_2O_3 \cdot MnSiO_3$	Tetr.	(111) pyramidal perfect at 70°	Brownish black to steel-gray	Black or brownish black	265
4.7–4.9	5–5.5	Hausmannite	Mn_3O_4	Tetr.	Basal perfect	Black, brownish black	Chestnut-brown	283
4.9–5.0	3–3.5	Greenockite	CdS	Hex.	None	Yellow	Yellow	243
4.9–5.3	5.5–6.5	Hematite (Specular Iron, Red Iron Ore)	Fe_2O_3	Rhomb.	None	Steel-gray, red, brown, black	Dark red, brownish red	259
5.0±	3.5–4	Pentlandite	(Fe,Ni)S	Isom.	(111)	Bronze-yellow	Bronze-yellow	240

TABLE I. STREAK AND SPECIFIC GRAVITY (*Continued*)

3. MINERALS WITH YELLOW, BROWN, OR RED STREAK (*cont.*)

G.	H.	Name	Composition	System	Cleavage	Color	Streak	Page
4.7–5.7 *cont.*								
5.1–5.2	5.5–6.5	Franklinite	$(Fe,Mn,Zn)(Fe,Mn)_2O_4$	Isom.	None	Iron-black	Black to reddish brown	302
5.3–7.3	6	Columbite (Tantalite)	$(Fe,Mn)(Cb,Ta)_2O_6$	Orth.	100 pinacoidal poor	Iron-black, brownish black	Dark red to black	313
5.4–5.7	4–4.5	Zinkite (Red Zinc Ore)	ZnO	Hex. Hemi.	Basal indistinct	Deep red to orange	Orange-yellow	257
5.5–5.6	2–2.5	Proustite (Light Ruby Silver)	Ag_3AsS_3	Rhomb.	$(10\bar{1}1)$ rhombohedral poor at 72°	Scarlet to brownish red	Scarlet to brownish red	249
5.7–7.2								
5.3–7.3	6	Columbite (Tantalite)	$(Fe,Mn)(Cb,Ta)_2O_6$	Orth.	100 pinacoidal poor	Iron-black, brownish black	Dark red to black	313
5.8–5.9	2.5–3	Pyrargyrite (Dark Ruby Silver)	Ag_3SbS_3	Rhomb.	$(10\bar{1}1)$ rhombohedral poor at 72°	Dark red to black	Purplish red to cherry-red	249
5.8–6.1	3.5–4	Cuprite (Red Copper Ore)	Cu_2O	Isom.	Indistinct	Ruby red, reddish black	Brownish red	257
5.9–6.1	2.5–3	Crocoite	$PbCrO_4$	Mono.	(110) prismatic good at 86°	Bright red	Orange-yellow	296
5.9–6.2	4.5–5	Scheelite	$CaWO_4$	Tetr.	(111) pyramidal good at 80°, 130°	White, yellow, brownish, greenish	White to yellowish	296
6.5–7.1	3.5–4	Pyromorphite	$Pb_5ClP_3O_{12}$	Hex.	None	Green, yellow brown, white	Yellow to white	308
6.6–7.2	3	Vanadinite	$Pb_5ClV_3O_{12}$	Hex.	None	Red, brown, yellow	White, pale yellow	309

6.8–7.1	6–7	Cassiterite ("Tin," Tinstone)	SnO_2	Tetr.	Indistinct	Brown to black, yellow, red rare	White, grayish, brownish	264
7.2–19								
5.3–7.3	6	Columbite (Tantalite)	$(Fe,Mn)(Cb,Ta)_2O_6$	Orth.	100 pinacoidal poor	Iron-black, brownish black	Dark red to black	313
7.2–7.5	5–5.5	Wolframite	$(Fe,Mn)WO_4$	Mono.	010 clinopinacoidal perfect	Dark gray, brown, black	Black, brownish black	295
7.3–7.7	5–5.5	Niccolite	NiAs, with Fe, Co, Sb, S	Hex.	None	Light copper-red	Brownish black	243
8.0–8.2	0.5–1	Cinnabar	HgS	Hex.	$(10\bar{1}0)$ prismatic, poor at 60°	Purplish to brownish black, pitch black	Scarlet to brownish red	242
8.8–8.9	2.5–3	Copper (Native Copper)	Cu, often with Ag, Bi, Hg, etc.	Isom.	None Malleable	Copper-red	Copper-red, shiny	227
9.0–9.7	5.5	Uraninite (Pitchblende)	UO_3, UO_2, Pb, Th, Zr, La, Y, He, Ra	Isom.	None	Greenish to brownish black, pitch black	Brownish to grayish black, olive-green	269
12.5–19.3	2.5–3	Noble Metal (Gold)	Au, with Ag, Cu, Fe, etc.	Isom.	None	Gold-yellow	Gold-yellow	225

4. MINERALS WITH COLORLESS, WHITE OR PALE COLORED STREAK

0.9–2.0								
0.9(1)	0–2.5	Ice (also water, snow)	H_2O	Hex.	None	Colorless, white, bluish	White	256
(0.9–)2.0	2–2.5	Sepiolite (Meerschaum)	$H_4Mg_2Si_3O_{10}$ (often with Cu,Ni)	Amor. (Mono.)	None	White, grayish, yellowish	White	360

TABLE I. STREAK AND SPECIFIC GRAVITY (*Continued*)

4. MINERALS WITH COLORLESS, WHITE OR PALE COLORED STREAK (*cont.*)

G.	H.	Name	Composition	System	Cleavage	Color	Streak	Page
0.9–2.0 *cont.*								
1.4–1.5	1.5–2	Mirabilite (Glauber Salt)	$Na_2SO_4 \cdot 10H_2O$	Mono.	100 pinacoidal perfect	White, colorless, yellowish	White	285
1.6	2.5	Carnallite	$KMgCl_3 \cdot 6H_2O$	Orth.	None	Milky, reddish	White	255
1.6–1.7	1	Ulexite	$NaCaB_5O_9 \cdot 8H_2O$	Mono.	?	White	White	297
1.7	2–2.5	Borax	$Na_2B_4O_7 \cdot 10H_2O$	Mono.	100 pinacoidal distinct	White, colorless, grayish, bluish, greenish	White	298
1.7–1.8	2–2.5	Epsomite (Epsom Salt)	$MgSO_4 \cdot 7H_2O$ (with Fe,Mn,Zn)	Orth.	010 pinacoidal distinct	White, colorless, gray	White	291
1.9–2	2	Melanterite (Copperas)	$FeSO_4 \cdot 7H_2O$ (with Cu,Zn,Mn)	Mono.	Basal perfect	Green, yellowish green, white	White	291
1.9–2	2–2.5	Sylvite	KCl	Isom.	(100) cubic perfect at 90°	White, colorless, grayish, bluish, reddish	White	252
1.95	2.5	Kernite	$Na_2B_4O_7 \cdot 4H_2O$	Mono.	Basal perfect	White	White	298
2.0–2.2								
2.0–2.1	1.5–2.5	Sulfur	S (traces of Te,Se,As)	Orth.	Indistinct	Yellow, rarely brown or gray	White, pale yellow	234
2.0–2.2	2.5	Kainite	$MgSO_4 \cdot KCl \cdot 3H_2O$	Mono.	100 and (110) at 40° and 101°	White to reddish	White	286

2.0–2.2	2.5	Chrysocolla	$CuSiO_3 \cdot 2H_2O$ often with CuO, Fe_2O_3, MnO_2, etc.	Amor.	None	Green, blue, brown to black	White to pale blue or green	398
2.0–2.2	4–5	Chabazite (a zeolite)	$CaAl_2Si_4O_{12} \cdot 6H_2O$, with Na, K, Ba, Sr	Rhom.	$(10\bar{1}1)$ rhombohedral good at 85°	White, yellow, flesh-red	White	397
2.1–2.2	2	Niter	KNO_3	Orth.	(011) domatic good at 70°	White, colorless, grayish	White	271
2.1–2.2	5.5–6.5	Opal (Tripoli, Infusorial Earth)	$SiO_2 \cdot nH_2O$	Amor.	None. Conchoidal fracture	White, yellow, red, green, gray, blue	White	398
2.1–2.2	3.5–4	Stilbite	$Na_2Al_2Si_6O_{16} \cdot 6H_2O$, with Ca	Mono.	010 pinacoidal perfect	White, grayish, red, brown	White	396
2.14	2.5–3	Trona	$HNa_3C_2O_6 \cdot 2H_2O$	Mono.	100 perfect	Gray, yellow	White	283
2.1–2.3	2.5	Chalcanthite (Blue Vitriol)	$CuSO_4 \cdot 5H_2O$, often with Fe, Mn, Zn, Co	Tric.	Indistinct	Deep blue, sky blue, greenish blue	White	292
2.1–2.3	5–6	Sodalite (Hauyne, Nosean, Lazurite)	$3NaAlSi_3O_8$ with NaCl, $CaSO_4$, Na_2SO_4 or Na_2S	Isom.	(110) dodecahedral poor at 60° and 90°	Gray, yellow, white, blue, green, red	White, pale blue	374
2.1–2.6	2–2.5	Halite (Rock Salt)	NaCl	Isom.	(100) cubic perfect	White, colorless, gray, reddish, bluish	White	252
2.2–2.3								
2.1–2.3	2.5	Chalcanthite (Blue Vitriol)	$CuSO_4 \cdot 5H_2O$ often with Fe, Mn, Zn, Co	Tric.	Indistinct	Deep blue, sky blue, greenish blue	White	292
2.1–2.3	5–6	Sodalite (Hauyne, Nosean, Lazurite)	$3NaAlSi_3O_8$ with NaCl, $CaSO_4$, Na_2SO_4 or Na_2S	Isom.	(110) dodecahedral poor at 60° and 90°	Gray, yellow, white, blue, green, red	White, pale blue	374

TABLE I. STREAK AND SPECIFIC GRAVITY (*Continued*)

4. MINERALS WITH COLORLESS, WHITE OR PALE COLORED STREAK (*cont.*)

G.	H.	Name	Composition	System	Cleavage	Color	Streak	Page
2.2–2.3 *cont.*								
2.1–2.6	2–2.5	Halite (Rock Salt)	NaCl	Isom.	(100) cubic perfect	White, colorless, gray, reddish, bluish	White	252
2.2–2.3	5–5.5	Natrolite (a zeolite)	$Na_2Al_2Si_3O_{10}\cdot 2H_2O$	Orth.	(110) prismatic good at 89°	White, colorless, gray, yellowish, reddish	White	395
2.2–2.3	1.5	Soda Niter	$NaNO_3$	Rhom.	(10$\bar{1}$1) rhombohedral perfect at 73½°	White, rarely brown, gray, yellow	White	270
2.2–2.3	5–5.5	Analcite	$NaAlSi_2O_6\cdot H_2O$, with H_2SiO_3	Isom.	None	White, colorless, gray, greenish, reddish	White	394
2.2–2.4	1–2	Glauconite (Greensand)	$KFeSi_2O_6\cdot H_2O$, with Al, Mg (varies)	Amor. (Mono.)	None	Yellowish to dark green	Light green to greenish white	373
2.3–2.4								
2.1–2.6	2–2.5	Halite (Rock Salt)	NaCl	Isom.	(100) cubic perfect	White, colorless, gray, reddish, bluish	White	252
2.2–2.4	1–2	Glauconite (Greensand)	$KFeSi_2O_6\cdot H_2O$ with Al, Mg (varies)	Amor.	None	Yellowish to dark green	Light green to greenish white	373
2.3–2.4	4.5–5	Apophyllite	$KF\cdot Ca_4Si_8O_{20}\cdot 8H_2O$ (varies)	Tetr.	Basal perfect	White, greenish, grayish, yellowish	White	362

2.3–2.4	5–5.5	Thomsonite (a zeolite)	SiO_2, Al_2O_3, CaO, Na_2O, H_2O (varies)	Orth.	010 and 100 pinacoidal good at 90°	White, greenish, brownish, gray	White	395
2.3–2.4	3.5–4	Wavellite	$(AlOH)_3P_2O_8 \cdot 5H_2O$	Orth.	(101) and 100 good at 73° and 90°	Green, yellow, white, brown	White	311
2.3–2.4	1.5–2	Gypsum (Selenite, Alabaster, Satin Spar)	$CaSO_4 \cdot 2H_2O$	Mono.	010 pinacoidal perfect, 100l pinacoidal good	White, gray, pink, yellow, blue, brownish black	White	289
2.3–2.4	2–2.5	Brucite	$Mg(OH)_2$, may have Fe, Mn	Rhom.	Basal perfect	White, grayish, bluish, greenish	White	268
2.3–2.4	2.5–3.5	Gibbsite	$Al(OH)_3$	Mono.	001 rare	White, tinted	White	267
2.3–2.5	4–4.5	Colemanite	$HCaB_3O_6 \cdot 2H_2O$	Mono.	010 and 001 pinacoidal good at 90°	White, colorless, gray, yellowish	White	298
2.3–2.6	3–4	Serpentine	$H_4Mg_3Si_2O_9$, often with Fe	Mono.	Indistinct	Yellowish to dark green, yellow, white	White	361
2.3–2.8	1–1.5	Vermiculite (Jefferisite)	Hydrous micas and chlorites	Mono.	Basal perfect	Yellow, brown, green	White	273
2.3–2.8	1–4	Garnierite	$H_4(Mg,Ni)_3Si_2O_9$ (varies)	Amor.	None	Yellowish green to emerald-green	White, greenish	361
2.4–2.5								
2.1–2.6	2–2.5	Halite (Rock Salt)	NaCl	Isom.	(100) cubic perfect	White, colorless, gray, reddish, bluish	White	252
2.3–2.5	4–4.5	Colemanite	$HCaB_3O_6 \cdot 2H_2O$	Mono.	010, 001 good	White, gray	White	298

Table I. Streak and Specific Gravity (*Continued*)

4. minerals with colorless, white or pale colored streak (*cont.*)

G.	H.	Name	Composition	System	Cleavage	Color	Streak	Page
2.4–2.5 *cont.*								
2.3–2.6	3–4	Serpentine	$H_4Mg_3Si_2O_9$, often with Fe	Mono.	Indistinct	Yellowish to dark green, yellow, white	White	361
2.3–2.8	1–1.5	Vermiculite (Jefferisite)	Hydrous micas and chlorites	Mono.	Basal perfect	Yellow, brown, green	White	373
2.3–2.8	1–4	Garnierite	$H_4(Mg,Ni)_3Si_2O_9$ (varies)	Amor.	None	Yellowish green to emerald green	White, greenish	361
2.4–2.5	5.5–6	Leucite (a feldspathoid)	$KAlSi_2O_6$	Isom.	Indistinct	White, gray, yellowish, reddish	White	374
2.4–2.5	5–6	Cancrinite	$6NaAlSiO_4{\cdot}CaCO_3$ with K, Cl, H_2O, etc.	Hex.	$(10\bar{1}0)$ prismatic perfect at 60°	White, gray, yellow, green, blue, pink	White, colorless	378
2.4–2.6	0.5–1	Kaolinite (Kaolin, China Clay)	$H_4Al_2Si_2O_9$ often with more SiO_2	Mono.	Basal perfect	White, gray, yellowish, reddish	White	364
2.4–2.6	0.5–1	Bauxite	$Al_2O_3{\cdot}2H_2O$ often with Fe_2O_3, Ca, Mg, Si	Amor.	None	White, gray, yellow, red	White	266
2.5–2.6								
2.1–2.6	2–2.5	Halite (Rock Salt)	NaCl	Isom.	(100) cubic perfect at 90°	White, colorless, gray, reddish, bluish	White	252

2.3–2.6	3–4	Serpentine	$H_4Mg_3Si_2O_9$, often with Fe	Mono.	Indistinct	Yellowish to dark green, yellow, white	White	361
2.3–2.8	1–1.5	Vermiculite (Jefferisite)	Hydrous micas and chlorites	Mono.	Basal perfect	Yellow, brown, green	White	373
2.3–2.8	1–4	Garnierite	$H_4(Mg,Ni)_3Si_2O_9$ (varies)	Amor.	None	Yellowish green to emerald green	White, greenish	361
2.4–2.6	0.5–1	Kaolinite (Kaolin, China Clay)	$H_4Al_2Si_2O_9$ often with more SiO_2	Mono.	Basal perfect	White, gray, yellowish, reddish	White	364
2.4–2.6	0.5–1	Bauxite	$Al_2O_3{\cdot}2H_2O$ often with Fe_2O_3, Ca, Mg, Si	Amor.	None	White, gray, yellow, red	White	266
2.5–2.6	6–6.5	Orthoclase (Potash feldspar)	$KAlSi_3O_8$, with Na, Ca	Mono.	001 and 010 pinacoidal good at 90°	White, red, gray, green, colorless	White	387
2.5–2.6	6–6.5	Microcline (Potash feldspar)	$KAlSi_3O_8$, with Na, Ca	Tric.	001 and 010 pinacoidal good at 90° ±	White, yellow, red, green	White	389
2.5–2.6	5–6	Nephelite (a feldspathoid)	$NaAlSiO_4$ with K, Ca, etc.	Hex.	$(10\bar{1}0)$ prismatic poor at 60°	Gray, white, reddish, green, yellow	White	376
2.5–2.8	1–4	Talc (Steatite, Soapstone)	$H_4Mg_3Si_4O_{12}$ (variable H_2O)	Mono.	Basal perfect	Apple-green, gray, white	White	363
2.57	3.5	Kieserite	$MgSO_4{\cdot}H_2O$	Mono.	Several	White, gray, yellow	White	285
2.6–2.7								
2.3–2.8	1–1.5	Vermiculite (Jefferisite)	Hydrous micas and chlorites	Mono.	Basal perfect	Yellow, brown, green	White	373
2.3–2.8	1 4	Garnierite	$H_4(Mg,Ni)_3Si_2O_9$ (varies)	Amor.	None	Yellowish green to emerald-green	White, greenish	361
2.5–2.8	1–4	Talc (Steatite, Soapstone)	$H_4Mg_3Si_4O_{12}$ (variable H_2O)	Mono.	Basal perfect	Apple-green, gray, white	White	363

TABLE I. STREAK AND SPECIFIC GRAVITY (*Continued*)

4. MINERALS WITH COLORLESS, WHITE OR PALE COLORED STREAK (*cont.*)

G.	H.	Name	Composition	System	Cleavage	Color	Streak	Page
2.6–2.7 *cont.*								
2.6–2.64	7	Chalcedony (Agate, Flint, Hornstone)	SiO_2	Hex.?	None. Conchoidal fracture	White, gray, brown, black, red	White	381
2.65	7	Quartz (Rock Crystal)	SiO_2	Hex.	None. Conchoidal fracture	White, colorless, purple (amethyst)	White, etc.	379
2.6–2.7	7–7.5	Cordierite (Iolite)	$Mg_2Al_4Si_5O_{18}$, with Fe, Ca, OH, etc.	Orth.	010 pinacoidal fair	Blue, violet, colorless	White	345
2.6–2.7	1.5–2	Vivianite (Blue Iron Earth)	$Fe_3P_2O_8 \cdot 8H_2O$	Mono.	Basal perfect	Light to dark green	White, greenish, grayish	313
2.6–2.8	6–6.5	Plagioclase (Na-Ca feldspar)	$NaAlSi_3O_8 + nCaAl_2Si_2O_8$	Tric.	001 and 010 pinacoidal good at 86°	White, colorless, gray, green, reddish, bluish	White	391
2.6–2.8	5–6	Scapolite (Wernerite)	$3NaAlSi_3O_8 \cdot NaCl + n3CaAl_2Si_2O_8 \cdot CaCO_3$	Tetr.	100 and (110) fair at 45° and 90°	White, gray, bluish, greenish, reddish	White	375
2.6–2.8	3.5–4	Alunite (Alumstone)	$KAl_3(OH)_6S_2O_8$, often with Na	Rhom.	Basal distinct	White, gray, reddish	White	294
2.6–2.8	7.5	Beryl	$Be_3Al_2Si_6O_{18}$, with H, Na, Cs, Li	Hex.	Indistinct	Green (Emerald), blue, yellow, pink,	White	341

2.6–2.8	5.5–6	Turquois	$CuO \cdot 3Al_2O_3 \cdot 2P_2O_5 \cdot 9H_2O$	Tric. Amor. ?	None. Conchoidal fracture	Sky-blue to apple-green	White, pale green	312
2.6–2.9	2–5	Collophanite	$Ca_3P_2O_8 \cdot nH_2O$	Amor.	None	Colorless	White	304
2.6–3.0	1–2.5	Chlorite	$H_4(Mg,Fe)_3 Si_2O_9 + nH_4 (Mg,Fe)_2Al_2SiO_9$	Mono.	Basal perfect	Light to dark green	White, greenish white, gray	371
2.7–2.8								
2.3–2.8	1–1.5	Vermiculite (Jefferisite)	Hydrous micas and chlorites	Mono.	Basal perfect	Yellow, brown, green	White	373
2.3–2.8	1–4	Garnierite	$H_4(Mg,Ni)_3Si_2O_9$ (varies)	Amor.	None	Yellowish green to emerald-green	White, greenish	361
2.5–2.8	1–4	Talc (Steatite, Soapstone)	$H_4Mg_3Si_4O_{12}$ (variable H_2O)	Mono.	Basal perfect	Apple-green, gray, white	White	363
2.6–2.8	6–5 6	Plagioclase (Na-Ca feldspar)	$NaAlSi_3O_8 + nCaAl_2Si_2O_8$	Tric.	001 and 010 pinacoidal good at 86°	White, colorless, gray green, reddish, bluish	White	391
2.6–2.8	5–6	Scapolite (Wernerite	$3NaAlSi_3O_8 \cdot NaCl + n3CaAl_2Si_2O_8 \cdot CaCO_3$	Tetr.	100 and (110) fair at 45° and 90°	White, gray, bluish, greenish, reddish	White	375
2.6–2.8	3.5–4	Alunite (Alumstone)	$KAl_3(OH)_6S_2O_8$, often with Na	Rhom.	Basal distinct	White, gray, reddish	White	294
2.6–2.8	7.5	Beryl	$Be_3Al_2Si_6O_{18}$, with H, Na, Cs, Li	Hex.	Indistinct	Green (Emerald), blue, yellow, pink	White	341
2.6–2.8	5.5–6	Turquois	$CuO \cdot 3Al_2O_3 \cdot 2P_2O_5 \cdot 9H_2O$	Tric. Amor. ?	None. Conchoidal fracture	Sky-blue to apple-green	White, pale green	312
2.6–2.9	2–5	Collophanite	$Ca_3P_2O_8 \cdot nH_2O$	Amor.	None	Colorless	White	304

TABLE I. STREAK AND SPECIFIC GRAVITY (*Continued*)

4. MINERALS WITH COLORLESS, WHITE OR PALE COLORED STREAK (*cont.*)

G.	H.	Name	Composition	System	Cleavage	Color	Streak	Page
2.7–2.8 *cont.*								
2.6–3.0	1–2.5	Chlorite	$H_4(Mg,Fe)_3Si_2O_9 + nH_4(Mg,Fe)_2Al_2SiO_9$	Mono.	Basal perfect	Light to dark green	White, greenish white, gray	371
2.7	(0.5)–3	Calcite (Calcspar)	$CaCO_3$ often with Mg, Fe, Mn, Pb	Rhom.	$(10\bar{1}1)$ rhombohedral perfect at 75°	White, colorless, gray, yellow, red, green, blue	White	271
2.7–2.8	2.5	Glauberite	$Na_2CaS_2O_8$	Mono.	Basal perfect	White, colorless, yellow, gray	White	285
2.7–2.8	4.5–5	Pectolite	$HNaCa_2Si_3O_9$, often with Mn	Mono.	100 and 001 pinacoidal good at 85°	White, grayish, reddish	White	349
2.7–2.8	2.5–3	Polyhalite	$K_2MgCa_2S_4O_{16}\cdot 2H_2O$	Tric.	100 distinct	Pink, red	White, red	289
2.7–3.0	2–3	Muscovite (Isinglass)	$H_2KAl_3Si_3O_{12}$, often with Na, Mg, Fe, etc.	Mono.	Basal perfect	White, gray, yellow, greenish, brownish	White	366
2.8–2.9								
2.6–3.0	1–2.5	Chlorite	$H_4(Mg,Fe)_3Si_2O_9 + nH_4(Mg,Fe)_2Al_2SiO_9$	Mono.	Basal perfect	Light to dark green	White, greenish white, gray	371
2.7–3.0	2–3	Muscovite (Isinglass)	$H_2KAl_3Si_3O_{12}$, often with Na, Mg, Fe, etc.	Mono.	Basal perfect	White, gray, yellow, greenish, brownish	White	366

2.8–2.9	1–2	Pyrophyllite	$H_2Al_2Si_4O_{12}$	Orth.	Basal perfect	White, apple-green, gray, yellow	White	366
2.8–2.9	2–3	Lepidolite (Lithia Mica)	$(OH,F)_2KLiAl_2Si_3O_{10}$	Mono.	Basal perfect	Pink, lilac, yellowish, gray, white	White	371
2.8–2.9	4.5–5	Wollastonite	$CaSiO_3$	{Mono. {Tric.	100 and 001 pinacoidal good at 84½°	White, grayish, yellowish, reddish	White	347
2.8–3.0	6–6.5	Prehnite	$H_2Ca_2Al_2Si_3O_{12}$, often with Fe	Orth.	Indistinct	Light green, gray, white	White	363
2.8–3.1	3.5–4	Dolomite	$CaMgC_2O_6$, often with Fe, Mn	Rhom.	$(10\bar{1}1)$ rhombohedral perfect at 74°	White, colorless, gray, red, green, brown	White	274
2.8–3.1	2–3	Biotite (Fe-Mg Mica)	$H_4K_2(Mg,Fe)_6Al_2Si_6O_{24} + nH_4K_2(Mg,Fe)_5Al_4Si_5O_{24}$	Mono.	Basal perfect	Black, brown, green, yellow, white	White	368
2.9–3.0								
2.6–3.0	1–2.5	Chlorite	$H_4(Mg,Fe)_3Si_2O_9 + nH_4(Mg,Fe)_2Al_2SiO_9$	Mono.	Basal perfect	Light to dark green	White, greenish white, gray	371
2.7–3.0	2–3	Muscovite (Isinglass)	$H_2KAl_3Si_3O_{12}$, often with Na, Mg, Fe, etc.	Mono.	Basal perfect	White, gray, yellow, greenish, brownish	White	366
2.8–3.0	6–6.5	Prehnite	$H_2Ca_2Al_2Si_3O_{12}$, often with Fe	Orth.	Indistinct	Light green, gray, white	White	363
2.8–3.1	3.5–4	Dolomite	$CaMgC_2O_6$, often with Fe, Mn	Hex. Rhom.	$(10\bar{1}1)$ rhombohedral perfect at 74°	White, colorless, gray, red, green, brown	White	274

TABLE I. STREAK AND SPECIFIC GRAVITY (*Continued*)

4. MINERALS WITH COLORLESS, WHITE OR PALE COLORED STREAK (*cont.*)

G.	H.	Name	Composition	System	Cleavage	Color	Streak	Page
2.9–3.0 *cont.*								
2.8–3.1	2–3	Biotite (Fe-Mg Mica)	$H_4K_2(Mg,Fe)_6Al_2Si_6O_{24} + nH_4K_2(Mg,Fe)_5Al_4Si_5 \cdot O_{24}$	Mono.	Basal perfect	Black, brown, green, yellow, white	White	368
2.9–3.0	3–3.5	Anhydrite	$CaSO_4$	Orth.	001, 100 and 010 pinacoidal good at 90°	White, gray, bluish, reddish, red	White, gray	286
2.9–3.0	3.5–4	Aragonite	$CaCO_3$, may have Sr, Pb	Orth.	(110) and 010 good at 64° and 58°	White, gray, yellow, green, violet	White	279
2.9–3.0	7.5–8	Phenacite	Be_2SiO_4	Hex. Rhom.	Indistinct	Colorless, yellow, pink, brown	White	329
2.9–3.0	2.5	Cryolite	Na_3AlF_6	Mono.	001 and (110) parting at 88° and 90°	White, colorless, grayish	White	255
2.9–3.0	5–5.5	Datolite	$CaBOHSiO_4$	Mono.	None. Conchoidal fracture	Greenish, colorless, yellowish, reddish	White	337
2.9–3.0	7	Boracite	$Mg_6Cl_2B_{14}O_{26}$	Orth.	Indistinct	White, tinted	White	297
2.9–3.1	5	Melilite (Gehlenite-Akermanite)	$Ca_2Al_2SiO_7 + Ca_2(Mg,Fe)Si_2O_7$	Tetr.	Indistinct	White, green, brown	White	340
2.9–3.2	5–6	Tremolite-Actinolite (Hornblende)	$H_2Ca_2(Mg,Fe)_5Si_8O_{24}$	Mono.	(110) prismatic good at 56°	White, gray, yellow, green	White, tinted	357
3.0–3.1								
2.8–3.1	3.5–4	Dolomite	$CaMgC_2O_6$, often with Fe, Mn	Rhom.	$(10\bar{1}1)$ rhombohedral perfect at 74°	White, colorless, gray, red, green, brown	White	274

2.8–3.1	2–3	Biotite (Fe-Mg Mica)	$H_4K_2(Mg,Fe)_6Al_2Si_6O_{24} + nH_4K_2(Mg,Fe)_5Al_4Si_5O_{24}$	Mono.	001 basal perfect	Black, brown, green, yellow, white	White	368
2.9–3.1	5	Melilite (Gehlenite-Akermanite)	$Ca_2Al_2SiO_7 + Ca_2(Mg,Fe)Si_2O_7$	Tetr.	Indistinct	White, green, brown	White	340
2.9–3.2	5–6	Tremolite-Actinolite (Hornblende)	$H_2Ca_2(Mg,Fe)_5Si_8O_{24}$	Mono.	(110) prismatic good at 56°	White, gray, yellow, green	White, tinted	357
3.0–3.1	6	Amblygonite	$LiAl(F,OH)PO_4$ often with Na, H_2O	Tric.	001 basal perfect	White, pale green, pale blue, yellowish	White	310
3.0–3.2	7–7.5	Tourmaline	$H_2Na(Mg,Fe)_4Al_6B_3Si_6O_{31} + H_2NaLi_2Al_8B_3Si_6O_{31}$	Rhom. Hemi.	Indistinct	Black, blue, pink, red, brown, green	White	343
3.0–3.2	5–6	Anthophyllite	$H_2(Mg,Fe)_7Si_8O_{24}$, may have Al	Orth.	(110) prismatic good at $54\frac{1}{2}$°	Gray, brown, green to emerald	White	356
3.0–3.2	4	Fluorite (Fluorspar)	CaF_2, may have Cl	Isom.	(111) octahedral perfect at $70\frac{1}{2}$°	White, yellow, green, blue, violet, colorless	White	254
3.0–3.9	3.5–4.5	Brown Spar (Magnesite, Siderite, Rhodochrosite)	$(Mg,Fe,Mn)CO_3$	Rhom.	$(10\bar{1}1)$ rhombohedral perfect at 73°	White, gray, brown, red, green	White	276
3.0–4.2	5.5–6	Allanite (Orthite)	$H(Ca,Ce)_2(Al,Fe)_3Si_3O_{13}$, also La, Y, etc.	Mono.	Indistinct	Brown, black	white	384
3.1–3.2								
2.9–3.2	5–6	Tremolite-Actinolite (Hornblende)	$H_2Ca_2(Mg,Fe)_5Si_8O_{24}$	Mono.	(110) prismatic good at 56°	White, gray, yellow, green	White, tinted	357

TABLE I. STREAK AND SPECIFIC GRAVITY (*Continued*)

4. MINERALS WITH COLORLESS, WHITE OR PALE COLORED STREAK (*cont.*)

G.	H.	Name	Composition	System	Cleavage	Color	Streak	Page
3.1–3.2 *cont.*								
3.0–3.2	7–7.5	Tourmaline	$H_2Na(Mg,Fe)_4Al_6B_3Si_6O_{31} + H_2NaLi_2Al_8B_3Si_6O_{31}$	Rhom. Hemi.	Indistinct	Black, blue, pink, red, brown, green	White	343
3.0–3.2	5–6	Anthophyllite	$H_2(Mg,Fe)_7Si_8O_{24}$, may have Al	Orth.	(110) prismatic good at 54½°	Gray, brown, green to emerald	White	256
3.0–3.2	4	Fluorite (Fluorspar)	CaF_2, may have Cl	Isom.	(111) octahedral perfect at 70½°	White, yellow, green, blue, violet, colorless	White	254
3.0–3.9	3.5–4.5	Brown Spar (Magnesite, Siderite, Rhodochrosite)	$(Mg,Fe,Mn)CO_3$	Rhom.	$(10\bar{1}1)$ rhombohedral perfect at 73°	White, gray, brown, red, green	White	276
3.0–4.2	5.5–6	Allanite (Orthite)	$H(Ca,Ce)_2(Al,Fe)_3Si_3O_{13}$ also La, Y, etc.	Mono.	Indistinct	Brown, black	White	384
3.1–3.2	6–6.5	Chondrodite	$Mg_5(F,OH)_2Si_2O_8$ often with Fe	Mono.	Basal fair	Brownish red, yellow, white	White	331
3.1–3.2	4.5	Apatite	$Ca_5(F,Cl)P_3O_{12}$ often with Sr, Mn, etc.	Hex.	Indistinct	Green, blue, violet, red, brown, white	White	306
3.1–3.2	6–7	Spodumene (a pyroxene)	$LiAlSi_2O_6$, often with Na	Mono.	(110) prismatic good at 87°	White, gray, yellow, green (*hiddenite*), pink (*kunzite*)	White	354

3.1–3.2	6.5–7.5	Andalusite (Chiastolite)	Al_2SiO_5	Orth.	(110) prismatic good at 89°	White, pink, brown, olive-green, black	White	336
3.1–3.3	3.5–4	Scorodite	$FeAsO_4 \cdot 2H_2O$	Orth.	Indistinct	Leek-green or liver-brown	White	312
3.1–3.5	5–6	Enstenite (Enstatite, Hypersthene)	$(Mg,Fe)SiO_3$	Orth.	(110) prismatic good at 88°	Gray, yellow, green, brown, black	White	350
3.2–3.3								
3.0–3.9	3.5–4.5	Brown Spar (Magnesite, Siderite, Rhodochrosite)	$(Mg,Fe,Mn)CO_3$	Rhom.	$(10\bar{1}1)$ rhombohedral perfect at 73°	White, gray, brown, red, green	White	276
3.0–4.2	5.5–6	Allanite (Orthite)	$H(Ca,Ce)_2(Al,Fe)_3Si_3O_{13}$, also La, Y, etc.	Mono.	Indistinct	Brown, black	White	384
3.1–3.3	3.5–4	Scorodite	$FeAsO_4 \cdot 2H_2O$	Orth.	Indistinct	Leek-green or liver-brown	White	312
3.1–3.5	5–6	Enstenite (Enstatite, Hypersthene)	$(Mg,Fe)SiO_3$	Orth.	(110) prismatic good at 88°	Gray, yellow, green, brown, black	White	350
3.2–3.3	6–7	Sillimanite (Fibrolite)	Al_2SiO_5	Orth.	010 pinacoidal perfect	White, gray, brown, greenish	White	337
3.2–3.4	6	Zoisite	$HCa_2Al_3Si_{13}$ often with Fe	Orth.	010 pinacoidal perfect	White, gray, brown, green, red	White	382
3.2–3.4	7	Dumortierite	$HBAl_8Si_3O_{20}$	Orth.	100 distinct	Blue, violet, pink	White, tinted	330

TABLE I. STREAK AND SPECIFIC GRAVITY (*Continued*)

4. MINERALS WITH COLORLESS, WHITE OR PALE COLORED STREAK (*cont.*)

G.	H.	Name	Composition	System	Cleavage	Color	Streak	Page
3.2–3.3 *cont.*								
3.2–3.5	6–7	Epidote (Pistacite)	$HCa_2(Al,Fe)_3Si_3O_{13}$ may have Mg, Cr, Mn	Mono.	001 basal distinct	Yellowish green, brown, black, gray, yellow, red	White, gray	383
3.2–3.6	5–6	Pyroxene (Diopside-Hedenbergite, Augite)	$Ca(Mg,Fe)Si_2O_6$ with Mg, Al (Augite)	Mono.	(110) prismatic good at 87°	Green, black, brown, white, gray	Greenish, brownish, gray, white	351
3.2–3.6	6.5–7	Olivine (Forsterite—Fayalite)	$(Mg,Fe)_2SiO_4$	Orth.	Indistinct	Yellowish green, brown, reddish	White, yellowish	331
3.3–3.4								
3.0–3.9	3.5–4.5	Brown Spar (Magnesite, Siderite, Rhodochrosite)	$(Mg,Fe,Mn)CO_3$	Rhom.	$(10\bar{1}1)$ rhombohedral perfect at 73°	White, gray, brown, red, green	White	276
3.0–4.2	5.5–6	Allanite (Orthite)	$H(Ca,Ce)_2(Al,Fe)_3Si_3O_{13}$, also La, Y, etc.	Mono.	Indistinct	Brown, black	White	384
3.1–3.5	5–6	Enstenite (Enstatite, Hypersthene)	$(Mg,Fe)SiO_3$	Orth.	(110) prismatic good at 88°	Gray, yellow, green, brown, black	White	350
3.2–3.4	6	Zoisite	$HCa_2Al_3Si_3O_{12}$, often with Fe	Orth.	010 pinacoidal perfect	White, gray, brown, green, red	White	382
3.2–3.4	7	Dumortierite	$HBAl_8Si_3O_{20}$	Orth.	100 distinct	Blue, violet, pink	White, tinted	330

3.2–3.5	6–7	Epidote (Pistacite)	$HCa_2(Al,Fe)_3Si_3O_{13}$ may have Mg, Cr, Mn	Mono.	Basal distinct	Yellowish green, brown, black, gray, yellow, red	White, gray	383
3.2–3.6	5–6	Pyroxene (Diopside-Hedenbergite, Augite)	$Ca(Mg,Fe)Si_2O_6$ with Mg and Al (Augite)	Mono.	(110) prismatic good at 87°	Green, black, brown, white, gray	Greenish, brownish, gray, white	351
3.2–3.6	6.5–7	Olivine (Forsterite—Fayalite)	$(Mg,Fe)_2SiO_4$	Orth.	Indistinct	Yellowish green, brown, reddish	White, yellowish	331
3.3–3.4								
3.3–3.4	6–7	Axinite	$HCa_3Al_2BSi_4O_{16}$, often with Mn, Fe, Mg	Tric.	010 pinacoidal distinct	Clove-brown, yellow, greenish, bluish, gray	White	338
3.3–3.5	6.5	Vesuvianite	$Ca_6Al_3(F,OH)Si_5O_{20}$, often with Mg, Fe, Mn	Tetr.	Indistinct	Brown, green, rarely yellow, white	White	339
3.3–3.5	6–7	Diaspore	$AlO{\cdot}OH$	Orth.	010 distinct	White, gray, brown, yellow	White	266
3.4–3.5								
3.0–3.9	3.5–4.5	Brown Spar (Magnesite, Siderite, Rhodochrosite	$(Mg,Fe,Mn)CO_3$	Rhom.	$(10\bar{1}1)$ rhombohedral perfect at 73°	White, gray, brown, red, green	White	276
3.0–4.2	5.5–6	Allanite (Orthite)	$H(Ca,Ce)_2(Al,Fe)_3Si_3O_{13}$, also La, Y, etc.	Mono.	Indistinct	Brown, black	White	384
3.1–3.5	5–6	Enstenite (Enstatite, Hypersthene)	$(Mg,Fe)SiO_3$	Orth.	(110) prismatic good at 88°	Gray, yellow, green, brown, black	White	350

TABLE I. STREAK AND SPECIFIC GRAVITY (*Continued*)

4. MINERALS WITH COLORLESS, WHITE OR PALE COLORED STREAK (*cont.*)

G.	H.	Name	Composition	System	Cleavage	Color	Streak	Page
3.4–3.5 *cont.*								
3.2–3.5	6–7	Epidote (Pistacite)	$HCa_2(Al,Fe)_3Si_3O_{13}$ may have Mg, Cr, Mn	Mono.	Basal distinct	Yellowish green, brown, black, gray, yellow, red	White, gray	383
3.2–3.6	5–6	Pyroxene (Diopside-Hedenbergite, Augite)	$Ca(Mg,Fe)Si_2O_6$ with Mg and Al (Augite)	Mono.	(110) prismatic good at 87°	Green, black, brown, white, gray	Greenish, brownish, gray, white	351
3.2–3.6	6.5–7	Olivine (Forsterite-Fayalite)	$(Mg,Fe)_2SiO_4$	Orth.	Indistinct	Yellowish green, brown, reddish	White, yellowish	331
3.3–3.5	6.5	Vesuvianite	$Ca_6Al_3(F,OH)Si_5O_{20}$ often with Mg, Fe, Mn	Tetr.	Indistinct	Brown, green, rarely yellow, white	White	339
3.3–3.5	6–7	Diaspore	$AlO{\cdot}OH$	Orth.	010 distinct	White, gray, brown, yellow	White	266
3.4–3.5	4.5–5	Hemimorphite (Calamine)	$H_2Zn_2SiO_5$	Orth. Hemi.	(110) prismatic good at 76°	White, colorless, yellowish, brownish, bluish	White	340
3.4–3.6	5–5.5	Titanite (Sphene)	$CaTiSiO_5$	Mono.	(110) at 66½°; (221) parting at 54°	Brown, black, yellow, gray, green, rose-red	White	338
3.4–3.6	8	Topaz	$Al_2(F,OH)_2SiO_4$	Orth.	Basal perfect	White, colorless, yellow, pink, bluish, greenish	White	334

3.4–3.7	5.5–6.5	Rhodonite	$MnSiO_3$ often with Ca, Fe, Zn	Tric.	110 and $1\bar{1}0$ prismatic good at $87\frac{1}{2}$°	Brownish red, flesh-red, pink, yellowish, greenish	White	348
3.4–3.8	6.5–7.5	Ugrandite (Uvarovite, Grossularite Andradite)	$Ca_3(Cr,Al,Fe)_2Si_3O_{12}$	Isom.	(110) dodecahedral parting at 60° and 90°	White, yellow, brown, red, green, pink, black	White	322
3.5–3.6								
3.0–3.9	3.5–4.5	Brown Spar (Magnesite, Siderite, Rhodochrosite)	$(Mg,Fe,Mn)CO_3$	Rhom.	$(10\bar{1}1)$ rhombohedral perfect at 73°	White, gray, brown, red, green	White	276
3.0–4.2	5.5–6	Allanite (Orthite)	$H(Ca,Ce)_2(Al,Fe)_3Si_3O_{13}$, also La, Y, etc.	Mono.	Indistinct	Brown, black	White	384
3.2–3.6	5–6	Pyroxene (Diopside-Hedenbergite, Augite)	$Ca(Mg,Fe)Si_2O_6$ with Mg and Al (Augite)	Mono.	(110) prismatic good at 87°	Green, black, brown, gray, white	Greenish, brownish gray, white	351
3.2–3.6	6.5–7	Olivine (Forsterite-Fayalite)	$(Mg,Fe)_2SiO_4$	Orth.	Indistinct	Yellowish green, brown, reddish	White, yellowish	331
3.4–3.6	5–5.5	Titanite (Sphene)	$CaTiSiO_5$	Mono.	(110) at $66\frac{1}{2}$°; (221) parting at 54°	Brown, black, yellow, gray, green, rose-red	White	338
3.4–3.6	8	Topaz	$Al_2(F,OH)_2SiO_4$	Orth.	Basal perfect	White, colorless, yellow, pink, bluish, greenish	White	334

TABLE I. STREAK AND SPECIFIC GRAVITY (*Continued*)

4. MINERALS WITH COLORLESS, WHITE OR PALE COLORED STREAK (*cont.*)

G.	H.	Name	Composition	System	Cleavage	Color	Streak	Page
3.5–3.6 *cont.*								
3.4–3.7	5.5–6.5	Rhodonite	$MnSiO_3$, often with Ca, Fe, Zn	Tric.	110 and $1\bar{1}0$ prismatic good at 87½°	Brownish red, flesh-red, pink, yellowish, greenish	White	348
3.4–3.8	6.5–7.5	Ugrandite (Uvarovite, Grossularite, Andradite)	$Ca_3(Cr,Al,Fe)_2Si_3O_{12}$	Isom.	(110) dodecahedral parting at 60° and 90°	White, yellow brown, red, green, pink, black	White	322
3.5	10	Diamond	C	Isom.	(111) octahedral difficult at 70½°	White, colorless, pale yellow, red, blue, green, black	White	230
3.5–3.7	4–5	Kyanite (Cyanite)	$AlSiO_5$	Tric.	100, 010 pinacoidal at 74°, 001 parting common	Blue, white, gray, green, nearly black	White	337
3.5–3.8	8.5	Chrysoberyl (Cymophane)	$BeAl_2O_4$	Orth.	(011) domatic, good at 60°	Light to dark green, greenish white, greenish brown, yellow	White	299
3.5–4.3	6.5–7.5	Pyralspite (Pyrope, Almandite, Spessartite)	$(Mg,Fe,Mn)_3Al_2Si_3O_{12}$	Isom.	(110) dodecahedral parting at 60° and 90°	Red, black, violet red, brownish red	White	322

3.6–3.9								
3.0–3.9	3.5–4.5	Brown Spar (Magnesite, Siderite, Rhodochrosite)	$(Mg,Fe,Mn)CO_3$	Rhom.	$(10\bar{1}1)$ rhombohedral perfect at 73°	White, gray, brown, red, green	White	276
3.0–4.2	5.5–6	Allanite (Orthite)	$H(Ca,Ce)_2(Al,Fe)_3Si_3O_{13}$, also La, Y, etc.	Mono.	Indistinct	Brown, black	White	384
3.4–3.7	5.5–6.5	Rhodonite	$MnSiO_3$ often with Ca, Fe, Zn	Tric.	110 and $1\bar{1}0$ prismatic good at 87½°	Brownish red, flesh-red, pink, yellowish, greenish	White	348
3.4–3.8	6.5–7.5	Ugrandite (Uvarovite, Grossularite, Andradite	$Ca_3(Cr,Al,Fe)_2Si_3O_{12}$	Isom.	(110) dodecahedral parting at 60° and 90°	White, yellow, brown, red, green, pink, black	White	322
3.5–3.7	4–5	Kyanite (Cyanite)	$AlSiO_5$	Tric.	110, 010 pinacoidal at 74°, 001 parting common	Blue, white, gray, green, nearly black	White	337
3.5–3.8	8.5	Chrysoberyl (Cymophane)	$BeAl_2O_4$	Orth.	(011) domatic, good at 60°	Light to dark green, greenish white, greenish brown, yellow	White	299
3.5–4.3	6.5–7.5	Pyralspite (Pyrope, Almandite, Spessartite)	$(Mg,Fe,Mn)_3Al_2Si_3O_{12}$	Isom.	(110) dodecahedral parting at 60° and 90°	Red, black, violet red, brownish red	White	322
3.6–3.8	7–7.5	Staurolite	$HFeAl_5Si_2O_{13}$, often with Mg, Mn	Orth.	010 pinacoidal poor	Yellow-brown, reddish black, gray	White, grayish	333

Table I. Streak and Specific Gravity (*Continued*)

4. MINERALS WITH COLORLESS, WHITE OR PALE COLORED STREAK (*cont.*)

G.	H.	Name	Composition	System	Cleavage	Color	Streak	Page
3.6–3.9 *cont.*								
3.6–4.6	7.5–8.5	Spinel (Picotite, Hercynite)	$(Mg,Fe)Al_2O_4$, also Mn, Cr, Zn	Isom.	Indistinct	Red, yellow, green, blue, brown, black	White, brown	299
3.7	3.5–4	Strontianite	$SrCO_3$, may have Ca	Orth.	(110) prismatic good at 63°	White, colorless, gray, greenish, yellowish	White	280
3.9–4.3								
3.0–4.2	5.5–6	Allanite (Orthite)	$H(Ca,Ce)_2(Al,Fe)_3Si_3O_{13}$, also La, Y, etc.	Mono.	Indistinct	Brown, black	White	384
3.5–4.3	6.5–7.5	Pyralspite (Pyrope, Almandite, Spessartite)	$(Mg,Fe,Mn)_3Al_2Si_3O_{12}$	Isom.	(110) dodecahedral parting at 60° and 90°	Red, black, violet red, brownish red	White	322
3.6–4.6	7.5–8.5	Spinel (Picotite, Hercynite)	$(Mg,Fe)Al_2O_4$, also Mn, Cr, Zn	Isom.	Indistinct	Red, yellow, green, blue, brown, black	White, brown	299
3.9–4.0	3–3.5	Celestite	$SrSO_4$, often with Ca, Ba	Orth.	(110) prismatic and basal at 76° and 90°	White, colorless, bluish, reddish	White	287
3.9–4.1	3.5–4	Sphalerite	ZnS, often with Fe	Isom. Tetrah.	(110) dodecahedral good at 60° and 90°	Yellow, brown, red, green, black, white	White, brown	237

3.9–4.1	9	Corundum	Al_2O_3	Rhom.	$(10\bar{1}1)$ rhombohedral parting at 86°, also 0001 parting	White, gray, brown to black	White	258
3.9–4.2	5–6	Willemite	Zn_2SiO_4 may have Mn (Troostite)	Rhom.	$(11\bar{2}0)$ prismatic at 60°	Yellow, green, brown, red, white	White	329
4.0–4.1	5.5–6	Tephroite	Mn_2SiO_4, often also Mg, Fe, Zn	Orth.	010, 100 pinacoidal poor at 90°	Ash-gray, flesh-red, brown	Pale gray	331
4.1–4.3	6	Rutile	TiO_2, often with Fe	Tetr.	Indistinct	Red, reddish brown, black	White, gray, pale brown	261
4.3–5.7								
3.6–4.6	7.5–8.5	Spinel (Picotite, Hercynite)	$(Mg,Fe)Al_2O_4$, also Mn, Cr, Zn	Isom.	Indistinct	Red, yellow, green, blue, brown black	White, brown	299
4.3–4.4	3–4	Witherite	$BaCO_3$	Orth.	Indistinct	White, grayish, yellowish	White	281
4.3–4.5	5	Smithsonite (Calamine in England)	$ZnCO_3$	Rhom.	$(10\bar{1}1)$ rhombohedral good at 72°	White, grayish, colorless, greenish, blue, pink, brown	White	278
4.3–4.6	2.5–3	Barite (Heavy Spar)	$BaSO_4$, may have Ca, Sr	Orth.	Basal and (110) prismatic good at 90° and 78½°	White, colorless, pale yellow, brown, red, blue	White	287
4.5–4.8	7.5	Zircon	$ZrSiO_4$, often with Fe, Hf, Th, etc.	Tetr.	Indistinct	Gray, brown, yellow, green, red, smoky	White	328
4.9–5.3	5–5.5	Monazite	$(Ce,La,Di)PO_4$, also Th, Y, etc.	Mono.	Indistinct	Yellow, greenish, brownish	White	309

TABLE I. STREAK AND SPECIFIC GRAVITY (*Continued*)

4. MINERALS WITH COLORLESS, WHITE OR PALE COLORED STREAK (*cont.*)

G.	H.	Name	Composition	System	Cleavage	Color	Streak	Page
4.3–5.7 *cont.*								
5.5–5.6	1–1.5	Cerargyrite (Horn Silver)	Ag(Cl,Br,I) may have Hg	Isom.	None	Pearl-gray, etc. turning to violet-brown	White	253
5.7–7.2								
5.9–6.1	4.5–5	Scheelite	$CaWO_4$, often with Mo, Cu	Tetr.	(111) pyramidal good at 80° and 50°	White, yellow, brownish, greenish, reddish	White	296
6.1–6.4	3	Anglesite	$PbSO_4$	Orth.	Basal and (110) prismatic poor at 90° and 76°	White, colorless, gray, brown, green	White	288
6.4–6.6	3	Cerussite (White Lead Ore)	$PbCO_3$	Orth.	Indistinct	White, gray, colorless, yellow, brown, etc.	White	281
6.5–7.1	3.5–4	Pyromorphite (Green Lead Ore)	$Pb_5ClP_3O_{12}$, often with As, Ca	Hex.	None	Green, yellow, brown, white, gray	Pale yellow, greenish yellow, white	308
6.6–7.2	3	Vanadinite	$Pb_5ClV_3O_{12}$, often with P, As	Hex.	None	Ruby red, brown, yellow	White, pale yellow	309
6.7–7.0	3	Wulfenite	$PbMoO_4$, may have Ca	Tetr.	Indistinct	Yellow, orange, olive, brown, gray	White	296
6.8–7.1	6–7	Cassiterite (Tinstone)	SnO_2, may have Ta, Fe	Tetr.	Indistinct	Brown to black, rarely yellow, red	White, grayish, brownish	264

Hardness and Streak

Some minerals are nearly always in a finely fibrous or minutely granular or lamellar condition. In such a condition they may seem to be softer than they really are. Their hardness can not be determined by producing a scratch on their surface, but only by using them to produce a scratch on the surface of some other mineral. In some cases this also is difficult, and therefore some minerals commonly found in this condition are included in the following tables both with their true hardness and also with their apparent hardness.

It should not be forgotten that any mineral will appear to be soft if it is found in a very finely divided but somewhat coherent mass. In the following table are included only minerals which are *often* found in this condition. Also, some minerals may have their hardness apparently increased because of the presence in them of some (finely divided) harder mineral. such as quartz.

The streak is used to establish subdivisions in this table.

OUTLINE OF TABLE II

MINERALS WITH A HARDNESS OF 1–2

1. Streak silver white, steel gray, or black
2. Streak blue or green
3. Streak yellow, red, or brown
4. Streak white, colorless, or pale

MINERALS WITH A HARDNESS OF 2–3

1. Streak silver white, steel gray, or black
2. Streak blue or green
3. Streak yellow, red, or brown
4. Streak white, colorless, or pale

MINERALS WITH A HARDNESS OF 3–4

1. Streak silver white, steel gray, or black
2. Streak blue or green
3. Streak yellow, red, or brown
4. Streak white, colorless, or pale

MINERALS WITH A HARDNESS OF 4–5

1. Streak silver white, steel gray, or black
2. Streak yellow, red, or brown
3. Streak white, colorless, or pale

OUTLINE OF TABLE II (*cont.*)

MINERALS WITH A HARDNESS OF 5–6

1. Streak silver white, steel gray, or black
2. Streak blue or green
3. Streak yellow, red, or brown
4. Streak white, colorless, or pale

MINERALS WITH A HARDNESS OF 6–7

1. Streak silver white, steel gray, or black
2. Streak blue or green
3. Streak yellow, red, or brown
4. Streak white, colorless, or pale

MINERALS WITH A HARDNESS OF 7–10

1. Streak white, colorless, or pale

Table II. Hardness and Streak

TABLE II. HARDNESS

MINERALS WITH HARDNESS 1–2

1. Streak silver white, steel gray, or black

G.	Name	Comp.	System	Cleavage	Color	Diagnostics	Page
1.9–2.3	Graphite	C	Rhom.	Basal perf.	Steel-gray to black	Black streak on porcelain	233
4.5–4.6	Stibnite	Sb_2S_3	Orth.	010 perf.	Lead-gray	Fuses at 1	245
4.6	Covellite	CuS	Hex.	Basal perf.	Indigo-blue	Indigo-blue color	244
4.7–4.8	Pyrolusite	MnO_2	Tetr.	(110) perf.	Black	Test for Mn	265
4.7–4.8	Molybdenite	MoS_2	Hex.	Basal perf.	Lead-gray	Greenish streak on porcelain	244
5.5–5.8	Chalcocite	Cu_2S	Orth.	None	Lead-gray	Color; sectile	245
6.4–6.5	Bismuthinite	Bi_2S_3	Orth.	010 perf.	Lead-gray	F. = 1; test for Bi	246
7.2–7.4	Argentite	Ag_2S	Isom.	None	Lead-gray	F. = 1.5; test for Ag	236
7.9–8.3	Sylvanite	$AuAgTe_4$	Mono.	010 dist.	Silver-white	F. = 1; test for Te	248

2. Streak blue or green

G.	Name	Comp.	System	Cleavage	Color	Diagnostics	Page
2.2–2.4	Glauconite	$KFeSi_2O_6 \cdot nH_2O$	Amor.	None	Green	Resembles chlorite	373
2.3–2.8	Garnierite	$H_4(Mg,Ni)_3Si_2O_9$ (varies)	Amor.	None	Apple-green	Color, earthy luster; test for Ni	361
2.6–2.7	Vivianite	$Fe_3P_2O_8 \cdot 8H_2O$	Mono.	010 perf.	Light to dark green, blue	Color; test for P	313
2.6–3.0	Chlorite	$H_4(Mg,Fe)_3Si_2O_9 +$ $H_4(Mg,Fe)_2Al_2SiO_9$	Mono.	001 perf.	Light to dark green	Green color, non-elastic folia	371
3.2–3.3	Crocidolite	$NaFe''Fe'''Si_3O_9$	Mono.	(110) perf.	Blue, green	Fibrous; fuses easily; insoluble	359

3. Streak yellow, red or brown

2.0–2.1	Sulfur	S	Orth.	Indist.	Yellow	Burns easily with SO_2 odor	234
2.4–2.6	Bauxite	$Al_2O_3 \cdot H_2O(Fe)$	Amor.	None	White to red	Infusible; test for Al	266
?	Carnotite	$K_2U_4V_5O_{11} \cdot 2H_2O$	Orth.	010 perf.	Yellow	Color; test for V	311
2.9–3.0	Erythrite	$Co_3As_2O_8 \cdot 8H_2O$	Mono.	010 perf.	Red, gray	Color; test for Co	312
3.4–3.5	Orpiment	As_2S_3	Mono.	010 perf.	Lemon-yellow	Color; test for As	247
3.5–3.6	Realgar	AsS	Mono.	010 dist.	Red to orange	Color; test for As	247
3.6–4.0	Limonite	$Fe_2O_3 \cdot nH_2O$	Amor.	None	Yellow, brown	Strongly magnetic after heating in R. F.	267
4.0–4.4	Goethite	$Fe_2O_3 \cdot nH_2O$	Orth.	010 perf.	Yellow, brown	Strongly magnetic after heating in R. F.	267
4.9–5.3	Hematite	Fe_2O_3	Rhom.	$(10\bar{1}1)$ part.	Red	Strongly magnetic after heating in R.F.	259

4. Streak white, colorless or pale

0.9	Ice (Snow)	H_2O	Hex.	None	White, bluish	Melts at 32° F.	256
1.0	Water	H_2O			White, tinted	Liquid	256
1.4–1.5	Mirabilite	$Na_2SO_4 \cdot 10H_2O$	Mono.	100 perf.	White	Water soluble	285
1.6	Carnallite	$KMgCl_3 \cdot 6H_2O$	Orth.	None	White, tinted	Bitter taste	255
1.65	Ulexite	$NaCaB_5O_9 \cdot 8H_2O$	Mono.	?	White	F. = 1; test for B	297
1.7–1.8	Epsomite	$MgSO_4 \cdot 7H_2O$	Orth.	010, (011)	White	Bitter, salty taste	291
1.9–2.0	Melanterite	$(Fe,Cu,Zn)SO_4 \cdot 7H_2O$	Mono.	001 perf.	Green, white	Sweet, astringent taste	291
1.97–1.99	Sylvite	KCl	Isom.	(100) perf.	White, tinted	Bitter taste; K flame	252
2.1	Niter	KNO_3	Orth.	(011)	Colorless	Cool salty taste; test for K	271

TABLE II. HARDNESS (*Continued*)

MINERALS WITH HARDNESS 1–2 (*cont.*)

4. Streak white, colorless or pale (*cont.*)

G.	Name	Comp.	System	Cleavage	Color	Diagnostics	Page
2.1–2.2	Tripoli	$SiO_2 \cdot nH_2O$	Amor.	None	White, gray	Test for Si	398
2.2–2.3	Soda Niter	$NaNO_3$	Rhom.	$(10\bar{1}1)$ perf.	White, tinted	Cool salty taste	270
2.3–2.4	Gypsum	$CaSO_4 \cdot 2H_2O$	Mono.	010	White, tinted	Cleavage; test for S	289
2.3–2.8	Vermiculite	Silicate of Al, Mg, Fe, H	Mono.	001 perf.	Yellow, red, green	Flexible folia; exfoliation	273
2.3–2.8	Garnierite	$H_4(Mg,Ni)_3Si_2O_9$(varies)	Amor.	None	Green	Color; earthy luster; test for Ni	361
2.4–2.6	Bauxite	$Al_2O_3 \cdot H_2O(Fe)$	Amor.	None	White to red	Infusible; test for Al	266
2.4–2.6	Kaolinite	$H_4Al_2Si_2O_9$	Mono.	001 perf.	White, tinted	Like clay; test for Al	364
2.5–2.8	Talc	$H_4Mg_3Si_4O_{12}$	Mono.	001 perf.	Apple-green, gray	Soapy feel; no test for Al	363
2.6–2.7	Vivianite	$Fe_3P_2O_8 \cdot 8H_2O$	Mono.	010 perf.	Light to dark green	Color; test for P	313
2.6–3.0	Chlorite	$H_4(Mg,Fe)_3Si_2O_9$ + $H_4(Mg,Fe)_2Al_2SiO_9$	Mono.	001 perf.	Light to dark green	Green color; non-elastic folia	371
2.7	Chalk	$CaCO_3$	Rhom.	$(10\bar{1}1)$ perf.	White, gray	Powder; effervescent with acid	273
2.8–2.9	Pyrophyllite	$H_2Al_2Si_4O_{12}$	Orth.	001 perf.	White, greenish	Greasy feel; test for Al	366
5.5–6.0	Cerargyrite	Ag(Cl,Br,I)	Isom.	None	Gray to brown	Waxlike; sectile, test for Ag	253

MINERALS WITH HARDNESS 2–3

1. Streak silver white, steel gray, or black

4.4–4.5	Enargite	Cu_3AsS_4	Orth.	(110) dist.	Gray-black	F. = 1; test for As	251
4.7–4.8	Pyrolusite	MnO_2	Tetr.	(110) perf.	Black	Test for Mn	265
4.9–5.4	Bornite	Cu_3FeS_4	Isom.	None	Red to brown	F. = 2.5; magnetic in R. F.	241
5.5–5.8	Chalcocite	Cu_2S	Orth.	None	Lead-gray	Color; sectile	245
5.5–6.0	Jamesonite	$Pb_2Sb_2S_5$	Mono.	001	Steel-gray	F. = 1; test for Pb and Sb	251
5.7–5.9	Bournonite	$CuPbSbS_3$	Orth.	Indist.	Gray to black	F. = 1; test for Pb, Sb, and Cu	250
6.4–6.5	Bismuthinite	Bi_2S_3	Orth.	010 perf.	Lead-gray	F. = 1; test for Bi	246
7.2–7.4	Argentite	Ag_2S	Isom.	Indist.	Lead-gray	F. = 1.5; test for Ag	236
7.4–7.6	Galena	PbS	Isom.	(100) perf.	Lead-gray	F. = 2; test for Pb	236
8.9	Copper	Cu	Isom.	None	Copper-red	Color; malleable	227
9	Calaverite	$AuTe_2$	Mono.	None	Brass to silver-white	F. = 1; test for Au	248
9.8	Bismuth	Bi	Rhom.	0001	Reddish silver	Color, cleavage	230
10–19	Noble Metal (Gold, Silver)	Au, Ag	Isom.	None	Yellow, white	Color; malleable	225

2. Streak blue or green

2.0–2.2	Chrysocolla	$CuSiO_3 \cdot 2H_2O$	Amor.	None	Blue, brown, black	F. = 7; test for Cu	398
2.6–3.0	Chlorite	$H_4(Mg,Fe)_3Si_2O_9 + H_4(Mg,Fe)_2Al_2SiO_9$	Mono.	001 perf.	Light to dark green	Green color; non-elastic folia	371

Table II. Hardness (*Continued*)

MINERALS WITH HARDNESS 2–3 (*cont.*)

3. Streak yellow, red or brown

G.	Name	Comp.	System	Cleavage	Color	Diagnostics	Page
2.0–2.1	Sulfur	S	Orth.	Indist.	Yellow	Burns with SO_2 odor.	234
2.4–2.6	Bauxite	$Al_2O_3 \cdot H_2O(Fe)$	Amor.	None	White to red	F. = 7; test for Al	266
2.7–2.8	Polyhalite	$K_2MgCa_2S_4O_{16} \cdot 2H_2O$	Tric.	100 dist.	Pink, red	F. = 1.5; soluble in HCl	289
2.9–3.0	Erythrite	$Co_3As_2O_8 \cdot 8H_2O$	Mono.	010 perf.	Red, gray	Color; test for Co	312
5.5–5.9	Ruby Silver (Pyrargyrite, Proustite)	$Ag_3(Sb,As)S_3$	Rhom.	Indistinct	Black to scarlet	F. = 1; test for Ag	249
5.9–6.1	Crocoite	$PbCrO_4$	Mono.	(110) poor	Hyacinth-red	Color; G. = 6 ±	296
6.6–7.2	Vanadinite	$Pb_5ClV_2O_8$	Hex.	None	Red, brown, yellow	F. = 1.5; test for Pb	309
8.0–8.2	Cinnabar	HgS	Rhom.	Indist.	Red	Volatile	242

4. Streak white, colorless or pale

G.	Name	Comp.	System	Cleavage	Color	Diagnostics	Page
1.0–2.0	Sepiolite	$H_4Mg_2Si_3O_{10}$	Amor.	None	White, tinted	Heat gives much H_2O and burnt odor	360
1.6	Carnallite	$KMgCl_3 \cdot 6H_2O$	Orth.	None	White, tinted	Bitter taste	255
1.7	Borax	$Na_2B_4O_7 \cdot 10H_2O$	Mono.	100 dist.	White, tinted	F. = 1 with swelling	298
1.7–1.8	Epsomite	$MgSO_4 \cdot 7H_2O$	Orth.	010 dist.	White	Bitter, salty taste	291
1.9–2.0	Melanterite	$(Fe,Cu,Zn)SO_4 \cdot 7H_2O$	Mono.	001 perf.	Green, white	Sweet, astringent taste	291
1.95	Kernite	$Na_2B_4O_7 \cdot 4H_2O$	Mono.	001, 100	White	B.B. swells; F. = 1.5	298
1.97–1.99	Sylvite	KCl	Isom.	(100) perf.	White, tinted	Bitter taste and K flame	252
2.0–2.2	Chrysocolla	$CuSiO_3 \cdot 2H_2O$	Amor.	None	Blue, brown, black	F. = 7; test for Cu	398
2.0–2.2	Kainite	$KMgClSO_4 \cdot 3H_2O$	Mono.	(110), 100	White to red	Sol. in H_2O	286
2.1	Trona	$HNa_3C_2O_6 \cdot 2H_2O$	Mono.	100 perf.	Gray, white	Sol. in H_2O	283

2.1–2.3	Chalcanthite	$(Cu,Fe,Co,Zn)SO_4 \cdot 5H_2O$	Tric.	Indist.	Blue	F. = 3; soluble in H_2O	292
2.1–2.6	Halite	$NaCl$	Isom.	(100) perf.	White, tinted	Salty taste	252
2.3–2.4	Brucite	$(Mg,Mn)(OH)_2$	Rhom.	0001 perf.	White, tinted	F. = 7; soluble in HCl	268
2.3–2.4	Gibbsite	$Al(OH)_3$	Mono.	001 rare	White, tinted	F. = 7; test for Al	267
2.3–2.6	Serpentine	$H_4Mg_3Si_2O_9$	Mono.	None	Green, yellow, white	F. = 6; test for Mg	361
2.4–2.6	Bauxite	$Al_2O_3 \cdot H_2O(Fe)$	Amor.	None	White to red	F. = 7; test for Al	266
2.4–2.6	Kaolinite	$H_4Al_2Si_2O_9$	Mono.	001 perf.	White, tinted	F. = 7; test for Al	364
2.6–2.9	Collophanite	$Ca_3P_2O_8 \cdot nH_2O$	Amor.	None	White, tinted	F. = 6; test for P	304
2.6–3.0	Chlorite	$H_4(Mg,Fe)_3Si_2O_9 + H_4(Mg,Fe)_2Al_2SiO_9$	Mono.	001 perf.	Light to dark green	Green color; non-elastic folia	371
2.7–2.8	Polyhalite	$K_2MgCa_2S_4O_{16} \cdot 2H_2O$	Tric.	100 dist.	Pink, red	F. = 1.5; sol. in HCl	289
2.7–2.8	Glauberite	$Na_2CaS_2O_8$	Mono.	001 dist.	White, tinted	F. = 2; sol. in HCl	285
2.7	Calcite	$CaCO_3$	Rhom.	(1011) perf.	White, tinted	Effervescent in HCl	271
2.7–3.0	Muscovite	$H_2KAl_3Si_3O_{12}$	Mono.	001 perf.	White, tinted	F. = 5; insoluble in acid	366
2.8–2.9	Lepidolite	Li mica	Mono.	001 perf.	Pink, lilac, yellow	F. = 2; crimson flame	371
2.8–3.1	Biotite	$H_4K_2(Fe,Mg)_6Al_2Si_6O_{24} + H_4K_2(Fe,Mg)_5Al_4Si_5O_{24}$	Mono.	001 perf.	Brown, black green	F. = 5; dark color	368
2.9–3.0	Cryolite	Na_3AlF_6	Mono.	001, (110)	White, gray	Cool salty taste	255
4.3–4.6	Barite	$BaSO_4$	Orth.	001, (110)	White, tinted	Insoluble; test for Ba	287
6.1–6.4	Anglesite	$PbSO_4$	Orth.	001 (110)	White, tinted	F. = 1.5; test for Pb	288
6.6–7.2	Vanadinite	$Pb_5ClV_2O_8$	Hex.	None	Red, brown, yellow	F. = 1.5; test for Pb	309
6.7–7.0	Wulfenite	$PbMoO_4$	Hex.	Indist.	Yellow, green, brown, gray	F. = 2; test for Mo	296

TABLE II. HARDNESS (*Continued*)

MINERALS WITH HARDNESS 3–4

1. Streak silver white, steel gray, or black

G.	Name	Comp.	System	Cleavage	Color	Diagnostics	Page
4.1–4.3	Chalcopyrite	$CuFeS_2$	Tetr.	Indist.	Brass yellow	F. = 2 to magnetic globule	241
4.2–4.4	Manganite	$MnO \cdot OH$	Orth.	010 perf.	Gray to black	F. = 7; test for Mn	268
4.3–4.5	Stannite	Cu_2FeSnS_4	Tetr.	Indist.	Grayish black	F. = 1.5; test for Cu, Sn	249
4.4–4.5	Enargite	$Cu_3(As,Sb)S_4$	Orth.	(110) dist.	Grayish black	F. = 1; test for As, Cu	251
4.4–5.1	Gray Copper (Tetrahedrite)	$Cu_{10}(Zn,Fe)_2(Sb,As)_4S_{13}$	Isom.	None	Gray to black	F. = 1.5; test for Sb, Cu	248
4.5–4.6	Pyrrhotite	$FeS(+S)$	Hex.	Indist.	Bronze	F. = 3; magnetic in R. F.	242
4.6–5.1	Pentlandite	$(Fe,Ni)S$	Isom.	(111) dist.	Bronze-yellow	F. = 1.5–2; magnetic in R. F.	240
4.9–5.4	Bornite	Cu_5FeS_4	Isom	None	Red to brown	F. = 2.5; magnetic in R. F.	241
5.3–5.7	Millerite	NiS	Rhom.	Indist.	Brass-yellow	F. = 1.5–2; test for Ni	243
5.7	Arsenic	As	Rhom.	0001	Tin-white	Volatile	229

2. Streak blue or green

G.	Name	Comp.	System	Cleavage	Color	Diagnostics	Page
3.7–3.8	Azurite	$Cu_3(OH)_2C_2O_6$	Mono.	(021)	Blue	F. = 3; test for Cu	282
3.9–4.0	Malachite	$Cu_2(OH)_2CO_3$	Mono.	001	Green	F. = 3; test for Cu	282
4.1–4.3	Chalcopyrite	$CuFeS_2$	Tetr.	Indist.	Brass-yellow	F. = 2; test for Cu	241
5.3–5.7	Millerite.	NiS	Rhom.	Indist.	Brass-yellow	F. = 1.5–2; test for Ni	243

3. Streak yellow, red or brown

3.9–4.1	Sphalerite	$(Zn,Fe)S$	Isom.	(110) perf.	Yellow to black	F. = 6–7; soluble in HCl	237
4.2–4.4	Manganite	$MnO{\cdot}OH$	Orth.	010 perf.	Gray to black	F. = 7; test for Mn	268
4.4–5.1	Gray Copper (Tetrahedrite)	$Cu_{10}(Zn,Fe)_2(Sb,As)_4S_{13}$	Isom.	None	Gray to black	F. = 1.5; test for Cu	248
4.9–5.0	Greenockite	CdS	Hex.	$(11\bar{2}0)$ dist.	Yellow	F. = 7; test for Cd	243
5.8–6.1	Cuprite	Cu_2O	Isom.	Indist.	Red, orange	F. = 3; test for Cu	257

4. Streak white, colorless or pale

1.95	Kernite	$Na_2B_4O_7{\cdot}4H_2O$	Mono.	001, 100	White	B. B. swells; F. = 1.5	298
2.0–2.2	Kainite	$KMgCl_3{\cdot}3H_2O$	Mono.	(110), 100	White to red	Soluble in H_2O	286
2.1–2.2	Stilbite	$Na_2Al_2Si_6O_{16}{\cdot}6H_2O$	Mono.	010 perf.	White, tinted	F. = 3 to white enamel	396
2.3–2.4	Wavellite	$Al(OH)_3P_2O_8{\cdot}5H_2O$	Orth.	(101), 010	Green, yellow, white	F. = 7, but swells	311
2.3–2.4	Gibbsite	$Al(OH)_3$	Mono.	001 rare	White, tinted	F. = 7; test for Al	267
2.4–2.6	Bauxite	$Al_2O_3{\cdot}H_2O(Fe)$	Amor.	None	White to red	F. = 7; test for Al	266
2.5–2.6	Serpentine (Chrysotile)	$H_4(Mg,Fe)_3Si_2O_9$	Mono.	None	Green, yellow, white	F. = 6; test for Mg	361
2.57	Kieserite	$MgSO_4{\cdot}H_2O$	Mono.	Several	White	Slowly soluble in H_2O	285
2.6–2.8	Alunite	$KAl(OH)_6S_2O_8$	Rhom.	Indist.	White, reddish	F. = 7; soluble in H_2SO_4	294
2.6–2.9	Collophanite	$Ca_3P_2O_8{\cdot}nH_2O$	Amor.	None	White, tinted	F. = 6; test for P	304
2.7	Calcite	$CaCO_3$	Rhom.	$(10\bar{1}1)$ perf.	White, tinted	Effervescent in acid	271
2.8–2.9	Lepidolite	Li mica	Mono.	001 perf.	Pink, lilac, yellow	F. = 2 with crimson flame	371
2.8–3.1	Dolomite	$Ca(Mg,Fe,Mn)C_2O_6$	Rhom.	$(10\bar{1}1)$ perf.	White, red, brown, green black	Only slight effervescent in cold acid	274

TABLE II. HARDNESS (*Continued*)
MINERALS WITH HARDNESS 3–4 (*cont.*)
4. Streak white, colorless or pale (*cont.*)

G.	Name	Comp.	System	Cleavage	Color	Diagnostics	Page
2.9–3.0	Aragonite	$CaCO_3$	Orth.	(110), 100	White, gray, yellow	Effervescent in acid; decrepitates	279
2.9–3.0	Anhydrite	$CaSO_4$	Orth.	001, 010, 100	White (to red)	F. = 5; test for Ca	286
3.0–3.2	Fluorite	CaF_2	Isom.	(111) perf.	Violet, blue, yellow, green, white, red	F. = 3; test for F	254
3.0–3.9	Brown Spar (Magnesite, Siderite, Rhodochrosite)	$(Mg,Fe,Mn)CO_3$	Rhom.	$(10\bar{1}1)$ perf.	White, gray, yellow, red, brown	Effervescent in hot acid	276
3.7	Strontianite	$SrCO_3$	Orth.	(110)	White	Effervescent in hot acid; test for Sr	280
3.9–4.0	Celestite	$SrSO_4$	Orth.	001, (110)	White, bluish	F. = 3.5–4; test for Sr	287
3.9–4.1	Sphalerite	$(Zn,Fe)S$	Isom.	(110) perf.	Yellow to black	F. = 6–7; soluble in HCl	237
4.3–4.4	Witherite	$BaCO_3$	Orth.	Indist.	White	Effervescent in HCl; test for Ba	281
4.3–4.6	Barite	$BaSO_4$	Orth.	001, (110)	White, tinted	Insoluble; test for Ba	287
6.4–6.6	Cerussite	$PbCO_3$	Orth.	Indist.	White, tinted	F. = 1.5; test for Pb	281
6.5–7.1	Pyromorphite	$Pb_5ClP_3O_{12}$	Hex.	None	Green, yellow, brown	F. = 2; test for Pb and P	308

1. Streak silver white, steel gray, or black

4.2–4.4	Manganite	MnO·OH	Orth.	010 perf.	Gray to black	F. = 7; test for Mn	268
4.5–4.6	Pyrrhotite	FeS(+S)	Hex.	Indist.	Bronze	F. = 3; magnetic in R.F.	242
7.3–7.8	Iron	(Fe,Ni)	Isom.	100 perf.	Steel-gray	F. = 7; test for Fe	228
14.–19.	Platinum	Pt	Isom.	None	Steel-gray	F. = 7; G. = 15 ±; insoluble	228

2. Streak yellow, red or brown

4.2–4.4	Manganite	MnO·OH	Orth.	010 perf.	Gray to black	F. = 7; test for Mn	268
5.4–5.7	Zinkite	ZnO	Hex.	0001 dist.	Red to orange	F. = 7; soluble in HCl; test for Zn	257

3. Streak white, colorless or pale

2.0–2.2	Chabazite	$CaAl_2Si_4O_{12}\cdot 6H_2O$	Rhom.	$(10\bar{1}1)$	White, pink, yellow	F. = 3; test for Al and Ca	397
2.3–2.4	Apophyllite	$KF\cdot Ca_4Si_8O_{20}\cdot 8H_2O$	Tetr.	001 perf.	White, tinted	F. = 2; test for Al and K	362
2.3–2.5	Colemanite	$HCaB_3O_6\cdot 2H_2O$	Mono.	010, 001	White, yellowish	F. = 1.5 with B flame	298
2.6–2.9	Collophanite	$Ca_3P_2O_8\cdot nH_2O$	Amor.	None	White, tinted	F. = 6; test for P	304
2.7–2.8	Pectolite	$HNaCa_2Si_3O_9$	Mono.	100, 001	White, tinted	F. = 2.5–3; test for Na and Ca	349
2.8–2.9	Wollastonite	$CaSiO_3$	Mono. Tric.	100, 001	White, tinted	F. = 4; test for Ca	347
2.9–3.1	Melilite	$Ca_2Al_2SiO_9 + Ca_2(Mg,Fe)Si_2O_9$	Tetr.	Indist.	White, green, brown	F. = 3; soluble in HCl	340

TABLE II. HARDNESS (*Continued*)

MINERALS WITH HARDNESS 4–5 (*cont.*)

3. Streak white, colorless or pale (*cont.*)

G.	Name	Comp.	System	Cleavage	Color	Diagnostics	Page
3.0–3.2	Fluorite	CaF_2	Isom.	(111) perf.	Violet, blue, yellow, green, white, red	F. = 3; test for F	254
3.0–3.9	Brown Spar (Magnesite, Siderite, Rhodochrosite)	$(Mg,Fe,Mn)CO_3$	Rhom.	$(10\bar{1}1)$ perf.	White, gray, yellow, red, brown	Effervescent in hot acid	276
3.1–3.2	Apatite	$Ca_5FP_3O_{12}$	Hex.	Indist.	Green, blue, red, brown, white	F. = 5.5; test for Ca and P	306
3.4–3.5	Hemimorphite	$H_2Zn_2SiO_5$	Orth.	(110) dist.	White, tinted	F. = 5; test for Zn	340
3.5–3.7	Kyanite	Al_2SiO_5	Tric.	100, 010 001	Blue, white, gray, green	F. = 7; test for Al	337
5.9–6.2	Scheelite	$CaWO_4$	Tetr.	(111) dist.	White, tinted	F. = 5, test for W	296

MINERALS WITH HARDNESS 5–6

Streak silver white, steel gray or iron black

G.	Name	Comp.	System	Cleavage	Color	Diagnostics	Page
3.7–4.1	Psilomelane	Mn, O, Ba, H	Amor.	None	Iron black	F. = 7; test for Mn	284
4.3–5.5	Ilmenite	$(Fe,Mn,Mg)TiO_3$	Tetr.	None	Black to brown	Test for Ti	261
4.9–5.2	Magnetite (Franklinite)	$(Fe,Mg,Mn,Zn)Fe_2O_4$	Isom.	None	Iron-black	Strongly magnetic	302
5.3–7.6	Columbite (Tantalite)	$(Fe,Mn)(Cb,Ta)_2O_6$	Orth.	Indist.	Black	F. = 5–5.5; test for Cb	313
5.9–6.2	Arsenopyrite	FeAsS	Mono.	Indist.	Silver to steel-gray	F. = 2 to magnetic globule	246

6.0–6.3	Cobaltite	CoAsS	Isom.	Indist.	Silver-white (reddish)	F. = 2–3; test for Co	239
6.4–6.6	Smaltite	$(Co,Ni)As_2$	Isom.	Indist.	Tin-white to steel-gray	F. = 2–2.5; test for Co, Ni	240
7.2–7.5	Wolframite	$(Fe,Mn)WO_4$	Mono.	010 perf.	Gray, black, brown	F. = 3–4; test for W	295
7.3–7.7	Niccolite	NiAs	Hex.	None	Copper-red	F. = 2; test for Ni	243
9.0–9.7	Uraninite	UO_2, U_2O_3, Pb, Th, etc.	Isom.	None	Black	F. = 7; test for U	269

2. Streak blue or green

2.6–2.8	Turquois	$CuO \cdot 3Al_2O_3 \cdot 2P_2O_5 \cdot 9H_2O$	Tric.	None	Blue, green	Test for Cu, P	312
2.9–3.4	Hornblende (Tremolite, Actinolite)	O, Si, Mg, Fe, Ca, Al, Na, H	Mono.	(110) perf.	Green, black, brown, gray	F. = 3–4; cleavage angle	357
3.0–4.2	Allanite	$H(Ca,Ce)_2(Al,Fe'')_3Si_3O_{13}$	Mono.	Indist.	Black	F. = 2.5 to magnetic glass	384
3.2–3.6	Pyroxene (Diopside, Hedenbergite, Augite)	$Ca(Mg,Fe)Si_2O_6$, often with Al, etc.	Mono.	(110) perf. 001 part.	Green, brown, black, white	F. = 4–4.5; cleavage angle	351

3. Streak yellow, red, or brown

2.9–3.4	Hornblende (Tremolite, etc.)	O, Si, Mg, Fe, Ca, Al, Na, H	Mono.	(110) perf.	Green, black, brown, gray	F. = 3–4; cleavage angle	357
3.0–4.2	Allanite	$H(Ca,Ce)_2(Al,Fe'')_3Si_3O_{13}$	Mono.	Indist.	Black	F. = 2.5 to magnetic glass	384
3.1–3.5	Enstenite (Enstatite, Hypersthene)	$(Mg,Fe)SiO_3$	Orth.	(110) perf.	Gray, green, yellow, brown, black	F. = 5; cleavage angle = 93°	350

TABLE II. HARDNESS (*Continued*)
MINERALS WITH HARDNESS 5–6 (*cont.*)
3. Streak yellow, red or brown (*cont.*)

G.	Name	Comp.	System	Cleavage	Color	Diagnostics	Page
3.2–3.6	Pyroxene (Diopside, Augite)	$Ca(Mg,Fe)Si_2O_6$ often with Al, etc.	Mono.	(110) perf.	Green, brown, black, white	F. = 4–4.5.; cleavage angle	351
3.6–4.0	Limonite	FeO·OH	Amor.	None	Yellow, brown, black	In R.F. becomes strongly magnetic	267
3.7–4.1	Psilomelane	Mn, O, Ba, H	Amor.	None	Iron-black	F. = 7. Test for Mn	284
4.0–4.4	Goethite	FeO·OH	Orth.	010	Yellow, brown, black	In R.F. becomes strongly magnetic	267
4.3–4.6	Chromite	$(Fe,Mg)(Cr,Al)_2O_4$	Isom.	Indist.	Black, brownish	F. = 7; test for Cr	300
4.3–5.5	Ilmenite	$(Fe,Mn,Mg)TiO_3$	Tetr.	None	Brownish red	Test for Ti	261
4.7–4.9	Hausmannite	$MnMn_2O_4$	Tetr.	001 perf.	Black, brownish	F. = 7; test for Mn	283
4.9–5.3	Hematite	Fe_2O_3	Rhom.	None	Steel gray, red, black	Strongly magnetic in R.F.	259
5.3–7.6	Columbite (Tantalite)	$(Fe,Mn)(Cb,Ta)_2O_6$	Orth.	Indist.	Black	F. = 5; test for Cb	313
7.2–7.5	Wolframite (Hübnerite)	$(Fe,Mn)WO_4$	Mono.	010 perf.	Gray, black, brown	F. = 3–4; test for W	295
7.3–7.7	Niccolite	NiAs	Hex.	None	Copper-red	F. = 2; test for Ni	243
9.0–9.7	Uraninite	UO_2, U_2O_3, Pb, Th, etc.	Isom.	None	Black	F. = 7; test for U	269

4. Streak white, colorless, or pale

1.9–2.3	Opal	$SiO_2 \cdot nH_2O$	Amor.	None	Colorless, varied	Contains H_2O	398
2.2–2.3	Analcite	$NaAlSi_2O_6 \cdot H_2O$	Isom.	None	White, tinted	F. = 3.5; H_2O in tube	394
2.2–2.3	Natrolite	$Na_2Al_2Si_3O_{10} \cdot 2H_2O$	Orth.	(110)	White, tinted	F. = 2.5; gelatinizes in HCl	395
2.2–2.5	Sodalite (Lazurite)	$3NaAlSiO_4 \cdot NaCl$	Isom.	(110) poor	Blue, gray, red, white, green	F. = 3.5–4; test for Cl	374
2.3–2.4	Thomsonite	$Ca_2Al_4Si_4O_{16} \cdot 5H_2O$	Orth.	100, 010	White, tinted	F. = 2; H_2O in tube	395
2.4–2.5	Leucite	$KAlSi_2O_6$	Isom.	Indist.	White, tinted	F. = 7; test for K	374
2.4–2.5	Cancrinite	$3NaAlSi_3O_8 \cdot CaCO_3$	Hex.	$(10\bar{1}0)$	White, tinted	F. = 2; effervescent in HCl	378
2.5–2.6	Nephelite	$NaAlSiO_4$	Hex.	Indist.	White, green, gray, red	F. = 4; test for Na	376
2.5–2.6	Orthoclase	$KAlSi_3O_8$	Mono.	001, 010	White, red, green	F. = 5; test for K	387
2.5–2.6	Microcline	$KAlSi_3O_8$	Tric.	001, 010	White, red, green	F. = 5; test for K	389
2.6–2.8	Plagioclase	$NaAlSi_3O_8 + CaAl_2Si_2O_8$	Tric.	001, 010	White, tinted	F. = 4–7; twinning striations	391
2.6–2.8	Scapolite (Wernerite)	$3NaAlSiO_4 \cdot NaCl + 3CaAl_2Si_2O_8 \cdot CaCO_3$	Tetr.	(100), (110)	White, tinted	F. = 3 with intumescence	375
2.6–2.8	Turquois	$CuO \cdot 3Al_2O_3 \cdot 2P_2O_5 \cdot 9H_2O$	Tric.	None	Blue, green	Test for Cu, P	312
2.9–3.0	Datolite	$HCaBSiO_5$	Mono.	None	Greenish, yellowish	F. = 2–2.5 with green flame	337
2.9–3.1	Melilite	$Ca_2Al_2SiO_9 + Ca_2(Mg,Fe)Si_2O_9$	Tetr.	Indist.	White, green, brown	F. = 3; soluble in HCl	340

Table II. Hardness (*Continued*)

MINERALS WITH HARDNESS 5–6 (*cont.*)

4. Streak white, colorless, or pale (*cont.*)

G.	Name	Comp.	System	Cleavage	Color	Diagnostics	Page
2.9–3.4	Hornblende (Tremolite, Actinolite	O, Si, Mg, Fe, Ca, Al, Na, H	Mono.	(110) perf.	Green, black, brown, gray	F. = 3–4; cleavage angle	357
3.0–3.1	Glaucophane	$H_2Na_2(Mg,Fe)_3Al_2Si_8O_{24}$	Mono.	(110) perf.	Blue, black	Color; cleavage angle	359
3.0–3.1	Amblygonite	$LiAl(F,OH)PO_4$	Tric.	001, 100	White, green, blue	F. = 2; test for P	310
3.0–3.2	Anthophyllite	$H_2(Mg,Fe)_7Si_8O_{24}$	Orth.	(110) perf.	Gray, green, brown	F. = 5; cleavage angle	356
3.0–4.2	Allanite	$H(Ca,Ce)_2(Al,Fe'')_3Si_3O_{13}$	Mono.	Indist.	Black	F. = 2.5 to magnetic glass	384
3.1–3.2	Apatite	$Ca_5FP_3O_{12}$	Hex.	Indist.	Green, blue, red, brown, white	F. = 5.5; test for Ca, P	306
3.1–3.5	Enstenite (Enstatite, Hypersthene)	$(Mg,Fe)SiO_3$	Orth.	010, (110)	Gray, green, yellow, brown, black	F. = 5; cleavage angle	350
3.2–3.6	Pyroxene (Diopside, Augite)	$Ca(Mg,Fe)Si_2O_6$ often with Al, etc.	Mono.	(110) perf. 001 part.	Green, brown, black, white	F. = 4–4.5; cleavage angle	351
3.4–3.5	Titanite (Sphene)	$CaTiSiO_5$	Mono.	(110)	Brown, black, yellow, green	F. = 4; wedge-shaped crystals	338
3.4–3.7	Rhodonite	$MnSiO_3$	Tric.	$110, 1\bar{1}0$	Red, pink, yellowish	F. = 3; test for Mn	348
3.9–4.2	Willemite	Zn_2SiO_4	Rhom.	$(11\bar{2}0)$	Yellow, green, red, brown	F. = 4.5–7; test for Zn	329
4.3–4.5	Smithsonite	$ZnCO_3$	Rhom.	$(10\bar{1}1)$ perf.	White, tinted	Effervescent; test for Zn	278
4.9–5.3	Monazite	$CePO_4$	Mono.	Indist.	Yellow, green, brown	F. = 7; test for P	309

MINERALS WITH HARDNESS 6–7

1. Streak silver white, steel gray, or black

3.7–4.7	Psilomelane	Mn, O, Ba, K, H	Amor.	None	Iron-black	F. = 7; test for Mn	284
4.7–4.8	Braunite	$Mn(Mn,Si)O_3$	Tetr.	(111) dist.	Brownish black to gray	F. = 7; test for Mn	265
4.9–5.2	Magnetite (Franklinite)	$(Fe,Mg,Mn,Zn)Fe_2O_4$	Isom.	None	Iron-black	Strongly magnetic	302
5.3–7.6	Columbite (Tantalite)	$(Fe,Mn)(Cb,Ta)_2O_6$	Orth.	Indist.	Black	F. = 5–5.5; test for Cb	313
4.8–4.9	Marcasite	FeS_2	Orth.	Indist.	Pale brass-yellow	F. = 2.5–3 to magnetic globule	246
4.9–5.2	Pyrite	FeS_2	Isom.	None	Brass-yellow	F. = 2.5–3 to magnetic globule; soluble in HCl	238

2. Streak blue or green

3.2–3.4	Dumortierite	$HBAl_8Si_3O_{10}$	Orth.	100 dist.	Blue, violet, pink	Strong pleoch.	330

3. Streak yellow, red or brown

3.7–4.7	Psilomelane	Mn, O, Ba, K, H	Amor.	None	Iron-black	F. = 7; test for Mn	284
4.1–4.3	Rutile	TiO_2	Tetr.	Indist.	Red, brown, black	F. = 7; test for Ti	261
4.7–4.8	Braunite	$Mn(Mn,Si)O_3$	Tetr.	(111) dist.	Brownish black to gray	F. = 7; test for Mn	265
4.9–5.3	Hematite	Fe_2O_3	Rhom.	None	Steel-gray, red, black	Strongly magnetic in R.F.	259
5.3–7.6	Columbite	$(Fe,Mn)(Cb,Ta)_2O_6$	Orth.	Indist.	Black	F. = 5–5.5; test for Cb	313
6.8–7.1	Cassiterite	SnO_2	Tetr.	Indist.	Brown, black, yellow, red	F. = 7; test for Sn	264

TABLE II. HARDNESS (*Continued*)

MINERALS WITH HARDNESS 6–7 (*cont.*)

4. Streak white, colorless, or pale

G.	Name	Comp.	System	Cleavage	Color	Diagnostics	Page
2.5–2.6	Orthoclase	$KAlSi_3O_8$	Mono.	001, 010	White, red, green	F. = 5; test for K	387
2.5–2.6	Microcline	$KAlSi_3O_8$	Tric.	001, 010	White, red, green	F. = 5; test for K	389
2.6–2.8	Plagioclase	$NaAlSi_3O_8 + CaAl_2Si_2O_8$	Tric.	001, 010	White, tinted	F. = 4–7; twinning striations	391
2.65	Quartz	SiO_2	Hex.	None	White, colored	F. = 7; glassy luster	379
2.8–3.0	Prehnite	$H_2Ca_2Al_2Si_3O_{12}$	Orth.	Indist.	Green, gray, white	F. = 2.5 with intumescence	363
2.9–3.0	Boracite	$Mg_3ClB_7O_{13}$	Isom.	Indist.	White, yellow, green	F. = 2 with green flame	297
3.0–3.1	Amblygonite	$LiAl(F,OH)PO_4$	Tric.	001, 010	White, green, blue	F. = 2; test for P	310
3.0–3.1	Glaucophane	$H_2Na_2(Mg,Fe)_3Al_2Si_8O_{24}$	Mono.	(110) perf.	Blue, black	Color; cleavage angle	359
3.1–3.2	Spodumene	$LiAlSi_2O_6$	Mono.	(110) perf.	White, green, pink	F. = 3.5 with crimson flame	354
3.1–3.2	Chondrodite	$(Mg,Fe)_5(F,OH)_2Si_2O_8$	Mono.	001	Brown, yellow, white	F. = 7; gelatinizes in HCl	331
3.2–3.3	Sillimanite	Al_2SiO_5	Orth.	100 dist.	White, brown, greenish	F. = 7; test for Al	337
3.2–3.4	Zoisite	$HCa_2Al_3Si_3O_{13}$	Orth.	010	Gray, brown, red, green	F. = 3–3.5 to blebby mass	382
3.2–3.5	Epidote	$HCa_2(Al,Fe)_3Si_3O_{13}$	Mono.	001	Green, brown, black	F. = 3–3.5; magnetic in R.F.	383
3.2–3.6	Olivine	$(Mg,Fe)_2SiO_4$	Orth.	Indist.	Green, reddish	F. = 4–7; gelatinizes in HCl	331

3.3–3.4	Axinite	$HCa_3Al_2BSi_4O_{16}$	Tric.	010	Brown, yellow, gray	F. = 2.5–3; test for B	338
3.3–3.5	Diaspore	$AlO{\cdot}OH$	Orth.	010 dist.	White, brown, yellow	F. = 7; test for Al	266
3.3–3.5	Vesuvianite	$Mg_2F_4Ca_{10}Al_4Si_9O_{34}$	Tetr.	Indist.	Brown, green	F. = 3; tetragonal crystals	339
3.4–3.7	Rhodonite	$MnSiO_3$	Tric.	110, $1\bar{1}0$	Red, pink, brown	F. = 3; test for Mn	348
3.4–3.9	Ugrandite (Garnet)	$Ca_3(Cr,Al,Fe)_2Si_3O_{12}$	Isom.	(110) part.	White, yellow, brown, red, green	Usually red	322
3.5–3.7	Kyanite	Al_2SiO_5	Tric.	100, 010, 001 part.	Blue, white, green	F. = 7; test for Al	337
3.7–4.3	Pyralspite (Garnet)	$(Mg,Fe,Mn)_3Al_2Si_3O_{12}$	Isom.	None	Red to black	Usually red	322
4.1–4.3	Rutile	TiO_2	Tetr.	Indist.	Red, brown, black	F. = 7; test for Ti	261
6.8–7.1	Cassiterite	SnO_2	Tetr.	Indist.	Brown, black, yellow, red	F. = 7; test for Sn	264

MINERALS WITH HARDNESS 7–10

Streak white, colorless, or pale

2.6–2.7	Cordierite	$Mg_2Al_4Si_5O_{18}$	Orth.	010	Blue, gray, violet, yellow	F. = 5–5.5; like quartz	345
2.6–2.8	Beryl	$Be_3Al_2Si_6O_{18}$	Hex.	Indist.	Green, blue, yellow, pink	F. = 5–5.5; hexagonal crystals	341
2.65	Quartz	SiO_2	Hex.	None	White, colored	F. = 7; glassy luster	379
2.9–3.0	Boracite	$Mg_3ClB_7O_{13}$	Isom.	Indist.	White, yellow, green	F. = 2 with green flame	297
2.9–3.0	Phenacite	Be_2SiO_4	Rhom.	Indist.	White, tinted	F. = 7; insoluble	329
3.0–3.2	Tourmaline	$H_8Na_2(Mg,Fe)_6B_6Al_{12}Si_{12}O_{62} + H_8Na_2Li_3B_6Al_{15}Si_{12}O_{62}$	Rhom.	Indist.	Black, blue, pink, brown, green	F. = 3–7; hexagonal crystals	343

Table II. Hardness (*Continued*)
minerals with hardness 7–10 (*cont.*)
Streak white, colorless, or pale (*cont.*)

G.	Name	Comp.	System	Cleavage	Color	Diagnostics	Page
3.1–3.2	Andalusite	Al_2SiO_5	Orth.	(110)	White, pink, brown, green	F. = 7; test for Al	336
3.2–3.4	Dumortierite	$HBAl_8Si_3O_{20}$	Orth.	100	Blue, pink	F. = 7; test for Al	330
3.4–3.6	Topaz	$Al_2(F,OH)_2SiO_4$	Orth.	001	White, yellow, pink	F. = 7; test for Al	334
3.4–3.9	Ugrandite (Garnet)	$Ca_3(Cr,Al,Fe)_2Si_3O_{12}$	Isom.	(110) part.	White, yellow, brown, red, green	Usually red	322
3.5	Diamond	C	Isom.	(111) difficult	White, tinted	H. = 10	230
3.5–3.7	Kyanite	Al_2SiO_5	Tric.	100, 010, 001 part.	Blue, white, green	F. = 7; test for Al	337
3.5–3.8	Chrysoberyl	$BeAl_2O_4$	Orth.	(011)	Green, brown, yellow	F. = 7; test for Al	299
3.6–3.8	Staurolite	$H_2FeAl_4Si_2O_{12}$	Orth.	010	Brown, black, gray	F. = 7; test for Al	333
3.6–4.6	Spinel	$(Mg,Fe)(Al,Cr)_2O_4$	Isom.	Indist.	Red, yellow, green, blue, brown	F. = 7; test for Al, Cr	299
3.9–4.1	Corundum	Al_2O_3	Rhom.	$(10\bar{1}1)$ part.	White, brown, blue, red, black	F. = 7; test for Al	258
4.5–4.8	Zircon	$ZrSiO_4$	Tetr.	Indist.	Gray, brown, yellow, green, red	F. = 7; test for Zr	328

Table III. Cleavage and Luster

Before attempting to use the following table the student should learn from personal experience the nature of cleavage, so that he can recognize it. He should break a piece of galena or calcite or halite and learn for himself how easy it is to produce cleavages in three directions in these minerals. He should notice the slight cracks which may often be discovered parallel with the cleavage surfaces, since these are useful in distinguishing between cleavage surfaces and crystal faces. He should break a piece of pyroxene or amphibole or feldspar and discover from his own experience that these minerals have cleavages in two directions, and not three. He should learn in the same way that mica or chlorite has cleavage in only one direction. Finally, he should break a piece of quartz or limonite and learn from experience what happens when a mineral has no cleavage.

So many minerals have no prominent cleavage that a list of them is too long to be useful. Furthermore minerals with good cleavage are often found in finely granular or lamellar aggregates with no apparent cleavage. This is the condition of diamonds used in diamond drilling and of the constituents of ordinary clay. But, if cleavage can be found, the mineral should be in one of the groups of Table III. Luster is used to establish the subdivisions.

Outline of Table III

MINERALS WITH ONLY ONE DIRECTION OF CLEAVAGE

1. With metallic luster
2. With nonmetallic luster

MINERALS WITH TWO DIRECTIONS OF CLEAVAGE

1. Two equally good cleavages
2. Two unequal cleavages

MINERALS WITH THREE DIRECTIONS OF CLEAVAGE

1. Three equally good cleavages
2. Three cleavages, not all equally good

MINERALS WITH FOUR DIRECTIONS OF CLEAVAGE

MINERALS WITH SIX DIRECTIONS OF CLEAVAGE

TABLE III. CLEAVAGE

MINERALS WITH ONLY ONE DIRECTION OF DISTINCT CLEAVAGE

1. With metallic luster

H.	Name	Composition	System	Cleavage	G.	Page
1–1.5	Molybdenite	MoS_2	Hex.	0001	4.7–4.8	244
1–2	Graphite	C	Hex.	0001	1.9–2.3	233
1.5–2	Sylvanite	$AuAgTe_4$	Mono.	010	7.9–8.3	248
1.5–2	Covellite	CuS	Hex.	0001	4.6	244
2	Stibnite	Sb_2S_3	Orth.	010	4.5–4.6	245
2	Bismuthinite	Bi_2S_3	Orth.	010	6.4–6.5	246
2–2.5	Bismuth	Bi	Rhom.	0001	9.7–9.8	230
2–3	Jamesonite	$Pb_2Sb_2S_5$	Orth.	001	5.5–6.0	251
3.5	Arsenic	As	Rhom.	0001	5.7	229
5–5.5	Hausmannite	$MnMn_2O_4$	Tetr.	001	4.7–4.9	283
5–5.5	Wolframite	$(Fe,Mn)WO_4$	Mono.	010	7.2–7.5	295
6	Columbite	$(Fe,Mn)(Cb,Ta)_2O_6$	Orth.	010	5.3–7.3	313

2. With nonmetallic luster

H.	Name	Composition	System	Cleavage	G.	Page
1	Carnotite	$K_2(UO_2)_2V_2O_8\cdot 4H_2O$	Orth.	001		311
1–1.5	Vermiculite	Sil. of Al, Mg, Fe, H, etc.	Mono.	001	2.3–2.8	273
1–2	Kaolinite	$H_4Al_2Si_2O_9$	Mono.	001	2.4–2.6	364
1–2	Pyrophyllite	$H_2Al_2Si_4O_{12}$	Orth.	001	2.8–2.9	366
1–2.5	Talc	$H_2Mg_3Si_4O_{12}$	Mono.	001	2.5–2.8	363
1–2.5	Chlorite	$\left\{\begin{array}{l}H_4(Mg,Fe)_3Si_2O_9+\\H_4(Mg,Fe)_2Al_2SiO_9\end{array}\right.$	Mono.	001	2.6–3.0	371
1.5–2	Gypsum	$CaSO_4\cdot 2H_2O$	Mono.	010	2.3–2.4	289
1.5–2	Mirabilite	$Na_2SO_4\cdot 10H_2O$	Mono.	100	1.4–1.5	285
1.5–2	Erythrite	$Co_3As_2O_8\cdot 8H_2O$	Mono.	010	2.9–3.0	312
1.5–2	Vivianite	$Fe_3P_2O_8\cdot 8H_2O$	Mono.	010	2.6–2.7	313
1.5–2	Orpiment	As_2S_3	Mono.	010	3.4–3.5	247
2	Melanterite	$(Fe,Cu,Zn)SO_4\cdot 7H_2O$	Mono.	001	1.9–2.0	291
2–2.5	Brucite	$Mg(OH)_2$	Rhom.	0001	2.3–2.4	268
2–3	Muscovite	$H_2KAl_3Si_3O_{12}$	Mono.	001	2.7–3.0	366
2–3	Lepidolite	Li mica	Mono.	001	2.8–2.9	371
2–3	Biotite	$\left\{\begin{array}{l}H_4K_2(Mg,Fe)_6Al_2Si_6O_{24}+\\H_4K_2(Mg,Fe)_5Al_4Si_5O_{24}\end{array}\right.$	Mono.	001	2.8–3.4	368
2.5	Glauberite	$Na_2CaS_2O_8$	Mono.	001	2.7–2.8	285
2.5–3	Polyhalite	$K_2MgCa_2S_4O_{16}\cdot 2H_2O$	Mono.	100	2.7–2.8	289
2.5–3	Trona	$HNa_3C_2O_6\cdot 2H_2O$	Mono.	100	2.1–2.2	283
2.5–3.5	Gibbsite	$Al(OH)_3$	Mono.	001	2.3–2.4	267

TABLE III. CLEAVAGE (*Continued*)

MINERALS WITH ONLY ONE DIRECTION OF DISTINCT CLEAVAGE (*cont.*)

2. With nonmetallic luster (*cont.*)

H.	Name	Composition	System	Cleavage	G.	Page
3–4	Witherite	$BaCO_3$	Orth.	010	4.3–4.4	281
3.5–4	Malachite	$Cu_2(OH)_2CO_3$	Mono.	001	3.9–4.0	282
3.5–4	Stilbite	$Na_2Al_2Si_6O_{16}\cdot 6H_2O$	Mono.	010	2.1–2.2	396
3.5–4	Alunite	$KAl_3(OH)_6S_2O_8$	Rhom.	0001	2.6–2.8	294
4–4.5	Zinkite	ZnO	Hex.	0001	5.4–5.7	257
4–4.5	Colemanite	$Ca_2B_6O_{11}\cdot 5H_2O$	Mono.	010	2.3–2.5	298
4.5–5	Apophyllite	$KF\cdot Ca_4Si_8O_{20}\cdot 8H_2O$	Tetr.	001	2.3–2.4	362
5	Melilite	$\left\{\begin{matrix}Ca_2MgSi_2O_7+\\ Ca_2Al_2SiO_7\end{matrix}\right.$	Tetr.	001	2.9–3.1	340
5–5.5	Goethite	$FeO\cdot OH$	Orth.	010	4.0–4.4	267
5–5.5	Thomsonite	$Ca_2Al_4Si_4O_{16}\cdot 5H_2O$	Orth.	010	2.3–2.4	395
6	Amblygonite	$LiAl(F,OH)PO_4$	Tric.	001	3.0–3.1	310
6–6.5	Zoisite	$HCa_2Al_3Si_3O_{13}$	Orth.	010	3.2–3.4	382
6–6.5	Prehnite	$H_2Ca_2Al_2Si_3O_{12}$	Orth.	001	2.8–3.0	363
6–6.5	Chondrodite	$Mg_5(F,OH)_2Si_2O_8$	Mono.	001	3.1–3.2	331
6–7	Diaspore	$AlO(OH)$	Orth.	010	3.3–3.5	266
6–7	Sillimanite	Al_2SiO_5	Orth.	010	3.2–3.3	337
6–7	Epidote	$HCa_2(Al,Fe)_3Si_3O_{13}$	Mono.	001	3.2–3.5	383
6–7	Axinite	$HCa_3Al_2BSi_4O_{16}$	Tric.	010	3.3–3.4	338
7	Dumortierite	$HBAl_8Si_3O_{20}$	Orth.	100	3.2–3.4	330
7–7.5	Cordierite	$Mg_2Al_4Si_5O_{18}$	Orth.	010	2.6–2.7	345
7–7.5	Staurolite	$H_2FeAl_4Si_2O_{12}$	Orth.	010	3.6–3.8	333
8	Topaz	$Al_2(F,OH)_2SiO_4$	Orth.	001	3.4–3.6	334
9	Corundum	Al_2O_3	Rhom.	0001 (part.)	3.9–4.1	258

MINERALS WITH TWO DIRECTIONS OF CLEAVAGE

1. Two equally good cleavages

2	Niter	KNO_3	Orth.	(011)	2.1	271
2.5–3	Chrysotile	$H_4(Mg,Fe)_3Si_2O_9$	Orth.?	(110)	2.3–2.5	361
3	Enargite	Cu_3AsS_4	Orth.	(110)	4.4–4.5	251
3.5–4	Strontianite	$SrCO_3$	Orth.	(110)	3.7	280
4.5–5	Hemimorphite	H_2ZnSiO_5	Orth.	(110)	3.4–3.5	340
5–5.5	Natrolite	$Na_2Al_2Si_3O_{10}\cdot 2H_2O$	Orth.	(110)	2.2–2.3	395
5–5.5	Titanite	$CaTiSiO_5$	Mono.	(110)	3.4–3.6	338
5–6	Enstenite (Enstatite and Hypersthene)	$(Mg,Fe)SiO_3$	Orth.	(110)	3.1–3.5	350

TABLE III. CLEAVAGE (*Continued*)

MINERALS WITH TWO DIRECTIONS OF CLEAVAGE (*cont.*)

1. Two equally good cleavages (*cont.*)

H.	Name	Composition	System	Cleavage	G.	Page
5–6	Pyroxene (Diopside, Hedenbergite, Augite)	$Ca(Mg,Fe)Si_2O_6$ (with Al_2O_3, etc.)	Mono.	(110)	3.2–3.6	351
5–6	Anthophyllite	$H_2(Mg,Fe)_7Si_8O_{24}$	Orth.	(110)	3.0–3.2	356
5–6	Hornblende (Tremolite, Actinolite)	Sil. of Mg, Fe, Ca, Al, Na, H	Mono.	(110)	2.9–3.4	357
5–6	Scapolite	$\left\{\begin{array}{l}3NaAlSi_3O_8\cdot NaCl+\\3CaAl_2Si_2O_8\cdot CaCO_3\end{array}\right.$	Tetr.	100	2.6–2.8	375
5.5–6	Arsenopyrite	$FeAsS$	Mono.	(110)	5.9–6.2	246
6–6.5	Glaucophane	$H_2Na_2(Mg,Fe)_3Al_2Si_8O_{24}$	Mono.	(110)	3.0–3.2	359
6–7	Spodumene	$LiAlSi_2O_6$	Mono.	(110)	3.1–3.2	354
6.5–7.5	Andalusite	Al_2SiO_5	Orth.	(110)	3.1–3.2	336
8.5	Chrysoberyl	$BeAl_2O_4$	Orth.	(011)	3.5–3.8	299

2. Two unequal cleavages

2.5	Kernite	$Na_2B_4O_7\cdot 4H_2O$	Mono.	001, 100	1.9	298
4–5 (also 6–7)	Kyanite	Al_2SiO_5	Tric.	100, 010	3.5–3.7	337
4.5–5	Pectolite	$HNaCa_2Si_3O_9$	Mono.	100, 001	2.7–2.8	349
4.5–5	Wollastonite	$CaSiO_3$	Mono.?	100, 001	2.8–2.9	347
6–6.5	Orthoclase	$KAlSi_3O_8$	Mono.	001, 010	2.5–2.6	387
6–6.5	Microcline	$KAlSi_3O_8$	Tric.	001, 010	2.5–2.6	389
6–6.5	Plagioclase	$\left\{\begin{array}{l}NaAlSi_3O_8+\\CaAl_2Si_2O_8\end{array}\right.$	Tric.	001, 010	2.6–2.8	391

MINERALS WITH THREE DIRECTIONS OF CLEAVAGE

1. Three equally good cleavages

1.5–2	Soda Niter	$NaNO_3$	Rhom.	$(10\bar{1}1)$	2.2–2.3	270
2–2.5	Halite	$NaCl$	Isom.	(100)	2.1–2.6	252
2–2.5	Sylvite	KCl	Isom.	(100)	1.9–2.0	252
2–2.5	Cinnabar	HgS	Rhom.	$(10\bar{1}0)$	8.0–8.2	242
2–3	Ruby Silver (Pyrargyrite and Proustite)	$Ag_3(Sb,As)S_3$	Rhom.	$(10\bar{1}1)$	5.5–5.9	249
2.5	Galena	PbS	Isom.	(100)	7.4–7.6	236
3	Calcite	$CaCO_3$	Rhom.	$(10\bar{1}1)$	2.7	271
3–3.5	Greenockite	CdS	Hex.	$(11\bar{2}0)$	4.9–5.0	243
3.5–4	Dolomite	$Ca(Mg,Fe,Mn)C_2O_6$	Rhom.	$(10\bar{1}1)$	2.8–3.4	274
3.5–4.5	Brown Spar (Magnesite, Siderite, Rhodochrosite)	$(Mg,Fe,Mn)CO_3$	Rhom.	$(10\bar{1}1)$	3.0–3.9	276

TABLE III. CLEAVAGE (*Continued*)

MINERALS WITH THREE DIRECTIONS OF CLEAVAGE (*cont.*)

1. Three equally good cleavages (*cont.*)

H.	Name	Composition	System	Cleavage	G.	Page
4.5	Iron	Fe	Isom.	(100)	7.3–7.8	228
5	Smithsonite	$ZnCO_3$	Rhom.	$(10\bar{1}1)$	4.3–4.4	278
5–6	Nephelite	$NaAlSiO_4$	Hex.	$(10\bar{1}0)$	2.5–2.6	376
5–6	Cancrinite	$3NaAlSiO_4 \cdot (Ca,NaH)CO_3$	Hex.	$(10\bar{1}0)$	2.4–2.5	378
5.5	Cobaltite	$CoAsS$	Isom.	(100)	6.0–6.3	239
7.5–8	Phenacite	$BeSiO_4$	Rhom.	$(11\bar{2}0)$	2.9–3.0	329

2. Three cleavages, not all equally good

H.	Name	Composition	System	Cleavage	G.	Page
2–2.5	Borax	$Na_2B_4O_7 \cdot 10H_2O$	Mono.	001, (110)	1.7	298
2–2.5	Epsomite	$MgSO_4 \cdot 7H_2O$	Orth.	010, (011)	1.7–1.8	291
2.5	Cryolite	Na_3AlF_6	Mono.	(110), 001	2.9–3.0	255
2.5–3	Kainite	$KMgClSO_4 \cdot 3H_2O$	Mono.	100, (110)	2.0–2.2	286
2.5–3.5	Barite	$BaSO_4$	Orth.	001, (110)	4.3–4.6	287
3	Anglesite	$PbSO_4$	Orth.	001, (110)	6.1–6.4	288
3–3.5	Anhydrite	$CaSO_4$	Orth.	001, 010, 100	2.9–3.0	286
3–3.5	Celestite	$SrSO_4$	Orth.	001, (110)	3.9–4.0	287
3.5–4	Aragonite	$CaCO_3$	Orth.	(110), 010	2.9–3.0	279
3.5–4	Azurite	$Cu_3(OH)_2(CO_3)_2$	Mono.	(021), 100	3.7–3.8	282
3.5–4	Manganite	$MnO(OH)$	Orth.	(110), 010	4.2–4.4	268
3.5–4	Wavellite	$(AlOH)_3P_2O_8 \cdot 5H_2O$	Orth.	(101), 010	2.3–2.4	311
4–5 (also 6–7)	Kyanite	Al_2SiO_5	Tric.	100, 010, 001 part.	3.5–3.7	337
4.5–5	Wollastonite	$CaSiO_3$	Mono.?	$100, 001, \bar{1}01$	2.8–2.9	347
5.5–6.5	Rhodonite	$MnSiO_3$	Tric.	$110, 1\bar{1}0, 001$	3.4–3.7	348
6–7	Rutile	TiO_2	Tetr.	(110), 001	4.1–4.3	261

MINERALS WITH FOUR DIRECTIONS OF CLEAVAGE

H.	Name	Composition	System	Cleavage	G.	Page
3.5	Kieserite	$MgSO_4 \cdot H_2O$	Mono.	$(11\bar{1}), (11\bar{3})$	2.57	285
3.5–4	Pentlandite	$(Fe,Ni)S$	Isom.	(111)	4.6–5.1	240
4	Fluorite	CaF_2	Isom.	(111)	3.0–3.2	254
4.5–5	Scheelite	$CaWO_4$	Tetr.	(111)	5.9–6.2	296
5–6	Scapolite	$\left\{\begin{array}{l} 3NaAlSi_3O_8 \cdot NaCl + \\ 3CaAl_2Si_2O_8 \cdot CaCO_3 \end{array}\right.$	Tetr.	(100), (110)	2.6–2.8	375
6–6.5	Braunite	$Mn_2O_3 +$	Tetr.	(111)	4.7–4.8	265
10	Diamond	C	Isom.	(111)	3.5	230

MINERALS WITH SIX DIRECTIONS OF CLEAVAGE

H.	Name	Composition	System	Cleavage	G.	Page
3.5–4	Sphalerite	$(Zn,Fe)S$	Isom.	(110)	3.9–4.1	237
6.5–7.5	Garnet (Pyralspite, Ugrandite)	$R_3''R_2'''(SiO_4)_3$	Isom.	(110) (rare parting)	3.4–4.3	322

Refractive Index

It is now so easy to measure approximately the index of refraction of an unknown mineral by using a microscope and a set of immersion liquids (see pages 157–161) of known refractive indices that a table based primarily on such data seems desirable. To learn the method, the student should practice with some known (powdered) mineral, such as quartz. A few grains of the powder should be mounted under a cover glass on a glass slide in a liquid of known index, say, 1.540, and (by means of using the Becke line or inclined illumination—see pages 157 and 158) it may be proved that the liquid has a lower index than either index of any grain. (To find each index, turn a grain to extinction, test its index, then turn the grain 90° to the next extinction position between crossed nicols, and test the index in this position.) Then put a few grains into another liquid of known index, say 1.550, and repeat the process. It will be discovered now that each grain has one index lower than that of the liquid and some have a second index higher than that of the liquid. By repeating this process with a third liquid of index 1.555 it will be found that both indices of every grain are lower than 1.555.

Minerals all of whose grains are dark between crossed nicols at all positions of rotation are isotropic (and either amorphous or isometric). They are found in Table IV, Part a. Minerals all of whose grains have one index of constant value (while the other varies from equality with it to a maximum difference found in grains with the strongest birefringence) are uniaxial and the constant index is that of the ordinary ray; it is called N_o. If the other index (designated N_e because it is the index of the extraordinary ray) is greater than N_o, the optic sign is +; if it is less, the sign is −. In any grain which is dark between crossed nicols in all positions of rotation, N_e is equal to N_o and so such a grain is especially useful in measuring N_o. Minerals all of whose grains have no constant value are biaxial and have three indices of refraction; the greatest, N_g, the middle or approximate "mean," N_m, and the least or "petty" index, N_p. In this case, also, it is easy to find the value of the index used in the table because any grain which is dark between crossed nicols in all positions of rotation has indices both of which are equal to N_m. Both uniaxial and biaxial minerals are listed in Table IV, Part b, in the order of increasing value of N_o or N_m.

A few minerals, like diamond, quartz, and fluorite, are very constant in composition and therefore their properties (including refractive indices) show no variation. But most minerals vary in composition and their refractive indices vary correspondingly. Many minerals for which no range of variation in index is shown in Table IV actually vary in composition (and therefore in properties), but the range of variation is unknown because very few measures have been made (in some cases, only one measure). This fact is due to various causes including scarcity of material in some cases; but it seems probable that it is due in large part to the widespread belief that a mineral, if pure, is fixed in composition and properties, and consequently a single accurate measure is supposed to be sufficient.

Minerals which are opaque even in very thin flakes are not included in this table.

OUTLINE OF TABLE IV. REFRACTIVE INDEX

a. ISOTROPIC MINERALS

b. ANISOTROPIC MINERALS

1. N_o or N_m is between 1.30 and 1.50
2. N_o or N_m is between 1.50 and 1.53
3. N_o or N_m is between 1.53 and 1.54
4. N_o or N_m is between 1.54 and 1.57
5. N_o or N_m is between 1.57 and 1.62
6. N_o or N_m is between 1.62 and 1.65
7. N_o or N_m is between 1.65 and 1.68
8. N_o or N_m is between 1.68 and 1.75
9. N_o or N_m is between 1.75 and 2.10
10. N_o or N_m is between 2.10 and 4.10

Table IV. Refractive Index

TABLE IV. REFRACTIVE INDEX

a. ISOTROPIC

N	Name	Composition	Cleavage	H.	G.	Page
1.333	Water	H_2O			1.0	256
1.41–1.46	Opal	$SiO_2 \cdot nH_2O$		5.5–6.5	2.0–2.2	398
1.434	Fluorite	CaF_2	(111) perfect	4	3.0–3.2	254
1.479–1.489	Analcite	$NaAlSi_2O_6 \cdot H_2O$		5–5.5	2.2–2.3	394
1.483–1.51	Sodalite	$NaAlSiO_4 \cdot NaCl$, etc.		5.5–6	2.1–2.5	374
1.509	Sylvite	KCl	(100) perf.	2–2.5	1.9–2.0	252
1.509	Leucite	$KAlSi_2O_6$		5.5–6	2.4–2.5	374
1.517 ±	Sepiolite	$H_8Mg_2Si_3O_{12}$		2–2.5	1–2	360
1.53–1.70	Allanite	$H(Ca,Ce)_2(Al,Fe''',Fe'')_3Si_3O_{13}$		5 ±	3.0–3.5	384
1.544	Halite	$NaCl$	(100) perf.	2–2.5	2.1–2.6	252
1.56–1.61	Bauxite	$Al_2O_3 \cdot nH_2O$		1	2.4–2.6	266
1.57–1.62	Collophanite	$Ca_3P_2O_8$, etc.		2–5	2.6–2.9	304
1.57–1.63	Chrysocolla	$CuSiO_3 \cdot nH_2O$		2–4	2.0–2.4	398
1.70–1.83	Pyralspite (Garnet)	$(Mg,Fe,Mn)_3Al_2(SiO_4)_3$	(110) parting	7–7.5	3.5–4.3	322
1.71–2.16	Spinel (Chromite)	$(Mg,Fe)(Al,Cr)_2O_4$		7.5–8.5	3.6–5.1	299
1.73–1.90	Ugrandite (Garnet)	$Ca_3(Al,Fe,Cr)_2(SiO_4)_3$	(110) parting	6.5–7	3.4–4.1	322
2.0–2.3	Limonite	$Fe_2O_3 \cdot nH_2O$		5–5.5	3.6–4.0	267
2.06–2.26	Cerargyrite	$Ag(Cl,Br,I)$		1–2	5.4–6.0	253
2.37–2.47	Sphalerite	$(Zn,Fe)S$	(110) perf.	3.5–4	3.9–4.1	237
2.419	Diamond	C	(111) difficult	10	3.5	230
2.849	Cuprite	Cu_2O		3.5–4	5.8–6.1	257

TABLE IV. REFRACTIVE INDEX (*Continued*)

b. ANISOTROPIC

N_o or N_m +	±	−	Name	N_g	N_p or $N_g - N_p$	System	Cleavage	H.	G.	Page
	1.30–1.50									
1.309			Ice	1.313	1.309	Hex.		1.5	0.92	256
1.339			Cryolite	.001		Mono.	001, (110)	2.5	2.9–3.0	255
1.396			Mirabilite	1.398	1.394	Mono.	100	1.5–2	1.4–1.5	285
1.40–1.46			Chrysocolla	1.54 ±	1.40–1.46	?		2–3	2.0–2.2	398
		1.455	Epsomite	1.461	1.433	Orth.	010	2–2.5	1.7–1.8	291
1.469			Tridymite	1.473	1.469	Orth.		7	2.27	379
		1.469	Borax	1.472	1.447	Mono.	100	2–2.5	1.7	298
		1.472	Kernite	1.488	1.454	Mono.	001, 100	2.5	1.91	298
1.475			Carnallite	1.494	1.466	Orth.		1–2	1.6	255
1.476			Natrolite	1.485	1.473	Orth.	(110)	5–5.5	2.2–2.3	395
1.478 ±			Melanterite	1.486 ±	1.47 ±	Mono.	(110), 001	2	1.9	291
	1.48–1.49		Chabazite	1.49 ±	1.48 ±	Rhom.	$(10\bar{1}1)$	4–5	2.0–2.2	397
		1.487 ±	Analcite	.001		?		5–5.5	2.2–2.3	394
		1.492	Trona	1.540	1.412	Mono.	100	2.5–3	2.1–2.2	283
	1.50–1.53									
1.50–1.57 +			Serpentine	.013		Mono.	(110) poor	2.5–4	2.3–2.6	361
		1.504	Stilbite	1.508	1.500	Mono.	010	3.5–4	2.1–2.2	396
1.504			Ulexite	1.520	1.491	Mono.		1	1.6–1.7	297
		1.505	Kainite	1.516	1.494	Mono.	100, (110)	2.5–3	2.0–2.2	286
		1.505	Niter	1.506	1.335	Orth.	(011)	2	2.1–2.2	271
1.508			Leucite	1.509	1.508	Ps.Isom.		5.5–6	2.4–2.5	374
	1.509–1.530		Cancrinite	1.509–1.530	1.500–1.535	Hex.	$(10\bar{1}1)$	5–6	2.4–2.5	378

1.513–1.532			Thomsonite	1.518–1.545	1.511–1.530	Orth.	010	5–5.5	2.3–2.4	395
		1.52–1.525	Microcline	1.523–1.527	1.515–1.52	Tric.	001, 010	6–6.5	2.5–2.6	389
		1.522–1.526	Orthoclase	1.525–1.528	1.517–1.521	Mono.	001, 010	6–6.5	2.5–2.6	387
1.523			Gypsum	1.530	1.521	Mono.	010	1.5–2	2.3–2.4	289
		1.526–1.548	Chalcanthite	1.534–1.550	1.513–1.530	Tric.		2–3	2.1–2.3	292
		1.524–1.528	Sepiolite	1.525–1.529	1.515–1.520	Orth.?		2–2.5	1.2	360
	1.53–1.54									
1.50–1.57+			Serpentine	.013		Mono.	(110) poor	2.5–4	2.3–2.6	361
1.513–1.532			Thomsonite	1.518–1.545	1.511–1.530	Orth.	010	5–5.5	2.3–2.4	395
		1.526	Chalcanthite	1.534–1.550	1.513–1.530	Tric.		2–3	2.1–2.3	292
	1.529–1.584		Plagioclase	1.536–1.589	1.525–1.576	Tric.	001, 010	6–6.5	2.6–2.8	391
		1.53–1.61	Scapolite	1.53–1.61	1.53±–1.57	Tetr.	(100), (110)	5–6	2.6–2.8	375
1.531–1.535			Kieserite	1.583–1.586	1.518–1.523	Mono.	$(11\bar{1}),(11\bar{3})$	3.5	2.57	285
		1.532	Glauberite	1.536	1.515	Mono.	001	2.5–3	2.7–2.8	285
		1.533–1.539	Chalcedony	1.533–1.539	1.526–1.532	Rhom.?		6	2.5–2.63	381
1.534–1.543			Wavellite	1.552–1.58	1.525–1.535	Orth.	(101), 010	3.5–4	2.3–2.4	311
	1.535–1.543		Apophyllite	Very weak		Tetr.	001	4.5–5	2.3–2.4	362
	1.536–1.568		Cordierite	1.542–1.573	1.533–1.558	Orth.	010	7–7.5	2.6–2.8	345
		1.536–1.549	Nephelite	1.536–1.549	1.532–1.544	Hex.	$(10\bar{1}0)$ poor	5–6	2.5–2.6	376
	1.54–1.57									
1.50–1.57+			Serpentine	.013		Mono.	(110) poor	2.5–4	2.3–2.6	361
		1.526–1.548	Chalcanthite	1.534–1.550	1.513–1.530	Tric.		2–3	2.1–2.3	292
	1.529–1.584		Plagioclase	1.536–1.589	1.525–1.576	Tric.	001, 010	6–6.5	2.6–2.8	391
		1.53–1.61	Scapolite	1.53–1.61	1.53±–1.57	Tetr.	(100), (110)	5–6	2.6–2.8	375
	1.535–1.543		Apophyllite	Very weak		Tetr.	001	4.5–5	2.3–2.4	362
	1.536–1.568		Cordierite	1.542–1.573	1.533–1.558	Orth.	010	7–7.5	2.6–2.8	345
		1.536–1.549	Nephelite	1.536–1.549	1.532–1.544	Hex.	$(10\bar{1}0)$ poor	5–6	2.5–2.6	376
1.543±			Chrysotile	1.555±	1.542±	Orth.?		2–3	2.3–2.5	361
1.544			Quartz	1.553	1.544	Hex.		7	2.65	379
		1.545–1.58	Vermiculite	1.545–1.58	1.525–1.56	Mono.	001	1–1.5	2.3–2.8	273
	1.55–1.68		Chlorite	1.55–1.68	1.54–1.67	Mono.	001	1–2.5	2.6–3.0	371

TABLE IV. REFRACTIVE INDEX (*Continued*)
b. ANISOTROPIC (*cont.*)

+	N_o or N_m ±	−	Name	N_g	N_p or N_g-N_p	System	Cleavage	H.	G.	Page
	1.54–1.57 (*cont.*)									
		1.55–1.57	Lepidolite	1.55–1.57	1.53–1.54	Mono.	001	2–3	2.8–2.9	371
1.554–1.567			Gibbsite	1.576–1.589	1.554–1.567	Mono.	001	2.5–3.5	2.3–2.4	267
		1.562	Polyhalite	1.567	1.548	Tric.	100	2.5	2.7–2.8	289
1.564–1.59			Brucite	1.584–1.60	1.564–1.59	Rhom.	0001	2–2.5	2.3–2.4	268
		1.564–1.70	Biotite	1.565–1.70	1.535–1.62	Mono.	001	2–3	2.7–3.3	368
		1.559–1.569	Kaolinite	1.56–1.57	1.553–1.563	Mono.	001	1–2.5	2.4–2.6	364
		1.568–1.602	Beryl	1.568–1.602	1.564–1.595	Hex.		7.5–8	2.6–2.9	341
	1.57–1.62									
	1.529–1.584		Plagioclase	1.536–1.589	1.525–1.576	Tric.	001, 010	6–6.5	2.6–2.8	391
		1.53–1.61	Scapolite	1.53–1.61	1.53 ±–1.57	Tetr.	(100), (110)	5–6	2.6–2.8	375
	1.55–1.68		Chlorite	1.55–1.68	1.54–1.67	Mono.	001	1–2.5	2.6–3.0	371
		1.564–1.70	Biotite	1.565–1.70	1.535–1.62	Mono.	001	2–3	2.7–3.3	368
		1.568–1.602	Beryl	1.568–1.602	1.564–1.595	Hex.		7.5–8	2.6–2.9	341
1.572			Alunite	1.592	1.572	Rhom.	0001	3.5–4	2.6–2.8	294
		1.575–1.59	Talc	1.575–1.59	1.538–1.545	Orth.?	001	1–2.5	2.5–2.8	363
1.576			Anhydrite	1.614	1.570	Orth.	001, 010, 100	3–3.5	2.9–3.0	286
		1.582–1.61	Muscovite	1.588	1.552	Mono.	001	2–3	2.7–3.0	366
		1.585	Soda Niter	1.585	1.337	Rhom.	$(10\bar{1}1)$	1.5–2	2.2–2.3	270
1.587–1.592			Colemanite	1.610–1.614	1.582–1.586	Orth.?	010, 001	4–4.5	2.3–2.5	298
		1.588	Pyrophyllite	1.600	1.552	Orth.?	001	1–2	2.8–2.9	366
		1.593–1.615	Amblygonite	1.598–1.63	1.578–1.61	Tric.	001	6	3.0–3.1	310
		1.597	Chrysocolla	1.598	1.575	?		2	2.4	398
1.598–1.604			Vivianite	1.627–1.637	1.579–1.582	Mono.	010, 100	1.5–2	2.6–2.7	313

1.605			Pectolite	1.636	1.600	Tric.	100,001	4.5–5	2.7–2.8	349
1.606–1.645			Chondrodite	1.62–1.66	1.59–1.64	Mono.		6–6.5	3.1–3.2	331
		1.61–1.64	Glauconite	1.61–1.64	1.59–1.61	Mono.	001	2	2.2–2.8	373
1.61–1.631			Topaz	1.617–1.638	1.607–1.629	Orth.	001	8	3.4–3.6	334
	1.61–1.66		Anthophyllite	1.62–1.68	1.60–1.65	Orth.	(110)	5–6	3.0–3.3	356
	1.613–1.70		Hornblende (Tremolite, Actinolite)	1.625–1.70	1.60–1.68	Mono.	(110)	5–6	2.9–3.4	357
1.617			Hemimorphite	1.636	1.614	Orth.	(110)	4.5–5	3.4–3.5	340
	1.62–1.65									
	1.55–1.68		Chlorite	1.55–1.68	1.54–1.67	Mono.	001	1–2.5	2.6–3.0	371
		1.564–1.70	Biotite	1.565–1.70	1.535–1.62	Mono.	001	2–3	2.7–3.3	368
1.606–1.645			Chondrodite	1.62–1.66	1.59–1.64	Mono.		6–6.5	3.1–3.2	331
		1.61–1.64	Glauconite	1.61–1.64	1.59–1.61	Mono.	001	2	2.2–2.8	373
1.61–1.631			Topaz	1.617–1.638	1.607–1.629	Orth.	001	8	3.4–3.6	334
	1.61–1.66		Anthophyllite	1.62–1.68	1.60–1.65	Orth.	(110)	5–6	3.0–3.3	356
	1.613–1.70		Hornblende (Tremolite, Actinolite)	1.625–1.70	1.60–1.68	Mono.	(110)	5–6	2.9–3.4	357
		1.62–1.70	Glaucophane	1.63–1.70	1.61–1.69	Mono.	(110)	6–6.5	3.0–3.4	359
1.62			Turquois	1.65	1.61	Tric.	$1\bar{1}0$	5.5–6	2.6–2.8	312
		1.620–1.633	Wollastonite	1.622–1.635	1.607–1.621	Tric.	100, 001	4.5–5	2.8–2.9	347
1.623			Celestite	1.631	1.622	Orth.	001, (110)	3–3.5	3.9–4.0	287
1.624–1.642			Prehnite	1.645–1.665	1.615–1.635	Orth.	001	6–6.5	2.8–3.0	363
1.63 ±			Garnierite	.01		Mono.	(110) poor	1–3	2.3–2.9	361
		1.63–1.69	Tourmaline	1.63–1.69	1.61–1.66	Rhom.		7–7.5	2.9–3.2	343
		1.632–1.66	Apatite	1.632–1.66	1.630–1.655	Hex.		4.5–5	3.1–3.2	306
		1.633–1.644	Andalusite	1.639–1.647	1.629–1.640	Orth.	(110)	6.5–7.5	3.1–3.2	336
	1.633–1.669		Melilite	1.64–1.67	1.633–1.658	Tetr.	(110), 001	5	2.9–3.0	340

TABLE IV. REFRACTIVE INDEX (*Continued*)
b. ANISOTROPIC (*cont.*)

N_o or N_m +	N_o or N_m ±	N_o or N_m −	Name	N_g	N_p or N_g-N_p	System	Cleavage	H.	G.	Page
	1.62–1.65 (*cont.*)									
1.637			Barite	1.648	1.636	Orth.	001, (110)	2.5–3.5	4.3–4.6	287
	1.65–1.68									
	1.55–1.68		Chlorite	1.55–1.68	1.54–1.67	Mono.	001	1–2.5	2.6–3.0	371
		1.564–1.70	Biotite	1.565–1.70	1.535–1.62	Mono.	001	2–3	2.7–3.3	368
	1.61–1.66		Anthophyllite	1.62–1.68	1.60–1.65	Orth.	(110)	5–6	3.0–3.3	356
	1.613–1.70		Hornblende (Tremolite Actinolite)	1.625–1.70	1.60–1.68	Mono.	(110)	5–6	2.9–3.4	357
		1.62–1.70	Glaucophane	1.63–1.70	1.61–1.69	Mono.	(110)	6–6.5	3.0–3.4	359
		1.63–1.69	Tourmaline	1.63–1.69	1.61–1.66	Rhom.		7–7.5	2.9–3.2	343
		1.632–1.66	Apatite	1.632–1.66	1.630–1.655	Hex.		4.5–5	3.1–3.2	306
	1.633–1.669		Melilite	1.64–1.67	1.633–1.658	Tetr.	(110), 001	5	2.9–3.0	340
		1.65–1.78	Allanite	1.66–1.80	1.64–1.77	Mono.		5.5–6	3.0–4.2	384
	1.651–1.864		Olivine	1.67–1.875	1.635–1.822	Orth.		6.5–7	3.2–4.4	331
	1.653–1.76		Enstenite (Enstatite, Hypersth.)	1.658–1.77	1.650–1.75	Orth.	(110)	5–6	3.1–3.9	350
		1.653	Datolite	1.670	1.625	Mono.		5–5.5	2.9–3.0	339
1.654			Phenacite	1.670	1.654	Rhom.	$(11\bar{2}0)$	7.5–8	2.9–3.0	329
1.654–1.744			Pyroxene (Diopside, Augite, etc.)	1.66–1.76	1.652–1.73	Mono.	(110)	5–6	3.2–3.6	351

		1.658 (−1.72)	Calcite (+ Mn)	1.658 (−1.72)	1.486 (−1.534)	Rhom.	(10$\bar{1}$1)	3	2.71 (−3.14)	271
1.658–1.67			Sillimanite	1.677–1.684	1.657–1.661	Orth.	010	6–7	3.2–3.3	337
	1.662		Erythrite	1.699	1.626	Mono.	010	1.5–2.5	2.9–3.2	312
		1.664	Strontianite	1.666	1.516	Orth.	(110)	3.5–4	3.7	280
1.665–1.675			Spodumene	1.676–1.682	1.660–1.668	Mono.	(110)	6–7	3.1–3.2	354
1.667			Boracite	1.673	1.662	Orth.		7	2.9–3.0	297
		1.676	Witherite	1.677	1.529	Orth.		3–4	4.3–4.4	281
		1.679–1.77	Dolomite	1.679–1.776	1.502–1.565	Rhom.	(10$\bar{1}$1)	3.5–4	2.8–3.4	274
	1.68–1.75									
		1.564–1.70	Biotite	1.565–1.70	1.535–1.62	Mono.	001	2–3	2.7–3.3	368
	1.613–1.70		Hornblende (Tremolite, Actinolite)	1.625–1.70	1.60–1.68	Mono.	(110)	5–6	2.9–3.4	357
		1.62–1.70	Glaucophane	1.63–1.70	1.61–1.69	Mono.	(110)	6–6.5	3.0–3.4	359
		1.63–1.69	Tourmaline	1.63–1.69	1.61–1.66	Rhom.		7–7.5	2.9–3.2	343
		1.65–1.78	Allanite	1.66–1.80	1.64–1.77	Mono.		5.5–6	3.0–4.2	384
	1.651–1.864		Olivine	1.67–1.875	1.635–1.822	Orth.		6.5–7	3.2–4.4	331
	1.653–1.76		Enstenite (Enstatite, Hypersth.)	1.658–1.77	1.650–1.75	Orth.	(110)	5–6	3.1–3.9	350
1.654–1.744			Pyroxene (Diopside, Augite, etc.)	1.66–1.76	1.652–1.73	Mono.	(110)	5–6	3.2–3.6	351
		1.658 (−1.72)	Calcite (+Mn)	1.658 (−1.72)	1.486 (−1.534)	Rhom.	(10$\bar{1}$1)	3	2.72 (−3.14)	271
		1.679–1.776	Dolomite	1.679–1.776	1.502–1.565	Rhom.	(10$\bar{1}$1)	3.5–4	2.8–3.4	274
		1.681 (−1.695)	Aragonite (+Pb)	1.685 (−1.699)	1.530 (−1.542)	Orth.	(110)	3.5–4	2.9–3.0	279
		1.684–1.691	Dumortierite	1.686–1.692	1.659–1.670	Orth.	100	7	3.3	330
		1.685–1.692	Axinite	1.689–1.696	1.679–1.684	Tric.	010	6–7	3.3–3.4	338

TABLE IV. REFRACTIVE INDEX (*Continued*)
b. ANISOTROPIC (*cont.*)

+	N_o or N_m ±	−	Name	N_g or N_g-N_p	N_p	System	Cleavage	H.	G.	Page
	1.68–1.75 (*cont.*)									
1.693–1.701			Willemite	1.712–1.726	1.693–1.701	Rhom.	$(11\bar{2}0)$	5–6	3.9–4.2	329
1.696–1.703			Zoisite	1.702–1.718	1.696–1.700	Orth.	010	6–6.5	3.2–3.4	382
		1.70–1.875	Brown Spar (Magnesite, Siderite, Rhodochrosite)	1.70–1.875	1.509–1.633	Rhom.	$(10\bar{1}1)$	3.5–4.5	2.9–3.9	276
		1.705–1.736	Vesuvianite	1.705–1.736	1.701–1.732	Tetr.		6.5	3.3–3.5	339
	1.715–1.77		Epidote	1.72–1.78	1.71–1.73	Mono.	001	6–7	3.2–3.6	383
1.715–1.74			Rhodonite	1.723–1.75	1.71–1.737	Tric.	110, $1\bar{1}0$, 001	5.5–6.5	3.4–3.7	348
1.722			Diaspore	1.750	1.702	Orth.	010	6–7	3.3–3.5	266
		1.722	Kyanite	1.729	1.713	Tric.	100, 010, 001	4–7	3.5–3.7	337
1.741–1.754			Staurolite	1.746–1.762	1.736–1.747	Orth.	010	7–7.5	3.6–3.8	333
1.747–1.749			Chrysoberyl	1.753–1.758	1.744–1.747	Orth.	(011)	8.5	3.5–3.8	299
	1.75–2.10									
		1.65–1.78	Allanite	1.66–1.80	1.64–1.77	Mono.		5.5–6	3.0–4.2	384
	1.651–1.864		Olivine	1.67–1.875	1.635–1.822	Orth.		6.5–7	3.2–4.4	331
	1.653–1.76		Enstenite (Enstatite, Hypersth.)	1.658–1.77	1.650–1.75	Orth.	(110)	5–6	3.1–3.9	350
		1.679–1.776	Dolomite	1.679–1.776	1.502–1.565	Rhom.	$(10\bar{1}1)$	3.5–4	2.8–3.4	274
		1.70–1.875	Brown Spar (Magnesite,	1.70–1.875	1.509–1.633	Rhom.	$(10\bar{1}1)$	3.5–4.5	2.9–3.9	276

			Siderite, Rhodochrosite)							
	1.715–1.77		Epidote	1.72–1.78	1.71–1.73	Mono.	001	6–7	3.2–3.6	383
1.741–1.754			Staurolite	1.746–1.762	1.736–1.747	Orth.	010	7–7.5	3.6–3.8	333
1.747–1.749			Chrysoberyl	1.753–1.758	1.744–1.747	Orth.	(011)	8.5	3.5–3.8	299
1.758			Azurite	1.838	1.730	Mono.	(021)	3.5–4	3.7–3.8	282
		1.768–1.771	Corundum	1.768–1.771	1.760–1.763	Rhom.		9	3.9–4.1	258
1.788–1.801			Monazite	1.837–1.849	1.787–1.800	Mono.	001	5–5.5	4.9–5.3	309
		1.849	Smithsonite	1.849	1.621	Rhom.	(10$\bar{1}$1)	5	4.3–4.5	278
1.83–1.96			Zircon	1.83–2.01	1.83–1.96	Tetr.		7.5	4.1–4.8	328
		1.875	Malachite	1.909	1.655	Mono.	001	3.5–4	3.9–4.0	282
1.883			Anglesite	1.895	1.878	Orth.	001 (110)	3	6.1–6.4	288
1.87–1.935			Sphene (Titanite)	1.94–2.05	1.84–1.915	Mono.	(110)	5–5.5	3.4–3.6	338
		1.895–2.06	Carnotite	1.92–2.08	1.75–1.98	Orth.	001	1		311
1.92 ±			Scheelite	1.94 ±	1.92 ±	Tetr.	(111)	4.5–5	5.9–6.2	296
1.989–2.013			Cassiterite	2.08–2.11	1.989–2.013	Tetr.		6–7	6.8–7.1	264
2.008			Zinkite	2.029	2.008	Hex.	0001	4–4.5	5.4–5.7	257
2.038			Sulfur	2.245	1.958	Orth.		1.5–2.5	2.0–2.1	234
		2.061	Pyromorphite	2.061	2.049	Hex.		3.5–4	6.5–7.1	308
		2.074	Cerussite	2.076	1.803	Orth.		3–3.5	6.4–6.6	281
	2.1–4.1									
		2.10–2.394	Goethite	2.11–2.40	2.05–2.26	Orth.	010	5–5.5	4.0–4.4	267
2.22–2.40			Wolframite	2.32–2.46 +	2.17–2.31 +	Mono.	010	5–5.5	7.1–7.5	295
	2.17–2.43		Columbite	.01 to .17		Orth.	100 poor	6	5.3–7.8	313
		2.25–2.42	Vanadinite	2.25–2.42	2.20–2.35	Hex.		3	6.6–7.2	309
2.37			Crocoite	2.66	2.31	Mono.	(110)	2.5–3	5.9–6.1	296
		2.38–2.42	Wulfenite	2.38–2.42	2.30–2.34	Tetr.	(111)	2.5–3	6.7–7.0	296
2.46			Hausmannite	2.46	2.15	Tetr.	001	5–5.5	4.7–4.9	283

TABLE IV. REFRACTIVE INDEX (*Continued*)
b. ANISOTROPIC (*cont.*)

N_o or N_m +	±	−	Name	N_g or N_g-N_p	N_p	System	Cleavage	H.	G.	Page
	2.1–4.1 (*cont.*)									
2.50–2.58			Greenockite	2.52–(2.57?)	2.50–2.58	Hex.	$(11\bar{2}0)$	3–3.5	4.8–5.0	243
		2.59–2.68	Realgar	2.61–2.70	2.46–2.54	Mono.	010	1.5–2	3.5–3.6	247
2.603–2.616			Rutile	2.889–2.903	2.603–2.616	Tetr.	(110)	6–7	4.1–4.3	261
2.72			Orpiment	Extreme		Mono.	010	1.5–2	3.4–3.5	247
		2.87–3.22	Hematite	2.87–3.22	2.71–2.94	Rhom.		5.5–6.5	4.9–5.3	259
2.913			Cinnabar	3.272	2.913	Hex.	$(10\bar{1}0)$	2–2.5	8.0–8.2	242
		3.08–3.09	Ruby Silver (Pyrargyrite)	3.08–3.09	2.79–2.88	Rhom.	$(10\bar{1}1)$	2–3	5.5–5.9	249
		4.046	Stibnite	4.303	3.194	Orth.	010	2	4.5–4.6	245

Glossary

Acicular. Needle-like.

Acid igneous rocks. Those containing much silica, part of which is in the form of quartz, if crystalline.

Acid taste. Sour, like that of sulfuric acid.

Adamantine luster. Like that of diamond or cerussite.

Alkaline taste. Resembling the taste of soda.

Alliaceous odor. Resembling the odor of garlic, as that of arsenic fumes.

Alluvial. Deposited by streams.

Amorphous. Having no crystal structure.

Amygdaloid. An igneous rock having gas cavities filled with secondary minerals.

Amygdule. The aggregate of secondary minerals filling a gas cavity in a volcanic rock.

Analyzer. The polarizing prism on a microscope (above the objective).

Anhedron. A single crystalline unit having no crystal faces.

Anhydrous. Containing no hydrogen (and therefore no water).

Anisotropic. Transmitting light with unequal velocity in different directions.

Argillaceous. Consisting of, or containing, clay.

Asterism. The property of showing a six- (or three-) rayed star of light on polished surfaces or through thin plates.

Astringent. Contracting or puckering the tissues in the mouth (or elsewhere).

Basal. Parallel to the basal pinacoid.

Basalt. Basic volcanic rock, dark colored and heavy.

Base. The form consisting of the face or faces parallel with the lateral axes.

Basic igneous rocks. Those low in silica and therefore rich in ferromagnesian minerals; heavy and generally dark colored.

Biaxial. Having two optic axes.

Birefringence. Ability to produce double refraction.

Bitter taste. Like that of epsom salts.

Bladed. Crystals which are long and flat, like knife blades.

Botryoidal. Like a bunch of grapes; consisting of closely grouped rounded masses.

Brachyaxis. The shorter lateral axis.

Brachydome. The crystal form whose faces are parallel with the brachy, or short, lateral axis and cut the other axes.

Brachypinacoid. The crystal form whose faces are parallel with the vertical axis and the brachyaxis.

Brittle. Breaking or crumbling readily under a blow or strain.

Capillary. Hair-like; much elongated (crystals).

Chatoyant. Having a changeable, wavy, silky sheen like that of a cat's eye in the dark; illustrated by satin spar and tiger's eye.

Clastic. Composed of fragments.

Cleavage. The capacity of some minerals to break along smooth planes which are always parallel with possible crystal faces. Also, the smooth planes thus produced are called cleavages.

Clinodome. The crystal form whose faces are parallel with the inclined (or clino) axis, and cut the other axes.

Clinopinacoid. The crystal form whose faces are parallel with the vertical and the inclined axes.

Columnar. Having moderate elongation in one direction, not necessarily prismatic.

Conchoidal fracture. Curved, shell-like surfaces produced by breaking some minerals, such as quartz.

Concretion. A rounded mass of mineral material (usually in concentric layers) formed in a cavity by deposition from solution.

Conglomerate. A rock composed of pebbles or fragments and finer material cemented together.

Contact deposits. Mineral masses formed at or near the contact of an igneous intrusion and caused by the latter.

Cruciform. Forming a cross, as twins of staurolite.

Cryptocrystalline. Crystalline, but not visibly so, even with a microscope. Crypto means hidden.

Crystal. A solid bounded by plane surfaces, which result from the regular arrangement of the constituent atoms or ions.

Crystalline. Having a natural internal regular arrangement of atoms or ions—external faces are not necessary.

Crystallization. The process of production of a regular arrangement of atoms or ions from a molecular aggregate such as a gas or liquid.

Cyclic. Turning in a cycle, as certain types of twinning.

Decrepitation. Violent breaking with a crackling sound, on sudden heating.

Deflagration. Sudden combustion; even flashing like gunpowder.

Dendritic. Branching like a tree or fern.

Detrital. Composed of fragments.

Diaphaneity. Capacity to transmit light.

Dimorphism. See polymorphism.

Dodecahedron. A crystal form of the isometric system whose twelve faces are parallel to one axis and cut the others at equal distances.

Dolomite. A rock composed (chiefly) of the mineral, dolomite.

Dome. A crystal form whose faces are parallel to a lateral axis and cut the other two axes.

Double refraction. The division of a ray of light into two parts (at the surface of a crystal) refracted at different angles.

Ductile. Capable of being drawn into wire.

Efflorescence. A surface coating or crust, often powdery, formed by evaporation.

Elastic. Returning to the original shape after bending, as thin sheets of mica.

End-member. A simple compound (or element) which is one limit of chemical variation of a mineral. The term is used even if the end-member is (so far as known) unstable in the given phase.

Equant. Having (nearly) equal dimensions in the three axial directions.

Etched. Having the surface roughened by solution or corrosion.

Ferric. Containing trivalent iron.

Ferrous. Containing divalent iron.

Ferruginous. Containing iron.

Fibrous. Having thread-like form, as in asbestus and satin spar.

Flexible. Capable of being bent without breaking, and without returning to the original position.

Fluorescence. The emission of (colored) light from within a substance when it is exposed to white light, or any similar vibrations, including cathode rays, X-rays, etc. The light given off is quite distinct from that reflected and also from that transmitted by the substance.

Foliated. Composed of thin layers or plates or folia.

Form. A crystal form includes all the faces required by the symmetry if one of them is present.

Fracture. A surface, usually curved or irregular, produced by breaking not along a cleavage or parting.

Friable. Readily broken into grains.

Fumarolic. Said of gases escaping around volcanoes, and also of minerals produced by them.

Fusibility. The ease or difficulty of melting or fusing a substance is measured by its fusibility.

Gabbro. A coarse-grained igneous rock consisting essentially of basic plagioclase and pyroxene.

Gangue. The minerals of no value in an ore.

Geniculated. Knee-shaped; illustrated by rutile and zircon twins.

Glide planes. Planes along which crystals can slip without breaking.

Gneiss. A coarse-grained rock with more or less distinct banding of the minerals, usually feldspathic.

Granite. A coarse-grained igneous rock consisting essentially of acid feldspar, quartz, and some ferromagnesian mineral.

Granular. Composed of visible grains.

Guano. A deposit of excrement of birds, modified by oxidation and leaching.

Habit. As the crystal form or forms change or the relative size of faces change, the crystal habit is said to change.

Hardness. The comparative ease or difficulty with which one mineral is scratched by another determines its hardness.

Hemimorphic. A crystal which is unlike at the two ends of one crystal axis is hemimorphic.

Hexagonal. Having six equal angles about an axis of sixfold symmetry. The system of crystallization having three equal horizontal axes at 60° and a fourth unequal vertical axis.

Hexoctahedron. The crystal form (isometric) having 48 faces.

Homeomorphous. Having similar crystal structure, though chemically unlike.

Hydrous. Containing hydrogen and therefore yielding water on heating.

Igneous rock. A rock formed from solidification of a magma (molten mineral matter), either at the surface, as volcanic rock, or within the earth, as plutonic rock.

Inclusion. A foreign material inclosed within a mineral.

Index of refraction. A number which expresses the relative velocity of light in a vacuum as compared with its velocity in a substance.

Interference. Combination of two light waves, no matter whether the amplitude of the resultant wave is less or even greater than the original waves.

Interference color. When two rays of white light interfere, color usually results because the difference of phase will cause some parts of white light to be destroyed and other parts to become stronger.

Interference figure. A telescopic image of the source of convergent light which has passed through an anisotropic crystal between crossed nicols.

Intumescence. The property of swelling and bubbling during fusion.

Inversion. The change from one arrangement of atoms to another without melting and without change of composition.

Iridescence. The property of showing various prismatic colors due to a thin surface film or films in minute crevices.

Isometric. The system of crystallization having three equal and interchangeable axes at right angles to each other.

Isomorphism. Literally, the same form; but it now means the capacity to intercrystallize to produce one substance.

Isostructural. Having the same crystal structure and related composition, but not necessarily isomorphous.

Isotropic. Literally, equal turning; that is, all the light striking any surface at a given angle is refracted the same amount; it is also true that light is transmitted with equal velocity in all directions by an isotropic substance.

Lamellar. Consisting of lamellae or laminae (thin sheets or layers).

Laminated. Consisting of laminae or lamellae.

Lava. Natural molten rock, as found around volcanoes, or the solid rock resulting from its cooling.

Lenticular. Lens-shaped, or approximately so.

Limestone. A rock composed chiefly of calcite. But rocks composed chiefly of dolomite are also sometimes called limestone.

Lodestone. A variety of magnetite which is a natural magnet; in rare cases pyrrhotite and platinum have this property.

Luminescence. The property of some minerals to transform other forms of energy into light and thus become luminous.

Luster. The appearance of a surface in reflected light.

Macroaxis. The longer lateral axis.

Macrodome. A crystal form whose faces are parallel with the macroaxis and cut the other two axes.

Macropinacoid. A crystal form whose faces are parallel with the vertical axis and also the macroaxis.

Macroscopic. Visible without the aid of a microscope; also called megascopic.

Magnetic. Capable of being attracted by a magnet.

Malleable. Capable of being hammered or rolled into a sheet.

Mammillary. Having a smooth surface with curved protuberances larger than those of the botryoidal surface.

Marble. Recrystallized limestone.

Meager feel. A rough or harsh feel.

Metallic luster. The surface sheen of a metal in reflected light.

Metamorphic rock. A rock (either igneous or sedimentary) that has been much changed, and recrystallized under the influence of high temperature or pressure or both. Called anamorphic by Van Hise.

Metastable. A crystalline state which is not truly stable, but may be long-enduring because of inertia, illustrated by crystals of tridymite at ordinary temperature.

Meteorite. A mineral mass that has fallen to the earth from outer space.

Micaceous. Composed of very thin plates or scales or sheets, like mica.

Microcrystalline. Composed of crystal units visible only with a microscope.

Minal. End-member.

Mineralizers. Substances such as hydrogen, fluorine, boron, sulfur, etc., which facilitate the formation of minerals by lowering viscosity, acting as catalytic agents, or otherwise.

Monoclinic. The system of crystallization having three unequal axes with two at an oblique angle and the third at right angles to these two.

Nicol prism or, briefly, **nicol.** A prism devised by William Nicol to produce light polarized in one plane.

Obsidian. Volcanic rock glass.

Ocherous. Earthy, powdery; usually red, yellow or brown.

Octahedron. An isometric crystal form whose eight faces cut all three axes at equal distances.

Oolitic. Consisting of small round particles, suggesting fish roe.

Opalescence. A milky or pearly internal reflection.

Optic axis. A direction in an anisotropic substance along which all light travels with the same velocity.

Orthodome. A crystal form whose faces are parallel with the orthoaxis and cut the other two axes.

Orthopinacoid. A crystal form whose faces are parallel with the orthoaxis and also the vertical axis.

Orthorhombic. The crystal system having three unequal axes at right angles to each other.

Oxide zone. The zone near the earth's surface penetrated by surface waters containing air and therefore tending to oxidize minerals.

Parting. The capacity for breaking along smooth planes, very much like cleavage. But cleavage is inherent in the crystal structure, while parting is caused by twinning or gliding, and is therefore confined to planes of twinning or gliding.

Pearly luster. A sheen like that of mother of pearl.

Pegmatite. An igneous rock of very coarse texture; the commonest kind is composed of feldspar, quartz, and mica.

Peridotite. A very basic igneous rock of coarse grain composed essentially of olivine usually with pyroxene.

Phase. The phase of a light wave is its distance measured in wave lengths from an assumed point of origin. In physical chemistry a phase is a homogeneous, physically distinct, portion of matter in a nonhomogeneous system; for example, at ordinary temperatures and pressures, H_2O has three phases, ice, water, and steam, but under low to high pressures there are at least six phases of ice. TiO_2 has three mineral phases: rutile, anatase, and brookite.

Phenocrysts. Large crystals in a ground mass of much smaller grain.

Phonolite. A volcanic rock unsaturated with silica and so composed essentially of a feldspathoid, such as nephelite, and feldspar with pyroxene and more or less amphibole and mica.

Phosphorescence. The *continued* emission of light by a substance (not incandescent) caused by exposure to heat, light, X-ray, or other source of energy and lasting for a time after the exposure.

Pinacoid. A crystal form whose faces are parallel to the lateral axes of a tetragonal or hexagonal crystal, or parallel to any two axes of an orthorhombic, monoclinic, or triclinic crystal.

Pisolitic. Composed of rounded units about as large as peas.

Placers or **placer deposits.** Accumulations of sand or gravel containing gold or other constituents of value.

Pleochroism. The selective absorption of light by a crystal often varies with directions of vibration of the light, and this may cause a mineral to transmit light of different colors in different directions, even with unpolarized light. This property is called pleochroism.

Plutonic rocks. Coarse-grained igneous rocks (which have crystallized at considerable depth).

Pneumatolytic. Formed by vapors (or superheated liquids under pressure) acting as mineralizers.

Polarization. The process of changing ordinary light, which vibrates in all directions normal to its path, into light vibrating in one (or two) definite directions (usually planes).

Polarizer. A device to produce light polarized in one plane.

Polymorphous. A substance which has two crystal phases at ordinary temperature and pressure is said to be dimorphous, for example—$CaCO_3$ as calcite and aragonite. If it has three crystal phases like TiO_2 in rutile, anatase, and brookite, it is trimorphous, or, in general, it is polymorphous.

Polysynthetic. Composed of many parts bound together; said of multiple twins.

Primary. A mineral which was formed (or introduced) at the time of formation of the rock of which it is a part is said to be primary.

Prism. A crystal form whose faces cut the lateral axes but are parallel with the vertical axis.

Pseudohexagonal (pseudotetragonal, etc.). Having a close resemblance to crystals of the hexagonal system, but not actually hexagonal (or tetragonal, etc.).

Pseudomorph. A mineral in the crystal form of a different mineral (due to alteration, replacement, or some other change).

Pyramid. A crystal form whose faces cut all three axes.

Pyritohedron. A form of the isometric system having twelve five-sided faces.

Pyroelectricity. The electric charges produced on different parts of a single crystal by heating.

Rectangular. Making right angles (90°).

Reflection. The turning back of light at a boundary or surface.

Refraction. The turning of transmitted light at a surface.

Refringence. The capacity of a substance to change the path of transmitted light; it is measured by the index of refraction.

Reniform. Kidney-shaped, or having a surface like that of a kidney with numerous small curved protuberances.

Reticulated. Having slender crystals or fibers crossing like the meshes of a net.

Rhombohedron. A crystal form of the hexagonal system having six faces intersecting at oblique angles, like a distorted cube.

Saline taste. Salty, like the taste of common salt.

Sandstone. A sedimentary rock composed of consolidated sand.

Scalenohedron. A crystal form of the hexagonal system having twelve faces, each a scalene triangle.

Schiller. A bronze-like luster.

Schist. A metamorphic rock characterized by well developed (nearly) parallel arrangement of some lamellar mineral, such as mica.

Seam. A thin vein: also, a thin bed in stratified rocks, as a seam of coal.

Secondary. A mineral which was formed after the time of formation of the rock of mineral aggregate of which it is a part is said to be secondary.

Sectile. Capable of being cut into slices or coherent shavings.

Sedimentary rock. A rock produced by deposition from solution or from suspension in water (or air).

Shale. A laminated sedimentary rock composed essentially of solidified mud, clay, or silt.

Silky luster. Having the sheen of silk or satin, owing to parallel lustrous fibers.

Skeleton crystals. Those with axes and edges defined, but empty in large part.

Slate. A fine-grained metamorphic rock easily split into broad thin sheets.

Specific gravity. The weight of a substance compared with that of an equal volume of water.

Specific heat. The amount of heat necessary to raise the temperature of one gram of the substance one degree centigrade.

Sphenoid. A crystal form having four faces, each an isosceles triangle; the faces are alternate faces of a dipyramid.

Splendent. Having a brilliant luster.

Stalactitic. Having the shape of a stalactite or icicle.

Stellate. Radiating so as to produce star-like forms.

Streak. The color of the powder of a mineral or of the mark made by rubbing it on a harder, slightly rough surface.

Striated. Marked by fine parallel lines or grooves.

Sublimate. A solid produced directly from a vapor.

Syenite. A coarse-grained igneous rock composed essentially of alkali feldspar, plagioclase, and ferromagnesian minerals. Without plagioclase it is an alkalisyenite.

Tarnish. A thin surface film formed by alteration (or deposition) which changes the color of a mineral.

Tenacity. The degree or character of cohesion of a substance.

Tetragonal. Having four equal angles about an axis of fourfold symmetry. This characterizes the tetragonal system of crystallization, which has three rectangular axes, the two lateral being equal, but the vertical unequal.

Tetrahedron. An isometric crystal form having four sides, each being an equilateral triangle. It has alternate faces of the octahedron.

Thermoelectricity. The electric current developed when the contact of two metals (connected by a wire) is heated or cooled.

Tough. Difficult to break: the opposite of brittle.

Translucent. Transmitting some light, but only after irregular refraction, so that objects cannot be seen through such a substance.

Transparent. Transmitting light freely, so that objects can be seen.

Trap rock. A general term for a basic igneous rock of fine grain.

Triboluminescence. The property of giving off light when rubbed or scratched.

Triclinic. The system of crystallization having three unequal axes intersecting each other at oblique angles.

Trigonal. Having three equal angles about an axis of threefold symmetry. Applied especially to the second division of the hexagonal system.

Twin. A symmetrical combination or intergrowth of two or more crystals.

Uniaxial. Having one (and only one) direction in which all light travels at the same velocity.

Valence. The relative capacity of atoms of an element to combine with atoms of some unit element like hydrogen or chlorine.

Vein. The mineral filling of a crack or fissure in rocks.

Vescicular. Having gas bubble cavities, as some volcanic rocks.

Vitreous luster. The sheen of broken glass.

Volcanic rock. The lava of a volcano which has solidified at or near the earth's surface.

Zonal. Arranged in layers or belts.

Zone. All the faces of a crystal which are parallel to one line belong to one zone.

Index

Names of minerals described are printed in boldface type; names of other minerals or synonyms or varieties are printed in italics. When there are several references the important one is printed in boldface type.