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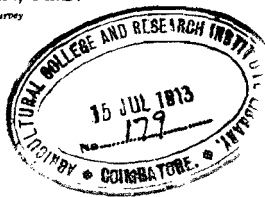
FOR THE DETERMINATION OF

Rock-Forming Minerals in
Thin Sections

BY

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Member U. S. Geological Survey



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PREFACE.

THE determination of rocks is largely based upon the identification of their component minerals, and since it is only in coarse, granular rocks that these can be identified megascopically, it is commonly necessary to employ microscopical methods. A knowledge of the usual appearance of the minerals as they occur in rock sections is not sufficient, because many of them are very similar, and one must be familiar with the application of the optical methods by which they are determined to secure accurate results.

Tables for the determination of minerals have heretofore been made of secondary importance in text books. In this volume the reverse method has been adopted and the descriptive tables make up the greater portion of the book. Theoretical discussions in optics have been avoided so far as possible, and only enough has been given to make clear that which is necessary for the practical determination of the minerals. The material has been condensed as much as is consistent with clearness, and all of the descriptions are given in as concise a form as possible.

Owing to the difficulty of having the pages of the index indented by machinery, it was found necessary to extend the leaves to the full width of the book, and to indicate the lines along which the student should cut the pages. After trimming along the lines shown, it will be found convenient to form another index guide by cutting off about one-half inch from the upper right hand corners of the pages descriptive of negative minerals.

PREFACE.

In the preparation of this book I have constantly referred to the fourth edition of Professors Rosenbusch and Wülfing's "Mikroskopische Physiographie der petrographisch wichtigen Mineralien," and to them my thanks are due for their kindness in granting me permission to reproduce certain diagrams and figures from their book. Among these are a number of the feldspar diagrams which I have redrawn and, in some cases, slightly modified. For convenience in showing the relation between the percentage proportions of the albite-anorthite molecules and the common names, I have inserted above each diagram these names, limiting them as the best usage seems to warrant. For the *mineral descriptions in Part III*, I have consulted the works of Rosenbusch, Lévy and Lacroix, Dana, Groth, and Hintze. Many of the methods in the chapter on the feldspars are from A. Michel-Lévy's "Etude sur la détermination des feldspaths" and I am greatly indebted to him for permitting me to reproduce his diagrams and the valuable color plate published in Lévy and Lacroix's "Minéraux des Roches."

The student who wishes more complete theoretical discussions of the principles underlying the optical methods, is referred to the works mentioned above and also to Professor Iddings' "Rock Minerals," which has appeared since the manuscript of this book was completed.

From the nature of the tables it is very probable that some errors have escaped my notice. I shall be glad to be notified of any such that may be found.

ALBERT JOHANNSEN.

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PART I.

INTRODUCTION.

Ornari res ipsa negat,

Contenta docere.

MANILIUS, Astronomica, 3, 29.

INTRODUCTION.

Light.

In a homogeneous medium, light is transmitted in straight lines without change of direction and by means of vibrations at right angles to the direction of movement.

The **intensity** of the light depends upon the amplitude of this movement, and the color ^{depends} ~~is~~ the rate. Extreme red light has about 443,000,000,000,000 waves in a second, while extreme violet has about 702,000,000,000,000.

When light is made to vibrate in a single plane, as by passing through a nicol prism, it is said to be **polarized**. Since the direction of vibration in the nicol prism of the analyzer is at right angles to that in the polarizer, the light is completely cut off in passing through the two.

Isotropic Media.

Substances in which the velocity of the transmission of light is independent of the direction of vibration are called **isotropic**. In such a body the form of the wave-surface may be represented by a sphere. Under the microscope the light from the polarizer is unchanged in passing through the mineral section, consequently it is completely cut off by the analyzer and no interference phenomena are produced. All sections of isotropic substances, therefore, are dark between crossed nicols, and remain so during the rotation of the stage.

Isotropic substances are of two classes: amorphous bodies and fluids, and crystals of the isometric system.

Amorphous substances have no crystalline character and

allow the light to vibrate with the same ease in all directions.

Isometric crystals have crystalline form, but the ease of vibration is the same in all directions.

Anisotropic Media.

In anisotropic media the velocity of the transmission of light varies with the direction. Anisotropic crystals are uniaxial or biaxial. In a uniaxial crystal the surface of wave velocities is an ellipsoid of rotation; in a biaxial crystal it approaches the form of an ellipsoid of three axes.

All substances that are not amorphous or of the isometric system are optically anisotropic. They may be divided into two groups:

1. **Uniaxial crystals**, or those which have but one optic axis; that is, but one direction along which there is no double refraction. The optic axis coincides with the crystallographic axis c , which is also the direction of either the greatest or least ease of vibration. Tetragonal and hexagonal crystals belong here.

2. **Biaxial crystals**, or those with two optic axes. To these belong orthorhombic, monoclinic, and triclinic crystals.

In the orthorhombic system the axes of maximum and minimum ease of vibration coincide with the crystallographic axes; in the monoclinic and triclinic systems they do not.

Index of Refraction.

A ray of light passing from one medium to another undergoes various changes; a part of the light does not enter the second medium but is reflected back, and a part is transmitted through the second medium but has its direction changed, that is, it is refracted.

Beyond a certain angle, characteristic for each mineral, light is totally reflected and none is refracted. The angle of incidence at which this takes place is called the **critical angle**.

The ratio of the sine of the angle of incidence to the sine of the angle of refraction is constant for the same media and is called the **index of refraction**. It is inversely proportional to the wave velocity. In isotropic media this index is the same in every direction, while in anisotropic media it varies in different directions.

Double Refraction.

A ray of light entering an anisotropic medium is resolved into two rays vibrating at right angles to each other with different velocities, although the difference in rate is very slight. When the ray is vibrating parallel to the direction of greatest ease of vibration, it advances fastest; and slowest when parallel to the direction of least ease. In consequence of the two different light velocities, there must be, also, two different indices of refraction. As the stage of the microscope is rotated, the axes of light vibrations will coincide with the planes of vibration of the nicols four times, at intervals of 90° , and will produce darkness each time.

This property of anisotropic crystals of resolving the light vibrations into two sets at right angles to each other, is called **double refraction**. Since in anisotropic minerals the rate of vibration is different in different directions, it follows that this difference is still found in the components of these rays after they have passed through the analyzer, consequently one of the waves reaches the eye slightly in advance of the other, although in the same plane after passing the analyzer. The interference of the two produces an **interference color**.

The directions of greatest and least ease of vibration, which are always at right angles to each other, and a third direction at right angles to these two, form the **axes of elasticity or vibration axes**. They are indicated by the German letters **a**, **b**, and **c**: **a** is considered the direction of greatest ease of vibration, also called the direction of maximum elasticity; **b** is the direction of intermediate ease of vibration or elasticity and **c** is the direction of least ease of vibration. All of these

velocities vary inversely as the indices of refraction. The planes of which these lines are the intersections are called the **principal optic sections**. They always contains two axes of elasticity.

Monochromatic Light.

In many observations, as for dispersion, etc. (see p. 32), monochromatic light is used. This may be produced by the absorption of certain rays by means of glasses or ray-filters, by monochromatic flames produced by vaporizing certain substances, or by means of a monochromator, which breaks white light into the spectrum. For use under the microscope all but the first are too complicated.

Optically Uniaxial Crystals.

Of the two rays of light resulting from the double refraction of a ray passing through a uniaxial crystal, one vibrates with equal velocity in every direction. This is called the **ordinary ray** and its wave-surface is a sphere. Its index of refraction is denoted by ω . The second ray is called the **extraordinary ray** and its index of refraction is denoted by ε . It passes through the crystal with different velocities in different directions, agreeing only in one direction with the ordinary ray. In this direction, consequently, there will be no double refraction, since the values of ω and ε are equal; in other words, this is an **axis of isotropy**. In the tetragonal and hexagonal systems this direction of greatest or least ease of vibration coincides with crystallographic c , which is also an optic axis. All waves moving at the same angle with this axis have equal velocities, consequently any section of the wave-surface figure at right angles to this axis is a circle, while every other section of the wave-surface is an ellipse.

Positive and negative uniaxial crystals. From the above it is seen that there are two kinds of uniaxial crystals. In one the extraordinary ray has its greatest velocity along the principal axis; in the other this is the direction of least velocity.

These relationships are shown in Figs. 1 and 2, which are sections through the centers of the wave-velocity figures. In Fig. 1 $\epsilon > \omega$, and in Fig. 2, $\epsilon < \omega$. The velocities shown are, as noted above, inversely proportional to the indices.

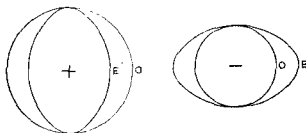


FIG. 1.

FIG. 2.

FIGS. 1 and 2.—Wave-surfaces of positive and negative uniaxial crystals. O = Ordinary ray. E = Extraordinary ray.

Optically positive (+) crystals. A uniaxial crystal is considered positive when crystallographic c is the direction of the least ease of vibration ($c = \tau$) and the index of refraction of the extraordinary ray is greater than that of the ordinary ray ($\epsilon > \omega$).

Optically negative (-) crystals. A uniaxial crystal is considered negative when crystallographic c is the direction of greatest ease of vibration ($c = \alpha$) and ($\epsilon < \omega$).

Principal optic section. A principal optic section is one containing the axes of greatest and least ease of vibration. In uniaxial crystals any section parallel to crystallographic axis c is a principal section.

Measure of the double refraction. The value of the double refraction is expressed by the difference between the indices. In a uniaxial crystal the difference between the values of ω and ϵ is greatest in sections parallel to the optic axis, and therefore this section shows the highest interference colors.

Optically Biaxial Crystals.

Besides crystals with an axis of isotropy, there are others with no axis of isotropy but with two optic axes. In these crystals the wave-surface approaches the form of a three-axis ellipsoid.

The index of refraction of the rays with vibrations parallel to **a** and advancing at right angles to **a**, in biaxial crystals, is represented by α .

The index of refraction of rays with vibrations parallel to **b** and advancing at right angles to **b**, in biaxial crystals, is represented by β .

The index of refraction of rays with vibrations parallel to **c** and advancing at right angles to **c**, in biaxial crystals, is represented by γ .

The positions of the axes of elasticity vary in different crystals. In orthorhombic crystals the axes of elasticity coincide with the crystallographic axes.

In monoclinic crystals one axis of elasticity coincides with crystallographic axis *b*; the other two axes of elasticity are inclined to crystallographic axes *a* and *c*, but are in the same plane.

In triclinic crystals no axis of elasticity coincides with, or is parallel to, a crystallographic axis.

Interference colors. In biaxial crystals the interference colors differ with the orientation of the section. They are highest in sections parallel to the plane of the optic axes, that is, in sections parallel to the plane of **a** and **c**. The value is $\gamma - \alpha$.

Optic axes are directions in a crystal in which the rays of light traverse it without being doubly refracted. (*A* and *C*,

Fig. 3.)

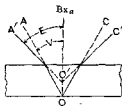


FIG. 3.—True and apparent axial angles.

Axial angle. The axial angle is the angle between the optic axes. The true value is expressed by $2V$, the apparent value in air by $2E$, and the value obtained by immersion in water, oil, etc., by $2H$. (Fig. 3.) When the value of the axial angle is less than 90° , it is called the **acute axial angle**; the other angle between the optic axes is the **obtuse axial angle**.

Bisectrix. The line bisecting the axial angle is called the

bisectrix. When it occurs in the acute axial angle, it is called the *acute bisectrix*; when in the obtuse axial angle, it is called the *obtuse bisectrix*. The bisectrices are the directions of maximum (σ) and minimum (τ) ease of vibration. (Bx_a in Fig. 3.)

Plane of the optic axes. The plane containing the two optic axes is called the plane of the optic axes. It necessarily also contains the directions of greatest and least ease of vibration.

Optic normal. The line at right angles to the plane of the optic axes, that is, the line at right angles to the plane of σ and τ , is called the optic normal. It is the direction of \mathbf{b} .

Optic binormals are the two optic axes.

Optically positive (+) biaxial crystals. The mineral is considered optically positive when τ is the acute bisectrix.

Optically negative (-) biaxial crystals. The mineral is considered optically negative when σ is the acute bisectrix.

Newton's color scale. Increasing the thickness of a section produces a rise in the interference tints until finally white of the higher orders appears. The thickness at which this is produced is different in different minerals. It is less in those having a large value for $\gamma - \alpha$.

The following table is modified from Quincke.*

Certain colors occur periodically in the table and are called orders. The violet, showing a wave difference of .000575 mm., is the most sensitive tint in the whole scale; a very slight increase or decrease in the wave length produces a marked change in the color. Decreasing the wave length by .000024 mm. changes it to a deep red, and increasing it .000014 mm. to indigo.

A list of the values of the maximum birefringences ($\gamma - \alpha$) of the different minerals is given in Part IV.

* G. Quincke: Poggendorff's *Annalen der Physik und Chemie*, 1866, p. 177.

NEWTON'S COLOR SCALE.
(Modified from Quincke.)

No.	Difference in Wave Length.	Phase Difference for Na Light.	Interference Colors Between Crossed Nicols.	Interference Colors Between Parallel Nicols.
1	0.000000 mm.	0	Black	Bright white
2	40	...	Iron gray	White
3	97	...	Lavender gray	Yellowish white
4	158	$\frac{1}{2}$	Grayish blue	Brownish white
5	218	...	Clearer gray	Brownish yellow
6	234	...	Greenish white	Brown
7	259	...	Almost pure white	Light red
8	267	...	Yellowish white	Carmine
9	275	...	Pale straw yellow	Dark reddish brown
10	281	...	Straw yellow	Deep violet
11	306	$\frac{1}{2}$	Light yellow	Indigo
12	332	...	Bright yellow	Blue
13	430	...	Brownish yellow	Grayish blue
14	505	$\frac{1}{2}$	Reddish orange	Bluish green
15	536	...	Red	Pale green
16	551	...	Deep red	Yellowish green
17	565	...	Purple	Lighter green
18	575	...	Violet	Greenish yellow
19	589	$\frac{1}{2}$	Indigo	Golden yellow
20	664	...	Sky blue	Orange
21	728	...	Greenish blue	Brownish orange
22	747	...	Green	Light carmine
23	826	...	Lighter green	Purplish red
24	843	...	Yellowish green	Violet purple
25	866	...	Greenish yellow	Violet
26	910	$\frac{1}{2}$	Pure yellow	Indigo
27	948	...	Orange	Dark blue
28	998	...	Bright orange red	Greenish blue
29	1101	...	Dark violet red	Green
30	1128	...	Light bluish violet	Yellowish green
31	1151	2	Indigo	Impure yellow
32	1258	...	Greenish blue	Flesh colored
33	1334	...	Sea green	Brownish red
34	1376	...	Brilliant green	Violet
35	1426	$\frac{1}{2}$	Greenish yellow	Grayish blue
36	1495	...	Flesh color	Sea green
37	1534	...	Carmine	Green
38	1621	...	Dull purple	Dull sea green
39	1652	...	Violet gray	Yellowish green
40	1682	...	Grayish blue	Greenish yellow
41	1711	...	Dull sea green	Yellowish gray
42	1744	3	Bluish green	Lilac
43	1811	...	Light green	Carmine
44	1927	...	Light greenish gray	Grayish red
45	2007	...	Whitish gray	Bluish gray
46	2048	...	Flesh red	Green

Compare color plate in Part IV.

Examination in Parallel Polarized Light.

Parallel polarized light is used to determine whether a mineral is singly or doubly refracting. In doubly refracting minerals it is used to observe the positions of the axes of vibration in relation to the crystallographic axes, the index of refraction, and the birefringence.

Isotropic Plates in Parallel Polarized Light.

If one inserts a flake of an isotropic mineral between the polarizer and analyzer of a microscope, there will be no alteration in the directions of vibration of the rays of light on account of the equal ease of vibration in every direction, consequently the field will remain dark for both colored and colorless minerals. This property of remaining dark between crossed nicols, in any position in its own plane or any other plane, is the most important characteristic of an isotropic mineral.

Anisotropic Plates in Parallel Polarized Light.

A plate of a transparent doubly refracting mineral which is not cut at right angles to an optic axis, when inserted between crossed nicols in white light, shows chromatic interference.

The intensity of the light (not intensity of color) depends upon the value of $\sin^2 2\phi$: in which ϕ is the angle which the optic principal section of the slide makes with the principal section of the polarizer or analyzer. When the optic principal section coincides with ($\phi = 0^\circ$) or is at 90° to that of the polarizer or analyzer, this value is equal to zero; consequently there will be extinction four times upon rotating the stage of the microscope. When $\sin^2 2\phi = 1$ the principal section is at 45° to the principal section of the polarizer or analyzer and the light intensity is at a maximum.

Anisotropic plates at right angles to an optic axis in parallel polarized light. In tetragonal and hexagonal crystals the principal crystallographic axis coincides with the optic

axis, therefore the optic axis is a direction of single refraction, and a basal plane between crossed nicols acts, in parallel light, as an isotropic body.

Superimposed anisotropic plates in parallel polarized light.

If two plates lie at right angles or parallel to each other, they act as a single plate with reference to the extinctions at 90° . When the directions of greatest and least ease of vibration correspond, the wave differences of the two are added, and the interference colors rise; when unlike ease of vibrations are parallel, the color sinks to the difference between the two wave lengths. If the wave differences are alike, the sum is equal to zero and darkness results, and the field of the microscope remains dark on rotating the stage.

Extinction.

Both uniaxial and biaxial crystals appear dark between crossed nicols when their principal sections coincide with the vibration planes of the nicols. For most determinations white light answers the purpose, and only for minerals having strong dispersion of the bisectrices is it necessary to use the more accurate monochromatic light. (See p. 6.)

Determination of extinction angles. (a) *To observe the extinction angle* the vibration directions of the analyzer and polarizer of the microscope must be at right angles. The stage, with the mineral section upon it, is turned until the point of darkness is reached. This operation should be repeated ten times, and then again ten times with the stage rotated 180° from the position in which the first observations were made. An average of the twenty readings will give the extinction angle.

(b) *With gypsum plate.* Since the eye is somewhat insensible to small variations in the intensity of light, there may be considerable variation in reading the position of extinction. To overcome this one may use a gypsum plate producing red of the first order. If the mineral section whose extinction is

to be determined is placed between crossed nicols, so that it covers only a part of the field of the microscope, and the gypsum plate is inserted in the slot of the microscope above it, the mineral will appear of a different color from the remainder of the field, since its vibrations are added to or subtracted from that of the gypsum. If the stage is now rotated until the entire field is uniformly colored, the axes of greatest and least ease of vibration of the mineral will coincide with the directions of the cross-hairs of the microscope, and the amount of rotation can be read from the graduated circle upon the stage.

(c) *Klein quartz plate.* The gypsum plate is only of use in the determination of the extinction of colorless minerals; for those that are highly colored a Klein quartz plate is used. This consists of a quartz plate 3.75 mm. in thickness and cut at right angles to the axis. In consequence of the circular polarization of the quartz, one may obtain different interference colors by turning the analyzer; among others red of the first order appears when the nicols are nearly parallel. For determining the extinction of colored minerals, that tint is chosen which is most sensitive to the extinction of that mineral. The method of determining the angle is the same as with the gypsum plate, except that in general the nicols are not crossed.

(d) *Bertrand ocular.* The most exact method for the determination of extinction is by means of a Bertrand ocular. This consists of an ocular containing two right and two left-handed quartz plates of the same thickness, cut perpendicular to the axis, and so inserted that the lines of contact between the four parts are exactly parallel to the principal sections of the nicol prisms (Fig. 4). When the lower and cap nicols are crossed and a doubly refracting plate is inserted between them, the adjacent quadrants become differently colored, while the diagonal ones are alike. Upon rotating the stage the four quadrants become uniformly colored when the principal sections of the mineral are parallel to those of the nicols. The

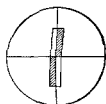


FIG. 4.—Bertrand ocular.

amount of rotation of the stage is the measure of the extinction.

Orientation. In tetragonal, hexagonal, and orthorhombic crystals the position of extinction is always parallel or symmetrical to the cleavage cracks.

In monoclinic crystals the extinction is parallel or symmetrical to the cleavage only in the zone parallel to the *b* axis. In all other sections the extinction is oblique.

In triclinic crystals the extinction directions are, in general, inclined to the cleavage lines.

Determination of the Relative Indices of Refraction of Minerals.

(a) *Becke's method** for the determination of the relative indices of refraction of minerals in contact with each other is to focus sharply upon the line of contact between them with a medium power objective in parallel light. The plane of contact between the two minerals should be nearly at right angles to the plane of the thin section and free from inclusions of dust, etc. The rays, passing from a denser to a rarer medium at less than the critical angle, will be reflected back into the denser medium, thus increasing the light emerging from it, while on the side of the rarer medium it will be decreased. In consequence there is a narrow bright band along the contact on the side of the denser medium. By raising the objective slightly this band passes in the direction of the denser medium. This is much more noticeable if the lower diaphragm of the microscope is partially closed. Knowing one of the minerals, the relative index of the other in contact is thus determined. This method is very delicate and a difference of refraction of 0.001 can be observed.

* F. Becke: Sitzungsberichte der K. K. Akademie der Wissenschaften zu Wien, vol. 102, 1893, pp. 358-376; Techernak's Mineralogische und petrographische Mitteilungen, v. 13, 1892-3, pp. 385-388.

Thus the indices of

anorthite, $n=1.580$,

labradorite, $n=1.559$,

andesine, $n=1.553$,

are all greater than

quartz, $n=1.551$;

which is greater than

nephelite, $n=1.545$,

oligoclase, $n=1.543$,

which is greater than

Canada balsam, $n=1.54+$;

which is greater than

albite, $n=1.531$,

orthoclase, $n=1.523$.

The use of this method in the determination of the feldspars is more fully explained in Part II, pp. 72-76.

(b) *Method of embedding of Schroeder van der Kolk.** If a substance is immersed in a fluid of exactly the same index of refraction, dispersion, and color, its boundaries will completely disappear and it will become invisible.

In applying this method to the determination of the index of refraction of a mineral, a fragment is immersed in a fluid having a certain index of refraction. Upon raising the tube of the microscope slightly (see preceding section), the bright line will move into the center of the mineral if this is of a higher index, and into the fluid if the reverse is true. By successive trials with liquids of different refractive indices, or by increasing or reducing the index of the fluid by the addition of another fluid of higher or lower index, the index of refraction of the mineral may be quickly found. Owing to the fact that the

* Tabellen zur mikroskopischen Bestimmung der Mineralien nach ihrem Brechungsindex, 1900.

dispersion of the mineral and the liquid are usually not the same, instead of completely losing its boundaries the mineral will show bright-colored bands around its edges. To determine the refractive index of the liquid, Schroeder v. d. Kolk used a total reflectometer. In applying this method to the determination of the feldspars, Michel-Lévy used a series of sixteen minerals with known indices as indicators instead of the reflectometer, and, since some of van der Kolk's solutions acted upon the minerals, he used Klein's solution variously diluted. In Schroeder v. d. Kolk's Tabellen is given a list of 200 minerals arranged according to their indices of refraction, and a series of fluids with different indices of refraction which are of use in these determinations. The following list is taken partly from his table and partly from Maschke's.*

Indices of refraction of immersion fluids.

Solution of mercury iodide in aniline and chinoline	$n = 2.2 +$
Phosphorus, solid.	$n = 2.144$
" molten.	2.075 †
Sulphur (molten at 110°).	1.93
Sulphur in iodo methylene	1.83
Bisulphide of carbon.	1.768
Iodo methylene	1.740
α -Monobrom naphthalene.	1.658
Anise oil.	1.639 ⁵⁶
α -Monochlor naphthalene.	1.639
Monoiodo benzene.	1.621
Cassia oil at 21°.	1.606
Cinnamon oil.	1.605
Bromoform.	1.588
Monobrom benzene.	1.561
Nitro benzene.	1.554
Clove oil.	1.544

* Wiedemann's Annalen der Physik und Chemie, vol. xi, 1880, pp. 722-734.

† Remains fluid for some time under a cover-glass. *

Canada balsam.....	1.542-1.55
Ethylene bromide.....	1.536
Monochlor benzene.....	1.527
Cedar oil.....	1.516
Benzene.....	1.501
Nylene.....	1.495
Beechnut oil.....	1.477
Almond oil at 21°.....	1.469
Carbon tetrachloride.....	1.466
Glycerine (1.23-1.25 sp. gr.) at 15.5°.....	1.460
Amyl alcohol at 15.5° C.....	1.4075
Water at 18° C.....	1.333

Except as marked, the temperature at which these indices were taken was approximately 15° C.

To obtain fluids of different indices, glycerine may be mixed with water, almond oil with amyl alcohol or with cassia oil, or cassia oil with amyl alcohol. It is thus possible to obtain a series of fluids of any desired index of refraction from 1.333 to 1.606.

Maschke used a series of mixtures of cassia oil and almond oil as follows:

Almond Oil.	Cassia Oil.	Index for D.
(1) 5 parts (by weight)	$\frac{1}{3}$ part	1.474 at 20.8°
(2) 5 " "	$\frac{1}{2}$ "	1.476 " 20.8°
(3) 5 " "	1 "	1.485 " 20.3°
(4) 5 " "	2 "	1.501 " 20.3°
(5) 5 " "	3 "	1.5105 " 20.6°
(6) 5 " "	4 "	1.519 " 20.6°
(7) 5 " "	5 "	1.526 " 20.3°
(8) 5 " "	6 "	1.533 " 20.3°
(9) 5 " "	7 "	1.5375 " 20.6°
(10) 5 " "	$7\frac{1}{2}$ "	1.540 " 20.0°
(11) 5 " "	8 "	1.543 " 20.6°
(12) 5 " "	9 "	1.5445 " 20.6°
(13) 5 " "	10 "	1.5466 " 20.6°

(14)	5 parts (by weight)	11 parts	1.551 at 20.8°
(15)	5 " "	12 "	1.552 " 20.8°
(16)	5 " "	13 "	1.555 " 20.8°
(17)	5 " "	14 "	1.560 " 20.8°
(18)	5 " "	15 "	1.5625 " 20.8°
(19)	5 " "	15 "	1.562 " 21.75°

Mixtures of cassia and almond oils should be kept in well stoppered bottles, for the index appreciably decreases by the oxidation of the cassia oil to cinnamic acid.

Tables of Mean Indices of Refraction.

See Part IV.

Determination of the Order of Birefringence.

The birefringence of a mineral (the difference between the indices, ω and ε , or γ and α , etc.), like the index, is characteristic for that mineral. When the indices are known the values of the birefringence in different directions can be computed or they can be approximately determined by comparing the colors seen under the microscope with those on a color scale.

Since the color seen in a mineral between crossed nicols is dependent upon the thickness of the section as well as upon the birefringence of the mineral, one must first compare the color with that of a known mineral to determine the thickness of the slide. Good slides vary but little in different parts of the section, and uneven grinding does not greatly interfere. *For comparison of colors and thicknesses, the plate prepared by Michél-Lévy* is of great service.* This is reproduced with some modifications in Part IV. Although it is not possible to reproduce the exact colors of nature, no difficulty will be found in determining the color seen.

* Lévy et Lacroix, *Les Minéraux des Rôches*.

The method of using the plate is as follows: The thickness of the section is first determined by observing the highest color shown by some known mineral. The inclined line of its birefringence on the plate is followed to that color, and the thickness is read at the left along the horizontal line. After observing the highest interference color of the unknown mineral, this color is found along the horizontal line giving the thickness of section, and the inclined intersecting line is followed upwards to the right, where the name of the unknown mineral will be found. The plate shows the maximum birefringences of the minerals, and one must observe a number of sections to be certain that the one chosen shows the highest color.

A list of the values of the maximum birefringences of different minerals is given in Part IV.

There are numerous methods and accessories used in determining the order of birefringence. Those of most importance are:

(a) *Quarter undulation mica plate.* When the a axis of the mica plate and that of the section are at right angles, the color seen between crossed nicols will drop one-quarter order in the scale: thus the first-order yellow will be reduced to white, while the second-order yellow will become green. This method can be used to advantage in distinguishing the lower orders.

(b) *Gypsum plate with red of the first order.* The first-order red can be separated from the higher orders by the use of a gypsum plate giving red of the first order. When the a axis of this plate and that of the section are at right angles, the color will drop through one order and become dark; a second-order red will be reduced to a first-order red. This method is of value for the middle orders.

(c) *Quartz wedge.* For the higher orders a quartz wedge may be used. The mineral section is turned until the directions of maximum and minimum ease of vibration make angles of 45° with the cross-hairs of the microscope; that is, the section is turned until the mineral is 45° off extinction. The

quartz wedge is inserted with its thin edge forward and its direction parallel to the r direction of the mineral. The interference colors, therefore, descend through the scale of Newton's colors, as the wedge is pushed forward, until the acceleration of the one exactly coincides with the retardation of the other, and, the vibrations neutralizing each other, the section appears dark. The mineral section is removed and the number of times (n) is counted, that the original color recurs on withdrawing the wedge. The original color must then have been of the $n+1$ order.

(d) *Mica compensator of E. von Fedorow.** In using this wedge the process is essentially the same as with the quartz wedge, but since it consists of sixteen step-like, overlapping, rectangular, mica plates, each 2 mm. shorter than the preceding and differing by one-quarter wave length from it, the order may at once be known by the position of the wedge. After removing the mineral slide, if the Bertrand lens is inserted, the separation lines between the plates can be more distinctly seen.

The following table is adapted from that given by Fedorow:

Order.	Crossed Nicols.	Diff. in Wave Length.	Order.	Parallel Nicols.
1.	†gray	0.000127 mm.	$\frac{1}{2}$	brownish yellow
1.	†pure white.	0.000255	$\frac{1}{2}$	dark violet-brown
1.	orange yellow.	0.000382	$1-\frac{1}{2}$	sky blue
1.	orange red.	0.000511	$1-\frac{1}{2}$	light yellowish
2.	blue.	0.000637	$1-\frac{1}{2}$	canary yellow
2.	green.	0.000765	$1-\frac{1}{2}$	yellowish orange
2.	yellow.	0.000892	$2-\frac{1}{2}$	intense violet blue
2.	orange-red.	0.001020	$2-\frac{1}{2}$	leek green
3.	indigo.	0.001147	$2-\frac{1}{2}$	chrome yellow
3.	smaragdite green	0.001275	$2-\frac{1}{2}$	light orange
3.	lemon yellow.	0.001402	$3-\frac{1}{2}$	pure violet
3.	orange.	0.001530	$3-\frac{1}{2}$	pure green
4.	violet-red.	0.001657	$3-\frac{1}{2}$	light yellowish
4.	grass green.	0.001785	$3-\frac{1}{2}$	light orange
4.	greenish yellow.	0.001912	$4-\frac{1}{2}$	light reddish blue
4.	rosa.	0.002040	$4-\frac{1}{2}$	light greenish

* Zeitschrift für Kristallographie, vol. 25, 1895, pp. 349-351.

† These colors are difficult of determination between crossed nicols, but sharply determinable between parallel nicols.

(e) *By parallel nicols.* The lower orders of gray are difficult of determination between crossed nicols, but sharply determinable when the nicols are parallel, as may be seen from the table above.

(f) *With the Amann birefractometer.* This consists of an ocular containing a quartz wedge which can be moved, by means of a screw, across one half of the field of the microscope. The method of use is similar to that of the ordinary quartz wedge. The mineral section is turned until its a direction is at right angles to that in the instrument. The point at which the two tints are neutralized and darkness occurs can be read directly from a scale engraved on glass and which moves with the wedge. A cap nicol must be used with this instrument. If the mineral fragment is isolated or at the edge of the section, it can be brought under the clear glass part of the ocular and a direct comparison made with the colors of the wedge.

(g) *With a Babinet compensator.* This instrument consists of two quartz wedges cut to very acute and equal angles, and so arranged that the a direction of one coincides with the c direction of the other. The lower wedge is movable by means of a micrometer screw; the upper wedge is stationary and has engraved upon it a cross to serve as a location point. When set at zero, the two wedges compensate and the resulting dark band coincides with the cross, while on either side are similar parallel bands of colors.

On inserting a mineral section with its vibration directions parallel to those of the compensator, the black band is displaced. The amount of motion necessary to bring it back to the cross can be read by means of the micrometer screw and is a measure of the birefringence.

(h) *With the Michel-Lévy comparateur.* The interference colors obtained by means of a movable quartz wedge are projected, by means of a prism in this instrument, into the field of the microscope, and the interference color of the mineral is determined by direct comparison.

Determination of the Relative Values of Two Vibration Directions.

(That is, the positive (+) or negative (-) character of the elongation of a mineral section.)

The mineral section is rotated between crossed nicols in plane polarized light to extinction. The cross-hairs of the microscope now coincide with one of the axes of vibration, while the other is at right angles to it. The section is rotated 45°, bringing the axes to the same angle with the cross-hairs, and the interference color is at its maximum. A mica plate is now inserted between the crossed nicols at the same angle, thus having its optic axes parallel to those of the mineral. The effect of this is to raise or lower the interference color of the crystal section. The colors will rise in the scale (p. 10 and colored plate), when similar axes have the same direction, and will fall when different axes are superimposed. In the first case the retardation of the mica plate is added to that of the mineral, and acts as a thickening of the section; in the latter it is subtracted and acts as a thinning of the section. Knowing the direction of α in the test plate, the relative positions of the directions of greater and less ease of vibration in the mineral section are known.

For thicker sections or strongly refracting crystals a gypsum plate or quartz or mica wedge may be used in a similar manner. A gypsum plate will produce an increase or decrease of a whole order. *If a wedge of quartz or mica is inserted with its vibration directions at right angles to those in the mineral, the colors will descend in the scale until the vibrations neutralize each other and the field of the microscope becomes dark. A rotation of 90° will produce a rise in color.*

When the direction of elongation of a mineral section approximately coincides with the axis of least ease of vibration (ϵ), the fragment is said to have **positive elongation**; when it approximately coincides with the axis of greatest ease of vibration

If the direction of crystallographic c in uniaxial crystals, or the acute bisectrix in biaxial crystals, is known, then the above, of course, also serves to determine the (+) or (-) character of the crystal, as well as the elongation. The mineral is positive if $\epsilon=c$ of uniaxial or the acute bisectrix of biaxial crystals, and negative if $a=c$ or the acute bisectrix.

Determination of the character of elongation of a mineral showing a wedge-shaped edge and, consequently, bands of interference colors between crossed nicols. It

often happens, in a rock slide, that some fragments of the mineral, whose elongation is to be determined, have edges which are not at right angles to the section. Where these edges occur at the periphery or in a cavity, they may be used to determine the elongation. If a quartz wedge is pushed forward the whole scale of Newton's colors will appear in a succession of bands which move in the same direction as the wedge when the axes correspond, and in the opposite direction when they do not. (Fig. 5.)

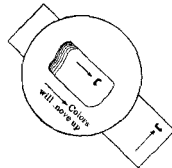


FIG. 5.—The vibration directions in the mineral and wedge are at right angles to each other.

Dichroism.

As the velocity of light varies in uniaxial crystals when it vibrates parallel or at right angles to the vertical axis, so there may be different degrees of absorption in these directions.

Pleochroism.

The alteration of color, in some minerals, with the alteration of the direction of transmission of the polarized ray, is called **pleochroism**. As biaxial minerals have three indices of refraction (α , β , γ), so also may they have different degrees of absorption in different directions, which is shown in polarized light when these directions are parallel to the plane of the polarizer. Since the absorption is dependent upon the wave

length of light, it may be that in one direction the red is ~~more~~ strongly absorbed than the blue, consequently, in transmitted light, such minerals show different colors when the light vibrates in different directions. The degree of absorption is usually written $a > b > c$, or $a = b > c$, etc.: the absorption axes being assumed to coincide with the axes of vibration, although they do not always do so.

Examination in Convergent Polarized Light.

Convergent light is used to separate uniaxial from biaxial crystals, to determine dispersion and the optical character, and to separate isotropic minerals from anisotropic ones cut at right angles to the optic axis.

Interference Figures.

Appearance in uniaxial minerals. (a) *Sections normal to the optic axis.* These show a symmetrical dark cross, due to



FIG. 6.—A uniaxial interference figure.

the extinction of all rays coinciding with the planes of the nicols, and a series of concentric rings, alternating light and dark in monochromatic light and showing the colors of the spectrum in white light (Fig. 6). During a rotation of the stage the arms of the dark cross remain stationary. An increase in the strength of the double refraction or an increase in the thickness of the slide causes the cross and rings to become more sharply defined and the distance between the rings to decrease.

(b) *Sections oblique to the optic axis.* The center of the cross will appear farther and farther toward the edge of the field of the microscope as the section is more and more oblique to the optic axis (Figs. 7-18), finally being entirely outside the field. On rotating the stage, the center of the cross (the point of emergence of the optic axis) will move in the same direc-



FIG. 7.



FIG. 8.



FIG. 9.



FIG. 10.



FIG. 11.



FIG. 12.

FIGS. 7-12.—Uniaxial interference figures. The center is toward the edge of the field of the microscope.



FIG. 13.



FIG. 14.



FIG. 15.



FIG. 16.



FIG. 17.



FIG. 18.

FIGS. 13-18.—Uniaxial interference figures. The center is beyond the field of the microscope.

tion as the stage, but the arms will always remain parallel to the cross-hairs. To distinguish such figures from biaxial interference figures showing only part of a bar, one needs only remember that in uniaxial minerals the arms remain parallel to the cross-hairs during the rotation of the stage.

(c) *Sections parallel to the optic axis.* These sections show hyperbole which are very similar to those seen in biaxial figures, except that they do not appear in the field until the stage is nearly in the 90° position, and then they move in, form a cross, which is seldom sharp, and very rapidly move out again in the direction of the principal axis. During the greater part of the rotation, therefore, they do not show in the field of the microscope.

The optic axis lies in the direction toward which the hyperbole leave the field. Its position may also be determined by the appearance of the interference colors. If the stage is turned 45° from the position in which the bars form a cross, there will appear a certain interference tint in the center of the field. Outward from this center there will be a fall in the color scale toward the quadrants in which the optic axis lies and a rise in the other two quadrants. This holds good for both (+) and (-) crystals. (Figs. 19 and 20.) In thick plates, or in



FIG. 19.

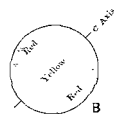


FIG. 20.

FIGS. 19-20.—Interference figures of uniaxial minerals cut parallel to the optic axes. Fig. 19. Quartz (+). Fig. 20. Apatite (-).

minerals having high double refraction, this is only observable at the center; beyond that, there is a uniform rise in colors.

Appearance in biaxial minerals. (a) *Sections perpendicular to the acute bisectrix.* These show in white light between crossed nicols, when the axial angle is less than the field of the micro-

the plane of the axes coincides with the cross-hairs. A black cross, and a series of colored curves (Fig. 21). At the point of emergence of each optic axis there will be a dark spot, and surrounding it a number of rings which unite at the center and form lemniscate curves around the two. On rotating the stage the cross dissolves into two hyperbolas whose poles are the loci of the optic axes. These bars revolve in an opposite direction from the stage and always have their convex side toward the acute bisectrix. (Figs. 21-26.) The



FIG. 21.



FIG. 22.



FIG. 23.



FIG. 24.



FIG. 25.



FIG. 26.

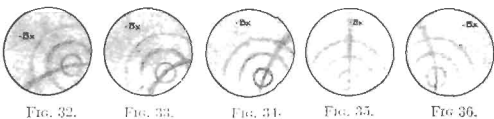
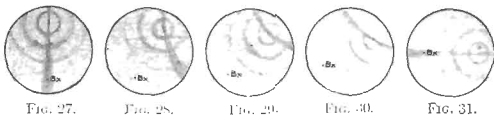
FIGS. 21-26. -Biaxial interference-figures. The section is cut at right angles to the acute bisectrix.

smaller the axial angle, the nearer together will be the loci of the optic axes, until finally the figure approaches the form given by a uniaxial mineral. When the axial angle is large neither of the loci will show, but the biaxial character can be determined by the movement of the bars.

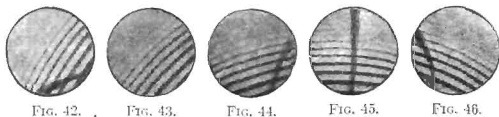
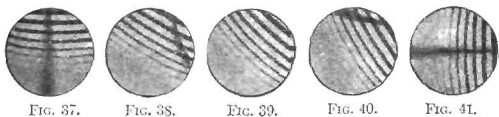
(b) *Sections perpendicular to the obtuse bisectrix.* When the axial angle is not too large, these show similar figures to those seen in sections cut at right angles to the acute bisectrix.

Generally, however, the angle is large, the axes suffer *total reflection* from the lower side of the section, and no figure is seen.

(c) *Sections inclined to the bisectrix.* More and more of one eye and less of the other is seen as the section is more and more



FIGS. 27-36.—Biaxial interference figures. One optic axis and the acute bisectrix emerge within the field of the microscope.



FIGS. 37-46.—Biaxial interference figures. The optic axes and the acute bisectrix emerge beyond the field of the microscope.

inclined. The convex side of the hyperbola is always toward the acute bisectrix and the arm rotates in a direction opposite to the turning of the stage. (Figs. 27-36 and 37-46.)

Sections at right angles to an optic axis. These show nearly circular concentric curves crossed by a single dark bar which is straight whenever it is parallel to the planes of vibration of the nicols (Fig. 47). Upon rotating the stage, this bar changes to a slightly curved hyperbola with its convex side toward the acute bisectrix. Sometimes the arm is not sharply defined, especially when the section is not quite at right angles to the optic axis, and the arm may show as a bar straight on one side and concave on the other (Fig. 48). The straight side is here toward the acute bisectrix. Upon turning the stage the arm rotates in the opposite direction.



FIG. 47.—Biaxial interference figure showing the emergence of an optic axis in the center of the field of the microscope.



FIG. 48.—Biaxial interference figure with the optic axis emerging beyond the field of the microscope.

Since light is dispersed in all biaxial crystals, a section can be actually at right angles to an optic axis only for a given color. The dispersion is generally so slight, however, that it may be overlooked, and one will see, in white light, a series of colored rings, whose tints will differ from the pure colors of Newton's scale more and more with increasing dispersion.

(c) *Sections parallel to the plane of the optic axes.* Sections cut parallel to the plane of the optic axes (perpendicular to the b axis) may be recognized in parallel polarized light by the fact that they show the highest interference colors. In convergent light they show figures similar to those shown by uniaxial crystals parallel to the optic axis. The hyperbolic arms come in from the sides very rapidly, darken the field, and, upon a very slight rotation, immediately disappear in the direction of the acute bisectrix. When the field is dark the axes a

and ϵ are parallel to the cross-hairs. Becke* has shown how one may determine the position of the acute bisectrix in this section. The method has already been described in reference to uniaxial figures (p. 26). The line uniting the quadrants containing the lower colors is the direction of the acute bisectrix, (a) in (-) and (ϵ) in (+) minerals. When the axial angle approaches 90° the color variation becomes indistinct; when $2V=90^\circ$ it disappears.

The above may be verified by using the gypsum plate, with red of the first order, as a mineral section.

In sections cut parallel to the plane of the optic axis the optical character of the mineral may also be determined by observing whether the acute bisectrix is a or ϵ .

Locating the points of emergence of the optic axes. (a) *In uniaxial minerals.* When the eye of a uniaxial figure is beyond the field, there is no difficulty in determining its position, as may be seen in Figs. 7 to 18. It is at the junction of the two bars.

(b) *In biaxial minerals.* The appearance of a biaxial figure, when the eyes are beyond the field of the microscope, is given in Figs. 37 to 46. (1) When the bisectrix is within the field, it is to be noted that the hyperbolæ come in from the sides upon which the eyes are located and disappear toward them. (2) When the bisectrix is outside the field of the microscope, the arm of only one hyperbola will be seen; the other arm, and consequently the bisectrix, is upon the convex side of the bar. (Figs. 27 to 46, and Fig. 48.)

The axial angle. *Apparent and true optic angle.* When a section of a biaxial mineral, cut normal to the acute bisectrix, is turned to the 45° position between crossed nicols, the distance between the hyperbolæ, that is, between the points of emergence of the optic axes, is a measure of the angle between these axes. Owing to the different rates of vibration for differ-

* Tschermak's Mineralogische und petrographische Mittheilungen, vol 16.

opt. axis, a section normal to one color will not be normal to the others, except in the orthorhombic system. If, however, the section is cut to the mean color, the result will be approximately correct. In Fig. 49, which is a cross-section through a slide, the angle BOA is one half the true axial angle and is represented by V . Owing to the change in direction of the ray in passing into air, the observed angle, E , is $BO'A'$. If the axial angle is acute, it is represented by $2E_a$ or $2V_a$; if it is obtuse, by $2E_o$ or $2V_o$.

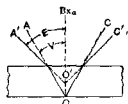


FIG. 49.—True and apparent axial angles.

Measurement of the axial angle. There are numerous methods for measuring the axial angle, but most of them are not applicable to the ordinary petrographical microscope, since the objective is too near the slide to permit turning about an axis.* If the slide is turned about the point O' (Fig. 49), with the line at right angles to the axial plane as an axis, until the line $O'C'$ coincides with the cross-hairs of the telescope of a goniometer, and is then turned until $O'A'$ coincides, the angle through which the section has been turned is the apparent axial angle, $2E$.

In a thin section under the microscope the angle can be determined by measuring the distance between the points of emergence of the axes with a micrometer eyepiece. The slide is turned until the hyperbolæ arc in the 45° position, after which the distance ($2d$) between them is measured. The distance of the point of emergence of an optic axis from the bisectrix was shown by Mallard to be proportional to the sine of the angle which it makes with the axis of the microscope. Thus $\sin E = \frac{d}{C}$, in which E is half the axial angle in air, d half the distance between the hyperbolæ, and C , a constant for each lens combination, which may be determined by using a mica flake whose axial angle is known and substituting in the for-

* A summary of methods for measuring the axial angle will shortly be published by Dr. Fred. E. Wright, in the *American Journal of Science*.

mula. By substituting these values in the equation $\sin V = \frac{\sin E}{n'}$, in which n' is the mean index of refraction of the mineral examined, the true value of the axial angle ($2V$) may be found.

If the section examined is not exactly at right angles to the plane of the optic axes, by the use of a tilting stage, it may be tipped until the bisectrix coincides with the axis of the microscope. There are numerous appliances which may be used for this purpose: **Klein's Universaldrehapparat**, **Fedorow's Universaltisch**, or a simple apparatus described by **Jaggar**.*

The determination of the axial angle may be made graphically by the **Mallard-Becke method**. With a camera lucida the hyperbolæ appearing in the field are transferred to a sheet of paper and, knowing the value of C , the angle may be plotted and measured.

Schwarzmann's axial angle scale may be used for the determination of $2E$. This is a scale made upon logarithmic principles, and from it the angle can be read direct. It consists of two parts, of which the lower is adjusted to the constant of a certain combination of lenses. The distance, D , upon the upper scale, will be found directly above the value of $2E$ for that distance. A different scale is used for each different lens combination.

Dispersion of the Optic Axes.

As light passing through a prism is separated into the spectrum, on account of the difference in wave lengths of different-colored rays, so the value of V and the loci of the hyperbolæ in the interference figures will vary with different wave lengths of light. This variation produces what is called the **dispersion of the optic axes**, and is recognized under the microscope by a change in the position of the loci of the axes. To indi-

* *American Journal of Science*, 3, 1897, p. 129.

cate this dispersion, red and violet rays are considered. ρ is used to indicate red light and ν to indicate violet light. Thus $\rho < \nu$ shows that the dispersion of red is less than that of violet.

Optical characteristics of the different systems. (a) *Orthorhombic system.* In the orthorhombic system the three vibration axes (\mathbf{a} , \mathbf{b} , \mathbf{c}) coincide with the crystallographic axes (a , b , c), and any of the former may coincide with any of the latter. These positions being fixed, the color distribution will be symmetrical with reference to both bisectrices, although the optic angle may differ. The plane of the optic axes always lies in one of the pinacoids. There may be two cases: $\rho > \nu$, in which the axes are more dispersed for red than for violet, and $\rho < \nu$. Fig. 50 shows a section through an orthorhombic crystal with

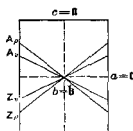


FIG. 50.—Section through an orthorhombic crystal with $\rho > \nu$.

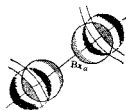


FIG. 51.—Dispersion in an orthorhombic crystal with $\rho > \nu$. (The solid lines and hatches may be colored blue, the dotted lines, red.)

the optical scheme $\rho > \nu$. Fig. 51 shows its dispersion in the interference figure. The dispersion is always least for that color which occurs within the circle nearest the bisectrix and which touches the concave side of the hyperbolæ when the section is in diagonal position. The colors in the two eyes are symmetrical with reference to the bisectrix.

(b) *Monoclinic system.* In the monoclinic system only the b axis coincides with an optic axis, and this shows no dispersion. The other two optic axes lie in the (010) plane and are at right angles to each other and to the one coinciding with b . There are three kinds of dispersion.

1. *Inclined.* In this the axial plane is parallel to (010) and $b = \mathbf{b}$. The color distribution will be symmetrical to the line joining the loci of the hyperbolæ, but not in the other direction. The intensity of the eyes will be different. One eye will be less intense, larger, and oval; the other, smaller, intense, and round. The distribution of color will depend upon the amount of dispersion of the axes. If this is slight the colors will be symmetrical with reference to the bisectrix. (Fig. 52,

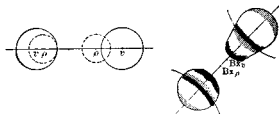


FIG. 52.—Inclined dispersion in a monoclinic crystal. Gypsum, with $\rho < \nu$. (The solid lines and hatchures may be colored blue; the dotted lines and dotted areas, red.)

gypsum $\rho < \nu$.) With stronger inclined dispersion (Fig. 53, diopside $\rho > \nu$), like colors will occur upon the same sides of the loci of the axes. The smaller eye, also, will be farther from the cross-bar at the bisectrix, and one hyperbola will be broader than the other.

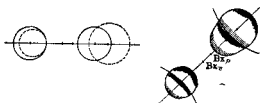


FIG. 53.—Inclined dispersion in a monoclinic crystal. Diopside, $\rho > \nu$. (The solid lines and hatchures may be colored blue; the dotted lines and dotted areas, red.)

2. *Horizontal.* Crystallographic b is the obtuse bisectrix, the acute bisectrix is in the clinopinacoid and the plane of the optic axes is perpendicular to (010). The axial figure will be symmetrical to the (010) plane only, and the figure must be dispersed as in Fig. 54. The colors will be symmetrical only to the one plane.

3. *Crossed*. Crystallographic b is the acute bisectrix and will remain unchanged for all colors of light. The obtuse bisectrix and the b axis are dispersed. There are no planes, but only a point of symmetry. This point is the locus of the acute bisectrix, which is the axis of symmetry (Fig. 55).

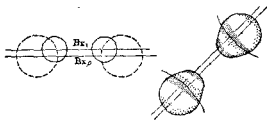


FIG. 54.—Horizontal dispersion in a monoclinic crystal $\rho < \nu$.

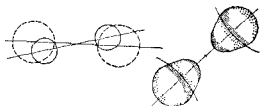


FIG. 55.—Crossed dispersion in a monoclinic crystal $\rho > \nu$. (The solid lines and hatchures may be colored blue; the dotted lines and dotted areas, red.)

c. *Triclinic system*. All of the vibration axes are dispersed in the triclinic system and the distribution of the colors in the interference figures is unsymmetrical throughout.

Determination of the Optical Character of the Crystal in Convergent Polarized Light.

In convergent polarized light the character of a mineral can be determined by inserting a mica or gypsum plate, or a quartz or mica wedge, above the interference figure.

Uniaxial crystals. (a) *Quarter undulation mica plate*. Upon inserting a quarter undulation mica plate, with its a direction parallel to the elongation, above the mineral and at 45° to the cross-hairs, the dark cross will separate, for positive minerals, as shown in Fig. 56 a. In negative minerals the position of the dark spots will be reversed, as Fig. 56 b. If the mica plate

has r for its long direction, the phenomenon will be reversed. The separation of the cross in the interference figure is caused by the one-fourth wave length ($\frac{1}{4}\lambda$) decrease in the rays vibrating in the ~~first and third~~ ^{two of the} quadrants, and the increase by $\frac{1}{4}\lambda$ in

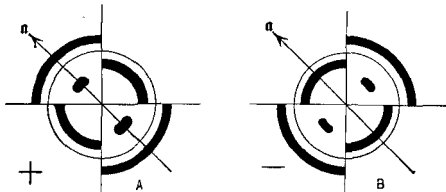


Fig. 56.—Determination of the optical character of a uniaxial crystal with the mica plate. (a) Positive. (b) Negative.

the others. The direction of the arrow upon the mica plate is usually that of r . The method for testing this direction is given in Part IV.

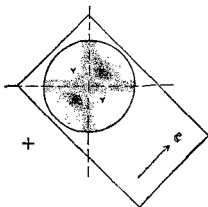


Fig. 57.

Determination of the optical character of a uniaxial crystal with the gypsum plate. Quartz (+).

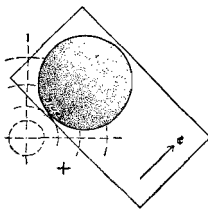


Fig. 58.

Determination of the optical character of a uniaxial crystal with the gypsum plate when the center of the cross is beyond the field of the microscope. Quartz (+).

(b) *Gypsum plate giving red of the first order.* If the double refraction of a mineral is weak, or the section is very thin, the mica plate is unsatisfactory, and a gypsum plate having a

thickness of 0.055 mm. and giving the first-order red may be used in a similar manner. With the a direction parallel to the elongation of the gypsum plate, positive crystals will be raised to blue in the ~~second~~^{NE} and ~~fourth~~^{SW} quadrants and reduced to yellow in the ~~first~~^{NW} and ~~third~~^{SE} (Fig. 57). For negative crystals the phenomenon is reversed. This accessory may be used even when the uniaxial cross is beyond the field of the microscope, by observing the location of the center (Fig. 58).

(c) *Quartz or mica wedge.* If the expansion or contraction of the rings cannot be recognized with a mica or gypsum plate, it can often be seen with a quartz or mica wedge. When such a wedge, with its a direction parallel to its length, is pushed with the thin edge foremost between crossed nicols, the colors in the first and third quadrants move away from the center.

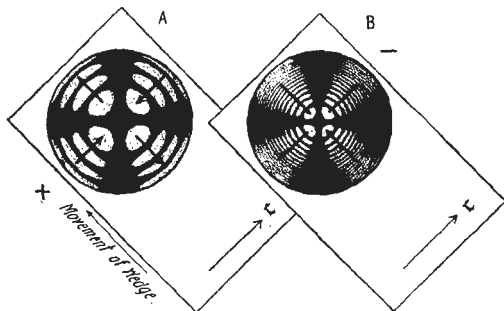


FIG. 59.—Determination of the optical character of a uniaxial crystal by means of a quartz wedge. (a) Quartz (+). (b) Calcite (-).

while in the second and fourth quadrants they move toward it (Fig. 59). With negative crystals or with r parallel to the long direction of the wedge, the phenomenon is of course reversed.

Biaxial crystals. (a) *Mica plate.* The phenomenon observed

upon inserting a quarter undulation mica plate above the interference figure of a biaxial mineral rotated until the hyperbolæ form a cross, is exactly the same as that seen in uniaxial minerals. For positive minerals the two black dots show along the direction of a of the mica plate and for negative minerals along the direction of c . (Fig. 56, *a*, *b*.) The mica plate is only of use when the hyperbolæ are well defined.

(*b*) *Gypsum plate.* Sections which show the emergence of the acute bisectrix but which show no isochromatic curves,

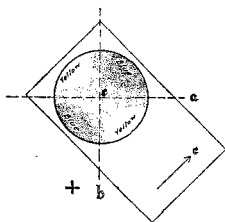


FIG. 60.—Determination of the optical character of a biaxial crystal in a section cut perpendicular to the acute bisectrix by means of the gypsum plate (+). (After Wulff.)

when turned upon the stage so that the hyperbolæ form a cross, are in parallel position. If a gypsum plate with its a direction to the N.W., S.E., is now inserted, the center of the field will appear red, and, in positive minerals (Fig. 60), the N.E., S.W. quadrants will be colored blue, while the other two will be yellow. The position of blue and yellow will be reversed in negative minerals or if the gypsum plate has its elongation parallel to c .

Sections which show the emergence of only one axis may be determined in the same way. The convexity of the hyperbolæ is always toward the acute bisectrix; in the interference figure shown in Fig. 61 it is, therefore, to the N.W. By rotating the stage so that the acute bisectrix is in this position, and inserting a gypsum plate with its a direction also N.W., S.E., in positive minerals the concave side of the curve will be colored yellow, while in negative minerals it will be colored blue. (Fig. 62.)

In sections cut parallel to the plane of the optic axes (pp. 26 and 29), the direction of the acute bisectrix may first be determined, and then, in parallel light, the optical sign of the mineral.

(c) *Mica or quartz wedge.* For minerals which are thick, or which are strongly doubly refracting and which show several isochromatic curves, it is better to use a quartz or mica wedge

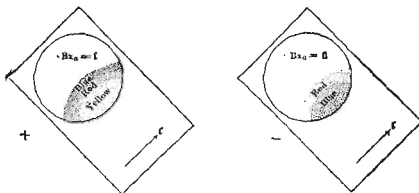
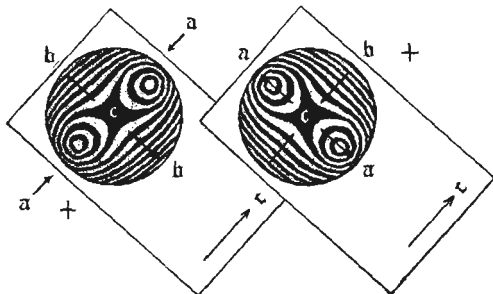


FIG. 61-62.—Determination of the optical character of biaxial crystals in sections showing the emergence of an optic axis by means of the gypsum plate. (After Wulfing.)

than a mica or gypsum plate. If, for example, a positive crystal (acute bisectrix = r) is placed under the microscope in the diagonal position (Fig. 63), and a quartz or mica wedge, with

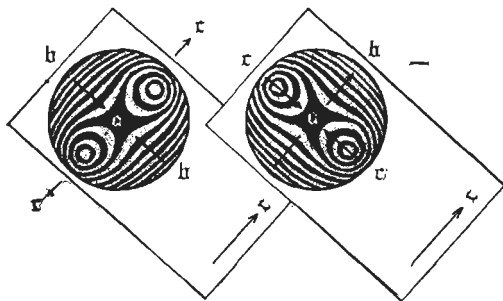


FIGS. 63-64.—Determination of the optical character of a positive biaxial crystal by means of a quartz wedge.

c parallel to its long direction, is inserted with the thin edge forward, the greatest case of vibration in the slide and plate will be at right angles to each other, and the insertion of the

wedge has acted as a thinning of the plate. On shoving the wedge forward, the rings will become less numerous and will appear to move from the center toward the center and then out along the wedge. If the section is turned 90° (Fig. 64) the insertion of the wedge acts as a thickening of the section, the lemniscate curves will apparently move along the wedge to the center and then out toward the eyes. In either case, in a positive mineral, with n as the long direction of the wedge, the colors move out of the field in the long direction of the wedge and into the field at right angles to it.

For a negative mineral, or with r as the long direction of the wedge, the reverse movements will take place. (Figs. 65 and 66.)



FIGS. 65, 66.—Determination of the optical character of a negative biaxial crystal by means of a quartz wedge.

If instead of turning the figure to the 45° position, it is placed in the parallel position with the hyperbolæ bars forming a cross, and one considers the center of a uniaxial interference figure as the emergence of the two optic axes of a biaxial mineral infinitely close together, or looks upon the bisectrix as located in the center of a uniaxial cross, the phenomena indicating the positive or negative character are alike in both cases. For

example, with the quartz wedge inserted with its *a* direction parallel to the elongation of the wedge, in either the uniaxial cross (Fig. 67) or the biaxial figure in parallel position (Fig. 68), the colors will move away from the center at right angles to

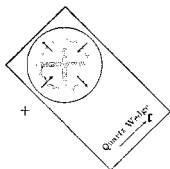


FIG. 67.

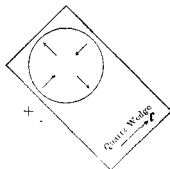


FIG. 68.

Fig. 67.—A positive uniaxial interference figure. The arrows indicate the movement taking place upon inserting a quartz wedge above the section.
 Fig. 68.—A positive biaxial interference figure with the principal sections nearly corresponding to those of the nicols. The arrows indicate the movement taking place upon inserting a quartz wedge above the section.

the wedge in negative, and the reverse way in positive minerals.

The optical character of a mineral may be determined

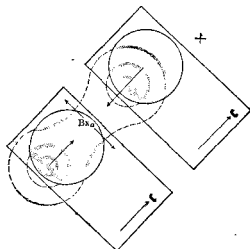
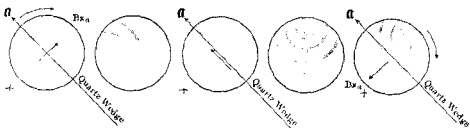


Fig. 69.—A biaxial interference figure showing the emergence of an optic axis. The arrow indicates the movement taking place upon inserting a quartz wedge above the section. The mineral is augite. (+).

with a quartz or mica wedge, even if the bisectrix emerges at the edge or entirely beyond the field of the microscope.

42 EXAMINATION IN CONVERGENT POLARIZED LIGHT.

The case is exactly similar to that just described, and is best seen from the following figures which are given for a positive (augite) and a negative mineral (epidote). (Figs. 69-75.) The



Figs. 70-74.—Movement of the left bar of Fig. 69 upon rotating the stage to the right, and movement of the colored rings upon inserting a quartz wedge.

arms in every case rotate in a direction opposite to that in which the stage is rotated. In these sections, which show only the emergence of one optic axis, account must carefully be taken of the position of the acute bisectrix, which is upon the convex

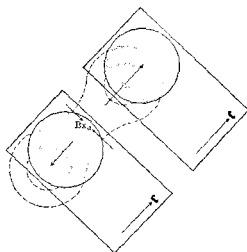


FIG. 75.

Fig. 75.—A negative biaxial interference figure. The arrows indicate the movement taking place upon inserting a quartz wedge above the section Epidote. (-).

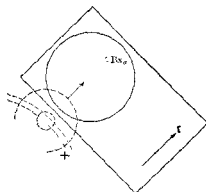


FIG. 76.

Fig. 76.—A positive biaxial interference figure. The arrows indicate the movement taking place upon inserting a quartz wedge above the section Olivine. (+).

side of the hyperbola, otherwise there will be confusion between the left optic axis of the (+) mineral and the right axis of th (-) mineral and *vice versa*. (Figs. 69 and 75.)

When the point of emergence of the optic axis is entirely outside the field, it is sometimes possible to tell the position of the bisectrix by the curve of the bar (Fig. 48). In this case the optical character can be determined in the same way, as is shown by Fig. 76 for olivine.

Optical Anomalies.

In certain minerals the optical behavior is different from what it should be according to the crystalline system. Thus, isomorphous crystals sometimes show double refraction (garnet, leucite, perovskite, etc.), or uniaxial minerals appear biaxial (quartz at times). The discussion of the cause of these anomalies is too long for this book, and the student is referred to Rosenbusch and Wülfing's *Mikroskopische Physiographie*, I, pp. 356-359, where the subject is fully treated and many references are given.

Measurements Under the Microscope.

Measurement of enlargement. The magnifying power of different combinations of objectives and oculars may be computed from the focal length of the combination, or may be directly measured by comparing the enlarged image of some object with its actual size. A small scale photographed on glass is placed upon the stage, the enlarged image is drawn by means of a camera lucida upon a sheet of paper and measured. The comparison may also be made by looking through the microscope with one eye and at a scale placed alongside with the other.

Measurement of lengths. A movable stage with micrometer screws working at right angles to each other serves best to measure actual size under the microscope. A micrometer eyepiece, whose divisions have been compared with a known scale for different combinations of lenses, may also be used.

Measurement of thicknesses. One may focus upon the top and bottom of a section and read the amount that the objec-

tive has been raised by means of the micrometer screw, applying a correction for refraction. If any mineral in the section is known, the thickness of the section, assuming it to have parallel faces throughout, may also be determined by the order of birefringence (cf., p. 19, and the colored plate in Part IV).

Measurement of angles. Angles may be measured under the microscope by moving the section until the point of the angle coincides with the cross-hairs of the microscope, bringing the two sides successively parallel to a cross-hair, and reading the angle through which the stage has been rotated.

Measurement of the axial angle. This subject has been fully treated above (p. 31).

PART II.

THE MINERAL GROUPS.

Spinel Group.

$R^{II}R^{III}_2O_4$, where R^{II} is Mg, Zn, Fe, and R^{III} is Al, Fe, Cr, Mn.

SPINELS:

PRECIOUS,	$MgO \cdot Al_2O_3$.	Colorless to pale red. light green, blue.
PLEONASTE,	$(Mg, Fe)O \cdot (Al, Fe)_2O_3$.	Green.
HERCYNITE,	$FeO \cdot Al_2O_3$.	Green.
GARNITE,	$ZnO \cdot Al_2O_3$.	Green.
PICOTITE,	$(Mg, Fe)O \cdot (Al, Fe, Cr)_2O_3$.	Yellow or brown.
MAGNETITE,	$FeO \cdot Fe_2O_3$.	Opaque, black.
CHROMITE,	$FeO \cdot Cr_2O_3$.	Brown or thin edges.

Optical anomalies are common in some varieties:

Reactions: The precious varieties are not affected by acids; those that are rich in iron are decomposed by long treatment with HF or H_2SO_4 or by fusion with alkali carbonates.

Occurrence and alteration.

*Spinel*s occur as original constituents in igneous rocks or secondary in metamorphic rocks, and are derived, according to Van Hise,* from almandite, biotite, corundum, diaspore, garnet, gibbsite, olivine, pyrope. They alter to mica, serpentine, and talc.

Magnetite occurs as an original constituent in igneous rocks and is very common. As a metamorphic mineral it is derived,

* C. R. Van Hise: A Treatise on Metamorphism. Monograph XLVII, U. S. Geological Survey.

according to Van Hise, from actinolite, ankerite, arfvedsonite, augite, biotite, bronzite, diopside, garnet, grünerite, hematite, hornblende, hypersthene, ilmenite, marcasite, olivine, pyrite, pyrrhotite, sahlite, and siderite. It alters to hematite, limonite, and siderite.

Chromite occurs as an original or as a metamorphic mineral in magnesium-rich igneous rocks, often in connection with serpentine. It is, in many cases, derived from olivine.

Garnet Group.

$R_3^{\text{II}}R_2^{\text{III}}\text{Si}_3\text{O}_{12}$, where R^{II} is Ca, Mg, Fe, Mn, and
 R^{III} is Al, Fe, Mn, Cr, Ti.

GROSSULAR: $\text{Ca}_3\text{Al}_2(\text{SiO}_4)_3$. Colorless, light green. No optical anomalies. Is usually fresh; known to alter to calcite, quartz, zoisite. Occurs in marbles, and calcareous schists and gneisses.

ALMANDINE: $\text{Fe}_3\text{Al}_2(\text{SiO}_4)_3$. Red to brownish. No optical anomalies. Generally unaltered, though known to alter to chlorite, hypersthene, and spinel. Occurs in granites, andesites, schists, and gneisses.

MELANITE: $\text{Ca}_3\text{Fe}_2(\text{SiO}_4)_3$. Brown. Optical anomalies not seen on account of the deep color. Generally fresh. Occurs in basic eruptive rocks rich in alkali; nephelite-syenites, phonolites, tephrites, leucitophyres; also in serpentine.

SPESSARTINE: $\text{Mn}_3\text{Al}_2(\text{SiO}_4)_3$. Blood-red. Unaltered. Occurs in contact rocks, quartzites, and schists, and in lithophyses in rhyolites.

COMMON GARNET: Mixture of the grossular, almandine, and melanite molecules. Red-brown to yellowish-red. Zonal structure and optical anomalies common. As a metamorphic mineral may be derived from vesuvianite. Alters to calcite, chlorite, epidote, hematite, hornblende, hypersthene, iron oxide, limonite, magnesite, magnetite, quartz, and siderite. Occurs in amphibolites, metamorphosed diabases, gabbros, pyroxenites, and in schists and gneisses.

PYROPE: $Mg_3Al_2(SiO_4)_3$. Blood-red. Kelyphite rims common. Alters to chlorite, enstatite, gibbsite, magnesite, quartz, serpentine, spinel, and talc. Occurs in peridotites and basalts.

UWAROWITE: $Ca_3Cr_2(SiO_4)_3$. Deep green, unaltered and with optical anomalies. Occurs in serpentines and is also found in marbles.

Separation from other minerals.

The strong index of refraction and insolubility in acids, united with isotropism, are characteristic of garnets. Spinel, only, resemble them, and from these they are separated by the presence of SiO_2 in garnets. Spinel usually have octagonal outlines, while garnets generally show many-sided polygons.

Sodalite Group.

SODALITE, $Al_2(SiO_4)_3 \cdot (Al, Cl) \cdot Na_4$.

NOSELITE, $Al_2(SiO_4)_3 \cdot AlSO_4Na \cdot Na_4$.

HAÜYNYTE, $Al_2(SiO_4)_3 \cdot AlSO_4Na \cdot CaNa_2$.

Sodalite, haüynite, and noselite occur as original constituents of igneous rocks, and are not known in schists and gneisses. Optical anomalies rare.

Separation.

Sodalite dissolves in HCl, and cubes of NaCl form upon drying the solution. If a few drops of a slightly acid solution of lead acetate are placed upon a thin section of sodalite, thin, flat needles of strongly doubly refracting lead chloride form over it.

Upon treating *noselite* and *haüynite* with HCl, gelatinous silica separates and they gelatinize in thin sections.

Upon drying a solution of noselite much NaCl and a little $CaSO_4$ separates; from haüynite much $CaSO_4$ separates.

Separation from other minerals.

The low indices of refraction distinguish the minerals of the sodalite group from other isotropic minerals except glass, fluorite, leucite, and analcite. Form and cleavage sepa-

rate them from glass; cleavage, lack of twinning, easy gelatinization and chemical reactions separate them from leucite and fluorite; form from analcite. Individual members of the group are separated by chemical means as given above.

Carbonate Group.

Calcite and *aragonite* may be separated by Meigen's method.* This has been modified by Panebianco, † who gives the following:

If calcite is boiled for one minute with a dilute cobalt nitrate solution, it becomes blue, and, after four minutes' boiling, lavender-blue. Aragonite, similarly treated, immediately becomes lilac and, with continued boiling, violet. The reaction for aragonite is very sensitive. In a mixture of one part of aragonite and nineteen parts of calcite, the color characteristic of the former will be produced.

Calcite and *dolomite* may be separated by observing the ease with which the powdered mineral is acted upon by cold HCl. They may also be separated by Lemberg's method.‡

A solution is made of

Aluminium chloride, dry.	4 parts
Logwood.	6 "
Water.	60 "

Boil half an hour, replacing the evaporating water, and filter.

If a few drops of this solution are placed upon a thin section of calcite and are allowed to stand for from five to ten minutes, and are then carefully washed off with water, the section will be colored violet; a section of dolomite will be unchanged.

Another method of separation is as follows:

If 1 gm. of calcite is boiled with 5 cc. of a 10% copper sul-

* Meigen: Neues Jahrbuch, Centralblatt, 1901, p. 577.

† G. Panebianco: Rivista min. crist. ital., vol. 28, 1902, p. 5.

‡ Zeitschrift: der deutschen geologischen Gesellschaft. Berlin, vol. xi, 1888, p. 357.

phate solution, the solution will become blue; with dolomite it will remain unchanged. If less calcite has been used than will replace the copper in the solution, upon adding ammonia to the filtrate the calcite solution will give no reaction, while the dolomite solution will become dark blue.

Magnesite is not affected by cold HCl; boiling HCl dissolves it with effervescence.

Siderite is soluble in HCl, and Fe is precipitated from a dilute solution, by adding ammonia.

Scapolite Group.

Isomorphous mixtures of two molecules, not known to occur pure in nature:

$\text{Al}_2(\text{Si}_3\text{O}_8)_3\text{Na}_4(\text{AlCl}) = \text{Ma} = \text{Marialite molecule.}$

$\text{Al}_6(\text{SiO}_4)_6\text{Ca}_2(\text{CaOCa}) = \text{Mc} = \text{Mcionite molecule.}$

DIPYR, A variety of mizzonite.

MIZZONITE, Me_1Ma_2 to Me_1Ma_3 .

WERNERITE, Me_3Ma_1 to Me_1Ma_2 .

MEIONITE, Me.

Optical anomalies are rare and show a separation in the interference cross of basal sections.

Occurrence and alteration.

The *scapolites* occur in crystalline limestones, often as the result of contact metamorphism in volcanic rocks, in crystalline schists, gneisses, and as an alteration product of feldspars. They alter to biotite, calcite, diaspore, epidote, gibbsite, kaolin, muscovite, quartz, and talc.

Separation.

The basic mixtures from Me to Me_2Ma_1 are decomposed by acids; Me_2Ma_1 to Me_1Ma_2 are but slightly affected, and marialite not at all.

Feldspars, cordierite, and zoisite have lower double refraction, are biaxial, and have different cleavage.

Quartz is (+), shows no cleavage, and has lower indices.

Prehnite and light-colored micas, with apparent uniaxial character, differ in cleavage.

Andalusite has lower double refraction and is biaxial.

Olivine Group.

MONTICELLITE, $MgCaSiO_4$.

FORSTERITE, Mg_2SiO_4 .

OLIVINE, $(Mg, Fe)_2SiO_4$.

FAYALITE, Fe_2SiO_4 .

Occurrence and alteration.

Monticellite occurs in the crystalline limestones. It is considered by many as isomorphous with olivine.

Forsterite rarely occurs in volcanic rocks. It is a mineral of dynamic and contact metamorphosed marbles, basic schists, and gneisses.

Olivine is usually an original mineral and occurs in the basic rocks, and as an accessory in basic schists, gneisses, and marbles. It alters to actinolite, anthophyllite, chromite, hematite, hercynite, iddingsite, limonite, magnesite, magnetite, opal, quartz, serpentine, siderite, spinel, and tremolite.

Fayalite occurs occasionally in volcanic rocks.

Separation.

Monticellite has a maximum birefringence of 0.017, while in the others it varies from 0.035 to 0.050. It is (-), while forsterite and olivine are (+). Fayalite has an index of 1.824 and a value of $2V$ about 50° , while monticellite has $n=1.660$ and $2V=37.5^\circ$.

Forsterite is (+). This separates it from all but olivine. Monticellite has lower birefringence, as given above. Occurrence is different from olivine, and it is generally colorless.

Olivine is (+). This separates it from all but forsterite,

which is a contact mineral of metamorphosed limestone. Monticellite has lower birefringence, as given above.

Fayalite is (-). This separates it from all but monticellite, which has much lower birefringence. Fayalite has $2V = 50^\circ$, while monticellite has 37.50° . Olivine has $2V = 88^\circ$, and has lower birefringence; 0.035 being the maximum, while the maximum in fayalite is 0.050.

Humite Group.

CHONDRODITE,	$Mg_3[Mg(OH,F)]_2(SiO_4)_2$.
HUMITE,	$Mg_6[Mg(OH,F)]_2(SiO_4)_3$.
CLINOHUMITE,	$Mg_7[Mg(OH,F)]_2(SiO_4)_4$.

The members of this group occur as masses in magnesian limestones and volcanic rocks bearing carbonates. Humite is orthorhombic; the other two are monoclinic with β equal to 90° , but with extinctions of 25° - 30° in chondrodite, and 7° - 15° in clinohumite. Humite may be mistaken for olivine, which it resembles in its alteration to serpentine. All of this group alter to brucite and serpentine.

Epidote Group.

ZOISITE,	$Ca_2(AlOH)Al_2(SiO_4)_3$.
PISTACITE,	$Ca_2(AlOH)(Al,Fe)_2(SiO_4)_3$.
PIEDMONTITE,	$Ca_2(AlOH)(Mn,Al)_2(SiO_4)_3$.
ORTHITE (Allanite),	$Ca_2(AlOH)(Al,Ce,Fe)_2(SiO_4)_3$.

Occurrence and alteration.

Zoisite is not known as an original constituent of igneous rocks. It occurs in schists, gneisses, and as an alteration of feldspar in the granitic rocks. It may be derived from corundum, diaspore, gibbsite, grossular, and plagioclase, and may alter to calcite, gibbsite, kaolin, and quartz.

Pistacite * (green epidote) is rarely, if ever, an original con-

* The name *Pistacite* is used in the following pages for the green epidote, and *Epidote* as the group term.

stituent of igneous rocks. It occurs secondary in metamorphosed igneous rocks and in schists, gneisses, and marbles. It is derived from anorthoclase, augite, biotite, garnet, hornblende, microcline, orthoclase, plagioclase, and scapolites; and may alter to calcite, gibbsite, kaolin, limonite, and quartz.

Piedmontite replaces epidote, where Mn is an important constituent in the rocks.

Orthite is a minor constituent of acid and intermediate eruptive and plutonic rocks; and occurs in metamorphosed schists, gneisses, and marbles.

Separation.

Zoisite has a maximum birefringence of 0.009, while the other members of the group have a maximum of 0.032. It usually has abnormal interference colors.

Piedmontite has strong characteristic pleochroism in red and violet tones.

Orthite, being brown, differs from pistacite in color, is (+), and has an extinction of $+36^\circ$, c:r, while pistacite has only $+3^\circ$.

Mica Group.

The micas may be divided into two classes:

1. The plane of the optic axes is normal to (010), and $b = c$.
 - a. ANOMITE. A magnesia-iron mica.
 - b. MUSCOVITE.
 - c. LEPIDOLITE.
 - d. PARAGONITE. The three latter are alkali micas.
2. The plane of the optic axes is parallel to (010), and $b = \bar{b}$.
 - e. BIOTITE.
 - f. PHLOGOPITE.
 - g. ZINNWALDITE. These are all magnesia-iron micas.

Separation from other minerals.

The micas can be mistaken only for other silicates showing perfect basal cleavage. The birefringence, very low in basal sections, (0.000 in phlogopite, 0.003 in muscovite, and 0.008 in

biotite) combined with the high birefringence in sections showing cleavage (0.044 in phlogopite, 0.038 in muscovite, and 0.040 in biotite), is very characteristic.

Chlorite has very low double refraction.

Brittle micas are softer, and do not spring back into their former position on bending.

Margarite has an extinction angle of $+6.5^\circ$.

Talc has a very small value for $2E$ (6° - 20°). It does not become blue with cobalt solution, nor does it give reactions for K or Na. It has orientation like the first group, $b \approx c$, which, with its lack of color, separates it from the second group. Its hardness is 1.0.

Separation of the micas.

The optical orientation separates the two groups.

Anomite is separated from *b*, *c*, and *d*, by being strongly pleochroic.

Muscovite and *paragonite* do not give Li reaction, which separates them from lepidolite. From each other they can only be separated chemically, muscovite being the K mica and paragonite the Na mica.

In the second group:

Zinnwaldite is separated by its Li reaction from all the micas but lepidolite. From this the orientation separates it.

Biotite has strong pleochroism, while in phlogopite it is weak. The value of $2E$ is always small in the latter, which is especially characteristic of the crystalline limestones and dolomites, often associated with pyroxene, amphibole, and serpentine. It has been described by Cross as occurring in madupite, orendite, and wyomingite, and by the writer, in mica peridotite.

Chlorite Group.

According to Tschermak the members of this group may be regarded as isomorphous mixtures of the amesite molecule $(H_4Mg_2Al_2SiO_9) = At$, and serpentine $(H_4Mg_3Si_2O_9) = Sp$.

PENNINE,	Sp ₂ At ₂ to SpAt.
CLINOCHLORE, (Ripidolite, Kobell).	SpAt to Sp ₂ At ₂ .
PROCHLORITE, (Chlorite, Kobell; Ripidolite, Rose).	Sp ₂ At ₂ to Sp ₂ At.
CORINDOPHILITE,	Sp ₂ At ₇ to SpAt ₄ .
AMESITE,	SpAt ₄ to At.

Occurrence and alteration.

Chlorite is very abundant as a secondary mineral, although not known as an original mineral. It occurs in altered igneous rocks, and in schists, gneisses, slates, etc.

Pennine and *clinocllore* are derived from biotite.

Prochlorite may be derived from almandine, anthophyllite, aragonite, augite, diopside, dolomite, epidote, fluorite, garnet, gypsum, haüynite, hornblende, noselite, sahlite, scapolites, tremolite, or zoisite.

Amesite may be derived from pyrope.

Separation from other minerals.

The low birefringence, peculiar interference colors, and pleochroism are characteristic of the chlorite group.

The Zeolites.

Isometric.	
ANACLITE,	NaAl(SiO ₃) ₂ + H ₂ O.
Tetragonal.	
APOPHYLLITE,	4H ₂ Ca(SiO ₃) ₂ + KFl + H ₂ O.
Hexagonal.	
HYDRONEPHELITE,	HNu ₂ Al ₃ (SiO ₄) ₂ + 3H ₂ O.
CHABAZITE,	(Ca, Na ₂)Al ₂ (SiO ₃) ₄ + 6H ₂ O.
GMELINITE,	(Na ₂₀ Ca)Al ₄ (SiO ₃) ₄ + 6H ₂ O.
Orthorhombic.	
THOMSONITE,	2(Na ₂₀ Ca)Al ₂ (SiO ₄) ₂ + 5H ₂ O.
NATROLITE,	Na ₂ Al ₂ Si ₂ O ₁₀ + 2H ₂ O.
Monoclinic.	
SOLECITE,	Ca(AlOH) ₂ (SiO ₃) ₂ + 2H ₂ O.
EPISTILBITE,	H ₄ CaAl ₆ (SiO ₃) ₂ + 3H ₂ O.
HEULANDITE,	H ₄ CaAl ₂ (SiO ₃) ₄ + 3H ₂ O.
ŠTILBITE,	(Na ₂₀ Ca)Al ₂ Si ₄ O ₁₆ + 6H ₂ O.
PHILLIPSITE,	2(K ₂₀ Ca)Al ₂ (SiO ₃) ₄ + 9H ₂ O.
HARMOTOME,	H ₂ (K ₂₀ Ba)Al ₂ (SiO ₃) ₂ + 5H ₂ O.
LAUMONTITE,	H ₄ CaAl ₂ Si ₄ O ₁₄ + 2H ₂ O.

The zeolites, with the exception of analcite, are always secondary minerals. They occur in almost every variety of eruptive rocks, especially in the more basic kinds, and also in altered sedimentary rocks. They are derived from many minerals, but especially from plagioclase, leucite, sodalite, etc., and generally occur as cavity fillings or in cracks.

Separation.

Analcite is isotropic or has weak anomalous double refraction.

Apophyllite, *hydronephelite*, *chabazite* and *gmelinite* are uniaxial. Of these *hydronephelite* contains no Ca. *Gmelinite* gelatinizes with HCl; the others are decomposed with separation of flocculent silica. *Chabazite* generally occurs in rhombohedral forms, nearly cubical, while *gmelinite* has an angle of about 68° .

Thomsonite and *natrolite* are biaxial and have parallel extinction. *Natrolite* has a birefringence of 0.012 (*Thomsonite* 0.028), $2V = 60^\circ$ - 62.5° (*Thomsonite* 87°).

The *monoclinic zeolites* are separated from the others by being biaxial and having inclined extinction. The extinction angle is above 9° in all but *heulandite*.

Heulandite, therefore, might be confused with the orthorhombic zeolites, *thomsonite* and *natrolite*. The elongation of *heulandite* is (-), of *natrolite* (+), of *thomsonite* (\pm). *Thomsonite* has $2E = 87^\circ$. (*Heulandite* = 0° - 55° .) Birefringence: *thomsonite* = 0.028, *heulandite* = 0.007, *natrolite* = 0.012. The other monoclinic zeolites are separated from *heulandite* by the larger extinction angles.

Of the remaining monoclinic zeolites, *scolecite*, *epistilbite*, *stilbite*, and *laumontite* are (-).

SCOLECITE,	$c: a = 17^\circ$,	$2E = 50^\circ$ - 60°	elongation (-).
EPISTILBITE,	$c: t = -9^\circ$,	$2E = 67^\circ$ - 83° ,	" (+).
STILBITE,	$c: a = 5^\circ$ - 8° ,	$2E = 52^\circ$,	" (-).
LAUMONTITE,	$c: t = +20^\circ$,	$2E = 54^\circ$ ca.,	" (+).

Pyroxene and Amphibole Groups.

Pyroxenes.

Orthorhombic.

ENSTATITE,	MgSiO ₃		G=3.1-3.3
BRONZITE,	(Mg,Fe)SiO ₃	Mg:Fe=8:1 to 3:1	3.2-3.3
HYPERSTHENE,	(Mg,Fe)SiO ₃	Mg:Fe=3:1 to nearly 1:1	3.4-3.5

Monoclinic.

I. With little or no aluminium.

DIOPSIDE,	CaMgSi ₂ O ₆		G=3.2-3.38
DIALLAG,	*		3.2-3.35
HEDENBERGITE,	CaFeSi ₂ O ₆		3.5-3.58

II. Aluminous.

AUGITE,	Ca(MgFe)Si ₂ O ₆ with (MgFe)(AlFe) ₂ SiO ₄		G=3.3-3.5
ÆGIRITE-AUGITE,	Augite, rich in ægirite molecule		

III. Alkali rich.

ÆGIRITE,	NaFeSi ₃ O ₆		G=3.5-3.6
ACMITE,	NaFeSi ₃ O ₆		3.5-3.6
SPODUMENE,	LiAlSi ₃ O ₆		3.1-3.2
JADEITE,	NaAlSi ₃ O ₆		3.33-3.35

IV. Containing Ca.

WOLLASTONITE,	Ca ₂ Si ₂ O ₆		G=2.8-2.9
PECTOLITE,	NaHCa ₂ Si ₃ O ₆		2.74-2.88

Separation.

Pyroxenes differ from amphiboles in having a prismatic angle of 87° (amphiboles 124°), generally less perfect cleavage, and the crystals are usually stouter. The pleochroism, also, is generally weaker, often wanting, and the extinction angle is greater.

Monoclinic pyroxenes are separated from the orthorhombic by having inclined extinction. Acmite, ægirite, and pectolite have extinction angles usually less than 5°, and may be confused with the orthorhombic pyroxenes, but basal sections show the emergence of an axis in convergent light, while the orthorhombic pyroxenes show the emergence of a positive bisectrix. Ægirite has different pleochroism, much higher double refraction, and (-) elongation, while all the orthorhombic pyroxenes have (+) elongation.

* Similar in composition to diopside, but often contains Al, sometimes in considerable amount: should then be classed with augite.

The mode of occurrence is about the same for all the orthorhombic pyroxenes.

Enstatite,	(+)	$2E = 135^\circ$.	Pleochroism: none.	Dispersion: $\rho < \nu$
Bronzite,	(+)	106°.	“ weak.	“ $\rho < \nu$
Hypersthene,	(-)	85°.	“ strong.	“ $\rho > \nu$

Bastite is (-), $2E \approx 20^\circ - 90^\circ$, pleochroism weak, dispersion $\rho > \nu$, birefringence weak. It is an alteration product of enstatite and bronzite.

Diopside,	$c: r = -39^\circ$	(+) $2V = 59^\circ$.
Diallage,	$c: r = -39^\circ$	(+) $2V = 59^\circ$ and less.
Hedenbergite	$c: r = -44^\circ$	(+) $2V = 60^\circ$.*
Augite,	$c: r = -45^\circ$ to 55°	(+) $2V = 60^\circ$.
Ægirite-augite,	$c: r > -55^\circ < -87^\circ$	(+)
Ægirite,	$c: a = -3^\circ$ to -6°	(-) $2V = 62^\circ$.
Acmite,	$c: a = -3^\circ$ to -6°	(-) †
Spodumene,	$c: r = -23^\circ$ to -26°	(+) $2V = 54^\circ - 60^\circ$.*
Jadeite,	$c: r = -33.5^\circ$	(+) $2V = 72^\circ$.
Wollastonite,	$c: a = +32^\circ$	(-) $2V = 69^\circ$ and less.*
Pectolite,	$c: a = -5^\circ$	(+) $2V = 60^\circ$. ‡

* Birefringence is 0.015 to 0.019.

† “ “ 0.050.

‡ “ “ 0.038.

Others have birefringence from 0.015 to 0.029.

Pleochroism: Weak or wanting in all but ægirite-augite, ægirite, and acmite.

Augite is sometimes quite strongly pleochroic in purple tones.

Ægirite and acmite have different color and pleochroism.

As seen above the chief mode of separating the monoclinic pyroxenes optically is by means of the extinction angles, which are characteristic as shown in Fig. 77.

Occurrence.

Diopside occurs in marbles, especially in those that are magnesium rich, in the crystalline schists, pyroxene granites, diorites, and lamprophyres.

Diallage occurs in gabbros and related rocks, and in peridotites and the serpentines derived from them.

Hedenbergite is rather common in some nephelite-syenites and in other basic syenites.

Augite is the most common of the pyroxenes in the igneous rocks. It also occurs in metamorphosed sedimentary and igneous rocks.

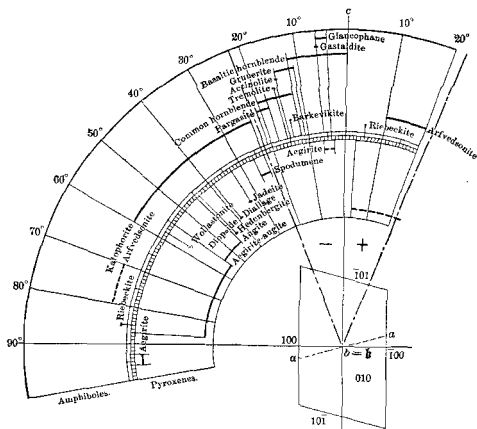


FIG. 77.—Maximum extinction angles in the Pyroxene and Amphibole groups. Solid lines indicate extinction angles from *c* to *t*; broken lines from *c* to *a*. The extinction angle in an amphibole is generally less than 23°; in a pyroxene it is generally greater.

Ægirite, *ægirite-augite*, and *acmite* occur in eruptive rocks that are rich in sodium, especially in the nephelite-syenites, phonolites, leucitophyres, and in some granites and syenites.

Spodumene occurs in pegmatitic masses in granites, gneisses, and schists; sometimes as an accessory constituent in normal granite and gneiss.

Jadeite is not a common mineral. It occurs in metamorphosed hornblende schists and metamorphosed limestones.

Wollastonite occurs as a contact mineral in crystalline limestones, as a metamorphic mineral in calcareous rocks,—marbles, schists, gneisses,—and in calcareous inclusions in eruptive rocks.

Pectolite occurs in cracks and druses within many basic eruptive rocks.

Amphiboles.

Orthorhombic.

ANTHOPHYLLITE,	$(Mg, Fe)SiO_3$	G = 3.1-3.2
GEDRITE,	$(Mg, Fe)_2Si_2O_6 \cdot MgAl_2SiO_6$	3.1-3.2

Monoclinic.

I. Containing little or no aluminium.

TREMOLITE,	$CaMg_7Si_8O_{22}$	G = 2.9-3.1
ACTINOLITE,	$Ca(Mg, Fe)_7Si_8O_{22}$	3.0-3.2
GRÜNERITE,	$FeSiO_3$	3.713

II. Aluminous.

COMMON HORNBLLENDE,	$Ca(Mg, Fe)_7Si_8O_{22}$ with $(Mg, Fe)_3(Al, Fe)_2Si_4O_{12}$ and $Na_2Al_2Si_2O_{12}$	G = 3.05-3.47
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PARGASITE.

KATOPHOBITE, No analyses.

BASALTIC HORNBLLENDE, Rich in iron and alkali molecules.

BARKEVIRITE.

III. Alkali rich.

a. Iron poor, light-blue color.

GLAUCOPHANE,	$Na_3AlSi_3O_{10} \cdot (Fe, Mg)SiO_3$	G = 3.103-3.113
GASTALDITE,	Contains more Al and less Fe.	

b. Iron rich, dark blue in color.

RJEBECKITE,	$Na_2Fe_2Si_4O_{12} \cdot FeSiO_3$	G = 3.3
ARFVEDSONITE,	$(Na_2CaFe)_4Si_4O_{12} \cdot (CaMg)_2(AlFe)_2Si_2O_{12}$	3.44-3.45

Separation.

Amphiboles differ from pyroxenes in having a prismatic angle of 124° (pyroxenes 87°), generally more perfect cleavage, and the crystals are usually longer, thinner, and sometimes fibrous. The pleochroism is generally stronger and the extinction angle smaller.

The orthorhombic amphiboles are separated from the monoclinic by having parallel extinction; from other minerals all

the amphiboles are separated by their prismatic cleavage of 124° .

The orthorhombic amphiboles occur in metamorphic schists and gneisses, and as contact minerals. Anthophyllite often occurs as an alteration product of olivine in serpentines and in rocks of the gabbro and peridotite families. It has been described as an original mineral in a mica-peridotite dike from the East Indies.

Anthophyllite,	(\pm)	$2V \geq 90^\circ$,	Dispersion $\rho \geq \nu$.
Gedrite,	(-)	$2V = 57^\circ - 79^\circ$,	Dispersion $\rho > \nu$.
	Extinction Angle.	Optical Char.	Axial Angle.
Tremolite,	$c:t = -16^\circ$	(-)	$2V = 87.5^\circ$.
Actinolite,	$c:t = -15^\circ$	(-)	$2V = 80^\circ$.
Grünerite,	$c:t = -11^\circ$ to -15°	(-)	$2V = \text{large}$.
Common hbl.,	$c:t = -12^\circ$ to -20°	(\mp)	$2V = 54^\circ$ to 84° .
Pargasite,	$c:t = -18^\circ$ to -21°	(+)	$2V = 52^\circ$ to 60° .
Katophorite,	$c:t = -23^\circ$ to -60°	(+)	$2V = \text{small}$.
Basaltic hbl.,	$c:t = 0^\circ$ to -12°	(-)	$2V = 80^\circ$.
Barkevikite,	$c:t = -14^\circ$	(-)	$2V = 54^\circ$.
Glaucophane,	$c:t = -4^\circ$ to -6°	(-)	$2E = 85.5^\circ$.
Gastaldite,	$c:t = -6^\circ$	(-)	$2E = 70^\circ$.
Riebeckite,	$c:t = -85^\circ$	(\pm)	$2V = \text{unknown}$.
Arfvedsonite,	$c:t = +10^\circ$ to $+20^\circ$	(\mp)	$2V = \text{large}$.
			Pleochroism.
			Non-pleochroic.
			Faint, in green tones.
			Colorless; light brown.
			Strong; green and yellow tones.
			Green and yellow tones.
			Red and yellow tones.
			Strong, green and brown tones.
			Brown tones.
			Colorless, yellowish green, blue.
			Ditto.
			Deep blue, light blue, yellowish green.
			Blue to greenish.

Riebeckite, arfvedsonite, and crossite have very low birefringence. This is high in basaltic hornblende and barkevikite, and between 0.016 and 0.026 in the others. Amphiboles are

determined chiefly by means of the extinction angles and pleochroism, which is colorless to greenish in the first three, in green and brown tones in the next five, and in tones of blue in the last four.

Occurrence.

Tremolite, *actinolite*, and *grünerite* occur in schists metamorphosed from carbonate rocks, especially those rich in magnesium and iron. In those in which the iron is not abundant, tremolite forms; where there is much ferrous iron, actinolite; and where iron is the chief or only carbonate, grünerite.

The *hornblendes*—*common*, *basaltic*, and *pargasite*—are very common in igneous rocks, metamorphic schists, and gneisses.

Katophorite occurs in a tinguaita dike in Norway.

Glaucophane occurs in schists, especially those derived from basic rocks which formerly contained much sodium.

Riebeckite occurs in igneous rocks rich in iron and sodium, as alkali granites, and in metamorphosed sedimentary and eruptive rocks.

Arfvedsonite occurs in soda-bearing igneous rocks, as nephelite-syenites, phonolites, tinguaites, and pantellerites.

THE DETERMINATION OF THE FELDSPARS.

Since the classification of a rock often depends upon the character of the feldspar occurring in it, its accurate determination is one of the problems of the petrographer. In the following pages are given the most common and the most helpful methods employed.

In all the members of the feldspar group the general characteristics are closely related. They are usually colorless, belong to the monoclinic or triclinic systems (although with close resemblance in angles, twinning, etc.), have a cleavage of 90° or nearly 90°, a hardness of between 6.0 and 6.5, and a specific gravity of from 3.84 in celsian, through 2.55 in orthoclase, to 2.76 in anorthite.

They may be classified as follows:

Monoclinic.	{	CELSIAN,	$BaAl_2Si_2O_8$	or	$BaO \cdot Al_2O_3 \cdot 2SiO_2$
		HYALOPHANE,	$(Ba_nK_n)Al_2Si_2O_{12}$		
		ORTHOCLASE,	$KAlSi_3O_8$	or	$K_2O \cdot Al_2O_3 \cdot 6SiO_2$
		SODA-ORTHOCLASE,	$(K_nNa_n)AlSi_3O_8$		
Triclinic.	{	MICROCLINE,	$KAlSi_3O_8$	or	$K_2O \cdot Al_2O_3 \cdot 6SiO_2$
		ANORTHOCLASE,	$(Na_nK_n)AlSi_3O_8$		
		ALBITE,	$NaAlSi_3O_8$	or	$Na_2O \cdot Al_2O_3 \cdot 6SiO_2$
		OLIGOCLASE,			
		ALBITE,			
		LABRADORITE,			
		BYTOWNITE,			
ANORTHITE,	$CaAl_2Si_2O_8$	or	$CaO \cdot Al_2O_3 \cdot 2SiO_2$		

Cleavage.

All of the feldspars have a good cleavage parallel to (001) and another, nearly as good, parallel to (010). The angle between these cleavage lines varies slightly in the different feldspars.

Celsian,	$001 \wedge 010 = 90^\circ$	$\beta = 64^\circ 58'$	$= 001 \wedge 100$
Hyalophane,	$001 \wedge 010 = 90^\circ$ for Ca, Or_2	$\beta = 64^\circ 16'$	$= 001 \wedge 100$
Orthoclase,	$001 \wedge 010 = 90^\circ$	$\beta = 63^\circ 56' 46''$	$= 001 \wedge 100$
Microcline,	$001 \wedge 010 = 89^\circ 30'$, circa.	$\beta = 116^\circ$	$= 001 \wedge 100$
Anorthoclase,	$001 \wedge 010 = 90^\circ 6' - 90^\circ 33'$	$\beta = 116^\circ 30'$	$= 001 \wedge 100$
Albite,	$001 \wedge 010 = 86^\circ 24'$	$\beta = 116^\circ 29'$	$= 001 \wedge 100$
Oligoclase,	$001 \wedge 010 = 86^\circ 32'$	$\beta = 116^\circ 22.5'$	$= 001 \wedge 100$
Andesine,	$001 \wedge 010 = 86^\circ 14'$	$\beta = 116^\circ 28.5'$	$= 001 \wedge 100$
Labradorite,	$001 \wedge 010 = 86^\circ 12'$	$\beta = 116^\circ 3'$	$= 001 \wedge 100$
Anorthite,	$001 \wedge 010 = 85^\circ 50'$	$\beta = 115^\circ 55.5'$	$= 001 \wedge 100$

As shown above, the angle between the crystallographic axes a and c varies between 64° and 65° in the monoclinic feldspars; and in the triclinic it remains within $30'$ of 116° ; in either case the actual acute angle is not far from 64° .

Chemical Composition.

Chemically the feldspars are silicates of aluminium with either potassium, sodium, calcium, or barium, or mixtures of these, and with iron and magnesium present in small amounts.

According to the law of Tschermak, the plagioclase feldspars are isomorphous mixtures of pure albite and anorthite mole-

cules. In a similar manner, according to Strandmark, the barium feldspars are isomorphous mixtures of pure celsian and orthoclase molecules.

The pure molecules are

Celsian,	$\text{BaAl}_2\text{Si}_2\text{O}_8 = \text{Ce}$.
Orthoclase,	$\text{KAlSi}_3\text{O}_8 = \text{Or}$.
Albite,	$\text{NaAlSi}_3\text{O}_8 = \text{Ab}$.
Anorthite,	$\text{CaAl}_2\text{Si}_2\text{O}_8 = \text{An}$.

Grouping the feldspars—

(After Strandmark.)

Celsian,	Ce_1Or_0 to Ce_0Or_2	contains from 16.5% to 39.5% BaO.
Hyalophane,	Ce_1Or_2 to Ce_0Or_2	“ “ 16.4% to 7.5% BaO.
Orthoclase,		“ “ 16.9% K_2O .
Anorthoclase,	Or_2Ab_3 to Or_1Ab_6	“ “ 7.1% to 10.1% Na_2O .

(After Tschermak.)

Albite series,	Ab_1An_4 to Ab_6An_1	contains from 11.79% to 10.27% Na_2O
Oligoclase series,	Ab_2An_3 to Ab_5An_2	“ “ 10.01% to 7.63% Na_2O
Andesine series,	Ab_3An_2 to Ab_4An_1	“ “ 6.91% to 6.56% Na_2O
Labradorite series,	Ab_1An_5 to Ab_2An_4	“ “ 5.73% to 3.77% Na_2O
Bytownite series,	Ab_1An_5 to Ab_2An_4	“ “ 2.82% to 1.55% Na_2O
Anorthite series,	Ab_1An_6 to Ab_6An_1	“ “ 1.55% to 0.0% Na_2O

Celsian.

Chemically varies from Ce_1Or_0 to Ce_0Or_2 . $G=3.84$.

Monoclinic. (+). Cleavage: (001), (010), good.

Occurs in plates, prisms, and grains.

Orientation: $b = \mathbf{b}$, $a : \mathbf{a} = -62^\circ$.

Colorless, non-pleochroic.

$\alpha = 1.584$, $\beta = 1.589$, $\gamma = 1.594$.

$\gamma - \alpha = 0.010$, $\gamma - \beta = 0.005$, $\beta - \alpha = 0.005$.

Carlsbad and Bavono twins occur.

$2V$ increases with the increase in Ce; above 90° of Ce the optical character is positive, and the axial angle in pure celsian is 94° .

Soluble in HCl with gelatinization.

Hyalophane.

Chemically varies from Ce_1Or_2 to Ce_1Or_6 .

Monoclinic. (-). Cleavage: (001), (010), good.

Occurs in tablets, prisms, and grains.

Orientation: $b = c$, $a : a = -G^\circ$.

Colorless, non-pleochroic.

$\alpha = 1.537$, $\beta = 1.540$, $\gamma = 1.542$.

$\gamma - \alpha = 0.005$, $\gamma - \beta = 0.002$, $\beta - \alpha = 0.003$.

Celsian and hyalophane show neither microcline structure nor polysynthetic twinning. They are, consequently, only likely to be confused with orthoclase and anorthoclase. From these they may be distinguished by the higher indices, larger extinction angles, higher specific gravities, and the chemical reactions of the barium feldspars. The different members of the barium feldspar series may be separated by their different specific gravities and their extinction angles on 010. (See Fig. 88.)

Orthoclase.

Chemically, $KAlSi_3O_8$. $H = 6$, $G = 2.54$.

Monoclinic. (-). Cleavage: (001), (010), good.

Occurs in plates, prisms, and grains.

Orientation: $b = c$, $a : a = \pm 5^\circ$. Extinction on (001) from (010) cleavage = 0° , on (010) from (001) cleavage = $\pm 5^\circ$.

Colorless, non-pleochroic.

$\alpha = 1.519$, $\beta = 1.523$, $\gamma = 1.525$.

$\gamma - \alpha = 0.006$, $\gamma - \beta = 0.002$, $\beta - \alpha = 0.003$.

Dispersion: $\rho > \nu$, very plain.

$2V = 70^\circ - 80^\circ$, $2E_{aa} = 120^\circ$ ca.

Twinning. *Carlsbad law.* The most common form of twinning is according to the Carlsbad law, in which the vertical axis is the twinning axis and the composition plane is a plane parallel to the c axis, usually (010). The twins are turned 180° with respect to each other (Fig. 86). In the (001): (100) zone the

extinction is parallel to the (010) cleavage and to the twinning line. When the twinning line shows on the (010) face, it makes an angle of $63^{\circ} 57'$ (β) with the (001) cleavage and of $\pm 21^{\circ}$ with the extinction of each individual. ($c:b = 19^{\circ} - 23^{\circ}$, Fig 85.) In this zone, as the sections depart from (010) and approach (100), the angle of the cleavage with the twinning line naturally increases

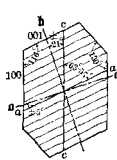


FIG. 78.

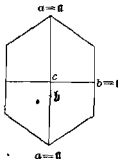


FIG. 79.

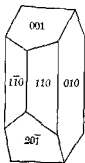


FIG. 80.

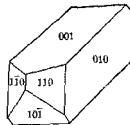


FIG. 81.

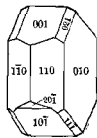


FIG. 82.

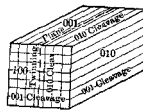


FIG. 83.

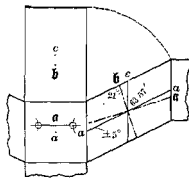


FIG. 84.

FIG. 78.—The (010) plane of an orthoclase crystal.

FIG. 79.—The (001) plane of an orthoclase crystal.

FIGS. 80-82.—Simple orthoclase crystals.

FIG. 83.—Simple orthoclase crystal showing cleavage lines and the position of the twinning plane in a Carlsbad twin.

FIG. 84.—A simple orthoclase crystal opened out to show the optical orientation.

from $63^{\circ} 57'$ to 90° . The extinction angle also changes from 21° to 90° , the increase being slight at first, but, as the section approaches the (100) face, the change of extinction angle becomes very rapid. In any section in this zone the twinning line bisects the extinction angle and the cleavage.

The (001):(010) zone of one individual of a Carlsbad twin almost coincides with the $(\bar{1}01):(010)$ of the other (Fig. 86). In all sections in this zone the cleavage cracks of one individual are parallel to the twinning line, and the extinction angle from this line varies from 0° on (001) to 3° to 7° (12° in soda-orthoclase) on (010). In the other individual the cleavage lines are at right angles to each other, and the extinction is parallel to them and to the twinning line. As the section approaches the (010) face, the extinction angle increases until it reaches $\pm 48^\circ$ on (010).

Baveno law. In Baveno twins the twinning axis is the line normal to (021), which is the composition plane (Fig. 87). In sections at right angles to this plane the twinning line is diagonal

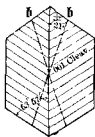


FIG. 85.

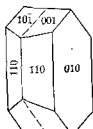


FIG. 86.

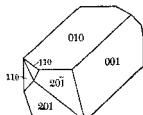


FIG. 87.

FIG. 85.—Extinction angle on the (010) face of a Carlsbad twin of orthoclase.

FIG. 86.—A Carlsbad twin of orthoclase.

FIG. 87.—A Baveno twin of orthoclase.

to the cleavage. The two parts extinguish at the same time and parallel to the cleavage, but the direction of \mathbf{a} in one individual is at right angles to \mathbf{a} in the other, and the interference figures lie at right angles to each other. In sections in the (001):(010) zone the cleavages of the two individuals are parallel to each other and to the twinning line. As the extinction angle in one increases from 0° to 7° , it decreases in the other in the same proportion.

Manebacher law. Manebacher twinning is comparatively rare. The (001) plane is the composition plane and the twinning axis is a line at right angles to it.

The low indices and low double refraction separate orthoclase and sanidine from the barium and plagioclase feldspars. As seen in Fig. 88, the indices of refraction are lower than

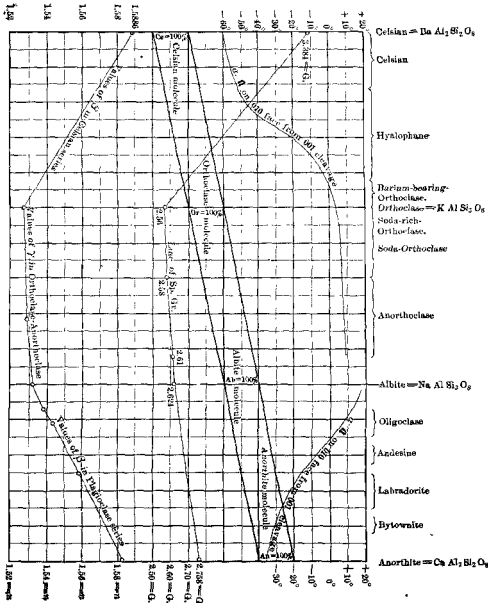


FIG. 88.—Diagram showing the comparative indices of refraction, specific gravities, chemical relations, and extinction angles on (001) faces of the feldspars from celsian to anorthite.

in any of the other feldspars, although anorthoclase, albite, and oligoclase-albite have indices lower than Canada balsam. From these they may be separated by the extinction

on (010) (see Fig. 95), upon which face it is lower than in orthoclase only in other feldspars with an index greater than Canada balsam. The polysynthetic twinning of the plagioclase feldspars usually distinguishes them, while in the barium feldspars, which are simply twinned like orthoclase, the values of the indices of refraction, double refraction, and specific gravity are entirely different.

Sanidine.

Chemically, crystal habit, indices and double refraction like orthoclase.

Like orthoclase its optical character is (-).

Orientation: Like orthoclase or sometimes $b = \mathfrak{b}$, $a : \mathfrak{a} = +5^\circ$ ca.

Dispersion for $b = \mathfrak{r}$, $\rho > \nu$; for $b = \mathfrak{b}$, $\rho < \nu$.

$2V$ much smaller than orthoclase. It varies from very small to 0° .

Carlsbad twinning frequent.

Distinguished from orthoclase by the orientation and the size of the optic angle; from the other feldspars in a manner similar to orthoclase.

Microcline.

Chemically, KAlSi_3O_8 , $H = 6.0$, $G = 2.54$.

Triclinic. (-). Cleavage: (001), (010), good.

Occurs in plates, prisms, and grains.

Orientation: Extinction on (010) = $+5^\circ$, on (001) = $+16^\circ$.

Colorless, non-pleochroic.

$\alpha = 1.519$, $\beta = 1.523$, $\gamma = 1.526$.

$\gamma - \alpha = 0.007$, $\gamma - \beta = 0.003$, $\beta - \alpha = 0.004$.

Dispersion: $\rho > \nu$, $2V = 71^\circ - 84^\circ$.

Polysynthetic twinning, albite and pericline, almost invariably occurs.

Twinning according to the pericline law. In this the twinning axis is parallel to b , and the composition plane is parallel to the rhombic section. When the twinning is polysynthetic, the striations appear on the (010) face.

Separated from orthoclase, with which it may be confused when untwinned, by its extinction on (001) and (010); generally by its polysynthetic twinning with "grating" structure. The indices of refraction are lower than in the plagioclase and barium feldspars. From anorthoclase it is separated by the extinction angles on (001) and (010) and by the larger axial angle of microcline.

Anorthoclase.

Chemically, Or_2Ab_3 to Or_1Ab_6 , $H=6.0$, $G=2.56-2.61$.

Triclinic. (-). Cleavage: (001), (010), good; $\Delta \pm 89^\circ$.

Occurs in plates, prisms, and grains.

Orientation: Extinction on (010) = $+4^\circ$ to $+10^\circ$; on (001) = $+1^\circ$ to $+4^\circ$.

Colorless, non-pleochroic.

$\alpha=1.523$, $\beta=1.528$, $\gamma=1.529$.

$\gamma-\alpha=0.006$, $\gamma-\beta=0.001$, $\beta-\alpha=0.005$.

Dispersion: $\rho > \sigma$, $2V=43^\circ-53^\circ$.

Sometimes has polysynthetic twinning, according to the albite and pericline laws, like microcline.

Separated from microcline by the extinction angles on (001) and (010) and by the smaller axial angle of anorthoclase.

Orthoclase has a larger axial angle.

The plagioclase feldspars have higher indices of refraction higher double refraction, and higher specific gravities.

The Plagioclase Feldspars.

The special characteristics of the different members of the plagioclase group are given in the following pages, and no general descriptions of the individual members are necessary here. For their separation from the preceding feldspars, the distinguishing marks have already been given under those feldspars. Further than that, Fig. 88 graphically shows the relationships.

Twinning. *Albite law.* This is the most common form of twinning in the plagioclase feldspars. The twinning axis is nor-

mal to (010), and the lamellæ are consequently parallel to this plane. The twinning is usually polysynthetic, and the striations show on the (001) and the (100) faces. Very often this twinning

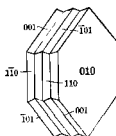


FIG. 89.—Albite and Carlsbad twinning combined.

is combined with the Carlsbad law, as in Fig. 89. When combined with the pericline law, the albite twinning may be recognized upon the (001) face, by the fact that the elongation of the twinning lamellæ lies in the direction of the axis of greatest ease of vibration (σ); while in pericline twinning this length is in the direction of the (τ) axis.

The determination of the plagioclase feldspars. The following are the most important methods used for the determination of the different members of the plagioclase group:

1. By specific gravities.
2. By the optical character of the mineral.
3. By the relative indices of refraction of the feldspar and some known mineral with which it is in contact. (Becke.)
4. By the index of refraction, according to Schroeder van der Kolk's embedding method.
5. By the extinction angle on cleavage flakes parallel to (001). (Schuster.)
6. By the extinction angle on cleavage flakes parallel to (010). (Schuster.)
7. By the position of emergence of the bisectrix in (010) plates.
8. By the extinction angle in Carlsbad twins upon the (010) face. (Michel-Lévy.)
9. By the extinction angle on sections at right angles to both (001) and (010). (Becker and Becke.)
10. By the extinction angle on sections at right angles to either bisectrix. (Fouqué.)
11. By the extinction angle on sections at right angles to the optic normal (\mathfrak{b}). (Fedorow.)

12. By the extinction angle on sections from the (001), (010) zone.
13. By the extinction angles on sections from the zone at right angles to (010). (Michel-Lévy.)
14. By the extinction angles on sections from the zone at right angles to (010), when the albite twinning is combined with Carlsbad twinning. (Michel-Lévy.)

1. *By specific gravities.* The specific gravity of minerals is an important constant in their determination, and is applicable to the separation of the feldspars. (Fig. 88.) For the purpose of determination, small fragments of the mineral should be separated under the microscope from the rock powder. Cleavage flakes can very often be obtained from the granular rocks or from the phenocrysts of effusive rocks. The value of the specific gravity is constant so long as the material used is pure and unaltered. Glassy inclusions or alterations to kaolin and zeolites reduce the value, while the inclusion of other minerals or the alteration to carbonates, mica, or saussurite increases it.

The following values are after Tschermak:

Orthoclase and microcline, sp. gr.	2.54-2.57
Anorthoclase series,	2.58-2.61
Albite series,	2.62-2.64
Oligoclase series,	2.64-2.66
Andesine series,	2.66-2.69
Labradorite series,	2.69-2.71
Bytownite series,	2.71-2.74
Anorthite series,	2.74-2.76

Day gives the following for artificial plagioclase feldspars:

Albite, Ab	2.605
Ab ₃ An ₁	2.649
Ab ₂ An ₁	2.660
Ab ₁ An ₁	2.679
Ab ₁ An ₂	2.710
Ab ₁ An ₅	2.733
Anorthite, An	2.765

2. *By the optical character of the mineral.* The optical character alone does not determine the kind of feldspar, but is of value when taken in connection with the index of refraction, birefringence, and other characteristics. According to the optical character, as determined in convergent polarized light the two groups are as follows:

<i>Negative (-) character.</i>	<i>Positive (+) character.</i>
Hyalophane.	Celsian.
Orthoclase.	Albite.
Sanidine.	Oligoclase-albite.
Microcline.	Andesine.
Anorthoclase.	Labradorite.
Oligoclase.	
Bytownite.	
Anorthite.	

The values of $2V$ and the optical characters are shown in Fig. 90.

3. *By the relative indices of refraction of the feldspar and some known mineral with which it is in contact.* (Becke method)

When the feldspar to be determined lies in contact with a known mineral, as quartz or nephelite, or even in contact with Canada balsam, its relative index may be found by the movement of the Becke line. (See Part I, pp. 14, 15.)

Mean values of the indices are as follows:

Celsian,	$\alpha = 1.584$	$\beta = 1.589$	$\gamma = 1.594$
Hyalophane,	1.542	1.545	1.547
Orthoclase,	1.519	1.523	1.526
Sanidine,	1.521	1.525	1.525
Anorthoclase,	1.523	1.528	1.529
Albite,	1.529	1.532	1.539
Oligoclase-albite,	1.534	1.538	1.543
Oligoclase,	1.540	1.544	1.547
Andesine,	1.549	1.553	1.555
Labradorite,	1.555	1.558	1.563
Bytownite,	1.561	1.564	1.569
Anorthite,	1.575	1.583	1.588
Quartz,	$\omega = 1.544$		$\epsilon = 1.553$
Nephelite,	1.542		1.537

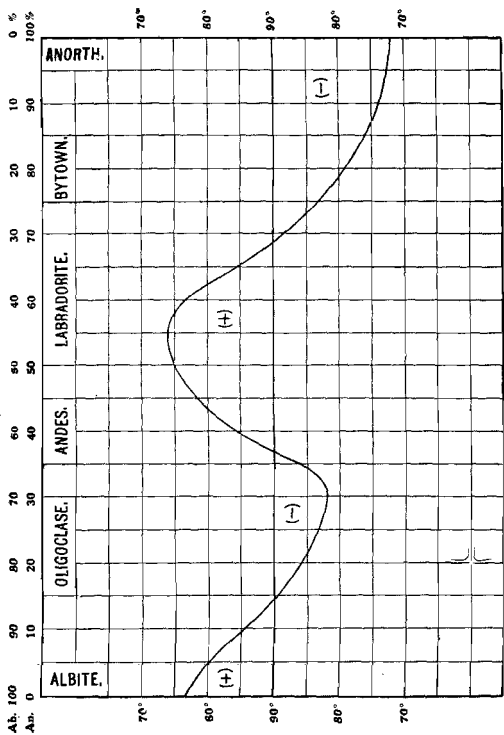


Fig. 90.—Curve showing the values of $2V$ and the optical characters of the lime-soda feldspars.

Canada balsam. $n = 1.542 +$ to $1.55 -$, depending upon the degree of heating which the balsam has undergone. It rarely rises higher than 1.545.

Select a place in the section where the extinction of the feldspar is parallel to that of the mineral with which it is in contact; its direction of greater ease of vibration will be parallel or at right angles to that of the other mineral. By the position of the Becke line the feldspars are thus divided into six groups, which are given by Rosenbusch as follows:

(Quartz: $\omega = 1.544$, $\epsilon = 1.553$.)

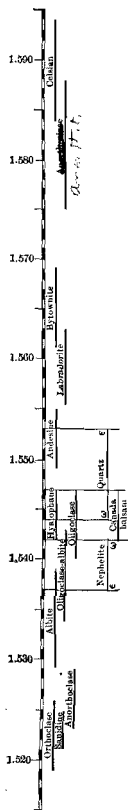
Group.	Parallel Position.		Crossed Position.		Feldspars.	
I.	$\omega > \alpha$	$\epsilon > \gamma$	$\omega > \gamma$	$\epsilon > \alpha$	Albite,	Ab- An ₃ An ₁
II.	$\omega > \alpha$	$\epsilon > \gamma$	$\omega \approx \gamma$	$\epsilon > \alpha$	Oligoclase,	{ Ab ₂ An ₁ -Ab ₃ An ₁ Ab ₁ An ₁ -Ab ₂ An ₁
III.	$\omega < \alpha$	$\epsilon > \gamma$	$\omega < \gamma$	$\epsilon > \alpha$		
IV.	$\omega < \alpha$	$\epsilon \approx \gamma$	$\omega < \gamma$	$\epsilon > \alpha$	Andesine,	{ Ab ₂ An ₂ -Ab ₂ An ₂ Ab ₁ An ₂ -Ab ₁ An ₁
V.	$\omega < \alpha$	$\epsilon < \gamma$	$\omega < \gamma$	$\epsilon \approx \alpha$		
VI.	$\omega < \alpha$	$\epsilon < \gamma$	$\omega < \gamma$	$\epsilon < \alpha$	Labradorite,	Ab ₁ An ₁ -An
					Bytownite,	
Anorthite.						

With the feldspars in any orientation adjacent to a basal section of quartz, or to a section parallel to c , which is that showing the brightest interference colors, the feldspars fall into two groups, according to whether the index is greater or less than 1.544 or 1.553.

After having separated the feldspars thus, they may be redivided by the optical character as in the preceding section.

Index $< \omega$ ($= 1.544$) of quartz.		Index $> \omega$ ($= 1.544$) of quartz.	
(+)	(-)	(+)	(-)
Albite.			
Oligoclase-albite.			
		< Oligoclase (-) >	
			Andesine.
			Labradorite.
			Bytownite.
			Anorthite.

FIG. 91.—Comparative mean indices of refraction of the feldspars, quartz, nephelite, and Canada balsam



Index $< \epsilon$ (≈ 1.553) of quartz. (+)	(-)	Index $> \epsilon$ (≈ 1.553) of quartz. (+)	(-)
Albite.			
Oligoclase-albite.			
	Oligoclase.		
	< Andesine (+) >		
		Labradorite.	
			Bytownite.
			Anorthite.

Where nephelite occurs in the rocks instead of quartz, that mineral may be used in a similar manner. Potassium feldspars and anorthoclase have all their indices lower than ϵ of nephelite.

(Nephelite: $\omega = 1.542$, $\epsilon = 1.537$.)

	In Parallel Position.	In Crossed Position.
Albite,	$\omega > \gamma$	$\epsilon > \alpha$
Oligoclase-albite,	$\omega > \gamma$	$\epsilon > \alpha$
Oligoclase,	$\omega > \gamma$	$\omega > \alpha$
Andesine,	} $\omega < \gamma$ }	} $\epsilon < \alpha$ }
Labradorite,		
Bytownite,		
Anorthite,		

With **Canada balsam** as a dividing line we have:

Albite is always less than Canada balsam.

Oligoclase-albite is usually less.

Oligoclase is the same.

Andesine, labradorite, etc., are always higher.

4. *By the index of refraction, according to Schroeder van der Kolk's embedding method.* This method was explained in Part I, pp. 15-18. Michel-Lévy, in his work on the feldspars,* applied this method to their determination, but since some of Schroeder's fluids acted upon the minerals, he substituted Klein's solution diluted to different indices. He determined the index of refraction of the diluted solution by employing a series of sixteen minerals, of known indices, as indicators.

Instead of Klein's solution, mixtures of oils of different refractive indices, or of oil and benzene may be used. The latter has this disadvantage: the benzene evaporates rapidly, and the

* Étude sur la détermination des feldspaths, etc., 1894, pp. 58-63.

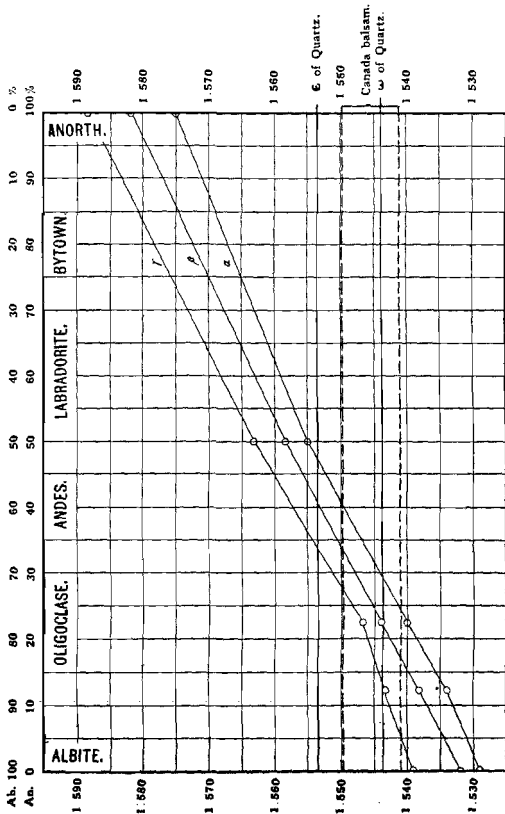


FIG. 92.—Curve showing the indices of refraction of the lime-soda feldspars. (Modified from Rosenbusch.)

index of the immersion fluid consequently rises. If one works rapidly and employs two indicators, one higher and one lower than the supposed index of the feldspar, by the changing of the index of the immersion fluid from low to high, the one fluid suffices for the determination. Wright* has recently used mixtures of cedar and clove oils and clove and cinnamon oils.

A list of refractive indices of fluids is given in Part I, pp. 16-17, and the comparative indices of the feldspars in Fig. 92.

5.-6. *By the extinction angle on cleavage flakes parallel to (001) and (010).* All extinction angles in the feldspars are measured from the *a* axis. Max Schuster† first made the observation that the extinction angles of the feldspars are fixed within certain limits, and that these extinction angles correspond to definite chemical combinations. With a plagioclase crystal orientated as in Fig. 93, Schuster considered extinctions

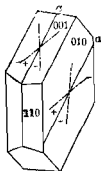


FIG. 93.

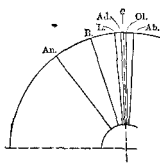


FIG. 94.

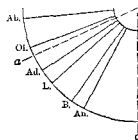


FIG. 95.

Fig. 93.—Positive and negative extinction angles in the feldspars.
 Fig. 94.—Extinction angles on the (001) faces of the lime-soda feldspars.
 Fig. 95.—Extinction angles on the (010) faces of the lime-soda feldspars.

on either face, when measured in the direction of the movement of the hands of a watch from the traces of the (010) and the (001) cleavage, as positive (+), and negative, when in the opposite direction. Schuster's values were:

* American Journal of Science, Vol. XXI, 1906, pp. 361-363.

† Über die optische Orientierung der Plagioklase, Tschermak's Mineralogische und petrographische Mitteilungen, 3, 1880, p. 117.

	Ex. on (001)	Ex. on (010)
Albite, pure,	+4° to +5°	+19°
Oligoclase, Ab ₃ An ₁	+1° 4'	+4° 36'
Andesine, Ab ₃ An ₂	-2° 12'	-7° 58'
Labradorite, Ab ₁ An ₁	-5° 10'	-16°
Bytownite, Ab ₁ An ₃	-17° 40'	-29° 28'
Anorthite,	-37°	-36°

As modified by Mallard's formula and computed for percentages of albite and anorthite,* they are:

	Ex. on (001)	Ex. on (010)	
Ab.	+ 4° 30'	+ 19°	} Albite and oligo- clase-albite
Ab ₉₅ , An ₅	+ 3° 57'	+ 16° 53'	
Ab ₉₀ , An ₁₀	+ 3° 21'	+ 14° 25'	} Oligoclase
Ab ₈₅ , An ₁₅	+ 2° 40'	+ 11° 33'	
Ab ₈₀ , An ₂₀	+ 1° 55'	+ 8° 17'	} Andesine
Ab ₇₅ , An ₂₅	+ 1° 04'	+ 4° 36'	
Ab ₇₀ , An ₃₀	+ 0° 07'	+ 0° 36'	} Labradorite
Ab ₆₅ , An ₃₅	- 0° 57'	- 3° 41'	
Ab ₆₀ , An ₄₀	- 2° 22'	- 7° 58'	} Bytownite
Ab ₅₅ , An ₄₅	- 3° 34'	- 12° 08'	
Ab ₅₀ , An ₅₀	- 5° 10'	- 16° 00'	} Bytownite-anor- thite and anor- thite
Ab ₄₅ , An ₅₅	- 7° 01'	- 19° 29'	
Ab ₄₀ , An ₆₀	- 9° 08'	- 22° 32'	} Bytownite
Ab ₃₅ , An ₆₅	- 11° 35'	- 25° 12'	
Ab ₃₀ , An ₇₀	- 14° 22'	- 27° 29'	} Bytownite-anor- thite and anor- thite
Ab ₂₅ , An ₇₅	- 17° 54'	- 29° 28'	
Ab ₂₀ , An ₈₀	- 21° 05'	- 31° 10'	} Bytownite-anor- thite and anor- thite
Ab ₁₅ , An ₈₅	- 24° 56'	- 32° 38'	
Ab ₁₀ , An ₉₀	- 28° 58'	- 33° 54'	} Bytownite-anor- thite and anor- thite
Ab ₅ , An ₉₅	- 33° 03'	- 35° 01'	
An.	- 37°	- 36°	

* Tschermak's Mineralogische und petrographische Mittheilungen, 5, 1882.

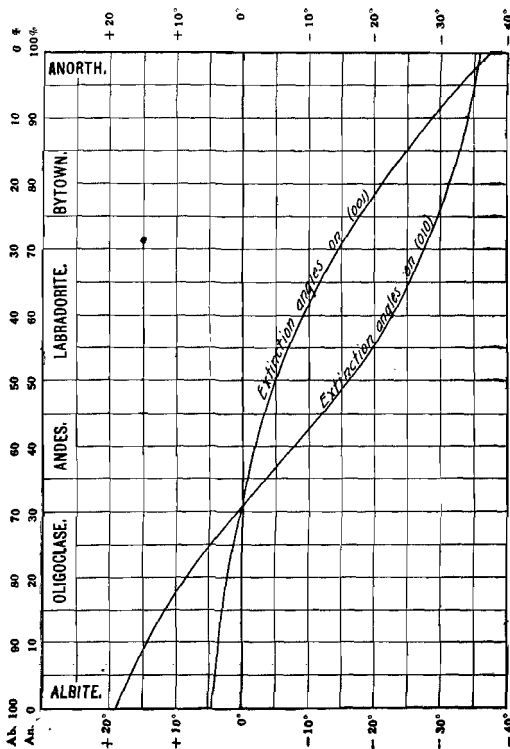


FIG. 96.—Extinction angles on the (010) and (001) faces of the lime-soda feldspars. (From the diagram constructed by Rosenbusch after the values of Max Schuster as modified by Mallard's formula.)

These are graphically represented in Fig. 96, from which it can be seen that there are upon the (001) face both positive (+) and negative (-) values up to 5° , making the feldspars, giving lower extinction angles, indeterminable unless the orientation of the section is known. Upon the (010) face there will be confusion if the extinction angle is less than 19° .

How to recognize the (001) face. These plates cannot be recognized in random thin sections of unknown feldspars, and one is obliged to obtain cleavage flakes. A fragment of the rock is crushed, not ground, in an iron or agate mortar, the powder is passed through a sieve with meshes of 0.5 mm., the dust floated off in water, the dark constituents separated by means of a heavy solution, and the remainder sorted under the microscope. A large part of the feldspar will be found to be in cleavage flakes along (001) and (010). Only flakes of less than 0.5 mm. in thickness and with parallel faces, which may be recognized by their uniform interference tints, are of use. The (001) flakes show albite twinning, while those along (010) do not. In the (001) sections the extinction is measured from the twinning lamellæ, in the (010) sections it is measured from the (001) cleavage.

How to recognize the (010) face. Upon the (010) face the albite twinning lamellæ are wanting; those according to the pericline law are sometimes seen. The crystal form (Fig. 97) is often shown in outline or by the zonal growth. The (001) cleavage is usually distinct, and is best seen when the diaphragm below the stage of the microscope is partially closed. In the acid feldspars the elongation is nearly parallel to *a*. The extinction is positive or negative, according to its direction from *a*, as shown in the figure and as explained above.

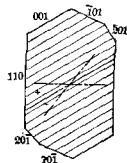


FIG. 97.—A (010) cleavage flake of plagioclase.

7. *By the position of emergence of the bisectrix in (010) plates.*
In convergent light the different feldspars show different posi-

tions of emergence of the bisectrix in (010) plates. In air they are as follows:

In albite the inclination is small and the bisectrix is positive.

In oligoclase the bisectrix is nearly normal to the face.

In andesine the inclination is nearly 20° to the top and left.

In labradorite, upon the left face, the axis is not in the field; only part of a bar, part of one system of axial rings, and a small part of the lemniscate curves appear.

In bytownite the appearance is the same as in labradorite, except that no lemniscate curves show.

In anorthite the axis emerges at the edge of the field.

8. *By the extinction angle in Carlsbad twins upon the (010) face (Michel Lévy).** The extinction angles of Carlsbad twins showing upon the (010) face are particularly characteristic. The twinning line bisects the extinction angle of the two individuals (ω) and also their (001) cleavages, which make an angle of approximately 128° with each other (Fig. 98). Albite twinning does not show upon the (010) face, unless the section is slightly inclined from this direction. In the values given below for the angles between the two extinctions, it is immaterial whether the crystal shows a simple Carlsbad twin or polysynthetic albite twinning in combination with the Carlsbad twin, provided the direction of the section is not far from (010).



FIG. 98.—The (010) face of a Carlsbad twin of plagioclase.

Albite,	$Ab_{96}An_5$	$\omega = 166^\circ$
Oligoclase-albite,	$Ab_{86}An_{14}$	$= 152^\circ$
Oligoclase,	$Ab_{75}An_{25}$	$= 130.5^\circ$
Andesine,	$Ab_{63}An_{37}$	$= 110.5^\circ$
Labradorite,	$Ab_{50}An_{50}$	$= 90.5^\circ$
Bytownite,	$Ab_{25}An_{75}$	$= 64.5^\circ$
Anorthite,	Ab_0An_{100}	$= 51^\circ$

These are graphically shown in Fig. 99.

* Etude sur la détermination des feldpaths, 1894.

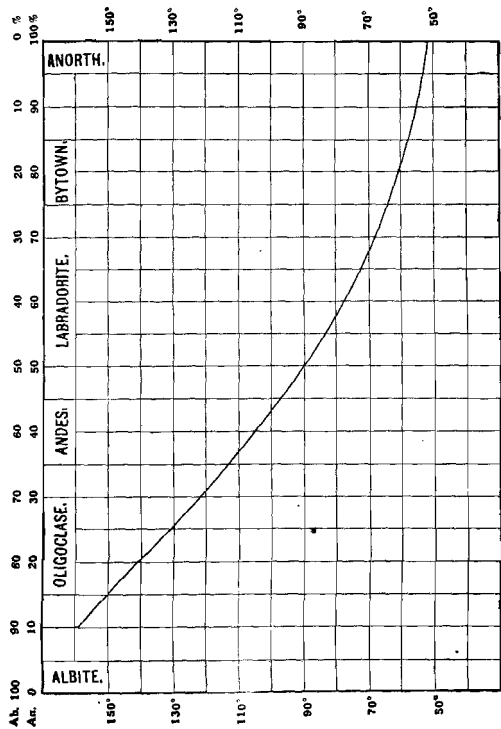


FIG. 99.—Curve showing the angle ω between the two extinctions in Carlsbad twins of lime-soda feldspars in (010) sections.

9. *By the extinction angle on sections at right angles to both (001) and (010).* (Method used by Becker* and Becke.†) These sections are easily recognizable in microlites and in phenocrysts of eruptive rocks by their nearly quadratic sections, and in the granular rocks by zonal growths with quadratic outlines. Sections at right angles to both (001) and (010) have the division lines between the albite twinning lamellæ and the (001) cleavage lines extending at right angles to the section: consequently, when the tube of the microscope is slightly raised or lowered, there will be no lateral displacement of these lines.

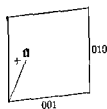


FIG. 100.

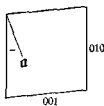


FIG. 101.

FIGS. 100-101.—Cross-sections at right angles to both (001) and (010) showing (+) and (-) character of extinction in plagioclase feldspars.

When twinning and cleavage lines are wanting in microlites, one needs but remember that the extinction angle from (010) to a is always less than 45° , consequently it is the smaller extinction angle. The small cross-sections, Figs. 100 and 101, show the directions of (+) and (-) extinction; the angles are shown in Fig. 102.

If the cross-section does not happen to be exactly at right angles to (001) and (010), it does not greatly matter, for the variation on tilting the section is small near this position. This method is good, because the increase in the extinction angle from albite to anorthite is rapid and uniform.

* U. S. Geological Survey. 18th Annual Report, part III, 1898, p. 34.

† Tschermak's Mineralogische und petrographische Mitteilungen. Vol 18, 1900, p. 556.

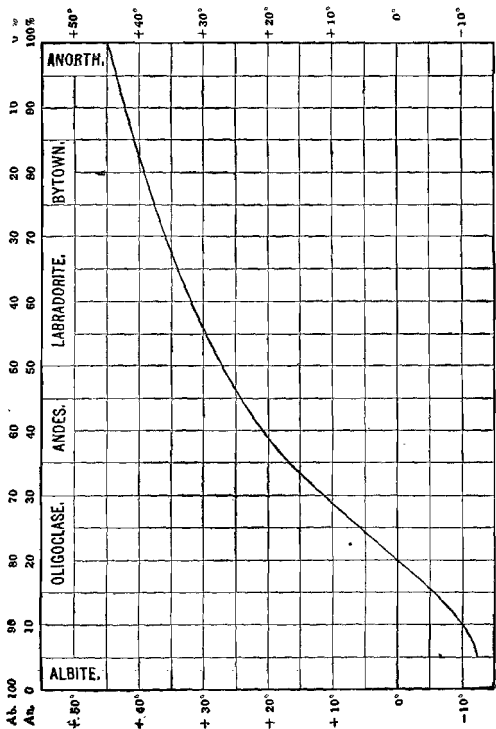


Fig. 102.—Extinction angles from *a* to the (010) cleavage of lime-soda feldspars in sections cut at right angles to both (010) and (001). (Becker and Dreyer's method.)

10. *By the extinction angle on sections at right angles to either bisectrix.* (Fouqué.*)

Sections cut at right angles to the bisectrices may be easily recognized by the fact that they show, in parallel light, an interference color intermediate between the maximum and minimum tints. In convergent light the interference figure will show as a cross in the center of the field, when the principal sections of the slide and nicols are parallel. This cross will open into two symmetrically located hyperbolæ, when the section is rotated into the diagonal position. The section must next be tested by means of a gypsum plate, to see whether it is at right angles to the α or the ϵ axis. If the line connecting the hyperbolæ has less ease of vibration than that at right angles to it, that is, if the ϵ direction connects the eyes while the β direction is at right angles to it and in the plane of the section, the slide is one which is cut at right angles to α and *vice versa*.

In sections at right angles to α the extinction angle is measured from the twinning lines (Fig. 103, solid line).

In sections at right angles to ϵ , in the basic feldspars, the extinction angle is measured from the trace of the twinning lines or of the (010) cleavage. (Fig. 103, dotted line.) In the acid feldspars the section at right angles to ϵ is very near the (010) face, and therefore shows neither twinning lamellæ nor (010) cleavage; the extinction is measured from the (001) cleavage. (Fig. 103, broken line.)

The following values are given by Fouqué. Sections at right angles to α give good values as high as Ab_1An_1 , and are of use when one can determine the positive or negative direction of extinction. The values in sections at right angles to ϵ are good in the basic feldspars.

* Contribution à l'étude des feldspaths des roches volcanique, Bulletin de la Société minéralogique de France, Vol. XVII, 1894, p. 306.

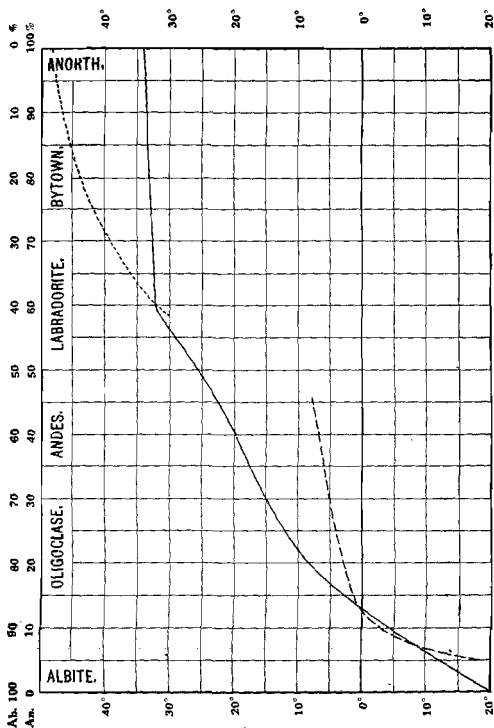


FIG. 103.—Extinction angles in sections of lime-soda feldspars cut at right angles to either bisectrix. Solid line: Extinction angles from the (001) cleavage in sections at right angles to *a*. Broken line: Extinction angles measured from the trace of (010) in sections at right angles to *t*. Dotted line: Extinction angles measured from the trace of (010) in section at right angles to *t*. (After the diagram constructed by Rosenbusch from the values given by Fouqué.)

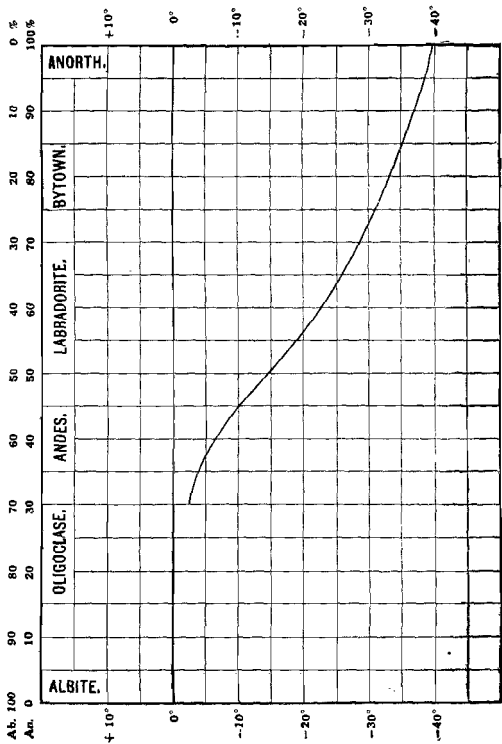
	Sections \perp to (a).		\perp to (c).	
Albite,	Ab ₉₅ An ₅	-13°	-19°	} Measured from the (010) cleavage
Oligoclase-albite,	Ab ₉₀ An ₁₀	-5°	-3°	
Oligoclase,	Ab ₇₅ An ₂₅	+12°	+4°	
Andesine,	Ab ₅₅ An ₄₅	+22.5°	+7.5°	
Labradorite,	Ab ₄₀ An ₆₀	+32°	+32°	
Bytownite,	Ab ₂₅ An ₇₅	+33°	+42°	
Anorthite,	An,	+34°	+48°	

11. *By the extinction angle on sections at right angles to the optic normal (b).* (Fedorow.)

The interference colors between crossed nicols in sections at right angles to the optic normal are the highest of any in that mineral. In thin sections of feldspar as usually cut for microscopical use, the colors seldom exceed yellow of the first order, and the highest color may be difficult of determination. A very convenient way of making the tints more distinct is to turn the nicols into parallel position. The tints are given on pp. 10 and 20. Extinctions in the acid feldspars from albite to andesine, in sections at right angles to an optic normal, vary only from +2° to -2°; but in the feldspars from andesine to anorthite they change rapidly from -6° to -39° (Fig. 104).

12. *By the extinction angle on sections from the (001), (010) zone.* (Extinction angles of microlites.) In sections from this zone the (001) and (010) cleavages are parallel. Spherulite rays and the microlites of the effusive rocks are bounded by these cleavages. In these sections the extinction angle increases from 0° to a different maximum in each feldspar. Basic oligoclase has the lowest maximum, and anorthite has the highest. Since it is impossible to obtain the positive or negative character of the extinction in microlites, albite and andesine cannot be separated; above 20° the method is good. (Fig. 105.)

Albite and andesine may be separated by the indices of refraction, and their extinction angles may then be used.

FIG. 104.—Extinction angles of lime-soda feldspars in sections cut at right angles to *b*. (Fedorow's method.)

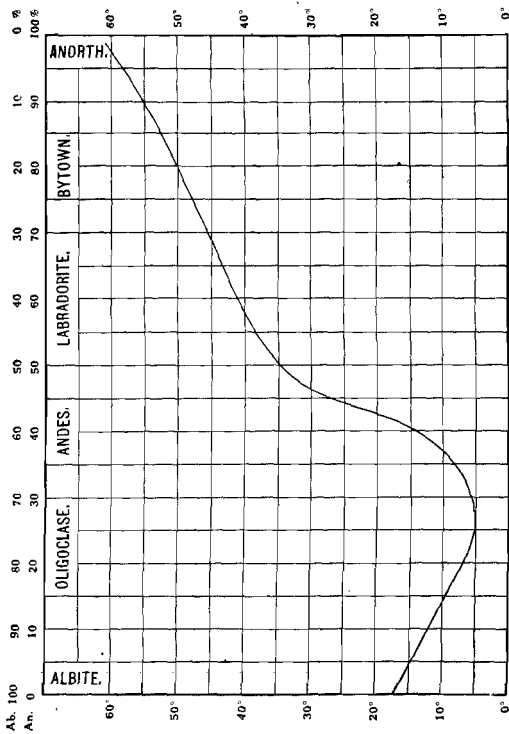


FIG. 105.—Extinction angles in mineralites of the lime-soda feldspars. Zone (010):(001). (After the diagram constructed by Rosenbusch. The right end should rise somewhat less steeply; the value assumed for the anorthite from Vesuvius, which was used in constructing the curve, being Ab_3An_{97} .)

13. *By the extinction angles on sections from the zone at right angles to (010) or the symmetrical zone.* (Statistical method of Michel-Lévy.*) Sections in this zone may be recognized as follows: (1) the albite twinning lamellæ are separated by very sharp lines, which, since they do not overlap, are not laterally displaced upon raising or lowering the tube of the microscope; (2) the extinction angle from the twinning line of the albite twins of one system is the same to the right as it is for the other to the left; and (3) if a section at right angles or very nearly at right angles to the twinning plane is turned until the twinning lines make an angle of 45° with the principal sections of the crossed nicols, the two systems of twins and the narrow strips where they overlap will become of uniform color, and the section will have the appearance of a simple crystal. The latter is the quickest and most sensitive method of finding sections in this zone.

Each section in the zone at right angles to (010) has equal extinction angles, varying from 0° to a maximum, on either side of the twinning line, but only one section gives the maximum extinction, which is different in each species of feldspar, as is also the position of this plane giving maximum extinction. (Fig. 106.)

This method is one of the most valuable for the determination of the feldspars, although confusion might arise if two species occur in the same rock, or if there are but few feldspar sections in the slide and none of them gives the maximum extinction. Another confusion arises in the positive and negative character of the extinction angles of albite and oligoclase-albite, on the one hand, and andesine on the other.

The number of sections occurring in a slide which give good results by this method is greatly increased by the fact that sections varying 10° or more from the true position may be used. In such sections the extinction angles on either side of the twinning lamellæ will not be the same, but half of the sum of the

* Annales des mines, 1877, pp. 392-471.

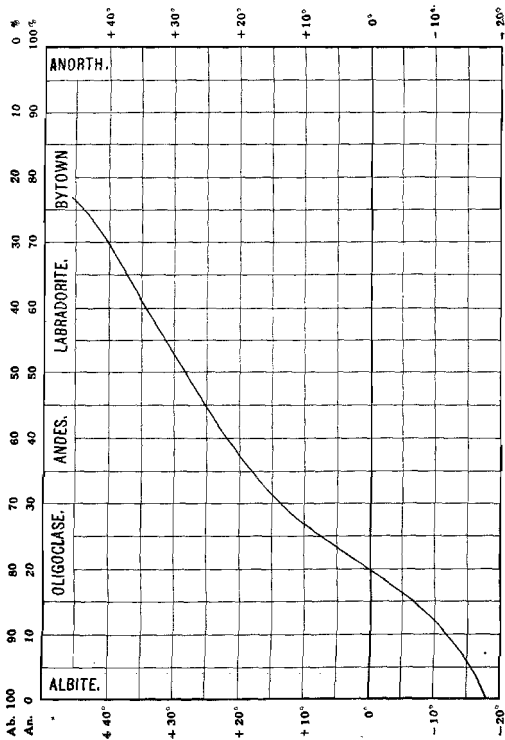


FIG. 106.—Maximum extinction angles in the lime-soda feldspars in the zone at right angles to (010), measured from the albite twinning lamellae. (Statistical method of Michel-Lévy.)

two angles very nearly coincides with the true values found in the zone.

The following values are given by Rosenbusch for the maximum extinction angles:

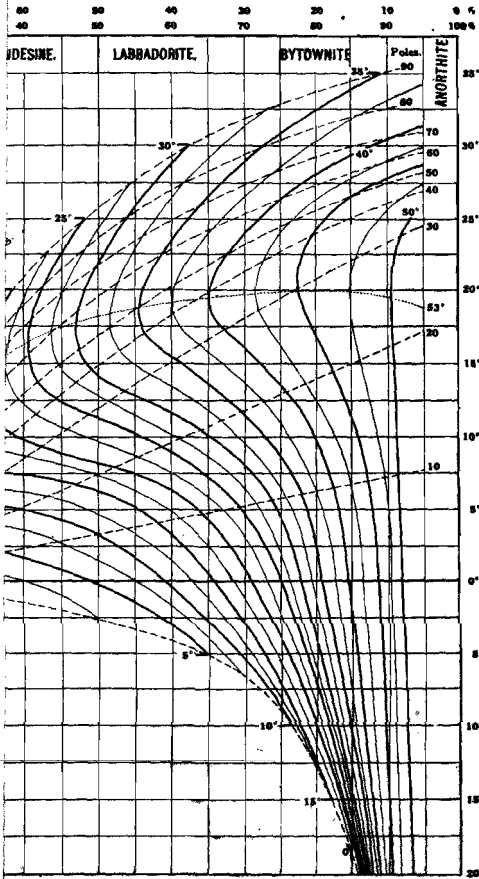
$Ab_{95}An_5$	-15.2°
$Ab_{86}An_{14}$	-7.7°
$Ab_{75}An_{25}$	$+6.8^\circ$
$Ab_{63}An_{37}$	$+19.3^\circ$
$Ab_{50}An_{50}$	$+28^\circ$
$Ab_{25}An_{75}$	$+43.7^\circ$
Ab_0An_{100}	90°

14. *By the extinction angles on sections from the zone at right angles to (010), when the albite twinning is combined with Carlsbad twinning.* (Michel-Lévy.) If the albite twins of the preceding section are combined with Carlsbad twins, the difference in extinction between the two systems will determine the feldspar. When these twins are in combination, the sections in the zone at right angles to (010) may be recognized by the fact that in the 45° position the albite twinning disappears and the crystal appears as a simple Carlsbad twin. If one turns the stage of the microscope so that the traces of the twinning planes are parallel to the cross-hairs of the microscope, the albite and Carlsbad twinning will both disappear and the feldspar be equally illuminated, except for the fact that the narrow lines, where the albite lamellæ overlap, will appear as fine black lines.

Michel-Lévy* has recently published very useful diagrams for the determination of plagioclase feldspars in this zone, with these twins combined. By observing the extinction angles, without considering the sign, the pole of the section chosen and the percentage of anorthite in the plagioclase may be determined from the diagram (Fig. 107).

* Étude sur la détermination des feldspaths, Troisième fascicule, 1904.

A section is chosen which gives approximately the maximum extinction in or very near the zone of symmetry, that is, one in which the position of greatest illumination, as explained above, is at 45° . (As in the preceding case, sections inclined as much as 10° from the perpendicular to (010) may be used.) The different values of symmetrical extinction of the two individuals of the Carlsbad twin are taken, and of these the smaller is found in the column at the left (Fig. 107) and the larger upon the curves. The vertical line at the intersection of the two gives the percentage of the anorthite molecule. The broken lines indicate the angles which the sections make with the (100) face. The size of this angle is indicated by the figures which are not followed by the degree ($^\circ$) mark in the diagram.



the lime-mica feldspars in sections from the zone at right angles to (110)
 (Carlsbad twinning). Solid lines, extinction angles; broken lines, poles.

To face page 64.

PART III.

EXPLANATION OF THE TABLES.

THE method of using the following tables needs but little explanation. A brief résumé of methods and a few cautions may be helpful.

The mineral is

Opaque. Observations are made with the analyzer out, color determined by incident light.

Isotropic or anisotropic. Observations made in polarized light, nicols crossed. With slightly isotropic minerals it may be necessary to make use of the gypsum plate (p. 12). Basal sections of uniaxial minerals are isotropic but give an interference figure.

Extinction parallel or inclined. Angles are measured from the cross-hairs of the microscope. For very small angles a Bertrand ocular (p. 13) may be used. In cases where the extinction angle of a mineral is less than 5° , it will be found under minerals having parallel extinction as well as under minerals having inclined extinction, thus allowing for slight errors in observation.

Color. Minerals nearly colorless, or which occur both colorless and colored, are given under both heads.

Pleochroism. Observed in plane polarized light.

Index greater or less than Canada balsam. Observed by Becke method (p. 14).

Maximum birefringence greater or less than quartz. In sections of normal thickness this may be determined at once

by the eye, using polarized light. In sections of unknown thickness containing quartz or any other known mineral, it may be determined by the quartz wedge, mica wedge, or compensator (pp. 18-21).

Uniaxial or biaxial character. Determined by obtaining interference figures (pp. 24-30).

Optical character. Determined with some accessory (pp. 35-43).

Value of birefringence. Obtained by comparison with known minerals by the use of some accessory (pp. 18-21). Amann's birefractometer and the Babinet compensator are excellent (p. 21).

Index of refraction. Determined by comparing (Becke method) the unknown mineral with one that is known or with the Canada balsam in contact, or by any of the methods given on pages 14 and 15. Care should be exercised in estimating the value of the index of refraction of a mineral, especially if it has medium or high relief, when there is no known mineral in the rock section with which to compare it. A colorless mineral with medium relief appears rougher than a colored one with high relief.

The spacing of the indices and the double refraction upon the diagrams is uniform until the very high figures are reached. Since few minerals occur here, and the difference in relief and birefringence is hard to estimate, this is of no importance. The length of the line under each mineral gives the range of its indices of refraction; the position of the line, its maximum birefringence.

After narrowing down the characteristics of an unknown mineral, one may find at that point, upon the plate, a group of several from which it can readily be separated by referring to the descriptive tables opposite, which are arranged in the same order as are the minerals upon the plates. When some of the properties of a mineral as, for example, its uniaxial or biaxial, or positive or negative character are indeterminable, it may be necessary to follow out two divisions; but even when it becomes necessary to look under both classes the known

properties will reduce the possible minerals to a small number.

Throughout the tables, the following form has been observed:
Name.—*Chemical composition*, *H* = Hardness, *G* = Specific gravity.

System. *Optical character of mineral* (+ or -).

Cleavage. *Cleavage angle*.

Habit. *Common form of occurrence, twinning, etc.*

Elongation. The principal zone or plane. *Optical character of elongation* (+ or -).

Optical orientation. Giving the extinction angles, etc.

Color.

Pleochroism.

Indices of refraction.

Birefringence.

Dispersion.

Axial angle.

Chemical and physical properties.

Other minerals which are similar and characteristics by which they may be distinguished.

The mineral is opaque.

Yellow by incident light.	Pyrite.
	Pyrrhotite.
Black by incident light.	Magnetite.
	Graphite.
	Ilmenite.
Thin edges transparent :	
Red	Hematite.
Brown.	Chromite.
	Picotite.

- Pyrite.**— FeS_2 , $H = 6.0-6.5$, $G = 4.9-5.21$.
 Isometric.
 Cleavage: Not seen in thin sections.
 Habit: Cubes, octahedrons, and irregular grains.
 By incident light: Yellowish with metallic luster.
 Non-magnetic; insoluble in HCl.
 Magnetite is black by incident light, and, when pulverized, is attracted by the magnet.
- Pyrrhotite.**— $\text{Fe}_n\text{S}_{n+1}$, $H = 3.5-4.5$, $G = 4.58-4.64$.
 Hexagonal.
 Prismatic cleavage; not seen microscopically.
 Habit: Irregular grains.
 By incident light: Bronze-yellow with metallic luster.
 Is somewhat attracted by the magnet when pulverized. Soluble in HCl.
 Pyrite is not attracted by the magnet and is insoluble in HCl.
- Magnetite.**— Fe_3O_4 , $H = 5.5-6.0$, $G = 4.9-5.2$.
 Isometric.
 Cleavage: (111), rarely seen under the microscope.
 Habit: Octahedrons, cubes, irregular grains, dust.
 By incident light: Metallic, bluish black.
 Attracted by magnet; soluble, even in thin sections, in HCl.
 Pyrite, ilmenite, chromite, and graphite are not attracted by the magnet.
 Pyrite, chromite, and graphite are insoluble in acids.
 Ilmenite is soluble with difficulty in acids and gives reaction for Ti.
- Graphite.**— C_n , $H = 1.0-2.0$, $G = 2.1-2.3$.
 Hexagonal.
 Cleavage: (0001), perfect.
 Habit: Hexagonal to rounded plates; scale-like and rod-like aggregates.
 By incident light: Metallic luster to dull black or steel-gray.
 Slowly consumed in BB. Insoluble in acids. Black streak.
 Molybdenite is not combustible, but gives off fumes of SO_2 and has a green streak.
- Ilmenite.**— FeTiO_3 , $H = 5.0-6.0$, $G = 4.5-5.0$.
 Hexagonal.
 Cleavage: Not distinct.
 Habit: Tabular, thin plates, scales.
 Elongation: (0001), lath-shaped.
 Madder to clove brown on thin edges. Submetallic luster.
 $\omega = \text{high}$, $\epsilon = \text{high}$.
 $\omega - \epsilon = \text{high}$.

Slowly soluble in hot HCl; with tin the solution becomes violet.
Very slightly or not attracted by the magnet. Characteristic alteration to leucoxene.

Magnetite is readily soluble in acids and is magnetic.

Hematite is red to yellow on thin edges.

Titaniferous magnetite; separation may be difficult. Different crystalline system.

Hematite.— Fe_2O_3 , $H = 5.5-6.5$, $G = 4.9-5.3$.

Hexagonal. (-).

Cleavage: Not distinct.

Habit: Tabular, thin plates, scales.

Elongation: (0001), lath-shaped. (+).

Red, yellowish, yellowish gray.

Pleochroism: O = brownish red, E = light yellowish red.

$\omega = 3.22$, $\epsilon = 2.94$.

$\omega - \epsilon = 0.28$.

Becomes magnetic in the reducing flame. Very slowly soluble in acids. Not attracted by magnet. Streak, red.

Magnetite is magnetic and readily soluble in HCl.

Limonite and earthy hematite may be confused.

Rutile is optically (+). Habit is different.

Chromite.— FeCr_2O_4 , $H = 5.5$, $G = 4.32-4.57$.

Isometric.

No cleavage.

Habit: Octahedrons, grains.

Incident light: Brownish black; thin edges same.

Insoluble in acids. Cr reaction.

Magnetite is magnetic and soluble in HCl.

Ilmenite gives Ti reaction.

Picotite.— $(\text{Mg,Fe})\text{O} \cdot (\text{Al,Cr,Fe})_2\text{O}_3$, $H = 7.5-8.0$, $G = 4.80$

Isometric.

Cleavage: Imperfect.

Habit: Grains, rarely octahedrons.

Yellow or brown to greenish brown on thin edges.

Index about 1.7.

Occurs as inclusions in olivine, rarely individuals in basalt, grains in hercynite, etc.

Chromite is distinguished by hardness specific gravity and chemically.

The mineral is **isotropic**.

The mineral is **isotropic**.

Colorless.

The mineral is isotropic.

Colorless.

Index of refraction is less than
that of Canada balsam.

The mineral is isotropic, colorless, index of refraction is less than that of Canada balsam.

(Arranged according to mean indices of refraction.)

The mineral forms crystals. . . .	Fluorite.	$n = 1.433$
	Sodalite.	1.483
	Noselite.	1.490
	Hallynite.	1.503
	Leucite.	1.508
The mineral fills cavities or is		
amorphous.	Opal.	$n = 1.443$
	Glass.	1.490
Cavity filling or attached crystals.	Analcite.	$n = 1.488$

- Fluorite.**— CaF_2 , $H=4.0$, $G=3.18-3.20$.
 Isometric.
 Cleavage: Perfect (111).
 Habit: Seldom shows crystal form; generally cavity and inter-space filling, or irregular or drop-like grains.
 Colorless to violet or purple. Color often irregularly or zonally distributed.
 Index: $n=1.4332-1.4340$.
 With H_2SO_4 gives off hydrofluoric acid which will etch glass; very slightly affected by other acids.
 Opal and sodalite groups have higher indices and are often slightly anisotropic.
 Opal has no cleavage.
 Sodalite group is attacked by weak acids and has (110) cleavage.
 Other colorless minerals usually have lower specific gravities and higher indices.
- Sodalite** — $(\text{SiO}_4)_2\text{Al}_2\text{HCl}\cdot\text{Na}_4$, $H=5.5$, $G=2.28-2.34$.
 Isometric.
 Cleavage: Sometimes fair (110).
 Habit: Cloudy quadratic, hexagonal, or rounded grains, often distorted.
 Colorless, bluish, greenish, light pink, red, yellowish.
 Index: $n_{\text{Na}}=1.4827-1.486$.
 Anomalous double refraction is rare.
 Gelatinizes with HCl ; crystals of NaCl form on drying. Gelatinizes even in thin sections with acetic acid.
 Isotropic grains (except glass, fluorite, leucite, and analcite) have higher indices.
 Glass has no cleavage and no crystal form.
 Leucite, fluorite, and analcite have different cleavage, gelatinize with greater difficulty, have twinning and different chemical reactions.
 Hallynite, noselite, and lazurite are separated by chemical tests, cleavage, and crystal form.
- Noselite.**— $(\text{SiO}_4)_2\text{Al}_2\text{AlSO}_4\text{Na}\cdot\text{Na}_6$, $H=5.5$, $G=2.27-2.50$.
 Isometric.
 Cleavage: Usually shows right-angled cleavage in cross-sections parallel to (100) and (110). Sections parallel to (111) show three series of lines cutting each other at 60° .
 Habit: Usually occurs as crystals, crystal fragments, or rounded grains.
 Colorless, blue, gray, brownish, red, yellow, and green. The color is often irregularly distributed or zonal.
 Index: $n_{\text{Na}}=1.495$.

Often has opaque borders, and is often altered. Gelatinizes easily with HCl, and few gypsum crystals and many NaCl crystals form. Sometimes shows optical anomalies.

Haüyinite gives many gypsum crystals in drying gelatine from HCl.

Sodalite has less perfect cleavage, and seldom has borders.

Haüyinite.— $(\text{SiO}_2)_2\text{Al}_2\text{Al}_2\text{O}_4\text{Na}\cdot\text{CaNa}_2$, H = 5.5, G = 2.27-2.50.
Isometric.

Cleavage: Cross-sections parallel to (100) and (110) show two systems at right angles.

Habit: Usually occurs in crystals (110), crystal fragments, or rounded grains.

Colorless, blue, gray, brownish, red, yellow, and green. Color often irregularly distributed or zonal.

Index: $n_{\text{ng}} = 1.496-1.504$.

Sometimes shows optical anomalies either about inclusions or as a dark cross. Haüyinite usually contains inclusions at the center or around periphery. It is often altered. Gelatinizes easily with HCl, and gypsum crystals result from the drying gelatine.

Noselite gives few gypsum crystals.

Sodalite has less perfect cleavage, and seldom has borders.

Leucite.— KAlSi_2O_6 , H = 5.5-6.0, G = 2.45-2.5.
Isometric.

Cleavage: Not noticeable; irregular cracks.

Habit: Six- or eight-sided to rounded grains. Very often contains inclusions in regular zones.

Colorless to gray.

$\omega = 1.508$, $\epsilon = 1.509$.

$\epsilon - \omega = .001$ and less. Optical anomalies; shows polysynthetic twinning.

HCl attacks leucite slightly in thin sections, but the powdered mineral is dissolved with a separation of silica.

All minerals but analcite differ from leucite in having higher indices and higher double refraction. The twinning and crystal form of leucite also distinguishes it.

Analcite and **sodalite** groups may be confused with isotropic leucite. Either may be distinguished by the greater resistance of leucite to HCl and by its micro-chemical reactions, giving isometric potassium fluosilicate crystals, while analcite gives hexagonal sodium fluosilicate crystals.

Opal.— $\text{SiO}_2 + \text{aq.}$, H = 5.5-6.5, G = 1.9-2.3.
Amorphous.

Cleavage: Wanting.

Habit: *Irregular grains, vein filling, druses; pseudomorphs after feldspar, augite, or other silicates.*

Transparent, colorless.

Index: Low, varying with aq. contents. Mean: 1.36-1.458.

Birefringence: Low. Anomalous double refraction in irregular patches and spots is not uncommon.

Analcite.— $\text{NaAlSi}_3\text{O}_8 + \text{H}_2\text{O}$, $H = 5.5$, $G = 2.15-2.18$.
isometric. (+).

Cleavage: Medium (100).

Habit: Druses or cavity filling, cloudy grains (211); pseudomorphs after leucite, nephelite, or sodalite.

Colorless, white.

Index: $n = 1.486-1.488$.

Birefringence: Anomalous weak double refraction with a separation into fields, occurs.

Becomes cloudy on heating strongly; soluble even in thin sections in acids.

Sodalite group differs in cleavage and chemically.

Leucite is attacked by HCl with difficulty. Analcite takes stain readily. Treating leucite with hydrofluosilicic acid produces isometric potassium fluosilicate crystals, while analcite so treated gives hexagonal crystals of sodium fluosilicate.

Garnets have much higher indices.

The mineral is *isotropic*.

Colorless.

Index of refraction is greater
than that of Canada balsam.

The mineral is isotropic, colorless, index of refraction is greater than that of Canada balsam.

(Arranged according to mean indices of refraction.)

Octahedrons: generally **quadratic** sections.

Spinel $n = 1.716$

Periclase 1.736

Polygonal sections and rounded grains.

Grossular (garnet) $n = 1.750$

Spessartine (garnet) 1.811

Spinel.— $MgO \cdot Al_2O_3$, $H = 7.5-8.0$, $G = 3.6-3.7$.

Isometric.

Cleavage: Wanting.

Habit: Generally in sharply defined quadratic (111) crystals.

Colorless to faint red, green, or blue.

Index: $n = 1.712-1.720$.

Not affected by acids. Never altered.

Periclasé is gray to yellow and has good cleavage.

Periclasé.— MgO , $H = 6.0$, $G = 3.642-3.674$

Isometric.

Cleavage: Good (100).

Habit: Grains, crystals (111).

White, gray, dark gray, yellow to brownish yellow.

Index: $n_{\alpha, \sigma} = 1.736$.

Dissolves in hot concentrated HCl; is colored brown in thin sections when moistened with silver nitrate.

Spinel, see above.

Grossular.— $Ca_3Al_2Si_3O_{12}$, $H = 7.0-7.5$, $G = 3.42-3.72$

Isometric.

Cleavage: Strong, irregular fractures.

Habit: (110), quadratic, hexagonal, or octagonal outlines, or irregular rounded grains.

Colorless to weak yellowish.

Index: $n_{\alpha, \sigma} = 1.744-1.757$.

Birefringence: Optical anomalies.

Insoluble in acids. Zonal structure common.

Periclasé and spinel: Separate by specific gravity, then test for SiO_2 .

Periclasé has a good cleavage.

Spinel is generally in (111) crystals.

Spessartine.— $Mn_2Al_2Si_2O_{11}$, $H = 7.0-7.5$, $G = 4.0-4.3$.

Isometric.

Cleavage: Strong, irregular fractures.

Habit: (110) grains; quadratic, etc., outlines.

Blood-red, yellowish red, red-brown, colorless.

Index: $n_{\alpha, \sigma} = 1.8105$.

Birefringence: Optical anomalies.

Insoluble in acids.

Spinel, periclasé, see above.

The mineral is isotropic.

Colored.

The mineral is isotropic.

Colored.

Index of refraction is less than that
of Canada balsam.

The mineral is isotropic, colored, index of refraction is less than that of Canada balsam.

(Arranged according to mean indices of refraction.)

The mineral forms crystals . . .	Fluorite	$n = 1.433$
	Sodalite	1.483
	Nephoselite	1.490
	Häüynite	1.503
	Leucite	1.508
Amorphous filling	Glass	$n = 1.490$

Fluorite.— CaF_2 , $H = 4.0$, $G = 3.18-3.20$.

Isometric.

Cleavage: Perfect (111).

Habit: Seldom shows crystal form; generally cavity and interspace filling, or irregular or drop-like grains.

Colorless to violet or purple. Color often irregularly or zonally distributed.

Index: $n = 1.4332-1.4340$.

With H_2SO_4 gives off hydrofluoric acid which will etch glass; very slightly affected by other acids.

Opal and sodalite groups have higher indices and are often very slightly anisotropic.

Opal has no cleavage.

Sodalite group is attacked by weak acids and has (110) cleavage.

Other colorless minerals usually have lower specific gravities and higher indices.

Sodalite.— $(\text{SiO}_4)_3\text{Al}_2 \cdot \text{AlCl} \cdot \text{Na}_4$, $H = 5.5$, $G = 2.28-2.34$.

Isometric.

Cleavage: Sometimes fair (110).

Habit: Cloudy, quadratic, hexagonal, or rounded grains, often distorted.

Colorless, bluish, greenish, light pink, red, yellowish.

Index: $n_{na} = 1.4827-1.486$.

Anomalous double refraction is rare.

Gelatinizes with HCl; crystals of NaCl form on drying. Gelatinizes even in thin sections with acetic acid.

Isotropic grains (except glass, fluorite, leucite, and analcite) have higher indices.

Glass has no cleavage and no crystal form.

Leucite, fluorite, and analcite have different cleavage, gelatinize with greater difficulty, have twinning and different chemical reactions.

Hattynite, noselite, and lazurite are separated by chemical tests, cleavage, and crystal form.

Noselite.— $(\text{SiO}_4)_3\text{Al}_2 \cdot \text{AlSO}_4 \cdot \text{Na} \cdot \text{Na}$, $H = 5.5$, $G = 2.27-2.50$.

Isometric.

Cleavage: Usually shows right-angled cleavage in cross-sections parallel to (100) or (110). Sections parallel to (111) show three series of lines cutting each other at 60° .

Habit: Usually occurs in crystals, crystal fragments, or rounded grains.

Colorless, blue, gray, red, yellow, or green. The color is often irregularly distributed or zonal.

Index: $n_{na} = 1.495$.

Often has opaque borders and is often altered. Gelatinizes easily with HCl, and few gypsum crystals and many NaCl crystals form. Sometimes shows optical anomalies.

Hatynite gives many gypsum crystals in drying gelatine from HCl.

Sodalite has less perfect cleavage, and seldom has borders.

Hatynit . $(\text{SiO}_2)_2\text{Al}_2\cdot\text{Al}_2\text{O}_3\cdot\text{Na}_2\text{O}\cdot\text{CaNa}_2$, H = 5.5, G = 2.27-2.50.

Isometric.

Cleavage: Cross-sections parallel to (100) or (110) show two systems at right angles.

Habit: Usually occurs in crystals (110), crystal fragments, or rounded grains.

Colorless, blue, gray, brownish, red, yellow, and green. Color often irregularly distributed or zonal.

Index: $n_{na} = 1.496-1.504$.

Sometimes shows optical anomalies either about inclusions or as a dark cross. Hatynite usually contains inclusions at the center or around periphery. It is often altered. Gelatinizes easily with HCl, and gypsum crystals result from the drying gelatine.

Noselite gives few gypsum crystals.

Sodalite has less perfect cleavage and seldom has borders.

Leucite.-- KAlSi_3O_8 , H = 5.5-6.0, G = 2.45-2.5.

Isometric.

Cleavage: Not noticeable, irregular cracks.

Habit: Six- or eight-sided to rounded grains. Very often contains inclusions in regular zones.

Colorless to gray.

$\omega = 1.508$, $\epsilon = 1.509$.

Birefringence: Very low, = 001. Optical anomalies; shows polysynthetic twinning.

HCl attacks leucite slightly in thin sections, but the powdered mineral is dissolved with a separation of silica.

All minerals but analcite differ from leucite in having higher indices and higher double refraction. The twinning and crystal form of leucite also distinguish it.

Analcite and sodalite group may be confused with isotropic leucite. Either may be distinguished by the greater resistance of leucite to HCl and by its micro-chemical reactions, giving isometric potassium fluosilicate crystals, while analcite gives hexagonal sodium fluosilicate crystals.

The mineral is **isotropic**.

Colored.

Index of refraction is greater
than that of Canada balsam.

The mineral is isotropic, colored, index of refraction is greater than that of Canada balsam.

(Arranged according to mean indices of refraction.)

Generally octahedrons or quadratic sections.

Spinel	$n =$ 1.718
Periclase	1.736
Hercynite (spinel) . .	1.749
Picotite (spinel)	1.7 ca.
Gahnite (spinel)	1.765
Pleonaste (spinel) . . .	high
Pyrrhite	high
Beckelite	high
Chromite	2.097
Perovskite	2.38

Rounded, quadratic, hexagonal, octahedral, etc., or irregular grains. Usually strong, irregular fractures. Generally completely isotropic or faint optical anomalies. Often show zonal structure.

Grossular (garnet) . . .	$n =$ 1.744
Pyrope "	1.744
Almandine "	1.810
Spessartine "	1.811
Uwarowite "	1.838
Melanite "	1.856

Spinel— $MgO \cdot Al_2O_3$, $H = 7.5-8.0$, $G = 3.6-3.7$.
Isometric.

Cleavage: Wanting.

Habit: Generally in sharply defined quadratic (111) crystals.

Colorless to faint red, green, or blue.

Index: $n = 1.712-1.720$.

Not affected by acids. Never altered.

Periclase is gray to yellow and has good cleavage.

Periclase— MgO . $H = 6.0$, $G = 3.642-3.674$.

Isometric.

Cleavage: Good (100).

Habit: Grains, crystals (111).

White, gray, dark gray, yellow to brownish yellow.

Index: $n_{\text{red}} = 1.736$.

Dissolves in hot concentrated HCl; is colored brown in thin sections when moistened with silver nitrate.

Spinel, see above.

Hercynite.— $FeO \cdot Al_2O_3$, $H = 7.5-8.0$, $G = 3.91-3.95$.

Isometric.

Habit: Grains, crystals (111).

Dark green.

Index: $n = 1.749$.

Insoluble in acids.

Pleonaste is only to be separated by chemical means.

Picotite.— $(Mg, Fe)(Al, Cr, Fe)_2O_4$, $H = 7.5-8.0$, $G = 4.08$.

Isometric.

Cleavage: Wanting.

Habit: Grains, rarely crystals (111).

Yellow, brown, greenish brown.

Index: $n = 1.7+$.

Reaction for chromium.

Chromite is distinguished chemically, by specific gravity, and by hardness.

Gahnite.— $ZnAl_2O_4$, $H = 7.5-8.0$, $G = 4.0-4.6$.

Isometric.

Cleavage: (111), indistinct.

Habit: (111) grains.

Green, greenish black.

Index: $n = 1.765$.

Reaction for Zn. Occurs in crystalline schists.

Pleonaste is distinguished chemically.

Pleonaste.— $(\text{Mg,Fe})(\text{Al,Fe})_2\text{O}_4$, H=8.0, G=3.82.

Isometric.

Cleavage: (111), imperfect.

Habit: Generally in sharply defined (111) quadratic crystals.

Green. By incident light or when opaque it is black without metallic luster.

Index: High.

Insoluble in acids, except concentrated H_2SO_4 .

Common in gneisses. Often included in garnets and cordierite.

Gahnite is distinguished chemically.

Pyrrhite—Calcium niobate or tantalate, H=5.5, G=4.1–4.3.

Isometric.

Cleavage: *Not observed.*

Habit: Crystals (111).

Orange-yellow to red.

Index: High.

Insoluble in HCl.

Spinelns are much harder.

Beckelite.— $\text{Ca}_2(\text{Ce,La,Di})_2\text{Si}_2\text{O}_{12}$, H=5.0, G=ca. 4.15.

Isometric.

Cleavage: (100) distinct.

Habit: Grains (111), (110).

Light yellow.

Index: High.

Birefringence: Large crystals show optical anomalies.

Chromite.— FeCr_2O_4 , H=5.5, G=4.32–4.57.

Isometric.

Cleavage: Wanting.

Habit: Irregular grains, crystals (111).

Opaque. By incident light, brownish black; same on thin edges.

Index: $n = 2.0965$.

Insoluble in acids. Chromium reaction with soda.

Perovskite.— CaTiO_3 , H=5.5, G=4.02–4.04

Isometric.

Cleavage: In large individuals distinct (100). Not seen in thin sections.

Habit: Octahedrons (111); sharp, sometimes rounded, cubes.

Grayish white, violet-gray, brownish to red-brown, rarely greenish gray.

Index: $n_{\text{max}} = 2.38$.

Anomalous double refraction in large individuals; often not seen in thin sections.

Insoluble in HCl, not magnetic, Ti reaction.

Ilmenite and **hematite** resemble perovskite when opaque, but are soluble in HCl and show different crystal outlines or are irregular.

Chromite, **picotite**, and **melanite** may be separated by combining specific gravity, solubility in HCl, and attraction by the magnet. In the separated material perovskite will show the presence of Ti, melanite will show SiO_2 and chromite Cr.

Grossular.— $\text{Ca}_3\text{Al}_2\text{Si}_3\text{O}_{12}$, H = 7.0–7.5, G = 3.42–3.72.

Isometric.

Cleavage: Wanting; shows irregular cracks.

Habit: (110), quadratic, hexagonal, or octagonal outlines or irregular rounded grains.

Colorless to weak yellowish.

Index: $n_a = 1.744$ –1.757.

Birefringence: Optical anomalies.

Insoluble in acids. Zonal structure common.

Spinel and **periclase** are separated by their specific gravities; then tested for SiO_2 .

Periclase has a good cleavage.

Spinel is generally in (111) crystals.

Pyrope.— $\text{Mg}_3\text{Al}_2\text{Si}_3\text{O}_{12}$, H = 7.0–7.5, G = 3.7–3.8.

Isometric.

Cleavage: Wanting; shows irregular cracks.

Habit: Rounded grains, never crystals.

Red to blood-red.

Index: $n = 1.741$ –1.750.

Kelyphite rims common. Occurs only in peridotites and their derivatives.

Spinels are separated by their specific gravities and the absence of SiO_2 .

Almandine.— $\text{Fe}_3\text{Al}_2\text{Si}_3\text{O}_{12}$, H = 7.0–7.5, G = 4.1–4.3.

Isometric.

Cleavage: Wanting; shows irregular fractures.

Habit: (110), (211), and grains. Quadratic, hexagonal, etc., outlines.

Red, in various tones, to brownish red.

Index: $n_a = 1.808$ –1.811.

Optical anomalies appear not to occur.

Insoluble in acids. Zonal structure common.

Spinels are separated by their specific gravities and the absence of SiO_2 .

Spessartine.— $\text{Mn}_2\text{Al}_2\text{Si}_2\text{O}_{12}$, H=7.0-7.5, G=4.0-4.3.

Isometric.

Cleavage: Wanting; shows irregular cracks.

Habit: (110), grains; quadratic, etc., outlines.

Blood-red, yellowish red, red-brown, colorless.

Index: $n_{\text{no}} = 1.8105$.

Birefringence: Optical anomalies.

Insoluble in acids.

Spinel and periclase are separated by their specific gravities and the absence of SiO_2 .

Periclase has good cleavage.

Spinel generally occur in (111) crystals.

Uwarowite.— $\text{Ca}_2\text{Cr}_2\text{Si}_2\text{O}_{12}$, H=7.5, G=3.51.

Isometric.

Cleavage: Wanting; irregular cracks.

Habit: (110), grains.

Deep green.

Index: $n = 1.838$.

Usually shows optical anomalies.

Alteration unknown. Confined to Cr rich serpentines, granular limestones, and dolomites.

Spinel are separated by their color, specific gravities, and the absence of SiO_2 .

Melanite.— $\text{Ca}_2\text{Fe}_2\text{Si}_2\text{O}_{12}$, H=7.0-7.5, G=3.8-4.1.

Isometric.

Cleavage: Wanting; shows irregular cracks.

Habit: Grains and crystals (110), (211).

Various tones of brown, sometimes green.

Index: $n_{\text{no}} = 1.8566$.

Optical anomalies, owing to deep color, hardly observable.

Zonal structure very common. Alterations wanting.

Occurs in phonolites, nephelites, tephrites, etc.

Spinel are separated by their specific gravities, the absence of SiO_2 , by crystal form, and want of zonal structure.

The mineral is **anisotropic**.

The mineral is anisotropic.

Parallel extinction.

The mineral is **anisotropic**.

Parallel extinction.

Colorless.