THIN-SECTION MINERALOGY

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TO

THE MEMORY OF

LEA McILVAINE LUQUER

1864–1930

PREFACE

The identification of many of the more common minerals encountered in thin sections of rocks may be accomplished by using simplified methods of optical mineralogy. It is not necessary to require the student to spend a large amount of time in studying the great volume of theoretical information necessary to acquire an advanced knowledge of the optics of crystals. If a more advanced knowledge of the subject is desired, however, practice in the optical identification of the common minerals is the first step in approaching the advanced phases of the subject.

This text draws upon material used in introductory courses of mineral optics both at Columbia University and at Stanford University. The treatment is intended to develop optical mineralogy for the beginning student, whether he happens to be interested primarily in the field of mineralogy, petrography, geology, chemistry, physics, or engineering. The principles outlined apply considerably beyond the field of mineralogy although the application is restricted to minerals.

The discussion of the subject has been made as nearly nonmathematical as possible for the sake of simplicity. A large number of illustrations have been used in proportion to the text since many features are best explained by diagrams. Data concerning the identification of minerals in fragments have been included to be of assistance in determining minerals not easily identified in thin section alone. Charts and tables are used to increase the speed of mineral determination by outlining a systematic procedure.

The preparation of the manuscript has been greatly aided by the friendly criticism of a number of coworkers in the field of optical mineralogy or petrography. Dr. George Tunell of the Geophysical Laboratory has read the chapters concerning optical theory and offered numerous suggestions. He has kindly discussed portions of the manuscript with several of his colleagues at the Geophysical Laboratory and has commented upon the results of such discussions. Dr. Clarence S. Ross of the U. S. Geological Survey examined the text prior to publication.

Dr. Waldemar T. Schaller of the U. S. Geological Survey, Professors R. J. Colony and William M. Agar of Columbia University, Dr. J. W. Greig of the Geophysical Laboratory, Professor Aaron C. Waters of Stanford University, and Professor L. E. Spock of New York University have also suggested a number of features. All have contributed most generously of their time and experience, for which we wish to express our appreciation. We are indebted to Mr. Paul H. Bird, graduate student of Columbia University, for advice in describing the technique of making thin sections. The line drawings of Part II have been made by Mr. Rudolph G. Sohlberg. In the proofreading of Part II we gratefully acknowledge the assistance of Miss Genevieve Rogers. The various optical companies mentioned in Chap. II have generously cooperated by furnishing illustrations of optical equipment.

In writing the text the description of the optical properties of mineral species (Part II) has been prepared by the senior author. The junior author has contributed the discussion included in Part I and also the determinative tables.

A. F. R.
P. F. K.

Stanford University,
Columbia University,
October, 1933.

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TABLE OF ABBREVIATIONS

n = index of refraction.[1]

n_α(alpha) = the index of the fast ray in biaxial minerals. The least index of refraction.[1]

n_β(beta) = the index of the ray at right angles to n_α and n_γ.

n_γ(gamma) = the index of the slow ray in biaxial minerals. The greatest index of refraction.

n_ϵ(epsilon) = the maximum (in positive) and the minimum (in negative) index of refraction of the extraordinary ray in uniaxial minerals.

n_ω(omega) = the index of refraction of the ordinary ray in uniaxial minerals. If $n_\omega < n_\epsilon$, the mineral is positive. If $n_\omega > n_\epsilon$, the mineral is negative. n_ω is constant in a given uniaxial mineral, while the index of the extraordinary ray varies from n_ω to n_ϵ.

n_1 and n_2 = the greatest and least indices of refraction of the two rays in any crystal section at random orientation.

X = the axis of greatest ease of vibration. Light vibrating parallel to X travels with maximum velocity.

Z = the axis of least ease of vibration. Light vibrating parallel to Z travels with minimum velocity.

Y = the intermediate axis at right angles to the plane of X and Z.

r = the dispersion for red.

v = the dispersion for violet.

2V = the axial angle within the mineral.

2E = the axial angle observed in air.

B_{xo} = obtuse bisectrix.

B_{xa} = acute bisectrix.

Ax. pl. = the plane of the optic axes.

Δ = retardation in mμ (millimicrons).

mμ = millimicron, millionth of a millimeter (0.000001 mm.).

μ = micron, thousandth of a millimeter (0.001 mm.).

t = thickness of a thin section. Usually given in hundredths of a millimeter (0.01 mm.).

a, b, and c = the crystallographic axes.

$\measuredangle \alpha, \beta, \gamma$ = angles between the crystallographic axes.

$(n_\gamma - n_\alpha)$ = double refraction for biaxial minerals.

$(n_\omega - n_\epsilon)$; $(n_\epsilon - n_\omega)$ = double refraction for uniaxial minerals.

H_1 = the slow ray of the Berek compensator.

H_2 = the fast ray of the Berek compensator.

e = the extraordinary ray.

o = the ordinary ray.

Length-fast (or negative elongation) = elongation parallel to the vibration direction of the fast ray.

Length-slow (or positive elongation) = elongation parallel to the vibration direction of the slow ray.

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[1] In places where confusion with the axial angles α, β, and γ is unlikely, α, β, and γ are often used for indices in abbreviated form instead of using n_α, n_β, and n_γ.

PART I
MINERAL OPTICS

CHAPTER I

THE PREPARATION OF THIN SECTIONS OF MINERALS AND ROCKS

Although students of mineralogy seldom prepare their own thin sections, every worker should know at least in a general way how thin sections are made. A student with natural dexterity may learn to make thin sections approaching those ground by professional section makers.[1] The speed may not equal that of the professional, but with a little care the section made may be just as good. A brief discussion of the methods used in section making will be given for the benefit of the beginner.

The technique employed depends largely upon the nature of the material. Grinding sections of ordinary igneous, sedimentary, and metamorphic rocks is a routine process. Friable or fractured rocks and unconsolidated materials, however, require special precautions not necessary in the case of compact specimens.

The various stages in the preparation of an ordinary rock section are illustrated in Fig. 1. The first stage represents the choice of material. A specimen suitable for effective study with the microscope is selected. Such a specimen may contain fine-grained minerals not easily studied by the unaided eye, structures that yield readily to examination with the microscope, or any one of those numerous minor features so effectively revealed by microscopic examination.

A chip of suitable size should be sawed or broken from the specimen. An ideal chip is flat and almost square, about ⅛ in. thick, and 1 in. square. A much better chip with flat surfaces can be prepared by sawing with a rock saw than by breaking. Either a diamond saw or a carborundum saw is

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[1] The following list is furnished for the convenience of readers who wish the names of technicians making thin sections:

Paul H. Bird, 1180 Amsterdam Ave., New York.
F. S. Reed & J. L. Mergner, 5519 Nevada Ave. N.W., Washington, D.C.
Alexander Tihonravov, 57 Pine Lane, Los Atlos, Calif.
W. Harold Tomlinson, Swarthmore, Pa.
Voigt and Hochgesang, Göttingen, Germany.
Joh. P. Jacobsen, Hovik, pr., Oslo, Norway.

satisfactory for this work. Ordinary saws consist of thin wheels of soft metal, impregnated on the margins with abrasive powder. The impregnated carborundum saw is ordinarily used since it is much less expensive and is entirely satisfactory for routine work.

Figure 2 illustrates an ordinary type of mineralogical saw. It may be a hard rolled copper disk which operates over a trough filled with carborundum and sludge. The edge of the rotating disk picks up carborundum and rubs it against the specimen. If a proper mixture of mud, carborundum, and water is maintained, it is possible to grind a narrow channel completely through an inch of solid quartz in 5 min.

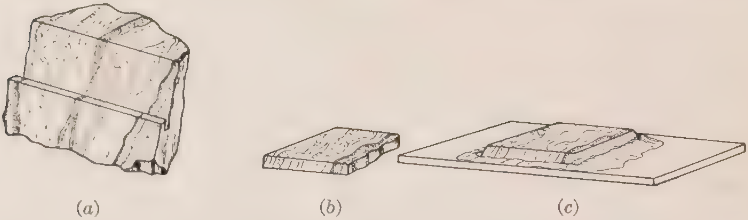

FIG. 1.—(*a*) A rock selected for a thin section and sawed to obtain a chip. (*b*) A sawed chip of proper dimensions for a thin section (bottom surface polished). (*c*) The chip mounted on a glass slide with Canada balsam ready for the first stage of grinding.

When the chip is ready, a smooth surface is polished on one side by utilizing successively 100, FFF, and 600 carborundum and finishing with $302\frac{1}{2}$ American Optical Company's emery. In case the rock is fairly soft, the first grinding with 100 carborundum is omitted. The 100 carborundum is too coarse and tends to destroy soft material.

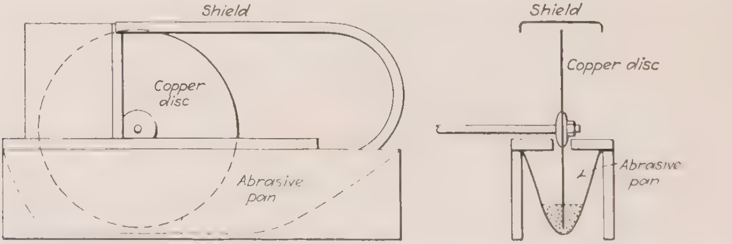

FIG. 2.—A mineralogical saw consisting of a hard rolled copper disc used with carborundum.

Mechanical grinding of thin sections usually takes place on flat laps constructed of suitable metal and faced to a plane flat surface. The laps should be at least 12 in. in diameter and should rotate at a speed of about 600 r.p.m. Bearings should be shielded against abrasive powder, and drive shafts should be arranged to transmit the power to the lap by friction if possible. The lap for fine grinding should be made of copper and grooved.

Great precautions concerning cleanliness are necessary throughout the entire process of preparing a thin section. A single grain of coarse grit rubbed against the slide at the wrong stage of the process will often destroy a thin section.

The smoothly ground but unpolished surface is cleaned and dried. It is then mounted on a glass object slide, employing Canada balsam as a cementing material. The balsam should be cooked slowly until a chilled drop will snap from the end of a needle when pressed against the thumb nail.[1] It should not be overcooked, since it then becomes too brittle and may even turn brown. While the balsam is still warm and liquid, the flat surface of the warmed chip is placed upon a slide having a cooked smear of Canada balsam. On cooling, the chip will be firmly cemented to the glass slide. The bond should be an even layer of balsam unbroken by air bubbles. If air bubbles are present, the chip should be warmed, removed, and remounted. The problem of properly cooking Canada balsam may be solved by using a plate with an interior chamber filled with glycerin to distribute the heat evenly, together with an expansion cylinder containing a thermometer for temperature control (Fig. 3).

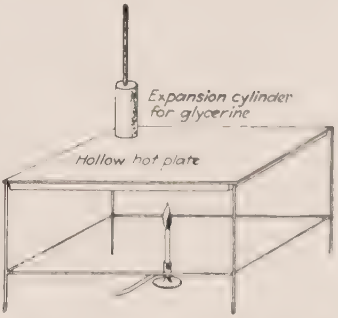

FIG. 3.—A hot plate containing a glycerine chamber and thermometer well for proper control in cooking Canada balsam. (*Developed by Paul H. Bird.*)

The exposed side of the mounted chip is ground with medium and fine carborundum and alundum. Alundum is utilized for the final grinding when the chip has reached a thickness of about 0.1 mm. The specimen is usually ground on a rotating lap and finished by hand on a smooth glass plate. A fine alundum or emery paste is used on the glass plate. The final grinding demands manual dexterity. The thin slice should be kept uni-

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[1] Balsam is first cooked about 2 min. at 160° C. It may then be warmed at 120° for mounting and heated again at 100° to attach the cover glass.

form in thickness during grinding, and the grinding continued until a thickness of about 0.03 mm. is attained. The thickness of the slide is controlled through the final stage by microscopic observation of the interference colors given by some known mineral in the section when covered with a film of water. Quartz is frequently present, in which case the interference colors due to this mineral should be almost entirely white or gray.

Small holders are useful for grinding the mounted chips. Such holders keep the opposite surfaces of the slide parallel and facilitate the process of fine grinding. Holders also permit the operator to grind several sections at the same time until the final stage is reached. Three holders form a useful combination. One holding six slides may be used to grind the chip to a thickness of about 0.5 mm.; the second, arranged for two slides, to carry the grinding to 0.1 mm.; and the third, holding a single slide, to complete the section. In case a holder is not available, a small cork may be cemented to the back of the slide with balsam.

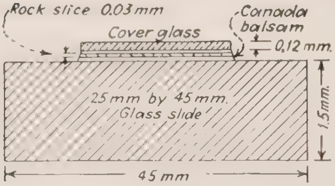

Fig. 4.—A cross section of the mounted rock slice (vertical scale exaggerated).

When the section is ground to the proper thickness, it is washed free from grinding powder and dried. Fresh balsam is then smeared over the surface of the slice, cooked, and a thin cover glass (thickness about 0.12 mm. or less) placed over it. The preparation is then cooled and excess balsam around the edge of the cover glass is dissolved with xylol, followed by a wash with kerosene. The thin section is now covered and ready for use (Fig. 4).

In case the slice is composed of substantial and compact material, it may be transferred from the glass slide on which it has been ground to another slide free from scratches. To effect the transfer, the slide holding the slice is smeared with balsam and heated on a hot plate as in covering. A clean slide smeared with balsam is placed on the hot plate next to the ground slide containing the chip, and the balsam cooked at the same time. When both smears of balsam are cooked, the slice is worked free from the ground slide with the aid of a toothpick and floated to the clean slide. It is then covered with a cover glass in the usual way.

Poorly consolidated materials require special treatment. Dr. C. S. Ross has developed the technique of making thin sections of friable materials in the petrographic laboratory of the U. S. Geological Survey. His methods apply to such substances as incoherent sands, tuffs, arkoses, soils, plastic clays, shales, or bentonites.

Two main problems are involved. The first is impregnating with some substance that will act as a binder; the second is to use grinding media that will not react with the material of the thin section and cause its disintegration. Kollolith,[1] balsam, or bakelite are recommended as binders. Petroleum oil, alcohol, ether, acetone, xylol, or water may be used for grinding media, depending upon the character of the material. Carborundum paper, carborundum, emery, or alundum serve as abrasives, and the grinding may be quickly done by hand on glass plates.

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[1] Manufactured by Voigt and Hochgesang, Göttingen, Germany.

CHAPTER II

THE POLARIZING MICROSCOPE

General Discussion.—The polarizing, or the petrographic, microscope, as it may be called, is used to the exclusion of other models in the study of thin sections of minerals and rocks. The lens system is similar to the lens system of the usual modern compound microscope. The instrument, however, contains several additional features which greatly increase its range of usefulness. The most distinctive are the polarizing and analyzing prisms and several accessories such as the Bertrand lens, mica plate, gypsum plate, and quartz wedge.

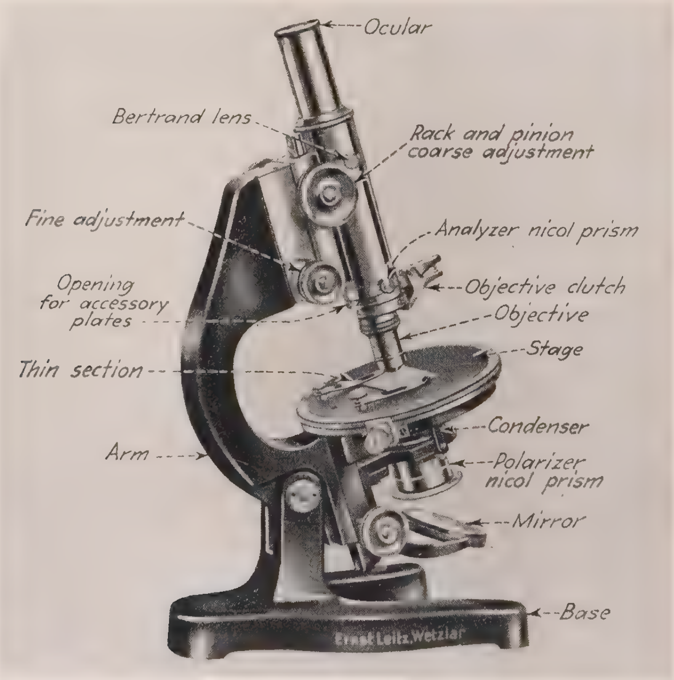

FIG. 5.—A student model petrographic microscope with parts marked. (*E. Leitz, Inc.*)

The principal parts of the usual polarizing microscope, beginning at the base and following along the path of light, may be enumerated as follows:

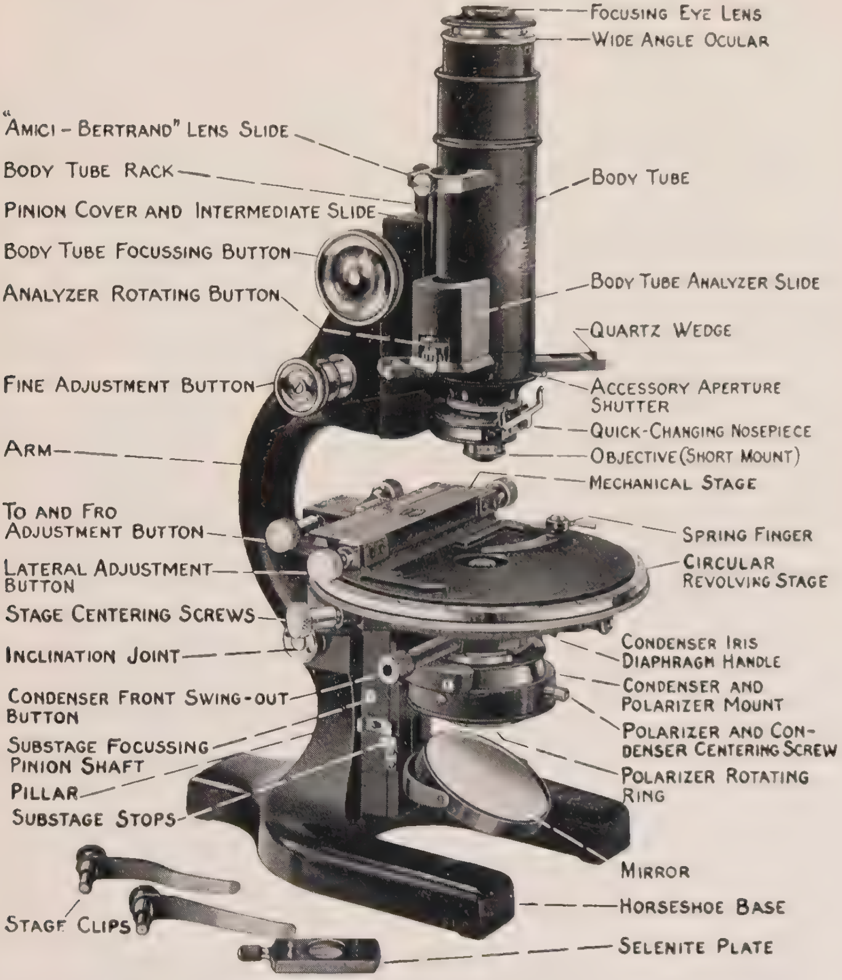

Fig. 6.—A student model petrographic microscope with a mechanical stage added. (*Spencer Lens Co.*)

Mirror, polarizing prism, condenser, auxiliary condenser, stage, objective, objective clutch, opening for accessory plates, analyzing prism, Bertrand lens, and ocular.

A brief discussion of each of these units will be given in succeeding paragraphs.

The names applied to the various parts of a well-known student model polarizing microscope (a type manufactured by E. Leitz, Inc.) are given in Fig. 5. The microscope illustrated may be considered either as a student model or as a model designed for routine forms of microscopic work. If necessary, however, practically all forms of ordinary investigation employing polarized light can be carried on with an instrument of this sort. It is only in cases of advanced research that a more elaborate microscope is required. Two other polarizing microscopes suitable for student use are illustrated in Figs. 6 and 7.

Fig. 7.—A student model microscope with accessories. (*Bausch and Lomb Optical Co.*)

The polarizing microscope is adapted for ordinary examination of minerals in plane-polarized light. The lower polarizing prism is left in place beneath the condenser and the upper prism is moved to one side. A full range of magnifications becomes possible with this arrangement. The microscope may also be used for examination of specimens between crossed nicols,[1] both prisms being inserted in the path of light. The path of light through the microscope with the latter set-up is shown in the sectional view (Fig. 8). Observation between crossed nicols is possible over the same range of magnifications as that employed in the case of a single nicol. A simple lens is often inserted above the analyzing prism to correct for the slight change in magnification due to the prism.

A third form of examination termed *conoscopic* is frequently used and consists of examination between crossed nicols in convergent polarized light. The sequence of units employed for the conoscopic set-up is illustrated in Fig. 9. The 16-mm. objective illustrated in the figure is serviceable for crystals of large areas. Ordinarily, either 8- or 4-mm. objectives are used when obtaining interference figures from small crystals.

Parts of the Microscope. *Oculars.*—Oculars used in modern petrographic microscopes are ordinarily of the Huygenian type or a simple modification. In combination with 40- and 16-mm. objectives or other objectives in the same range of magnification, Huygenian oculars are employed. Where combinations giving higher magnifications are desired, the ocular is similar to the Huygenian ocular but contains a specially corrected eye-lens arrangement giving a flat field. This adjustment is particularly important for photomicrography.

In the Huygenian ocular the stop is located between the two lenses. An ocular of this type is frequently called a negative ocular. The Ramsden ocular with the stop below the two lenses is in contrast described as a positive ocular. The arrangement of the stops in the two types is shown in Fig. 10: *a* represents the Huygenian ocular, and *b* the Ramsden type.

Compensating oculars are constructed to accompany apochromatic objectives. Some manufacturers claim that in order to secure the best results, oculars magnifying more than ten times should be of this type. Ordinary 5 × and 10 × oculars are illustrated in Figs. 11*a* and 11*b* and are satisfactory for most work.

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[1] The word *nicol* is frequently used in a broad sense in referring to either the polarizing or the analyzing prisms. The prism used, however, may not be strictly speaking a Nicol prism.

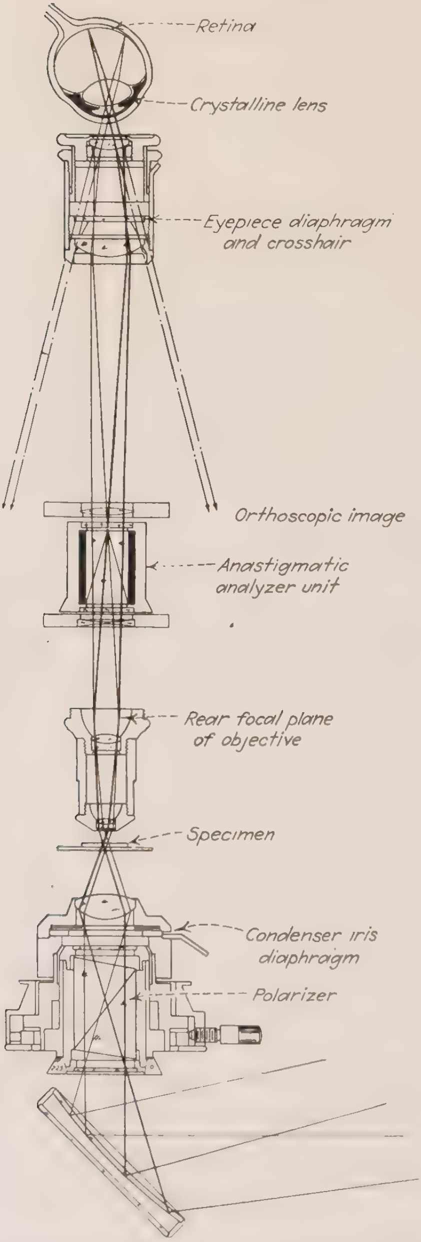


FIG. 8.—A diagram illustrating the path of light through the microscope for ordinary observation with crossed nicols. (*Spencer Lens Co.*)

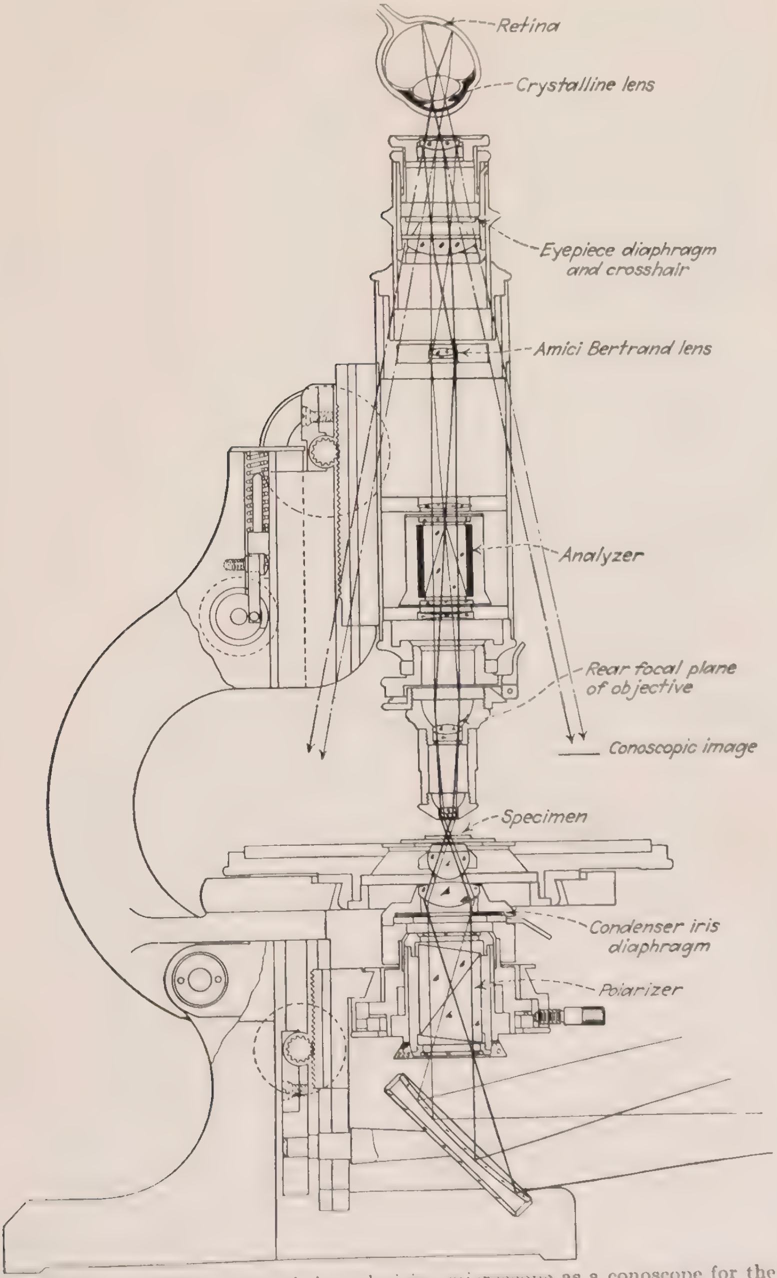


FIG. 9.—A sectional view of the polarizing microscope as a conoscope for the study of interference figures and also for high magnifications. (*Spencer Lens Co.*)

Objectives.—Achromatic objectives are used for thin-section studies and are usually supplied by the manufacturers as standard equipment; 40-, 32-, and 16-mm. achromatic objectives, and even a 4-mm. one, will serve for most studies. In the case of achromatic objectives correction of aberrations of the image becomes more difficult with high eyepiece magnification, and only the best achromatic objectives will give satisfactory results with an eyepiece magnification of 12 × or greater. A cross section of a 4-mm. achromatic objective is shown in Fig. 12, and views of several cut objectives appear in Fig. 13.

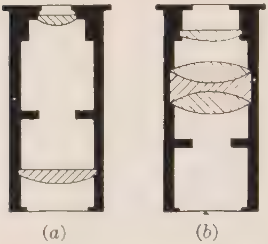


Fig. 10.—Sections of positive and negative oculars. (*a*) The Huygenian ocular (a negative ocular). (*b*) The Ramsden ocular (a positive ocular).

Apochromatic objectives have been constructed to provide additional color correction beyond that usually given by achromatic objectives. In this type of objective practically all of the images produced by the different colors of the spectrum lie in the same plane and are equally sharp. The lenses are made of

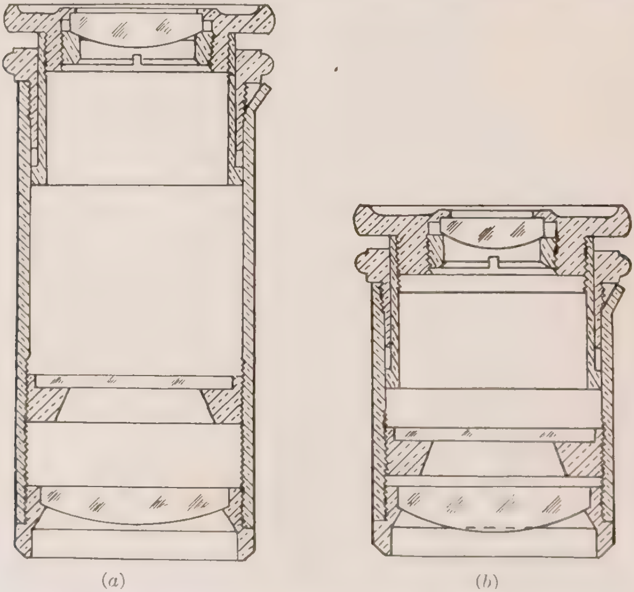


Fig. 11.—(*a*) 5 × ocular with eye lens adjustable for focus on the crosshairs. (*b*) 10 × ocular with eye lens adjustable for focus on the crosshairs.

combinations of fluorite and glass. The difficulty of securing good fluorite and the practical difficulties in their manufacture are considerable; consequently the cost is greater than the cost of ordinary achromatic objectives. However, these objectives are seldom necessary for thin-section studies.

The principal features of an objective which are of interest to the student are the initial magnification, the numerical aperture, the focal length, and the working distance.

The focal length may be employed in determining the approximate initial magnification of an objective. The optical tube length divided by the focal length equals the initial magnification. Several manufacturers stamp the initial magnification for a standard mechanical tube length[1] on the objective. This figure multiplied by the power of the eyepiece gives the magnification for a standard tube length. This should be corrected, however,

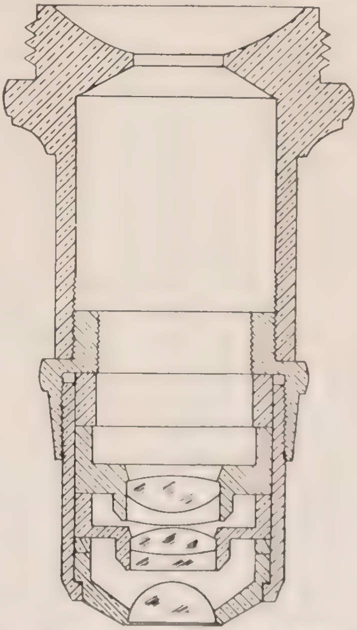
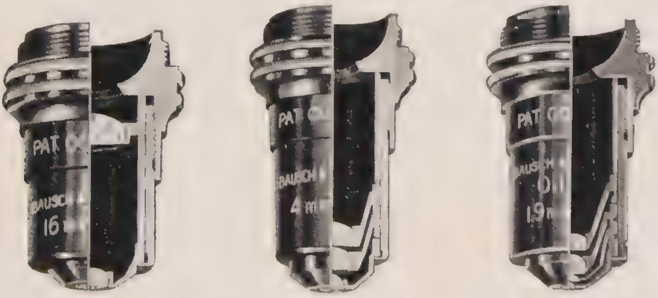


FIG. 12. A cross section of a 4-mm. achromatic objective.



(a) (b) (c)

FIG. 13.—Sectional views of objectives. (a) Achromatic objective 16 mm. (b) Achromatic objective 4 mm. (c) Apochromatic objective 1.9 mm. oil immersion. (*Bausch and Lomb Optical Co.*)

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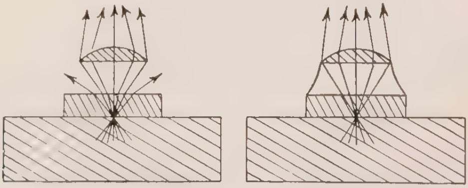
[1] Bausch and Lomb, and Spencer Lens Co. = 160 mm. Leitz = 170 mm. Winkel-Zeiss = 170 mm.

when the analyzing prism is inserted (unless the prism mount contains a correcting lens). Corrections can be determined by using stage and eyepiece micrometers.

The numerical aperture of a lens is the numerical aperture of the largest cone of light which the lens can cover from an object point at the principal focus. N. A. (the numerical aperture) equals $n \sin \mu$, where n is the index of refraction of the medium in front of the lens[1] and μ is one-half the angle of the cone of light entering the lens. Objectives of high numerical aperture have an increased resolving power.

The working distance is the distance between the objective and the top of the cover glass of the microscope slide when the objective is in focus.



(*a*) (*b*)

Fig. 14.—Diagram illustrating the convergence of light by means of cedar oil placed in front of the lens of an oil-immersion objective. (*a*) Air alone without cedar oil. (*b*) With cedar oil.

Oil-immersion objectives are used for high magnifications where a fine degree of resolving power and correction are required. The effect of cedar-oil immersion on the cone of light entering the front lens of an oil-immersion objective is shown in Fig. 14. A considerable advantage is also gained by placing a drop of oil between the auxiliary condenser lens and the microscope slide. The working distance of an oil-immersion objective is very short; the lenses are difficult to manufacture and are consequently expensive. A good immersion objective, however, gives a beautiful field with high magnification. The objective should be handled carefully, especially in focusing. After use the oil should be removed by the use of lens paper moistened with xylol or benzine.

Microscope Accessories. The accessories provided with the microscope generally include a quartz wedge, gypsum pl

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[1] Air ($n = 1$) in the case of a dry objective, and specially prepared cedar oil ($n = 1.515$) in an oil-immersion objective.

mica plate. These are marked with arrows indicating the fast- and slow-ray vibration directions and are mounted in frames to fit the opening in the tube of the microscope between the objective and the analyzer.

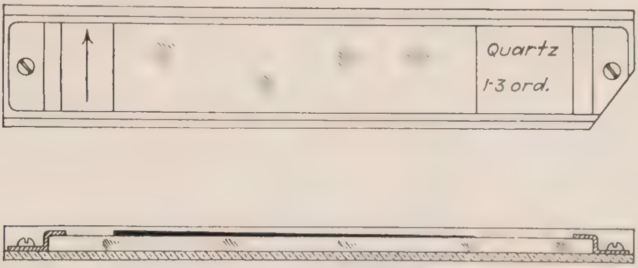


Fig. 15.—The quartz wedge mounted on a glass plate and in a metal frame. (*Spencer Lens Co.*)

The quartz wedge is ground to produce interference colors from the beginning of the first to the end of the third or fourth order. It is marked and mounted as shown in Fig. 15.

The mica plate and gypsum plate (German = *Glimmer* and *Gips*) together with a centering pin are illustrated in Fig. 16.

(*a*) (*b*) (*c*)

Fig. 16.—The gypsum plate (*a*), mica plate (*b*), and a centering pin (*c*). (*E. Leitz, Inc.*)

N' is the slow-ray direction in the mica and gypsum plates (Leitz microscope).

Analyzer. The prism mounted in the tube of the microscope above the objective is known as the analyzer. It is usually [illegible]t on a sliding mount so that it may be inserted or withdrawn from the optical axis at will. The plane of vibration is usually either perpendicular or horizontal in the field of view.

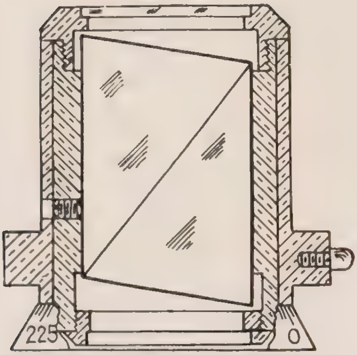


Fig. 17.—Sectional view of a polarizing prism. (*Spencer Lens Co.*)

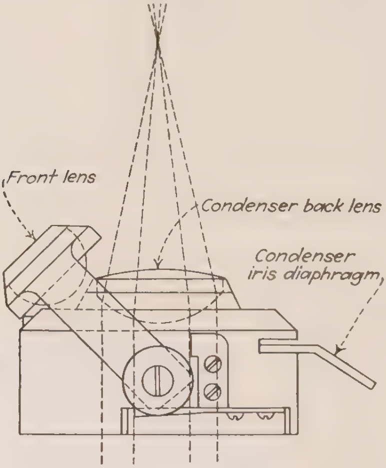


Fig. 18.—A section illustrating the construction of the condenser system. (*Spencer Lens Co.*)

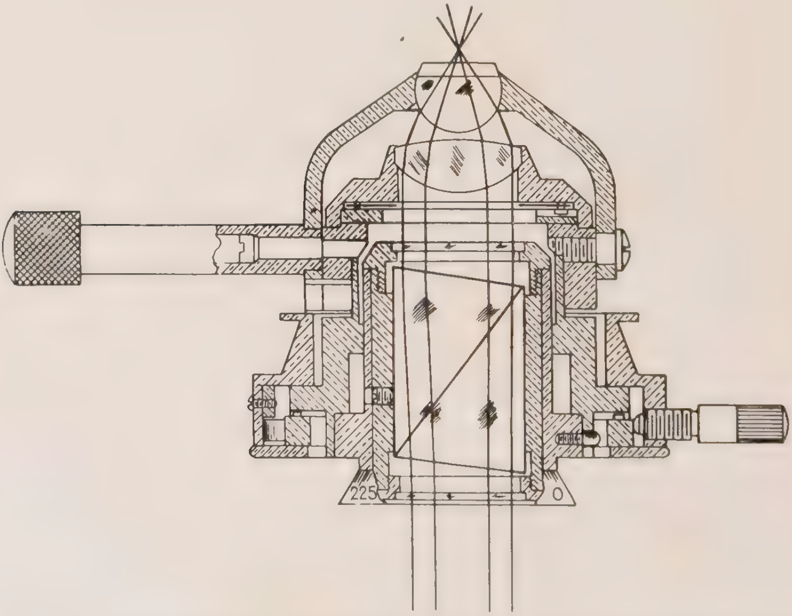


Fig. 19.—The arrangement of the polarizer below the condenser. (*Spencer Lens Co.*)

More elaborate microscopes are fitted with a means for rotating the analyzer through 90°.

Polarizer.—The prism mounted in the substage system below the condenser is known as the polarizer. It is arranged for any adjustment through 360° but is usually kept adjusted to a plane at right angles to the plane of the analyzer. The position of the polarizer in its mounting is shown in Fig. 17.

Bertrand Lens.—This lens is inserted in the tube of the microscope between the ocular and the analyzer. It serves to bring the image of an interference figure into the focal plane of the ocular.

Interference figures may be observed without the Bertrand lens if the ocular is removed.

Condenser.—Three components may be present in a condenser system of the type selected for illustration. In ordinary examination with low-power objectives a lens component with an illuminating aperture of about 0.22 is used. When working with high power or obtaining interference figures, another condenser on a movable mounting swings across the axis (Fig. 18). This suffices for all objectives of N. A. up to 1.0. In the case of higher numerical apertures a special lens is inserted in place of the condenser in the movable mounting.

The arrangement of the condenser, together with the various adjustments for the polarizer, is shown in Fig. 19.

Iris Diaphragm.—The iris diaphragm is attached to the lower side of the tube which holds the polarizer. It serves to reduce the cone of light, lessening the illumination of the field of view, and causes objects to stand out with increased relief. The diaphragm is useful in the application of various tests when determining indices of refraction with the microscope.

Mirror.—The mirror is usually reversible with one surface plane and the other concave. The plane mirror surface is suitable for low-power microscopic work. The concave mirror converges the light upon the object. It is especially useful in high-power examination.

Fine Adjustment.—It is advantageous to have the fine adjustment graduated so as to permit the measurement of the displacement of the tube to within 2.5 μ (thousandths of a millimeter). The adjustment is used both for measuring depth and for focusing on objects at high magnifications. The relationship between a coarse and fine adjustment and the detail of the fine adjustment for one type of microscope are illustrated in Fig. 20.

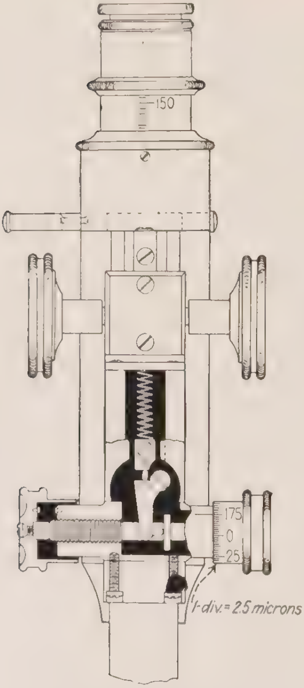


Fig. 20.—The fine adjustment. (*Spencer Lens Co.*)

Berek Compensator.—The compensator is designed to fit the tube slit above the objective in the same opening used for the gypsum and the mica plates. It is employed in the determination of the order of interference colors between crossed nicols.

The plate is inserted with the vibration directions opposed to those of the mineral being examined. The compensator is adjusted until the color of the mineral is neutralized (becomes gray). The amount of adjustment of the compensator necessary to bring this about is a measure of the retardation. A view of the Berek compensator appears in Fig. 21.

Precautions to Be Observed in the Use of the Microscope.—Even under the best conditions microscope work produces a certain amount of strain upon the eyes. It is essential, therefore, to employ the best possible conditions of work in order to reduce such strain to a minimum.

Fig. 21.—The Berek compensator. (*E. Leitz, Inc.*)

The student should assume an erect but not too rigid position. Such a position with the microscope tube inclined allows him to work with maximum comfort.

Both eyes should be kept open while looking through the instrument. If it is difficult to do this at first, a shield should be placed over the eye not in use. It is also a good plan to learn to observe equally well with either eye and not to develop the so-called *microscope eye.*

In laboratories requiring a large amount of routine microscopic work an attachment known as the *euscope* has been devised for projecting the image of the field on a small shielded viewing screen. The observer is seated directly in front of the screen and looks forward into a viewing box with the image on a screen at the opposite end as shown in Fig. 22.

Fig. 22.—The euscope developed originally for biological work but found to be useful for mineralogical work as well. (*Bausch and Lomb Optical Co.*)

The euscope has several applications for routine work. A ground glass may be inserted on the front of the instrument and used for microprojection. Grating lines may be ruled on the ground glass corresponding to the divisions of a stage micrometer, in which case the euscope will serve for microscopic measurement of grain size. The instrument is also adapted to hold a camera for taking photomicrographs of thin sections.

Care of the Instrument.—A polarizing microscope is an expensive piece of equipment. Properly used, it should last a lifetime. If not handled carefully, it may become useless with very little real service. Most of the precautions to be observed in the use of the instrument are such as should be applied to any piece of fine apparatus. A few, however, are of special nature and should be definitely mentioned.

Fine-textured lens paper, or, still better, a camel's-hair brush, should be used for cleaning all optical parts. This applies to the ocular, the objectives, the substage system, the mirror, and the two nicols.

Objectives should be brought into focus by moving the tube of the microscope upward rather than downward. Possibility of contact between the lower lens of the objective and the thin section is thus avoided. High-power or oil-immersion objectives should be cleaned with lens paper and xylol or benzine (not alcohol).

Chemicals should not be used on the stage unless special precautions are taken to protect the objective. Objectives may be protected by the use of cover glasses fastened to the lower lens. Occasionally an old objective is reserved for chemical work alone.

Magnification.—The microscope is primarily an instrument for magnification. It is worth while, therefore, to form at the outset an idea of the enlargement of the field of view with the various lens systems available. The following table outlines the various magnifications at the eye for different combinations of objectives with an equivalent focus of 40, 32, 16, 8, 4, and 2 mm. (oil immersion) and also oculars magnifying five, ten, and fifteen times, respectively.

MAGNIFICATIONS[1]

Type of objective	Equivalent focus, millimeters	Magnification number	Magnifications with oculars			Working distance, millimeters	N. A.
			5×	10×	15×		
Achromatic........	40	3.2	16	32	48	34.5	0.12
Achromatic........	32	4.3	22	43	65	27.0	0.15
Achromatic........	16	10	50	100	150	5.8	0.25
Apochromatic......	8	23	115	230	345	0.85	0.65
Apochromatic......	4	46	230	460	690	0.20	0.95
Apochromatic (oil immersion)......	2	92	460	920	1380	0.11	1.32

Tube length: 170 mm.

Image distance: 250 mm.

[1] After Leitz.

An accurate check of the magnification of the field of view in the microscope can be obtained by using a stage micrometer (Fig. 23). The stage micrometer is a glass slide carefully ruled into hundredths of a millimeter. It serves not only as a comparison object for determining the magnification of the microscope but also may be used to give the magnification of drawings, of projections, and of photomicrographs.

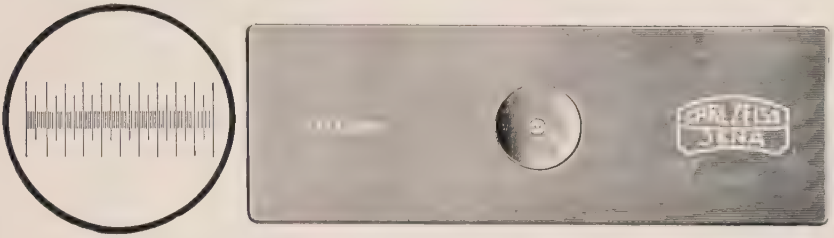
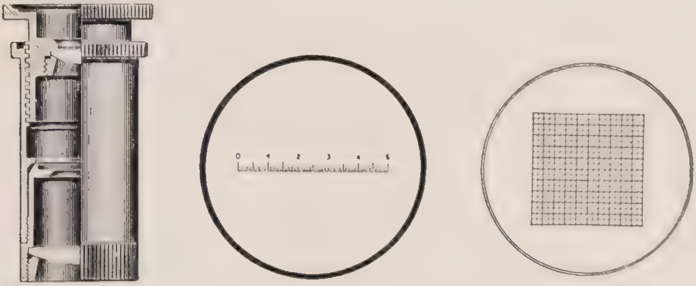


FIG. 23.—The stage micrometer. (*Carl Zeiss, Inc.*)

Micrometer eyepieces are also utilized when the dimensions of particular objects in the field of view are desired (Fig. 24*a*). Such eyepieces are useful in determining the axial angle of interference figures with the microscope. The eyepieces should be calibrated with the aid of the stage micrometers for various objectives. The dimensions represented by the divisions in the micrometer ocular (Fig. 24*b*) as observed at the eye are governed by relations between the objective, the eyepiece, the tube length, and by the presence or absence in the optical train of the analyzer.



(*a*) (*b*) (*c*)

FIG. 24.—(*a*) Micrometer ocular. (*b*) Scale in a micrometer ocular. (*c*) Grating micrometer. (*Carl Zeiss, Inc.*)

Micrometer eyepieces of the grating type (Fig. 24*c*) are employed to measure the areas of grains or fragments in the microscope field. These are also calibrated for different lens combinations with a stage micrometer.

Fig. 25.—Various types of artificial illumination for the microscope. (*a*) Small substage lamp. (*b*) Strong lamp for general utility. (*c*) Arc lamp for special studies or projection. (*Bausch and Lomb Optical Co.*)

Illumination.—At ordinary magnifications a good north light with a broad clear sky forms an excellent source of illumination for the polarizing microscope.

In case such illumination is not available, artificial daylight lights can be successfully employed. These consist of ordinary electric bulbs mounted in cases with a special blue-glass light filter in the path of the illumination. Two types are illustrated in Fig. 25.

At high magnifications and for photomicrographic work a mechanical-feed arc lamp is sometimes used. The beam from the arc is very warm and should always be passed through a cooling cell of water in order to avoid injuring the cement in the prisms of the microscope (unless special prisms are employed).

Adjustment of the Polarizing Microscope.—Four separate steps can be outlined as necessary to arrange the polarizing microscope in order for the examination of rock sections:

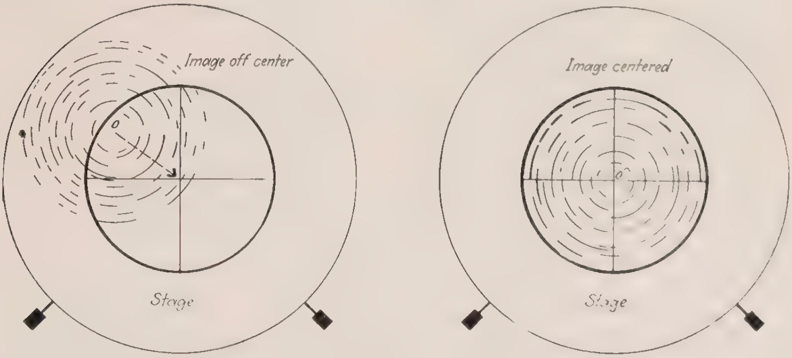


FIG. 26.—Diagram illustrating centering the field of view in the microscope.

1. Centering the stage with the field.
2. Crossing the nicols.
3. Testing the crosshairs.
4. Determining the vibration plane of the lower nicol.

1. *Centering the Stage with the Field.*—The stage is centered with the field by means of the centering screws on the side of either the objective or the stage (Fig. 26). In some microscopes both are adjustable. A simple procedure is usually followed. While looking through the instrument at the field of view on the slide, rotate the stage. The images of objects on the stage of the microscope describe concentric circles of rotation. The purpose of centering is to bring the center of these circles of rotation into coincidence with the axis of the microscope marked by the intersection of the crosshairs. This is accomplished by alternately moving the centering screws and checking the position

of the center of the circle of rotation until the center falls on the intersection of the crosshairs through 360° of rotation.

2. *Crossing the Nicols.*—The planes of vibration of the two prisms should be set at right angles to each other. The plane of vibration of the analyzer is usually fixed by the manufacturer either from left to right or up and down as one observes the microscopic field. The lower nicol is adjusted at right angles by rotating it in the substage collar until the field becomes dark with both nicols in the path of light. The nicols should remain in the position giving maximum darkness.

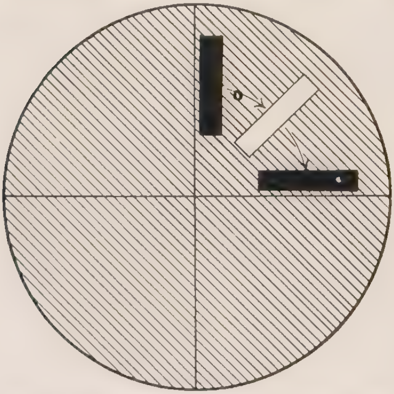


FIG. 27.—Testing the adjustments of the crosshairs with natrolite fragments.

3. *Testing the Crosshairs.*—The crosshairs in the ocular may be either the spiderweb type or lines engraved on a glass plate. In either case it is important that the hair lines be parallel to the planes of vibration of the two nicols. Ordinarily these are set by the optical firm supplying the microscope, and the ocular is so arranged that it will not fit the tube of the microscope in other than the correct position. The adjustment should be checked occasionally, however, and in case the alignment is inaccurate, the crosshairs should be reset by an experienced technician.

A slide containing elongated rectangular crystals of natrolite (Fig. 27) is useful to test the setting of the crosshairs with the planes of the nicols.[1] The natrolite becomes dark between crossed nicols when the edges of the crystals are parallel to the vibration directions. A slide containing a small natrolite crystal may be placed upon the stage between crossed nicols and turned until it becomes dark. If the crosshairs are in adjustment, the web lines should be parallel or at right angles to the straight lines of the crystal. This is true in each of the four positions of extinction. In 45° intermediate positions the natrolite will show maximum illumination.

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[1] If natrolite is not available, any crystalline material with straight-line edges and parallel extinction may be substituted.

4. *Determining the Vibration Plane of the Lower Nicol.*—After the other adjustments have been made, the vibration direction of the lower nicol can be determined with either fibrous tourmaline fragments or a rock section containing biotite showing cleavage.

Tourmaline (Fig. 28*a*) has maximum absorption when it is oriented with the *c*-axis (usually the long direction of a crystal or fragment) in a direction at right angles to the plane of vibration of the polarizing prism. Biotite (Fig. 28*b*), on the other hand, is darkest when the cleavage is parallel to the vibration direction. Note the positions of greatest and least darkness, observing with the upper nicol thrown out from the tube. These indicate either the vibration direction or the normal to the vibration direction, depending upon whether the slide is biotite or tourmaline.

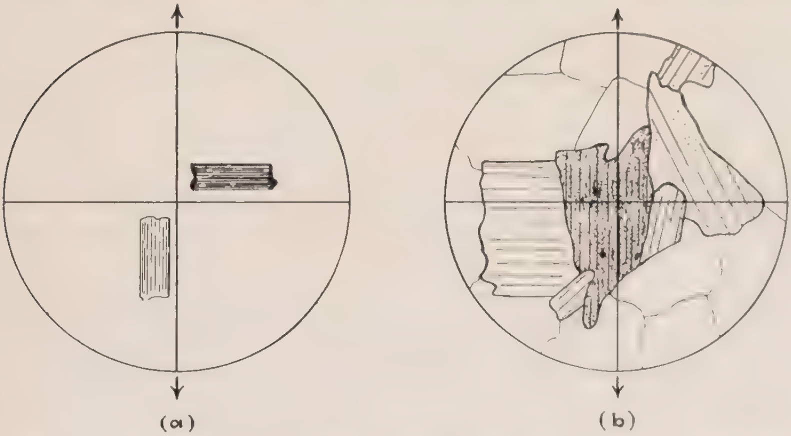

FIG. 28.—Determining the vibration plane of the lower nicol. (*a*) Elongated tourmaline fragments. (*b*) Biotite in thin section.

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Much useful information may be obtained from the catalogues of various optical firms:

Bausch and Lomb Optical Co., Rochester, N.Y.
E. Leitz, Inc., 60 East Tenth St., New York.
Spencer Lens Co., Buffalo, N.Y.
Carl Zeiss, Inc., 475 Fifth Ave., New York.

CHAPTER III

A SUMMARY OF THE PROPERTIES OF LIGHT

Theories of Light.—Since light crosses interstellar space penetrates transparent solids or liquids, and also travels through a vacuum, a medium has usually been postulated by which it could be conveyed. The medium is the ether, which has been assumed to permeate all matter and to pervade all space. Modern studies have shown, however, that in order to account for certain things the ether must be endowed with the most extraordinary physical properties, and according to some concepts it is unnecessary. The source of the light and its effect on the eye are apparent, but some explanation must be advanced to account for its transmission.

Several prominent theories have been advanced. According to one, a beam of light consists of a stream of minute particles, or "corpuscles," given off at high velocity by the sun or any luminous body. The corpuscles travel through space in straight lines and eventually reach the eye. This is generally referred to as the corpuscular theory, a theory which received much attention because it was supported by the famous physicist Sir Isaac Newton.

Another theory was first advanced by the Dutch scientist Christian Huygens in the latter part of the seventeenth century. According to Huygens, the ether is supposed to vibrate and light is transmitted through it by the vibration of particle after particle in waves. The phenomena of light such as reflection, refraction, diffraction, and interference may be readily explained in accordance with this theory. The theory of Huygens, however, failed to explain the apparent rectilinear motion of light and was not accepted by Newton.

A modification of the wave theory was proposed by the Scottish physicist James Clerk Maxwell (1873), who considered light as made up of waves but said that the waves were electromagnetic. According to Maxwell, a wave consists of rapidly alternating electric and magnetic fields normal to each other and normal to the direction of propagation of light. Hertz (1888) succeeded in producing waves having properties similar to light waves by electricity. As a result of the work of Maxwell, Hertz, and other experimenters, the electromagnetic theory of wave motion was for a time generally accepted.

Toward the end of the last century evidence began to appear that did not accord with the electromagnetic theory. It was found that the space around certain metals would become electrically conductive when the metal was exposed to light. Then the electron was discovered in 1897, and it was assumed that the photoelectric effect was due to the emission of electrons as the metal became exposed to light. This was based on the fact that expulsion means energy, and it was presumed that the energy in the case of the photoelectric effect would come from light. However, the energy given by light is so small that it could not account for the emission of electrons. This led to the assumption that the light was concentrated in points and not uniformly distributed. At about this time Planck developed the assumption that radiating oscillators in a black body radiate energy discontinuously in units called *quanta*. Einstein in 1905 suggested that the absorption of light in the photoelectric process might also be in quantum units. Later experiment demonstrated that the quanta of Einstein were of the same size as those postulated by Planck.

As a result of these more recent developments the explanation of light seems to rest upon two contradictory theories, the wave theory being more appropriate for phenomena such as reflection, refraction, interference, diffraction, and polarization, while the quantum theory is more applicable to the recent discoveries in the field of X-rays, radiation, and photoelectricity. Speaking of the two theories, Einstein has recently stated as follows:

> We have good proof that both waves and particles exist. Our present effort is to understand how this is, to find a theory that will unify the nature of light. The composition of a two-point view has not yet been found. It is a quest of science in which our present methods are imperfect.

Nomenclature of the Wave Theory.—The nomenclature of the wave theory used in this text is summarized in the following paragraphs.

Vibration direction = electric vector = electrical displacement. The vibration direction lies in the wave front and is not perpendicular to the ray in anisotropic crystals except in limited directions.

Wave Front.—The surface determined at a given instant by all the parts of a system of waves traveling along the same direction and in the same phase. In space, in air, or in any other optically isotropic media when light moves along parallel lines the wave front is perpendicular to the direction of transmission.

Wave Length.—The distance between two successive crests or troughs, or any corresponding distance along the wave (denoted by the Greek letter lambda, λ). λ is usually measured in millionths of a millimeter ($m\mu$).

Beam.—A group of light waves following along the same path. A familiar example is the white beam of a motion-picture projector clearly visible in the dusty atmosphere of the theater. Beams can be made narrower and narrower.

Ray.—The limiting case of a beam is a single line and is called a ray. The ray is perpendicular to the electrical field and follows the direction of propagation of the energy. It indicates the direction of the transmission of the wave motion.

Refractive Index.—The refractive index is equal to the ratio of the wave-normal velocity in a vacuum to the wave-normal velocity (not the ray velocity) in the medium whether isotropic or anisotropic.

Frequency.—The number of vibrations in a given unit of time. Ordinarily several trillion per second in the case of light waves.

Phase.—The relative position of corresponding points on different waves moving along the same line. Two points on waves are in the same phase when they are in the same relative position in regard to the crest or trough of the wave and are both moving either toward or away from the line of transmission. Two points are in opposite phase when in the same relative position but moving in opposite directions with reference to the line of transmission. Other phase differences may occur.

The phase difference may be termed more appropriately the *path difference.*

Amplitude.—The maximum displacement of a wave from the line of transmission.

Period.—The time interval necessary for a wave to undergo a complete oscillation.

Crest.—The point of the wave with the maximum upward displacement.

Trough.—The point of the wave with the greatest downward displacement.

Monochromatic Light.—Light of a single wave length. In practical tests light is frequently used covering a small range of wave lengths but appearing as one color to the eye.

Light Vector.—The action of light may be described as depending upon the periodic alternation of a right vector which lies parallel to the plane of the wave front and in isotropic media is perpendicular to the direction of propagation. In anisotropic media the vector is still parallel to the plane of the wave front but, aside from certain limited positions, is not perpendicular to the direction of propagation.

In the case of monochromatic light the light vector follows the laws of simple-harmonic motion, the vibration period T depending upon the color of the monochromatic light. The wave length λ—*i.e.*, the distance between two successive like points on a wave train—is equal to the velocity of propagation v multiplied by the vibration period:

$$\lambda = vT$$

In any transparent mass λ is fixed and v varies with T. The intensity of light is the average of the intensities in the various light vector quadrants and varies with the amplitude.

If the light wave is electromagnetic, there must be two vector movements in the system. In isotropic media these are transverse and perpendicular to each other, one limited by the magnetic field of force, the other by the electric field of force. These are connected with two other vectors distinguished in isotropic media by their magnitude and in anisotropic media also through variation in direction. These two vectors may be called the *electric vector* and the *magnetic vector*. The first of these measures the electrical displacement, the second the magnetic displacement or induction. Maxwell has worked out equations applicable to the movement of these vectors (although the movement had been originally worked out before vector analysis was introduced). Experimental evidence has shown that the vibration direction of light corresponds to the electrical displacement (electric vector) in isotropic bodies. In anisotropic bodies it has been shown to correspond to either the electrical displacement (electric vector) or the electrical field. In the electromagnetic theory light is assumed to correspond to the electrical displacement (electric vector), an assumption made plausible by the conception of light as an electrolysis.

Speed of Light.—Light waves travel along the direction of transmission at a speed of approximately 186,284 miles per second. The same law of frequency used in the case of sound applies to light and is expressed by the equation:

$$n = \frac{v}{\lambda}$$

or

$$v = n\lambda$$

In this equation the frequency n is obtained by dividing the velocity v by the wave length λ. In the case of violet light ($\lambda = 0.000037$ cm.) the velocity ($v = 186{,}284$ miles per second) divided by the wave length gives a frequency of 800,000,000,000,000 (eight hundred trillion) vibrations per second.

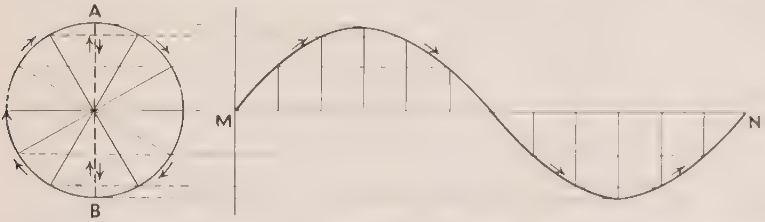

Fig. 29.—The harmonic curve produced by movement around a circle combined with motion along a straight line.

Wave Motion.—An idea of the behavior of light waves may be gained by a study of waves generated by simple-harmonic motion and uniform rectilinear motion.

Simple-harmonic motion is uniform motion in a circular path as it would appear projected on the diameter of a circle. If a particle as illustrated in Fig. 29 is assumed to move clockwise around the circumference of a circle, occupying various positions in turn, the projections on the vertical diameter AB will be at the intersections with the horizontal dotted lines shown in the figure. If observed from the side along the plane of the circle, the particle will appear to oscillate back and forth with varying velocity. If, in addition to the harmonic motion, the particle moves along a straight line MN at a uniform rate (rectilinear motion), it will no longer move in a circular path but will follow a curve of the type illustrated in the projection. The projection on the vertical diameter of the circle, however, will still be the same. The curve is a harmonic curve, which has the form of a sine curve.

Differences in path produce a number of resultant forms when two or more waves follow the same line (Fig. 30). Two sets of waves may be equal and opposite, thus nullifying each other (Fig. 30*a*). Other sets may be equal in amplitude and wave length but differ in phase. The latter sort will produce a resultant *R* of intermediate crest and increased amplitude (Fig. 30*b*).

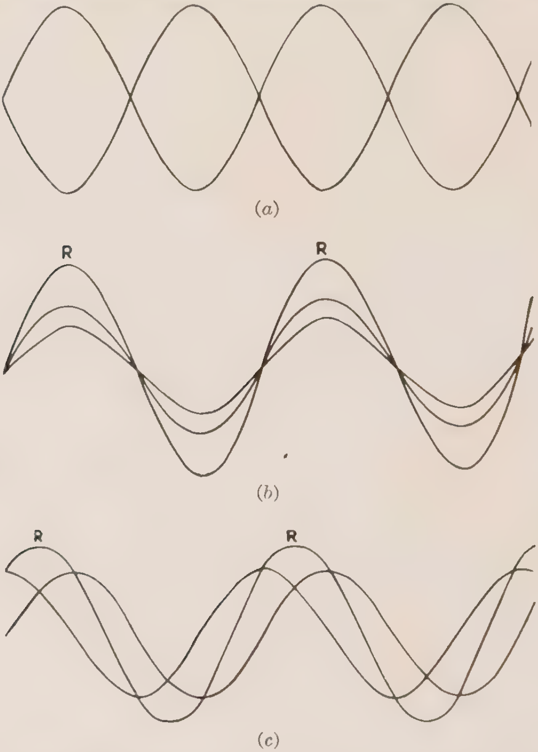

Fig. 30.—Combinations of waves produced by several phase differences. (*a*) The path difference is ½ λ, and the two waves are equal and opposite in phase. (*b*) The resultant wave (R) produced by two equal waves of slight path difference. (*c*) The resultant wave (R) produced by two waves of equal length and identical phase, but differing in amplitude.

When two waves are equal in phase, wave length, and period but differ in amplitude, a resultant *R* is produced of the same phase and wave length with increased amplitude (Fig. 30*c*).

The Color of Light. The brightness of a ray is determined by the amplitude of the wave vibration. Light, on entering various bodies, undergoes a change in velocity. A corresponding change must occur, therefore, in either the wave length or the frequency. Since the vibration period remains the same for a given color, the change occurs in the wave length. The wave length will differ even for the same color in different bodies; thus the number of vibrations per second or the frequency of the waves reaching the eye determines the color.

Waves of visible light vary in length, the longest being red and the shortest violet. The portion of the spectrum directly visible to the eye varies between relatively narrow limits. The extreme wave length of red light is 0.0000759 cm., and the relative wave length of extreme visible violet is 0.0000393 cm. In terms of millimicrons (the units commonly employed in dealing with light), the figures are:

Red light = 759 $m\mu$
Violet light = 393 $m\mu$

White light, or ordinary light, is a combination of all of the different wave lengths visible to the eye in one simultaneous effect. When only one wave length is observed, light is singly colored, or monochromatic. White light may be considered composed of seven different colors. These grade into each other, forming a continuous spectrum. The colors of the spectrum are frequently represented by arbitrarily chosen wave lengths representing mean values of the various colors, as follows:

Red = 700 $m\mu$
Orange = 620 $m\mu$
Yellow = 560 $m\mu$
Green = 515 $m\mu$
Blue = 470 $m\mu$
Indigo = 440 $m\mu$
Violet = 410 $m\mu$

The electromagnetic spectrum extends far beyond the range of visible light. The mechanisms by which the different radiations are produced, however, must be much different because of the great difference in frequency.

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CHAPTER IV

REFRACTION

Snell's Law. The Index of Refraction.—When light passes obliquely from one medium to another in which it travels with a different velocity, it undergoes an abrupt change in direction. This abrupt change in direction is known as *refraction.*

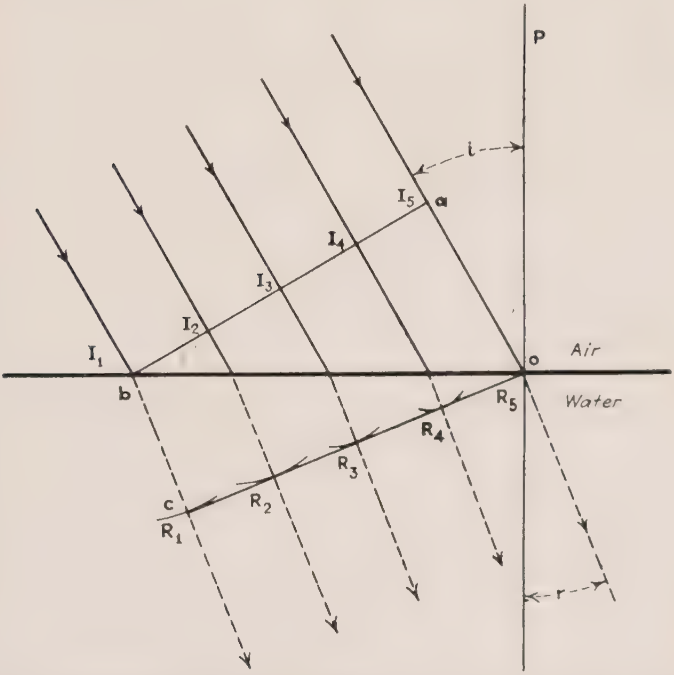

FIG. 31.—Light being refracted on passing from a rare into a denser medium.

Let us suppose, for example, that a rare medium—air—is in contact with a denser medium—water—as illustrated in Fig. 31. An incident beam I strikes the surface of the water obliquely, making an angle i with a perpendicular P. When the trace of the plane normal to the incident beam I strikes the surface at I_1, the point I_5 is still a considerable distance above the bounding plane. The positions I_2, I_3, and I_4, together with corresponding intermediate points, are also above the surface.

Let the beam advance until the ray at I_5 has reached R_5. During this advance the ray at I_1 has penetrated the denser medium and has continued with diminished velocity until it has arrived at the circumference of a circle with a radius I_1R_1, which represents the distance traveled in the denser medium. Similarly, I_2 has penetrated to the circumference R_2, I_3 to R_3, and I_4 to R_4. A tangent common to these circles represents the new wave front, and the new beam is perpendicular to the new wave front.

In the above construction the distances I_5R_5 and I_1R_1 may be considered proportional to the relative velocities of light in the two media.

It is apparent from the relationship of the lines of the diagram that

$$\sin i = \frac{ao}{bo}$$

or

$$bo = \frac{ao}{\sin i}$$

also,

$$\sin r = \frac{bc}{bo}$$

or

$$bo = \frac{bc}{\sin r}$$

Since bo is common, the equations may be combined, and

$$\frac{ao}{\sin i} = \frac{bc}{\sin r}$$

or

$$\frac{ao}{bc} = \frac{\sin i}{\sin r}$$

The index of refraction is determined by the distance light will travel in a given time interval through a transparent substance as compared with air. In Fig. 31 light travels the distance ao in air, while it travels the distance bc in water. It follows, therefore, that the index of refraction

$$n = \frac{ao}{bc}$$

or

$$n = \frac{\sin i}{\sin r}$$

It appears from the above equation that for any angle of incidence *the ratio of the sine of the angle of incidence to the sine of the angle of refraction is a constant.* It is also true that the respective velocities of light in the two media bear the same ratio. The relationship between the sines of the two angles and the velocities is known as Snell's law. It was discovered by Snell in 1621 but was not made known until after his death.

Let n be the index of refraction of a transparent material referred to air.[1] Then V = the velocity in air, and v = the velocity in the transparent material; also,

$$n = \frac{V}{v}$$

If n_1 and n_2 are the indices of refraction of two different materials, then

$$\frac{n_1}{n_2} = \frac{v_2}{v_1}$$

Thus the indices of refraction of two transparent substances are inversely proportional to the velocities of light in the two media.

The angles i and r may be measured experimentally for many substances, thus determining n. The index of refraction depends both upon the substance and upon the kind of light. The indices of isotropic substances or general values are designated by the letter n. The extreme values for hexagonal or tetragonal minerals are designated by n_ϵ and n_ω. Orthorhombic, monoclinic, and triclinic crystals have their extreme values designated by n_γ (greatest), n_α (least), and n_β, the value in a direction at right angles to the two others.[2] The following table gives examples of values for the indices of refraction of several well-known minerals that occur throughout the normal range:

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[1] The refractive index of dry air at 760 mm. pressure referred to a vacuum is only slightly different from unity (1.000274 at 15° C.); therefore indices of refraction of material substances referred to air are approximately equal to their indices referred to a vacuum (the latter are called the *absolute refractive indices*).

[2] In American technical journals dealing with optical descriptions of minerals most authors omit the letter n and use the Greek letters α, β, γ, ϵ, and ω alone in recording indices of refraction outside the isometric system.

Minerals	(Na$_D$)	Indices of refraction
Fluorite	....	$n = 1.4338$
Quartz[1]	....	$n_\epsilon = 1.5533$; $n_\omega = 1.5442$
Calcite[1]	....	$n_\omega = 1.6585$; $n_\epsilon = 1.4863$
Apatite[1]	....	$n_\omega = 1.6461$; $n_\epsilon = 1.6417$
Aragonite[1]	....	$n_\alpha = 1.5301$; $n_\beta = 1.6816$; $n_\gamma = 1.6859$
Garnet (grossularite)	(Yellow)	$n = 1.7714$
Sphalerite	(Yellow)	$n = 2.3692$

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[1] Quartz, calcite, and apatite are anisotropic with a range of values for refractive indices between n_ϵ and n_ω, the two extremes. Refractive indices of aragonite vary between n_γ and n_α.

Ordinarily, transparent minerals with a high index of refraction (1.9 or more) have the brilliant appearance called adamantine luster, while minerals with a lower index of refraction have a vitreous luster.

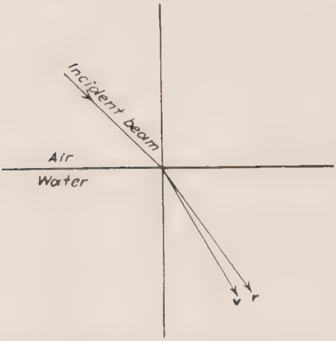


FIG. 32. —Variation in the angles of refraction for light of different colors.

Dispersion.—The index of refraction for the violet end of the spectrum is greater than for the red end of the spectrum, and on refraction red is deviated less than violet. The ordinary refraction of the two is indicated in Fig. 32.

The difference between the index of refraction for red and the index for violet is often briefly referred to as the dispersion. A prism cut as illustrated in Fig. 33 produces a beautiful display of spectrum colors. The difference between the angle d_r and the angle d_v registers the dispersive power of the prism.

Minerals differ widely in their dispersive power. One having the least dispersion is fluorite; a mineral with one of the highest values is diamond. The "fire" or brilliant play of colors of the cut diamond is due to the high dispersion from the prism-like faceted gem stone. Fluorite, on the other hand, if cut and faceted appears correspondingly dull. Because of its low dispersion optically clear fluorite is in demand for microscope lenses of high magnification to be corrected for chromatic variation. Comparative figures for the dispersion of fluorite and the diamond are given:

Fluorite		Diamond	
Illumination	Index of refraction, *n*	Illumination	Index of refraction, *n*
Red K(A'), $\lambda = 768.2$	1.43095	Red (B line)	2.40735
Violet H(G'), $\lambda = 434.1$	1.43963	Violet (H line)	2.46476
Dispersion	0.00868	Dispersion	0.05741

All minerals have some dispersive power, but fluorite and diamond represent approximately the two extremes.

On account of the dispersion of minerals, accurate determinations of indices of refraction are made with monochromatic light.

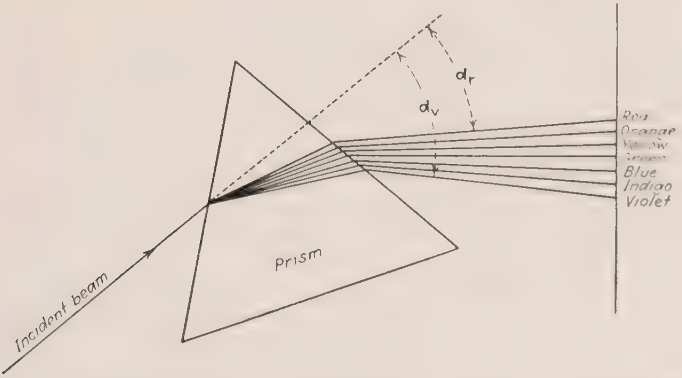


FIG. 33.—Diagram illustrating the dispersive power of a prism. (Color positions are only approximated.)

In routine study, however, the highest accuracy is seldom necessary, and white light is generally employed. As a matter of fact, white light as usually employed in determining mineral indices gives an average value for practical purposes somewhat comparable to yellow. The dispersive effect with white light is also extremely useful for several common tests.

Critical Angle.—In the formula $n = \sin i / \sin r$ the angle of incidence may vary between 0 and 90°. When $i = 0°$, the incident beam strikes the bounding surface at right angles. Sin *i* in this case = 0, and *r* must also equal 0. Thus an incident beam going from a rarer medium into a denser one is not refracted to either side but merely suffers a loss of velocity.

If $i = 90°$, $\sin i = 1$, and the equation becomes $n = 1/\sin r$. In this case, since n is a constant for a particular substance, the angle of refraction also becomes fixed. When $i = 90°$, the angle of refraction is known as the *critical angle.* The critical angle is important in the practical determination of indices of refraction.

Total Reflection.—Figure 34 shows light going from water into air (or from a denser medium into a rarer medium). A ray striking the surface of the water vertically from below continues out into air along the same path. If the path deviates from the vertical, the beam is refracted—*i.e.*, bent away—from the perpendicular at the surface. When an angle of 48°31′ with the vertical is reached (the critical angle), the beam grazes the surface. For any angle greater than the critical angle, however, light is reflected downward. This phenomenon is known as *total reflection.*

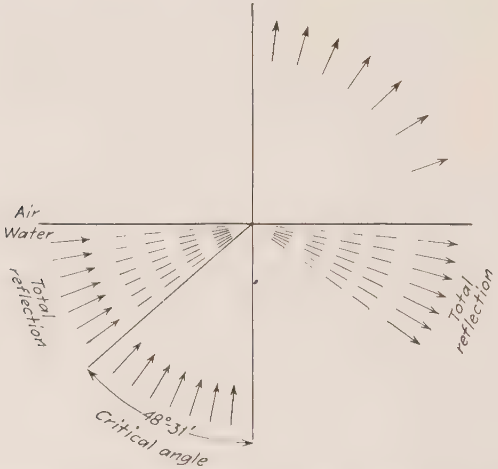


Fig. 34.—The relation between refraction of light passing from a dense medium into a rare medium and reflection beyond the critical angle.

If the angle with the perpendicular is increased until light travels along the surface between the air and water or strikes the surface at a grazing incidence, the beam is turned downward at the critical angle on the opposite side of the perpendicular to the bounding surface.

The same principle applies to all dense substances in contact with air. In practical determinations with a refractometer a glass hemisphere of high refractive index serves as the dense medium; light is directed against the hemisphere by a mirror, and the critical angle is determined with a measuring telescope.

Indices of Refraction of Anisotropic Minerals.—Optically, minerals belong to two classes: (1) isotropic and (2) anisotropic.

Minerals such as opal, glass, and other substances lacking regular internal structure and other minerals such as diamond, garnet, spinel, fluorite, etc., crystallizing in the isometric system are isotropic. Minerals crystallizing in the other crystal systems are anisotropic.

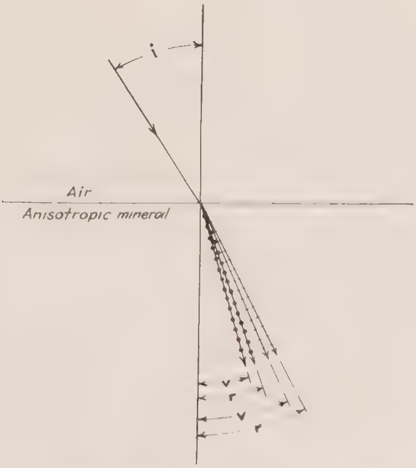


Fig. 35.—A diagram illustrating the variation of the angle of refraction for red and violet in an anisotropic mineral.

Light traveling through anisotropic minerals is doubly refracted as well as refracted. Thus a beam of monochromatic light passing obliquely from air into an anisotropic medium is not only bent to one side but is also broken into two beams. At the same time each of the two beams is polarized—*i.e.*, limited to a single plane of vibration, as will be explained in the chapter on polarized light. In addition each beam is differently refracted for different colors of light.

Double refraction of two rays occurring in anisotropic minerals is illustrated in Fig. 35. The incident beam is broken into two sets of rays, white light producing two dispersed spectra with opposite directions of vibration. Monochromatic red light will yield two angles of refraction, and monochromatic violet light will also yield two different angles. In each case of monochromatic light and also in the case of white light the directions of vibration are opposed but may not be exactly at right angles in the mineral. On emerging into air on the opposite side of a mineral plate, however, the vibration is at right angles.

Measurement of Indices of Refraction by Refractometers.—Several types of refractometer have been devised for determining the indices of refraction of liquids or of solids. A glass hemisphere is utilized in different ways.

Figure 36 illustrates the determination of the index of refraction by the method of total reflection. Light is directed against the surface of a glass hemisphere from below at an angle of refraction greater than the critical angle. The light rays are reflected downward from the upper surface of the hemisphere and emerge on the opposite side. The material to be determined, either a mineral plate with a polished lower surface or a liquid, is placed on the hemisphere. If the material is a mineral plate, a thin film of oil of high refractive index is placed between the hemisphere and the mineral. The light from the mineral is reflected through the hemisphere in part and produces an image in the observing telescope focused at *o*, as illustrated in the figure. The upper half of the field will be dark, while the lower half is illuminated (or *vice versa* if the image is inverted). If monochromatic light is used and the mineral is isotropic, the boundary between

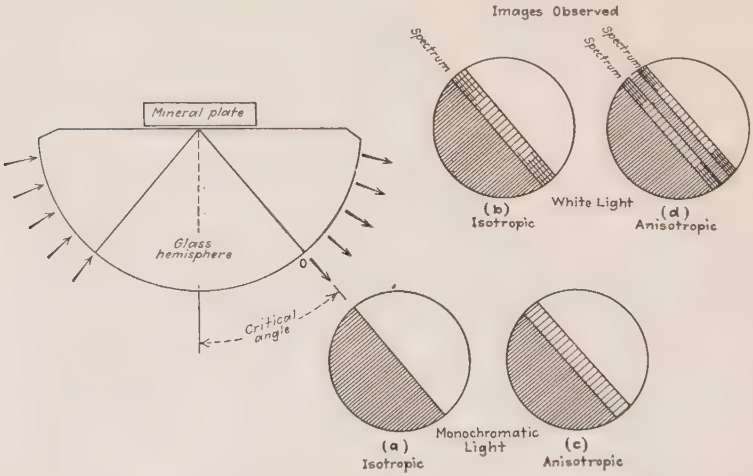


FIG. 36.—Illumination from below in determining the critical angle by total reflection.

the light and dark areas will be sharp, marking the critical angle accurately (Fig. 36*a*). On the other hand, in the case of white light the colors of the spectrum lie *between* the light and dark areas (Fig. 36*b*). If the mineral is anisotropic and the observation occurs with monochromatic light, two boundary lines will be seen spaced a short distance apart (Fig. 36*c*). If an anisotropic mineral is observed with white light, the two boundaries will be marked by spectra (Fig. 36*d*). When the anisotropism is not strong, the two spectra frequently overlap. The light waves of each image from the anisotropic mineral are polarized at right angles to the other.

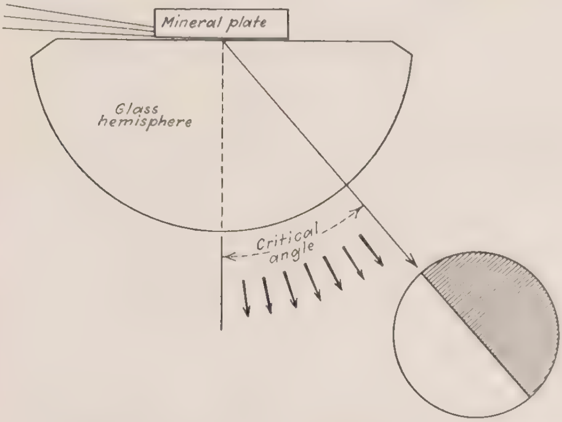
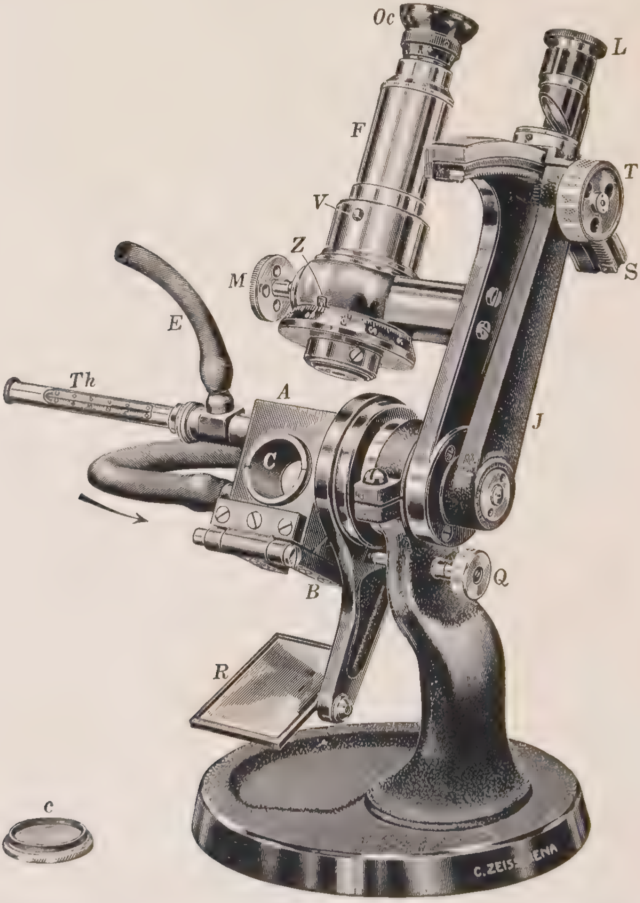


Fig. 37.—Determination of the index of refraction with the incident beam grazing the surface of the hemisphere.

Instruments operating on this principle are arranged with graduated scales and verniers for measuring the critical angle. When the critical angle is known, the index of refraction is computed from Snell's law, sin i being equal to 1. The wave length is controlled at the source by using monochromatic light.

The method of grazing incidence can be applied with the same glass hemisphere used for the method of total reflection. Light enters the mineral from the side and is refracted downward through the hemisphere as shown in Fig. 37. In this case the upper half of the field of view is dark, while the lower half is illuminated. Otherwise, the same principles prevail that apply to the other method. The contrast between the two fields is more pronounced when the mineral is illuminated by grazing incidence.

Whether employing total reflection or grazing incidence, the index of refraction of the glass hemisphere must be accurately known. This is usually ascertained by determining the index



AB = double prism in cooling chamber
C = illuminating prism
E = cooling tube; water circulates in direction of arrow.
F = telescope tube
J = holding arm for movable sector
L = reading lens
M = adjustment for compensator
Oc = eyepiece
Q = clamp
R = illuminating mirror sending light to *AB*
S = sector with engraved scale
T = turning gear
Th = thermometer
V = adjustment screw
Z = compensator scale

FIG. 38.—The Abbe refractometer. (*Carl Zeiss, Inc.*)

of refraction by total reflection in reference to air with the mineral plate removed, before determining the index of refraction of the mineral. The index of the liquid used for mounting the mineral plate can also be determined by total reflection if a few drops are smeared on the upper surface of the hemisphere. The refractive index equation for the determination of the mineral may be stated:

$$n\ (\text{mineral}) = n\ (\text{glass}) \times \sin r$$

where n (mineral) = index of refraction of the mineral
n (glass) = index of refraction of the hemisphere
r = critical angle for the mineral as read with the refractometer

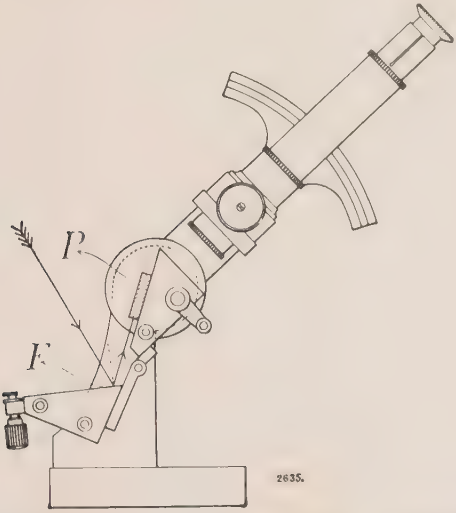


FIG. 39.—Sectional view of the refractometer. (*Carl Zeiss, Inc.*)

The glass used in constructing hemispheres has a high index of refraction, usually about 1.80. The mineral should have a polished surface to be placed toward the hemisphere, and a liquid with a high index of refraction is pulled by capillary attraction between the mineral and the hemisphere. Methylene iodide ($n = 1.74$) is usually preferred for this purpose.

Figure 38 is an illustration of one of the standard Abbe (Zeiss) refractometers commonly used in determining the indices of refraction of liquids (also of minerals and crystals). The refractive index is read off a graduated sector, and the instrument may be quickly set for reading directly. A scale is arranged in the image of the eyepiece which gives the values of indices of refraction for all angles within the range of the instrument, which extends from $n_D = 1.3$ to $n_D = 1.7$.

A refractometer of this type consists essentially of a double prism *AB* which receives the liquid to be tested, a telescope for viewing the line of the critical angle, and a scale sector *S* for reading the angle. The double prism is made up of an illuminating prism *F* (Fig. 39) with a ground-glass surface and a refracting prism *P* which operates on the principle of grazing incidence. The refracting prism takes the place of the glass hemisphere in other refractometers. A compensating device is inserted in the telescope to approximate monochromatic light (D line of sodium). The refractometer is usually adjusted for use by testing the instrument with a glass plate of known index.

Index of Refraction by the Prism Method.—In Fig. 40 a beam of monochromatic light strikes the prism *ABC*. At *AB* the beam R is bent toward the perpendicular *OP*. At *BC* the beam R′ emerges and is bent away from the perpendicular *O′P′*. R′ continues in a straight line from this point, making an angle of deviation *d* with the original direction.

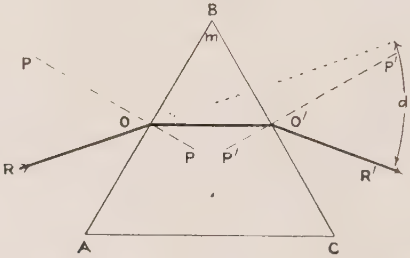


Fig. 40.—A beam of light bent to one side by passing through a glass prism.

If the angle R′ is known when the angle *d* is the minimum which can be observed when the prism is turned with respect to the beam (the angle of minimum deviation), and the angle *m* of the prism is also known, the index of refraction of the glass of the prism may be computed. The formula by which the index is computed is

$$n = \frac{\sin \tfrac{1}{2}(d + m)}{\sin \tfrac{1}{2}m}$$

m = angle of the prism
d = angle of minimum deviation of the beam
n = index of refraction of the prism

The above formula is particularly useful for determining the indices of refraction of glass prisms, transparent crystals, and hollow prisms filled with oil. A prism is adjusted vertically on a one-circle goniometer, and the prism angle measured by obtaining reflections first from one side and then from the other and reading the angle on the graduated circle. With the same set-up a beam of light is passed through the prism and the angle of minimum deviation is measured. The index of refraction is then computed directly from the formula given above, utilizing the angle of the prism and the angle of minimum deviation.

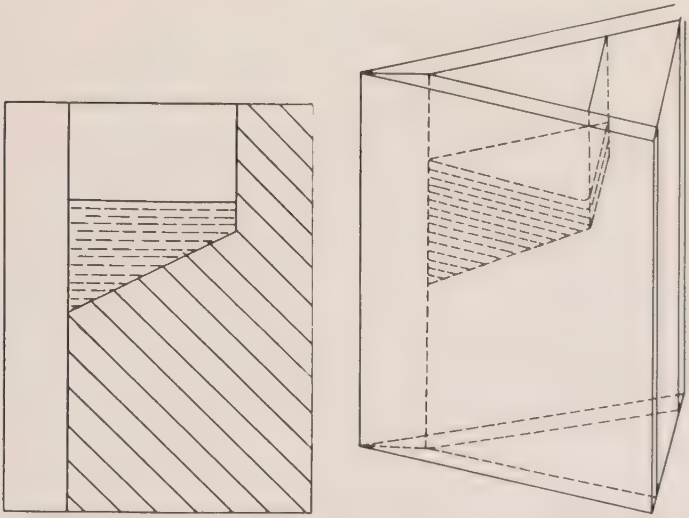


Fig. 41.—Glass prism to be mounted in a goniometer foi determining the indices of refraction of liquids. (Hollow space for liquid in upper portion of wedge between the plates.)

Hollow prisms made of specially ground thin glass or plates with parallel surfaces or selected glass slides cut and cemented together are useful for determining the indices of refraction of liquids. Figure 41 illustrates a hollow prism made of glass plates of equal thickness and having parallel surfaces. Bakelite may be used to cement the glass plates to a solid prism. In ordinary determinative work, one prism cut at 45° is usually sufficient. Two prisms, one cut at 30° for high determinations and one at 60° for lower values, may be employed. Occasionally microscopic slides will possess the parallelism of surfaces required for the prism walls. Such slides should be tested by observing the reflection of a hanging window cord drawn taut by a suspended weight, or some other suitable straight line, from both surfaces of the slide. The slide should be held close to the eye to observe this and turned until the reflections from both the upper and the lower surface can be seen at the same time. If the straight lines are parallel and uniformly distant in each image, the slide is satisfactory. It should also be tested in two perpendicular positions. When a good slide is found, it should be cut into two pieces, one for each side of the prism. The two parts are beveled and cemented[1] to a solid glass wedge. If the walls of the hollow prism are made of glass with parallel sides, correction for the glass is not necessary. It is best, however, to assume an exaggerated bevel and mount the two sides in opposed positions. Any existing lack of parallelism will be largely corrected in this way. Index of refraction determinations using this method are useful for determining the indices of refraction of liquids beyond the range of commercial refractometers. The method is also suitable when a refractometer is not available and as a check when it is available.[2]

If the same prism is always used, a chart may be prepared giving the index of refraction corresponding to each angle of minimum deviation. If the chart covers the range of indices of refraction from 1.400 to 1.850, it will include all ordinarily determined values. Indices of refraction may be determined with the light of a sodium flame obtained by holding an asbestos sheet previously saturated in salt in a fan-flame burner. Light from a mercury-vapor arc or white light transmitted through a standard color filter is also occasionally employed. A helium-gas tube gives an ideal sodium line.[3]

One of the best methods of securing a sodium flame has been reported by F. Lowell Dunn, M.D., of Omaha, Neb. He uses a *coarse* alundum filtration crucible filled with salt and suspends it over a Méker burner. A molten hemisphere of NaCl forms in the bottom of the crucible which gives a sodium flame of extremely high intensity. The burner should be placed under a hood and at a safe distance from the microscope.

Special light bulbs giving a strong sodium light have been developed by the General Electric Company. These require

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[1] Bakelite resinoid, baked at 70° C. for 10 hr. and followed by baking at 125° for 10 hr., will make a solid prism. Bakelite varnish containing china oil is affected by index liquids and should be avoided.

[2] Hollow prisms of several types have been developed by Dr. E. S. Larsen of Harvard University, Dr. C. S. Ross of the U. S. Geological Survey, and Dr. H. E. Merwin of the Geophysical Laboratory.

[3] Employed in the laboratories of the U. S. Geological Survey.

about 20 min. to acquire the proper color value but after developing the correct intensity furnish an excellent source of illumination.

The refractive indices of the various types of glass used in optical equipment are determined to the eighth decimal place with sodium light, mercury-vapor light, and several other light sources. Such precision is not employed in examining minerals with the microscope, nor is it possible without a special goniometer.

The Determination of the Index of Refraction with the Microscope.—The index of refraction of a mineral is seldom determined completely in examination of thin sections. The slices are mounted in Canada balsam, and the usual test consists in ascertaining whether a given mineral has an index of refraction greater or less than balsam. The indices of adjacent minerals are also compared with each other.

The indices of refraction of adjacent transparent substances can be compared in several ways. The two most useful methods are the method of central illumination and that of oblique illumination.

A method of direct determination with the microscope exists, but unfortunately it is not sufficiently accurate with thin sections.

The Method of Central Illumination.—The test is best made with a magnification of 80 or greater, with the diaphragm partly closed. It is quite sensitive to small differences in refractive indices at such magnifications. If monochromatic light is employed, it is possible to distinguish between the indices of refraction of two minerals even when they differ by as little as one in the third place of decimals.

The test may be applied to thin sections of transparent minerals in comparing their relative indices of refraction with adjacent minerals or balsam. The phenomenon used in making the test depends upon the total reflection of light incident at more than the critical angle when passing from a mineral of greater to a mineral of lesser index in a thin section. The test is employed for comparing the indices of refraction of the various minerals of thin sections with balsam, for comparing the minerals with each other when observed in contact, and for comparing fragments of minerals with various immersion media in which they may be mounted. Light enters the section from below and is transmitted through both media. At the bounding edge both reflection and refraction take place and a portion of the entering beam is bent either to one side or to the other depending upon the relative indices of refraction of the adjacent media. If the two indices happen to be the same, no refraction takes place. In case the index of refraction of one is greater than the other, light will strike an inclined boundary between the two in some place at an angle greater than the critical angle. A portion of the beam will be deflected toward the mineral with the greater index. If the boundary between the media is not inclined, grazing incidence may occur, bringing about the same effect. The deflection results in a light blur, visible through the microscope just inside the boundary of the mineral grain of greater index. The blur is more apparent if the iris diaphragm is partly closed and if the tube of the microscope is slightly raised.

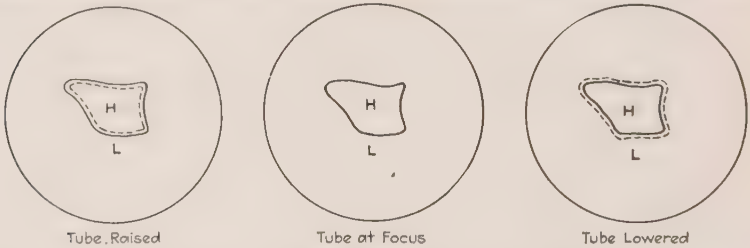

Fig. 42.—Central illumination, $n >$ balsam.

It forms an irregular white line; and as the tube is raised still farther, an illusion is produced, the line appearing to move toward the center of the mineral. If the tube is lowered, the effect is reversed.

Since the index of balsam is known (approximately 1.537) minerals may be quickly divided into two groups, one with indices greater than balsam, the other with indices less than balsam. It is convenient to remember in making the test that when the tube is *raised*, the line moves toward the medium having the *higher* refractive index. Conversely, when the tube is *depressed*, the line moves toward the medium having the *lower* index (Fig. 42).

Explanation of the White-line Effect.—Hotchkiss has given an explanation of the refraction and reflection involved in the method of central illumination. The construction shown in Fig. 43 is modified from his explanatory diagram.

Two minerals *A* and *B* are assumed to be in contact in a thin section with a vertical bounding plane YZ. *A* is the mineral with a lesser index ($n = 1.50$), and *B* has a greater index, 1.70. A cone of light rays strikes the two minerals from below, divided evenly on both sides of the bounding plane. The cone of light may be represented by the rays 1, 2, 3, and 4 with angles of inclination as indicated in the diagram.

The critical angle in mineral *B* with respect to the bounding plane is 62°10′. The half cone of light within *B*, therefore, strikes the surface YZ at an angle greater than the critical angle and is totally reflected. The half cone of light within *A*, however, is split at the bounding surface, part being refracted into *B* and part being reflected back into *A*. The comparative intensity of the reflected and refracted rays depends upon the character of the bounding plane. If the contact surface is highly polished, more light is reflected and less refracted. If the surface is rough, as is usually the case, more light is refracted into *B*.

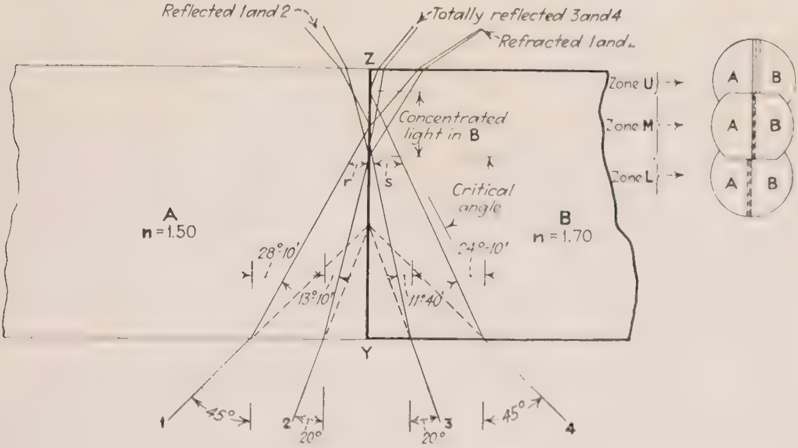

Fig. 43.—A theoretical explanation of the movement of the light line in central illumination. (*Modified from Hotchkiss.*)

A zone of light is concentrated within the mineral of higher index opposite M. Within this vertical distance nearly all of the light of the cone is concentrated in *B*. If the plane of focus of the microscope is brought within this zone, a band of light is visible within the mineral with a higher index. If the plane of focus is elevated by raising the microscope tube to zone *U*, the band becomes broader and furnishes the illusion of moving toward the center of *B* and away from the bounding plane. If the plane of focus is lowered to zone *L*, on the other hand, a greater concentration of light is present in r than in s, and the light band will appear to be within the mineral with a lower refractive index. The circles adjacent to the brackets and indicating the vertical extension of the zones are intended to illustrate the positions of the white line corresponding to different elevations of the plane of focus.

Oblique Illumination.—The method of inclined or oblique illumination is more convenient for making the same relative comparisons of refractive indices outlined above, but at a magnification of about 50 or lower. A larger area of the thin section is included within this field, and the method allows the observer quickly to compare a large number of mineral grains; also it provides an easier interpolation of values between two mounting media.

The effect is best observed without a condenser lens. Oblique illumination may be secured by inserting a card below the stage cutting off half of the light. This darkens one-half of the field, at the same time allowing the opposite half to be illuminated largely by oblique rays (Fig. 44). A similar effect may be secured by inserting a narrow card in the accessory slot above an objective of moderate power (with the condenser in the system). This effect may be either the same or reversed depending upon the focal length of the condenser.

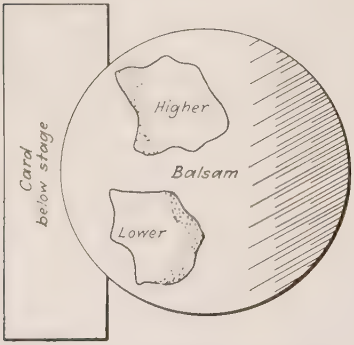

FIG. 44.—Illustrating oblique illumination with the condenser removed. Higher = mineral grain, $n >$ balsam. Lower = mineral grain, $n <$ balsam.

Individual crystals of minerals will be unevenly illuminated by the method of oblique illumination. One side of the mineral will be dark, while the opposite side will be light. When the card is inserted below the objective, the shadow will appear either on the side of a mineral toward the dark half of the field or away from it. When the shadow appears on the side away from the dark half, the index of refraction of the mineral in question is greater than that of the adjacent medium; if on the side next to the dark half, the index of the mineral is less. In case the index of refraction of the mineral is about equal to the index of the mounting material, and white light is employed, one side will be blue while the other is red. When the card is inserted in the accessory opening, the shadow in the mineral is on the side of the field next to the dark area if the index of the mineral is greater than balsam.[1]

The index of a known mineral should be tried first when making this test in order to be sure of the set-up in the microscope.

The Immersion Method as an Auxiliary to Thin-section Study.—Comparative refractive-index determinations as employed in examining thin sections are not sufficient for modern procedure in mineral identification. Whenever possible, grains of minerals are isolated from the sample from which the thin section has been cut in order to make index determinations with fragments, making use of liquids having predetermined indices of refraction. This procedure greatly increases the certainty and accuracy of thin-section studies. The immersion method is easily applied to the study of fragments of the isolated minerals separated from samples before or after the section has been cut.

The liquids used for index determinations should be stable, nearly colorless, and should have no chemical effect upon the minerals examined. A large number of liquids have been suggested by various investigators[2] in an attempt to satisfy these conditions and at the same time cover the major portion of the range of refractive indices encountered in minerals. Present-day procedure usually involves mixing certain liquids in varying proportions and determining the indices of refraction of the mixtures with a refractometer. It is customary to prepare a set of liquids with indices of refraction of 1.450, 1.455, 1.460, 1.465, etc. . . . up to a limit of 1.740. A considerable number of bottles is required for such a group of liquids. These are usually kept in a dark place and are painted black on the outside to keep out the light. A less elaborate set of liquids with values 1.50, 1.51, 1.52, 1.53 . . . etc., is frequently used. Such a set requires half the number of bottles, is more quickly stand-

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[1] Another simple way to secure the effect of oblique illumination suggested by Dr. J. D. H. Donnay consists in shading the field by partially inserting the frame containing the analyzing nicol.

[2] A complete description of the immersion method coupled with tables for the identification of minerals by means of refractive indices and other optical properties has been published by E. S. Larsen in *U. S. Geol. Survey Bull.* 679. See also references at the end of the chapter to studies by H. E. Merwin.

ardized, and with careful mixing of drops on a slide will yield results accurate to ±0.003.

Common liquids for immersion media are as follows:

Liquid	Approximate Index of Refraction
Water	1.333
Isoamyl isovalerate[1]	1.428
Kerosene[2]	1.466
Petroleum oil	1.475
α-monobromnaphthalene[3]	1.658
Methylene iodide	1.740
Solution of methylene iodide and sulphur up to	1.794

[1] Eastman Kodak Co., Rochester, New York.

[2] A clear, highly refined product, called government oil, having the value given above is sold by Leeds & Northrup Co.

[3] Monochlornaphthalene, or "halowax oil" ($n = 1.63$), has been found by a number of workers to be equally satisfactory and more economical. It is sold by the Bakelite Corporation.

In the preparation of the liquids, isoamyl isovalerate and kerosene may be mixed to form liquids up to 1.466 in indices of refraction. Kerosene and halowax oil may be used for mixtures between 1.466 and 1.63. Halowax oil and methylene iodide may be mixed to form liquids with indices of refraction between 1.63 and 1.74. Satisfactory liquids with indices of refraction above 1.74 are hard to obtain. Mixed melts of sulphur and selenium or piperine and arsenic and antimony triiodides are used for high-index determinations. The melts are prepared in advance and arranged in a series of mixtures. The values of the indices of the mixtures are determined by the prism method. A small prism of the transparent melt is made and mounted on the stage of a goniometer. Both the angle of the prism and the angle of minimum deviation are measured. The index of refraction is then computed as previously explained for the prism method. The melt is molded into the form of a prism by using two cover glasses placed at an angle of 30° to each other. The melt is poured into the space between and allowed to cool. When cold, the cover glasses will break away, leaving a prism with smooth surfaces. Great care must be used not to overheat, or the indices of the piperine mixtures will vary greatly. When the index of the melt has been determined, the material is placed in a sealed tube and filed for future use. When applied, the ground-up material is melted around fragments of minerals and the indices are compared by the method of central illumination.

Refractive index determinations of minerals follow a routine procedure. Since the index of refraction of the liquid is known, the method of central illumination or that of oblique illumination may be used to compare the indices of refraction of the mineral fragments with the index of refraction of the liquid. As soon as the index of the mineral is determined to be greater or less than the liquid, the slide is placed in a cleaning jar and another mount is prepared, using a liquid with a different index. By utilizing a number of liquids and making repeated comparisons the indices of refraction of a mineral may be ascertained within reasonably narrow limits. In case the mineral is isotropic, having only one index of refraction, it is customary to determine the index of the mineral to within two or three in the third place of decimals. When minerals are anisotropic, having indices of refraction that vary with direction, equal accuracy is possible, but more comparisons are necessary to determine different values.

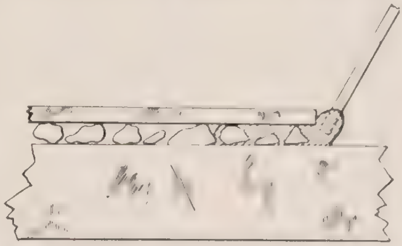

FIG. 45.—Immersion of mineral grains.

Fragments of varying size may be used or fragments of the mineral may be screened to between 100 and 120 mesh in size and scattered over a small portion of the surface of a glass slide. Excellent fragments of proper size may be produced by crushing small chips between glass slides and grinding until grit disappears. The fragments are then covered with a small cover glass. A drop of some inert liquid of known refractive index is brought into contact with the edge of the cover glass by using a small glass rod. Capillary action then draws the liquid between the cover glass and the glass slide, completely immersing the mineral grains and leaving the top of the cover glass clean (Fig. 45).

It is not always advisable to place the cover glass over dry fragments and allow the liquid to be drawn around each grain by capillary attraction as explained above. To cite a specific instance, it may be desired to find the index of refraction of a mineral with a value between two liquids such as 1.555 and 1.560. In this case a drop of liquid 1.555 is placed upon a slide, and a drop of liquid 1.560 of the same size is placed near by but not quite touching the first drop. The mineral powder is then sprinkled between the drops, and both the drops and the powder are mixed with a needle, small wire, or small stirring rod. A small cover glass is then placed over the mixture, pressed down to remove air globules, and the mount is ready for microscopic examination. The index of the mixed liquid should be about 1.5575.

For hexagonal or tetragonal minerals n_ϵ and n_ω are determined; for orthorhombic, monoclinic, or triclinic minerals n_α, n_β, and n_γ. In these determinations it should be remembered that each mineral grain in the field of the microscope is doubly refracting with values n_2 and n_1. Furthermore, when a crystal is in the position of extinction, the planes of vibration of n_2 and n_1 are parallel to the vibration planes of the nicols.

The determination of n_ϵ and n_ω, or n_α and n_γ usually resolves itself into a search with successive liquids until both the upper and lower limits of n_2 and n_1 for a given mineral are located. The difference between the two values equals the maximum double refraction of the mineral. It should be remembered, however, that cleavage or structure may limit the positions in which minerals will come to rest on the slide. In such cases the two extremes may not be obtained unless fragments are turned by moving the cover glass or interference figures are used to check the orientation.

The determination of n_β in biaxial minerals may be carried out in two ways. If interference figures[1] on or near a bisectrix or an optic axis can be obtained for several grains in different liquids, the determination of n_β is simple. This is due to the fact that the index of the ray vibrating at right angles to the axial plane is n_β. It is also convenient to remember that any grain in a position to give an optic axis figure yields rays with the index n_β in all directions. If such interference figures are not obtainable, and specific information concerning the position of n_β in fragments is not known, the value can still be determined by a process of elimination as explained below.

For each fragment shown in the field of the microscope somewhere between n_2 and n_1 is the value n_β. In certain fragments either n_2 or n_1 may equal n_β, but from the consideration of biaxial crystals it can be shown that both n_2 and n_1 will never at the

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[1] The optics of interference figures will be discussed in Chap. VI.

same time either exceed or be less than n_β in the same fragment. Thus n_β may be located by varying the liquids and observing both n_2 and n_1 in a number of fragments. In Fig. 46 assume the vertical lines to indicate the measured grains of a certain mineral. The horizontal lines cover the range in indices of refraction for different grains having different values of n_2 and n_1. It will be observed that all lines cross or meet 1.680, this being the value of n_β; also that no lines exceed 1.699, which is the value of n_γ; and that no lines are less than 1.662, which is the value of n_α. If fragments with weak double refraction are tried in successive liquids, testing both n_2 and n_1 in each case, the value of n_β can soon be approximated within narrow limits.

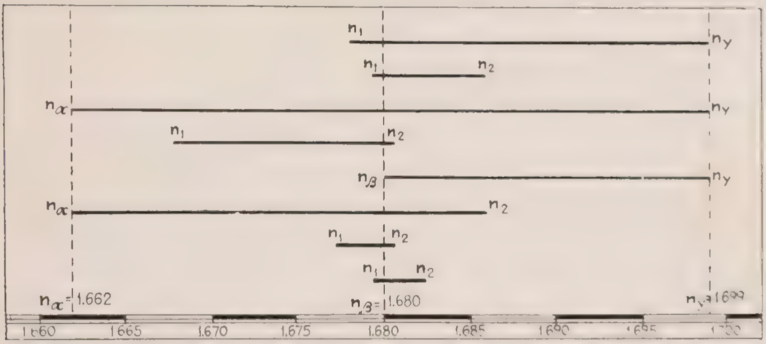

FIG. 46.—The determination of n_β in irregular non-orientated fragments.

It is convenient as a confirmation of the determination of optic sign to remember that when $(n_\beta - n_\alpha)$ is decidedly greater than $(n_\gamma - n_\beta)$, the mineral is optically negative. If, on the other hand, $(n_\beta - n_\alpha)$ is decidedly less than $(n_\gamma - n_\beta)$, the mineral is positive.

Relief.—Certain minerals stand out strongly in the field of the microscope, others are moderately visible, while frequently the mineral is hardly visible at all. This appearance or visibility of outline and surface is described as *relief*.

The relief of a mineral mounted in balsam depends upon the difference between the index of refraction of the mineral and balsam. Minerals with low indices of refraction (cryolite, $n = 1.364$) and high indices of refraction (spinel, $n = 1.75$) have strong relief. On the other hand, such a mineral as apophyllite has approximately the same index of refraction as balsam and consequently is hardly visible in thin section.

Anisotropic minerals with a wide divergence between the two extremes of refractive indices exhibit a variation in relief as the stage of the microscope is rotated. Calcite furnishes one of the best illustrations of this feature. The ray vibrating parallel to the short diagonal of the cleavage rhombohedron has nearly the same index as balsam. When this direction is parallel to the lower nicol, a calcite cleavage fragment on the stage of the microscope shows low relief. When the cleavage fragment is turned at right angles until the long diagonal is parallel to the lower nicol, light travels through the mineral with the velocity of the higher index, and the same grain stands out with high relief. A number of common minerals vary in relief with direction.

The relief of a mineral may be estimated as *low*, *moderate*, *high*, or *extremely high*. In the tables to follow such a descriptive term is given for each mineral.

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CHAPTER V

PLANE POLARIZED LIGHT IN MINERALS

Polarized Light.—In the foregoing it has been assumed for descriptive purposes that light may be considered as wave motion. This condition holds for ordinary white light or for monochromatic light of any sort. It is also assumed that the vibrations take place in all directions around the line of transmission. Under certain conditions, however, the tendency to vibrate in all directions around the line of transmission is modified, and the waves become restricted for the most part to a single direction of vibration. When its vibration direction is thus restricted, light is said to be *polarized*.

Polarized light may be produced in a number of ways. One of the simplest illustrations of polarization is furnished by the reflection of light from a polished table top. Light reflected obliquely from such a polished wooden surface is partially polarized. If the reflection is examined through a rotating nicol prism, the field of view in the prism will darken whenever the vibration plane of the nicol is at right angles to the plane of reflection of the polished surface.

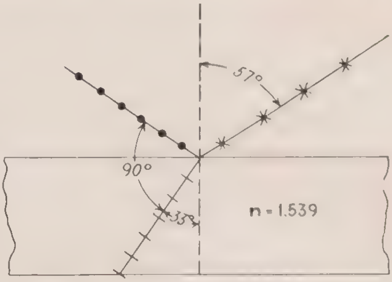

FIG. 47.—Polarization by reflection.

Light reflected and refracted obliquely from mirrors is partially polarized. According to Brewster, the polarization in the case of a glass plate is a maximum when the directions of reflection and refraction are 90° apart (Fig. 47). When these two directions are at such an angle, the angle r becomes the complement of the angle i, and the formula $n = \sin i \cos r$ may be written $\sin i/\cos i = \tan i = n$. Thus, at the angle of maximum polarization the tangent of the angle of incidence equals the index of refraction of the reflecting substance. Consequently, when the index of refraction of the substance is known, the angle of maximum polarization may be obtained from a table of tangents. The angular relationships for a plate $n = 1.539$ are shown in Fig. 47. Figure 48 is a sectional view of an old-fashioned polariscope employing reflection from glass plates to obtain polarized light. The instrument was used before the advent of the modern polarizing microscope to produce polarized light for the study of mineral plates.

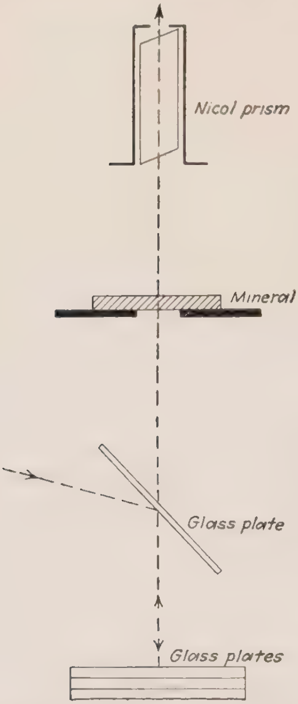

FIG. 48.—Polarization by reflection in a polariscope.

Polarization by Absorption.—Certain anisotropic minerals absorb light strongly in one direction but not in the other. Light traveling in a direction at right angles to the direction of absorption passes through the mineral and is plane polarized. There are also variations in absorption, some rays being more absorbed than others. Here it is frequently advantageous to know the directions of maximum and minimum absorption.

Tourmaline provides one of the best examples of this phenomenon among common minerals. Large transparent tourmaline

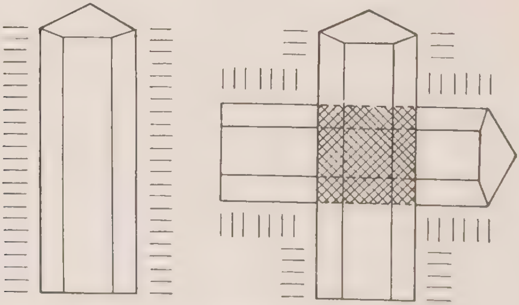

FIG. 49. Polarization by tourmaline.

crystals are frequently cut in plates with the optic axis of the crystal parallel to the plane of the plate. Light vibrating parallel to this direction passes through the crystal with a minimum of absorption. That vibrating at right angles is almost completely absorbed. Direct examination of a single crystal with the eye does not reveal this condition. Observation through either a Nicol prism or another plate of tourmaline cut in a similar fashion is necessary to detect the polarization. When the plane of the nicol is at right angles to the optic axis of the tourmaline plate, the crystal appears dark. Also, when the directions of the two superimposed tourmaline plates are at right angles to each other, the overlapping portion is dark (Fig. 49).

Double Refraction (**Birefringence**).—Light passing through transparent minerals other than amorphous minerals or minerals crystallizing in the isometric system undergoes polarization into two rays. The two rays vibrate at an angle to each other which is normally not far from 90°. The precise determination of the angle between the two rays is a matter of careful physical measurement as demonstrated by F. E. Wright. Consequently in discussing double refraction the amount of variation from 90° will not be considered, and the two rays will be considered in simple terms as about at right angles.

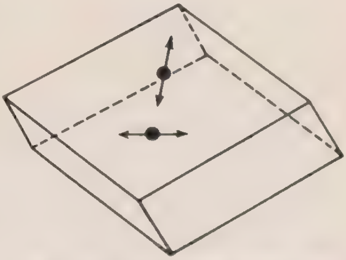

FIG. 50. Two images composed of waves polarized at right angles in transparent calcite or Iceland spar.

The most obvious illustration of polarization by a mineral occurs in transparent calcite, or Iceland spar. Objects viewed through a cleavage plate of Iceland spar appear double; if a cleavage face of calcite is placed over a dot marked on a piece of paper, the dot will appear to the eye as two dots (Fig. 50). The light giving rise to one dot will be composed of waves vibrating parallel to the long diagonal; that giving rise to the other will be composed of waves vibrating parallel to the short one. The two light rays have been differently refracted. This is due to the fact that the indices of refraction of the two rays are different. Substances such as calcite are doubly refracting (or birefringent).

The cleavage form of calcite, the rhombohedron, is illustrated in Fig. 51 with the principal axis in the vertical position. If the opposite vertices of the calcite cleavage having threefold symmetry are ground to triangular surfaces and polished, light may be passed directly through parallel to the principal crystallographic axis [perpendicular to (0001)]. Such light vibrates in all directions and is not doubly refracted. This direction along which light passes without double refraction is the optic axis in either hexagonal or tetragonal crystals and agrees in direction with the principal crystallographic axis (the *c*-axis).

If light passing along the optic axis is examined by means of a Nicol prism it is found that there is no double refraction and the mineral appears isotropic. In any other direction, however, double refraction results. In the latter cases light is polarized into two rays vibrating at right angles to each other, one vibrating at right angles to the optic axis, the other in a plane through the optic axis. The former is known as the *ordinary ray;* the latter is called the *extraordinary ray.* The ordinary ray vibrates in a direction at right angles to the optic axis and parallel to the long diagonals of the rhombic faces of the cleavage rhombohedron. The extraordinary ray vibrates in a plane passing through the optic axis and also passing through the short diagonal. In some minerals the extraordinary ray is the fast ray; in others it is the slow ray.

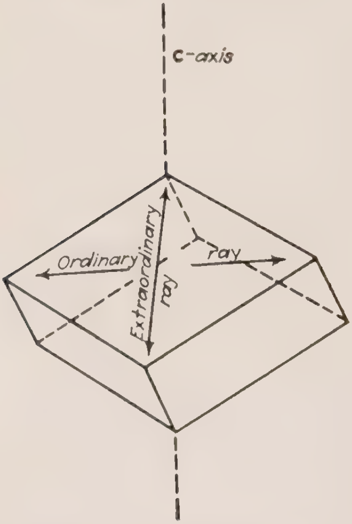

Fig. 51.—The extraordinary and ordinary rays in a calcite cleavage.

Nicol Prism.—The Nicol prisms in the polarizing microscope utilize the principle of double refraction to produce polarized light. Optically clear calcite is used, and a prism is made of two parts cemented together with Canada balsam. The two halves are cut as shown in Fig. 52 and are then cemented together to form a prism of the type illustrated in Fig. 53. Light entering the base of the prism is broken into extraordinary and ordinary rays. The extraordinary ray has an index of refraction $n = 1.516$ at the angle of incidence for the prism; the ordinary ray has an index of refraction $n = 1.658$. The index of the extraordinary ray is close to the index of refraction of balsam, $n = 1.537$. The index of the ordinary ray, however, is considerably greater.

Both rays strike the cementing plane of balsam obliquely. The obliquity of the ordinary ray exceeds the critical angle between the ordinary ray and balsam. As a result, it is not refracted through the balsam but is reflected to the side of the prism. Since the extraordinary ray does not exceed the critical angle between the extraordinary ray and balsam, it passes on through the prism with little deviation.

The extraordinary ray is polarized with one plane of vibration; consequently, the light emerging from the prism and made up entirely of the extraordinary ray is plane polarized. Thus the Nicol prism affords a simple device for producing plane-polarized light.

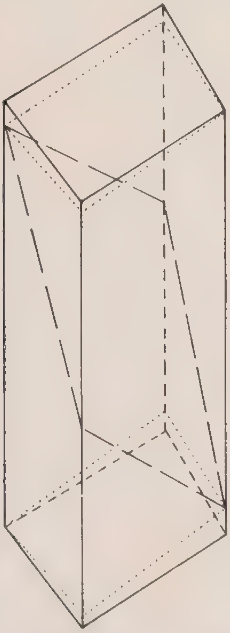

FIG. 52.—A cleavage of calcite marked for cutting to form a Nicol prism.

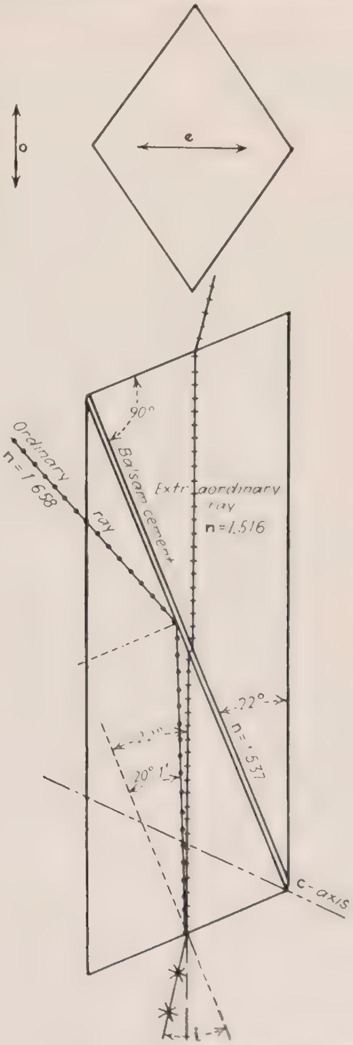

FIG. 53.—The polarization and deviation of light in a Nicol prism.

Interference between Crossed Nicols.—When two Nicol prisms are superimposed with their planes of vibration at right angles to each other, the nicols are said to be crossed. The polarizing microscope is normally adjusted with the Nicol prisms in this position, the plane of each nicol remaining fixed but the upper nicol movable either in or out of the tube of the microscope. Crossed nicols produce darkness when the stage is unoccupied or when it holds optically isotropic amorphous materials such as glass or opal or when it holds optically isotropic crystals of the isometric system of crystallization. Minerals crystallizing in crystal systems other than the isometric are anisotropic and in most positions produce interference colors between crossed nicols.

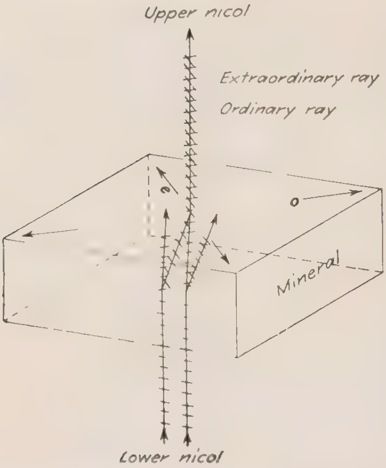

FIG. 54.—The vibration directions of the extraordinary and ordinary rays in an anisotropic mineral illuminated with polarized light.

In Fig. 54 polarized light is shown passing through a mineral plate after leaving the lower nicol. Light strikes the lower surface of the mineral plate vibrating in one plane. On entering the plate it is broken into two sets of rays. Both sets of rays are polarized, and light travels with different velocities along them. As a result, when the two sets of rays emerge on the upper side

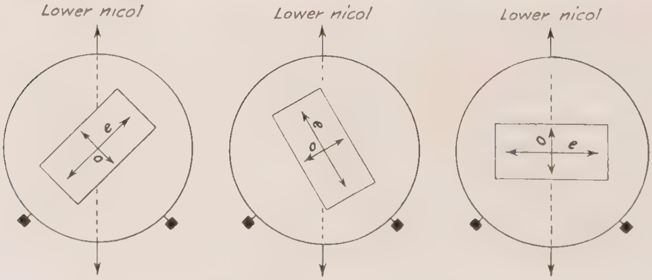

FIG. 55.—A mineral plate on the microscope stage showing several positions of the doubly refracting rays.

of the plate, one set has traveled farther than the other and extraordinary rays will travel along the same direction as ordinary rays both vibrating almost at right angles and having traveled different distances. Both travel along a straight line to the upper nicol and continue to vibrate at right angles.

The location of the planes of vibration is determined by the position of the mineral. If the position of the mineral plate on the stage is changed as shown in Fig. 55, the vibration planes of the emerging rays are also shifted.

After leaving the mineral plate, the two rays of the mineral, *e* and *o* in Fig. 56, continue to the analyzer. Here one of the rays *e* is broken into two components *eo′* and *ee′*, the ordinary ray *eo′* being refracted to the side of the nicol, and the extraordinary ray *ee′* continuing through the upper half of the nicol. The separation of the rays follows the same principle already explained in the discussion of the Nicol prism. The other ray *o*, from the mineral, is also broken into two rays in the analyzer. One component *oo′* is reflected to the side, and the other *oe′* continues along the plane of the analyzer. As a result of this selection, two rays in the upper half of the analyzer *ee′* and *oe′* emerge as extraordinary rays vibrating in the same plane. Although these two rays are vibrating in the same plane, each has traveled a different distance. In consequence the two are in a position to interfere, and the resultant effect produced upon the eye is an interference color.

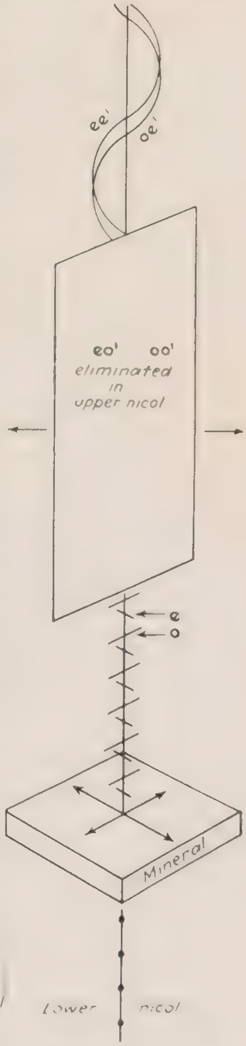

FIG. 56.—Sorting of rays by the upper nicol when the nicols are crossed.

The interference color produced depends upon the nature of the light and the amount of retardation of one set of waves with respect to that of the other. The retardation can be determined and is expressed by the Greek letter Δ. The value of Δ is expressed in millimicrons (millionths of a millimeter = $m\mu$), the same units used to measure the wave length of light.

The retardation may be changed through a wide range by (1) varying the thickness t of the mineral, (2) changing the orientation in such a way as to change the indices of refraction n_1 and n_2 of the two rays emerging from the mineral. This relationship may be expressed by the equation

$$\Delta = t(n_2 - n_1)$$

In the equation, t represents the thickness of the mineral expressed in millimeters, n_2 is the greater index of refraction, and n_1 is the lesser index of refraction for a particular orientation.

Path Difference.—The two rays emerging from the polarizer differ in phase, or in other words they have a path difference P. This difference is equal to the retardation divided by the wave length:

$$P = \frac{\Delta}{\lambda}$$

Since it has just been shown that

$$\Delta = t(n_2 - n_1)$$

it follows that

$$P = \frac{t(n_2 - n_1)}{\lambda}$$

When the retardation is some whole multiple of a wave length ($n\lambda$), the waves emerging from the upper nicol become equal and opposite in phase. The resultant is then equal to zero and the field produced is dark (Fig. 57).

When the retardation is $[(2n + 1)/2]\lambda$, the components of the waves in the plane of the upper nicol are equal and on the same side of the line of transmission. The resultant wave is equal to the sum of the two components, and maximum intensity results (Fig. 58).

Interference Colors.—If the mineral plate lies with the planes of vibration parallel and perpendicular to the planes of the two nicols, no light passes through the analyzing nicol and the mineral is in a position of extinction. On the other hand, if the plate is rotated to either side, the field of the upper nicol is no longer dark but becomes illuminated with interference colors. The interference colors vary with the thickness of the mineral section, the nature of the mineral, the way in which the mineral section is cut, and the light employed. The explanation of the relationship of these various factors involves many

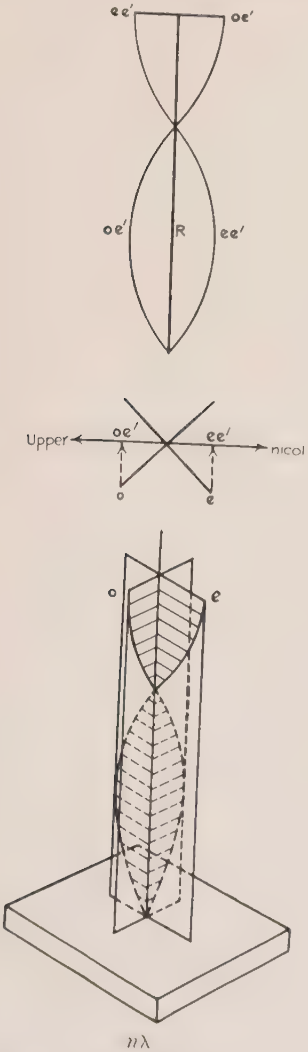

FIG. 57.—Resolution of waves in upper nicol for retardation of even wave-length multiples.

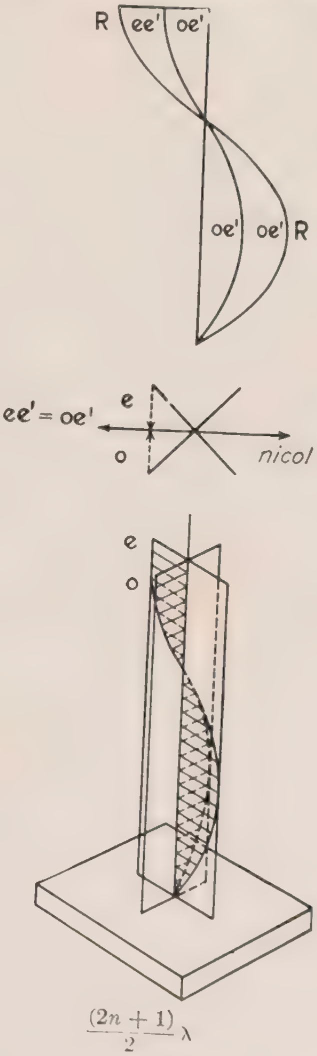

FIG. 58.—Resolution of waves in upper nicol for retardations of one-half wave-length multiples.

of the principles of optical mineralogy. It is desirable for the sake of simplicity to consider the variables one at a time.

If the thickness of a mineral plate between crossed nicols is changed, the orientation remaining the same, a change in interference color ensues. One of the best ways to illustrate this phenomenon is by means of a wedge such as the quartz wedge which accompanies the polarizing microscope.

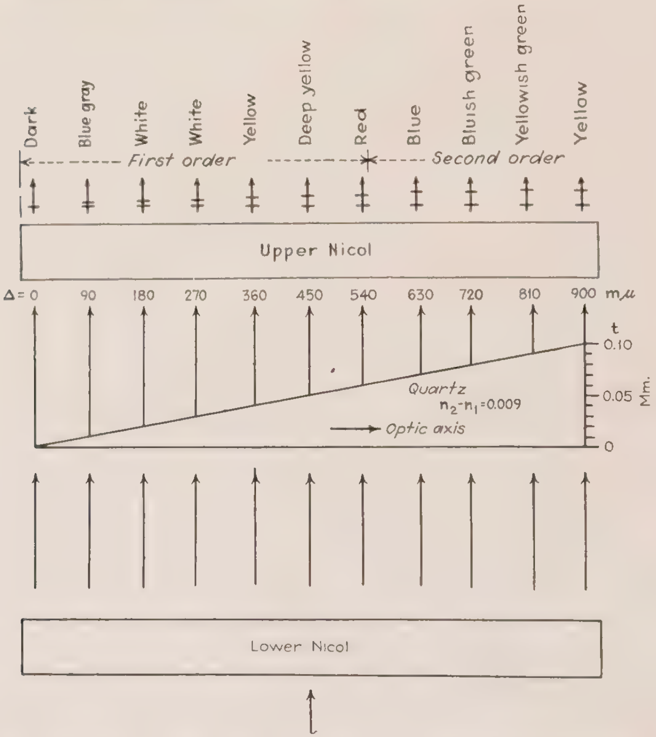

FIG. 59.—Interference colors due to a portion of a quartz wedge between crossed nicols with white light.

Figure 59 is a diagram illustrating a portion of a quartz wedge cut along the *c*-axis and varying in thickness from 0.0 to 0.10 mm. The wedge is placed between crossed nicols in a position at 45° to the planes of the nicols. In this position it becomes brilliantly illuminated with interference colors. The colors, however, gradually merge into each other and change as one observes different thicknesses along the wedge. Any one thickness, however, forms a uniform band of one color across the wedge.

The quartz wedge should be placed on the stage of the microscope and moved back and forth in order to observe the full range of color due to varying thickness.

Each portion of the wedge is subject to the equation

$$\Delta = t(n_2 - n_1).$$

In this case, however, since the optic axis of the wedge remains parallel to the stage, $(n_2 - n_1)$ is fixed and equals 0.009. Consequently, the retardation Δ varies with the thickness t.

When t is zero, the retardation in any light is also zero, and the field of view is dark. When t increases, a definite sequence of colors ensues, with white light. Starting with gray and continuing through bluish gray, white, yellow, orange, in the order named, the colors become striking to the eye. In the thicker portion of the wedge, however, less contrast appears; and in wedges several times as thick the colors at the thick end become faint iridescent tints.

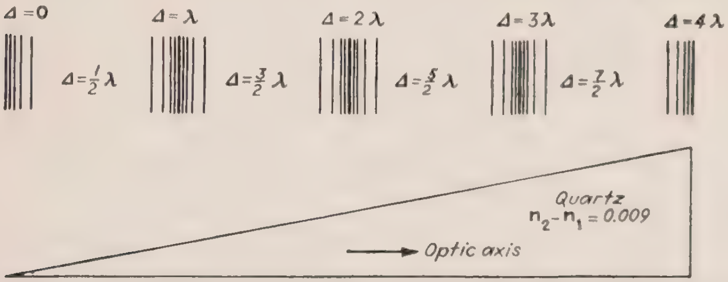

FIG. 60.—Alternate dark and light bands produced by monochromatic light with a quartz wedge between crossed nicols.

If the source of illumination is changed and monochromatic light is used in the system, a different effect is produced as illustrated in Fig. 60. In this case when the thickness reaches such a point that the retardation becomes equal to one wave length, the two monochromatic waves are equal and opposite in phase and nullify each other, causing darkness. As a result, dark bands will occur at all points where the retardation is a whole multiple of λ. Conversely at multiples of $\frac{1}{2}\lambda$, maximum intensity will occur. Here the two waves are equal and in the same phase.

The interference colors due to white light are a subtraction of all of the various wave lengths of the spectrum from white.

The method by which the various interference colors are related to their monochromatic components is illustrated by Fig. 61.

The various monochromatic beams on passing through a wedge produce dark bands at different thicknesses. Likewise maximum intensity occurs at corresponding intermediate intervals. The difference between the wave lengths at the opposite end of the spectrum is such, however, that the first dark band for violet occurs almost in the first position of maximum intensity for red. For violet the band is approximately 410 mμ. Since the wave length for red is about 700 mμ the maximum intensity for red occurs at 350 mμ, ($\frac{1}{2}\lambda$). When the thickness and double refraction are such that the retardation equals 410 mμ, no violet is present in the resultant interference color. The percentage of maximum intensity for red at the same time is about 83 per cent.

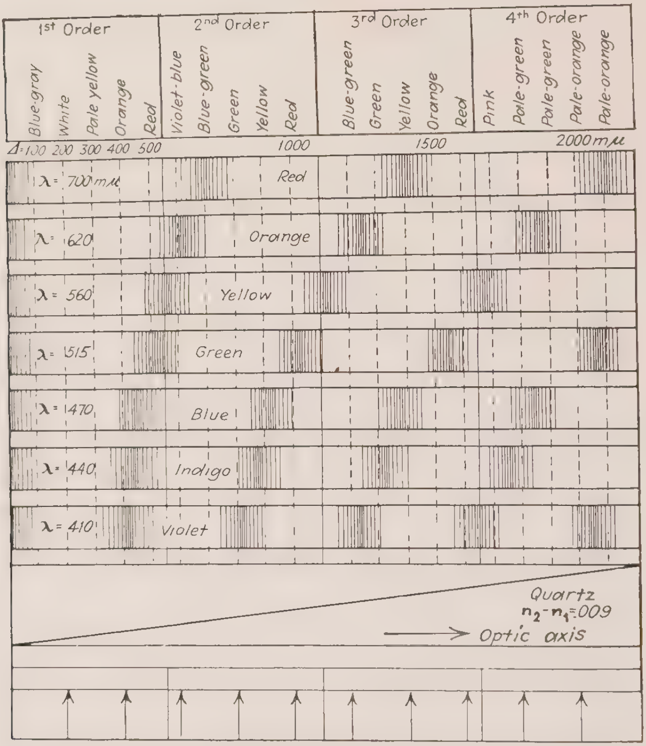

Fig. 61.—The relationship between interference colors due to monochromatic light and colors due to white light.

Since the maximum intensity for red occurs at $\frac{1}{2}\lambda$ or 350 mμ, the percentage intensity at 410 mμ would be

$$\frac{2(\lambda r - \lambda v)}{\lambda r} \times 100 = \frac{2(700 - 410)}{700} \times 100 = 83 \text{ per cent}$$

If the wave lengths are known, it is possible to compute the percentage of any given monochromatic light present in an interference color of a given retardation.

Application of the Color Chart to the Study of Minerals.—The *interference color chart* is constantly employed in the study of minerals by means of polarized light. The maximum double refraction, or the greatest difference between n_2 and n_1, is approximately constant for a given mineral. If this constant is substituted in the equation $\Delta = t(n_2 - n_1)$, a straight-line curve is the result. In the case of quartz, for example,

$$(n_2 - n_1) = 0.009.$$

If various thicknesses are assumed as shown in Fig. 62, the corresponding retardation Δ may be determined directly. Knowing the normal sequence of colors for a given retardation, it is possible either to predict the color of quartz of a given thickness or to tell the thickness of quartz having a given interference color, provided the quartz is in such a position that $n_2 - n_1$ is a maximum.

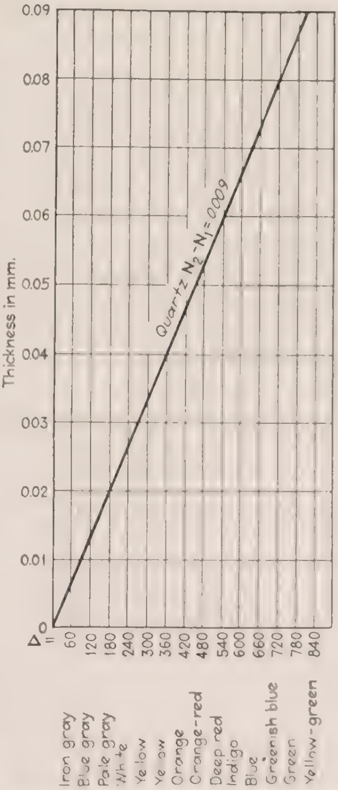

FIG. 62 Variation in double refraction with thickness in the case of quartz.

This relationship is not only true for quartz but may be applied with the exception of a few special instances to all anisotropic minerals studied with the petrographic microscope. The color chart (facing page 146) gives the lines of maximum double refraction for the common minerals.

In the color chart interference colors with Δ less than 550 mμ are said to belong to the *first order*. Violet ($\Delta = 550$) belongs at the boundary of the first order. This is known as *sensitive violet*, since a small change either way produces a decided color difference. From violet $\Delta = 550$ to violet $\Delta = 1128$ the colors belong to the second order. From violet $\Delta = 1128$ to violet $\Delta = 1652$ they belong to the third order. Above the fourth order colors are not easily separated. The colors at the end of the first order and the beginning of the second are the most striking and brilliant. At the end of the fourth order they merge into each other, forming tints of green and pink tending toward grayish white. These colors are quite distinct from the blue gray, white, and yellowish white of the lower first order. Uncertainty concerning the order of a given color may be overcome by using a mica plate. The mica plate is cut with such thickness that it either increases or decreases the retardation of a section by about $\frac{1}{4}\lambda$ (red). Such an increase or decrease in the lower first or second orders produces a set of colors entirely different from that in the case of a similar change in higher orders. For example, in the case of first-order yellow $\Delta = 400$ mμ, an increase in Δ of 175 mμ will result in violet $\Delta = 575$ mμ, while a decrease of the same amount will produce white $\Delta = 225$ mμ. The same increase or decrease in retardation above the fourth order would produce little change perceptible to the eye.

Determination of Retardation with a Berek Compensator.—M. Berek (1913) described a rotary calcite compensator of simple mechanical construction. A calcite plate 0.1 mm. thick, cut normal to the optic axis, rests on a rotating axis in a metal holder similar to the frame usually used for the gypsum and mica plates. The frame is held fast in the accessory slot of the microscope by a spring. The rotation of the compensator plate is registered on a graduated drum attached to the axis of rotation. The drum is graduated with a vernier reading to tenths and may be calibrated in degrees.

The plate in the compensator is held in a small ring which may be easily removed and a plate of different thickness substituted. The range of the plate ordinarily employed covers retardations from zero to the fourth order.

The axis of rotation of the compensator is arranged diagonally to the polarization planes of the two nicols. If the planes of the nicols are north-south and east-west, the tube slot holding the compensator will be northwest-southeast. The compensator is marked with two arrows: H_1, parallel to the axis of rotation or along the accessory slot, is the slow-ray vibration direction; H_2, at right angles to the axis of rotation, indicates the trace of the projection of the plane containing the inclined *c*-axis of calcite and marks the fast-ray vibration direction.

The compensator is first set with the plate horizontal within the frame and inserted. Between crossed nicols a large dark cross will appear in the field. When this cross coincides with the crosshairs of the microscope, the compensator is in the zero position (see Fig. 63). If the compensator drum is then turned either to the left or to the right, the various orders of interference colors appear in the field in a sequence corresponding to the order of the quartz wedge.

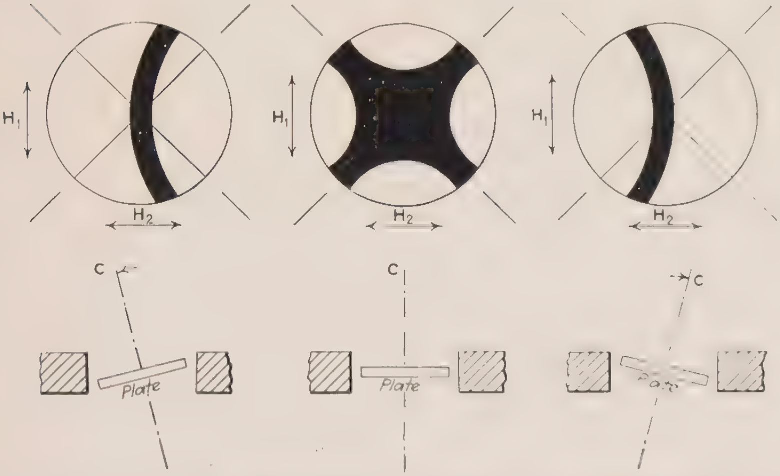

FIG. 63.—The vibration directions and movement of the color rings in the field of the ocular when using the Berek compensator.

The compensator may be used to determine the retardation of a mineral grain between crossed nicols as follows: The grain in question is moved to the center of the field and placed in the 45° position with the slow-ray vibration direction of the mineral parallel to H_2 of the compensator. The compensator is then inserted and rotated first to the right and then to the left, stopping in each case when the interference color of the mineral has been completely reduced to extinction. The measured difference between the opposite readings is divided by two, and the value inserted in a simple formula supplied by the makers of the instrument. Solution of the formula gives the correct retardation for the mineral grain.

A view of the Berek compensator is shown in Fig. 21. Figure 63 indicates the views obtained in the microscope field with the compensator plate horizontal and rotated either to the right or to the left. The vertical sections below indicate the inclination of the *c*-axis, while the upper diagrams represent corresponding microscope fields. With monochromatic light, light and dark bands are produced on either side of a central cross. With white light, the bands on either side of the dark cross indicating the zero position are colored.

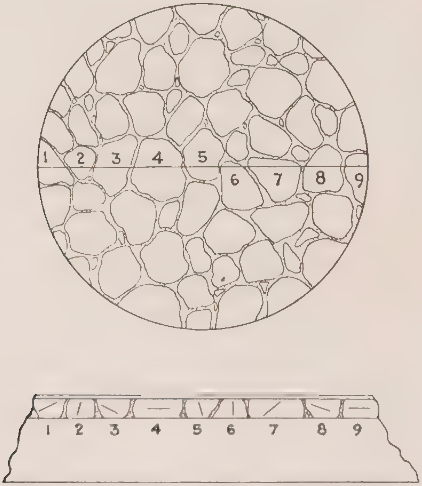

Fig. 64.—Determination of thickness of section in quartzite.

When the compensator is inserted above a doubly refracting crystal in a thin section, the dark cross disappears. As the plate is rotated, however, the interference colors are changed until complete compensation occurs as mentioned above.

Determination of Thickness of Section.—Let us suppose that Fig. 64 represents a thin section containing numerous small quartz grains in innumerable random orientations. For purposes of illustration we shall refer to grains 1 to 9 inclusive along the horizontal crosshair in the field of the microscope. These grains are orientated with their optic axes lying in the positions shown in the sectional view. Most are inclined; occasionally a few are vertical; and a few are horizontal. The horizontal axes are in the correct position to provide a maximum value of $(n_2 - n_1)$. Since all are of uniform thickness, the grains with horizontal axes will show the highest order of interference color, which is likewise the interference color with maximum retardation. In any section of uniform thickness which has a large number of grains, as in the case illustrated, the grains giving the highest-order interference color as observed by means of the color chart will be grains in a position to exhibit the maximum $(n_2 - n_1)$. In the case at hand grain 4 is in the correct position. If grain 4 should show an interference color of straw yellow, the thickness of the section as determined by the color chart would be 0.03 mm. Other interference colors will be shown in the thin section, but only those with an approximately horizontal position will be as high in the first order as straw yellow.

In any thin section, if sufficient grains of a known mineral are present in random orientation and the highest order of interference color can be determined, it is possible to ascertain the thickness of section by reference to the color chart. It is also possible to reverse the process if the thickness is known and determine the double refraction of an unknown mineral. Likewise in a slide containing two or more minerals, one of which is known, it is possible to determine the thickness of the section from the known mineral and determine the double refraction of the unknown minerals from the determined thickness and the observed interference colors. These considerations are extremely useful in studying minerals with the polarizing microscope.

Direction of the Vibration of Slow or Fast Rays. It is frequently important to ascertain the planes of vibration of the two rays vibrating at right angles in an anisotropic mineral grain. The two rays have different indices of refraction, the one with the greater index being the slow ray, and the one with the lesser index, the fast ray. The determination of the fast- and slow-ray directions is accomplished between crossed nicols, the location of the two rays being established by observing the position of extinction. When the mineral becomes dark, the vibration directions of the two rays are parallel to the planes of vibration of the Nicol prisms. Since the planes of vibration of the nicols are parallel to the crosshairs in the ocular, the vibration planes in the mineral will also be parallel to the crosshairs when in the extinction position.

A mica plate or a gypsum plate is used to tell which of the two rays is fast and which is slow. When the positions of the vibration directions of the rays are ascertained, the mineral is turned from extinction to the position of maximum interference. Next, either the gypsum or the mica plate is inserted in the tube of the microscope with the slow-ray vibration direction parallel to one of the vibration directions of the mineral. If the order of color increases, the parallel direction is the slow-ray vibration direction of the mineral. If it decreases, the direction represents the fast ray. One direction being known, the other is the opposite. The mica plate is usually used for minerals with weak double refraction, while the gypsum plate is employed in the case of stronger double refraction. When the mineral has very strong double refraction, a quartz wedge may be used.

Extinction.—When a mineral plate or grain or a portion of a doubly refracting crystal is dark between crossed nicols, it is said to lie in the position of extinction. Frequently minerals have prominent cleavage lines or crystal boundaries which enable one definitely to locate the angle at which extinction occurs with respect to the crystallographic axes. In the absence of a reference line, the extinction angle cannot be determined.

Parallel Extinction.—Frequently minerals have a single plane of cleavage. The traces of the cleavage planes appear in thin sections as irregularly spaced parallel lines. If the mineral becomes dark between crossed nicols with the cleavage parallel to the vibration directions of the two nicols, the extinction is said to be parallel.

A number of minerals crystallize in such a way that sections are elongated, square, or rectangular. Square or rectangular cleavage patterns may also be observed. If these minerals become dark between crossed nicols with the cleavage directions parallel to the vibration planes of the nicols, they are said to have parallel extinction.

Inclined or Oblique Extinction.—Many minerals extinguish between crossed nicols when cleavages or crystal boundaries lie at oblique angles to the planes of vibration of the two nicols. These are said to have inclined extinction.

In this case it is necessary to know the position of either the fast-ray vibration direction or the slow-ray vibration direction in the mineral grain. The extinction angle is usually determined in terms of the slower of the two rays, or the one having the greater index of refraction. The nature of the two rays is determined with one of the accessory plates of the microscope.

Several different angles of extinction are usually observed for the same mineral in a given section. The maximum reading on the slow-ray vibration direction with the plane of vibration of the analyzer is a convenient value to determine. In the case of observation with the microscope the stage is rotated until the mineral lies in a position of extinction. The upper nicol is then pushed to one side, and the angle between the vertical crosshair (parallel to one of the nicols) and the cleavage line or crystal boundary is determined by readings on the graduated stage of the microscope. The nicols are then crossed again and the crystal turned to the extinction position, the angle being measured. Next, the direction of vibration of the slow ray is verified by using an accessory plate. A series of readings should be repeated with different crystals until it seems certain that the largest angle for a particular mineral has been found. When the angle is determined, it is necessary to refer to a description of the optical directions in the crystal in order to ascertain the proper reference plane for the extinction angle.

Symmetrical Extinction.—A number of minerals form cleavage patterns or crystals with rhombic cross sections. In many instances these become dark between crossed nicols when the planes of vibration of the nicols are parallel to the diagonals of the rhombic patterns. Extinction of this type is described as symmetrical. Several minerals forming crystals with square outlines may also yield symmetrical extinction.

Elongation.—Occasionally crystal grains develop with an elongated habit and straight edges. These may have a lathlike shape under the microscope, may resemble small needles, may occur in long crystals, or may show several other shapes of similar development.

When such crystals are anisotropic, it is possible to determine the fast- and slow-ray vibration directions with one of the marked accessory plates. In case the vibration direction of the slow ray of the crystal is parallel to the long direction, the mineral is said to have *positive elongation*. When the vibration direction of the slow ray lies across the crystal in the short direction, the mineral has *negative elongation*. These two terms may be stated briefly as *length-slow* and *length-fast*, length-slow indicating that the vibration direction of the slow ray is parallel to the length of the crystal, and length-fast indicating the parallelism of the vibration direction of the fast ray.

Anomalous Interference.—Occasionally minerals normally assumed to be isotropic become anisotropic and give interference effects between crossed nicols. The abnormal production of interference colors often of a low order is called anomalous. Figure 113 represents a thin section of garnet photographed between crossed nicols. Banding of the anomalous colors indicates an internal structure in the garnet. X-ray studies show that the same garnet is still isometric in crystallization, so the colors are truly anomalous.

Interference colors and structural patterns may be produced by strain in the crystals. According to Crookes the great Cullinan diamond, measuring almost 4 in. across, exhibited pronounced anisotropism due to strain.

Vesuvianite in thin section often shows an unusual sequence of interference colors, Berlin blue predominating. Although this mineral is tetragonal and normally doubly refracting, the interference colors do not follow the color chart and are anomalous. Clinozoisite, zoisite, brucite, and chlorite also furnish anomalous interference colors.

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CHAPTER VI

CONVERGENT POLARIZED LIGHT

General Statement.—The lens combination used in the microscope for obtaining interference figures is usually described as conoscopic. The usual arrangement produces interference figures visible in the field of the ocular. Such figures are particularly useful for determining the optical directions in crystals. Their interpretation involves the principles outlined in the preceding chapter on polarized light, combined with an understanding of the crystallization of minerals.

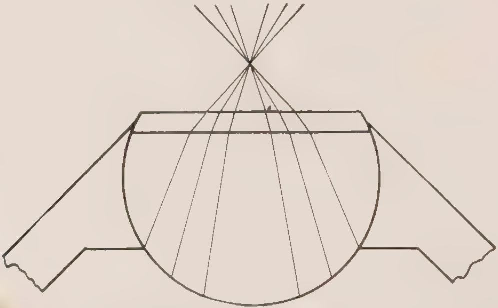


Fig. 65.—Convergent light produced by the front lens of the condenser.

In obtaining interference figures of small crystals, it is necessary to exercise particular care to have all of the elements in the optical train in exact alignment and properly centered. It is best to use a moderately high magnification, preferably a 4-mm. objective, although an 8-mm. objective is sometimes satisfactory and may be more easily manipulated. The auxiliary condenser should be inserted across the axis of the microscope below the stage. The front lens of the condenser throws a concentrated convergent beam against the mineral plate (Fig. 65). Some microscopes are also provided with a diaphragm between the polarizer and the lower component of the condenser. The diaphragm limits the field of view and helps to improve the outer portion of the interference figure. A Bertrand lens is inserted in the tube of the microscope above the analyzer. This lens brings the image of the interference figure into focus on the focal spot of the ocular. The figure then becomes visible to the observer through the ocular. Good figures of small size can be obtained by removing the ocular and not using the Bertrand lens. A black disc with a small hole in the center, or any one of several appliances designed for this purpose, may be used to replace the ocular when an interference figure is obtained without the Bertrand lens.

Two types of interference figures are given by anisotropic minerals: uniaxial and biaxial. Minerals crystallizing in the hexagonal and tetragonal systems are uniaxial, while those crystallizing in the orthorhombic, monoclinic, and triclinic systems are biaxial. Occasionally biaxial crystals have such a small axial angle as to appear uniaxial, and conversely on certain occasions normally uniaxial crystals may become biaxial due to strain. Such variations should be examined with caution when encountered, yet they need not disturb the student's confidence in the interpretation that tetragonal or hexagonal crystals are uniaxial, while monoclinic, orthorhombic, and triclinic crystals are biaxial.

Formation of Interference Figures.—Convergent light passing through a crystal plate causes variation in retardation between crossed nicols. This variation in retardation has many points in common with the variation in retardation obtained with the quartz wedge as described in the discussion of parallel polarized light. The use of the quartz plate instead of a wedge and of convergent polarized light instead of parallel polarized light produces interference colors dependent upon the convergence of the beam. The varying angle of illumination of the oblique rays results in varying values of n_2 and n_1 for a doubly refracting mineral. Varying values of n_2 and n_1 in turn cause varying retardation.

When a quartz plate is being examined the most striking interference effect occurs with the optic axis of the plate at right angles to the microscope stage. The same fundamental considerations that have been demonstrated to hold true in the case of the wedge also apply to the plate. Here, however, the thickness remains constant, while the double refraction $(n_2 - n_1)$ varies with the retardation, depending upon the direction. The angle of incidence on the quartz plate due to the convergent beam employed varies from 0 at the center of the field to a maximum on either edge. As a result, the difference $(n_2 - n_1)$ also changes from 0, at the center where the incident beam is parallel to the optic axis, to considerably greater values at the edge of the field. Darkness or total extinction occurs at the center of the field and where the vibration directions of the inserted plate are parallel to the vibration directions of the nicols, resulting in a black cross for quartz. The explanation lies in the fact that convergent light strikes the surface of a mineral plate not only along a straight line, as in a section of a quartz wedge illuminated by parallel polarized light, but also radially around the center. Consequently, vibration directions will be arranged tangentially and radially throughout 360° of rotation. As a result, vibration directions of the extraordinary and ordinary rays from the plate will be parallel to the vibration planes of the nicols in certain directions. The two directions are directions of extinction and in general uniaxial minerals form dark cross arms at 90° (Fig. 66). In biaxial minerals the positions of extinction show greater variation, and the interference figure is no longer a simple cross but changes as shown in Fig. 67. The different orders of color in the field are arranged in concentric circles around the center of the cross. Other factors remaining the same, the number of color bands observed in a particular field is dependent upon the thickness of the plate and the double refraction of the mineral.

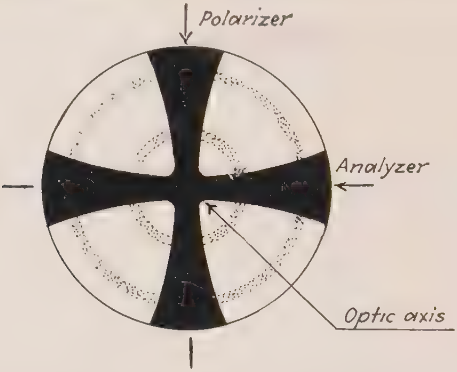


FIG. 66.—A uniaxial interference figure looking down on an optic axis.

Monochromatic light produces alternate dark and light bands in interference figures. The dark bands correspond to retardations of $n\lambda$, while the intermediate maximum colored bands correspond to a retardation of $\frac{(2n+1)\lambda}{2}$. The relationship is similar to that which results when monochromatic light is passed through a quartz wedge. The colors in interference figures produced by white light are actually a combination of the different monochromatic wave lengths due to the varying oblique angle of illumination. This is analogous to the interference color chart where white light results as a summation of the various monochromatic wave lengths due to variation in thickness.

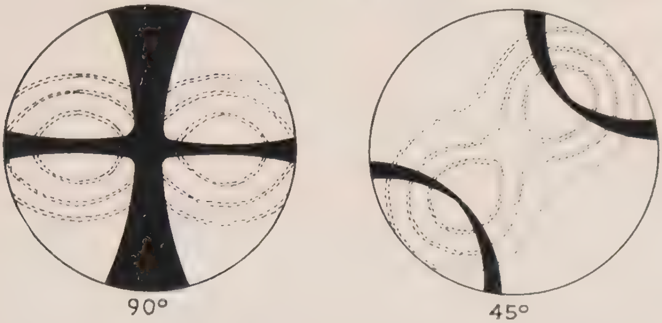


Fig. 67.—A biaxial interference figure in 90° and 45° positions.

Uniaxial Interference Figures.—Hexagonal and tetragonal minerals yield the characteristic axial cross of a uniaxial interference figure when viewed in the direction of the optic axis. If the optic axis of the mineral (the same in direction as the crystallographic *c*-axis) coincides with that of the microscope, the uniaxial figure will be centered with the two arms crossing at the intersection of the crosshairs in the microscope.

However, if the optic axis is inclined to the axis of the microscope, the point of intersection of the cross arms will fall away from the intersection of the crosshairs. It frequently falls outside the field of the microscope. If the center of the axial cross does not coincide with the center of the field, the point of intersection of the arms will move around the crosshair intersection when the stage is rotated, describing a circle and returning to its original position after rotating 360°. The intersection of the cross arms marks the point of emergence of the optic axis, and its deviation from the center of the field is a measure of the angle between the optic axis and the axis of the microscope.

Although uniaxial figures are frequently eccentric in position, the cross arms remain parallel to the planes of vibration of the nicols. Because of this fact the arms sweep the field first from one side, then from another as the stage is rotated. It is important to note whether the arms remain parallel to the crosshairs, since arms in certain biaxial figures also cross the field. The latter are curved or crescent shaped, however, and swing across the field rather than sweep parallel to the nicols. Several eccentric positions of a uniaxial figure are shown in Fig. 68.

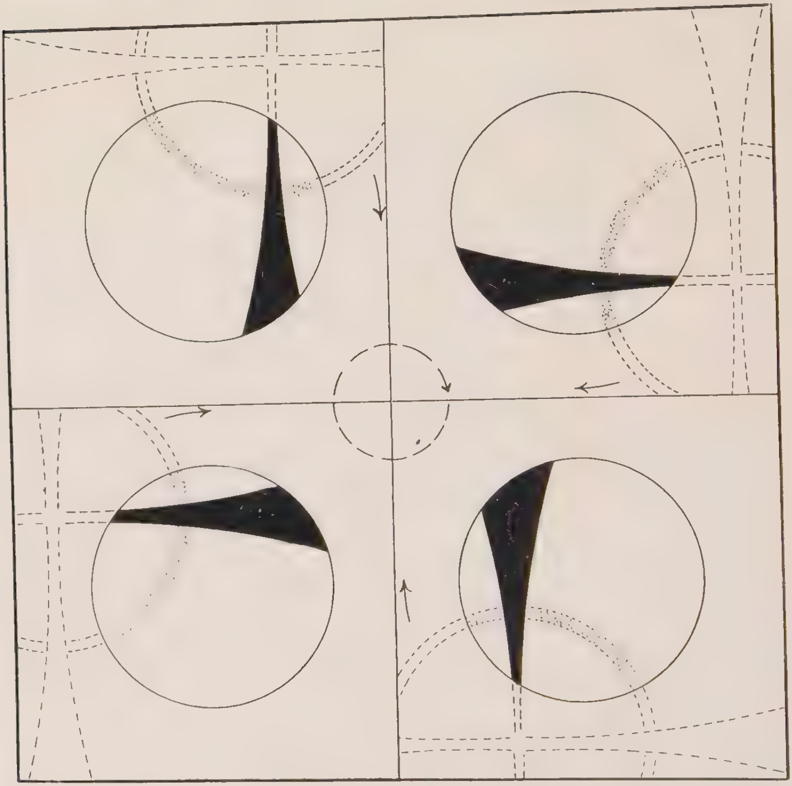
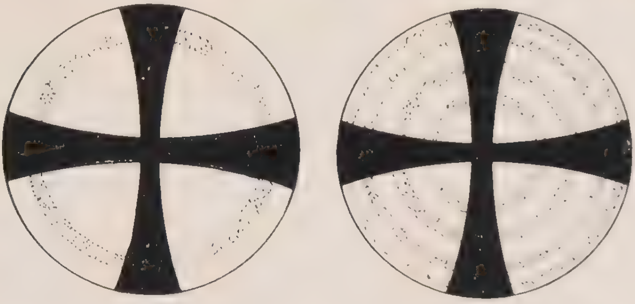


Fig. 68.—Uniaxial interference figure in eccentric positions. Dotted lines indicate the movement of the figure around the field of the microscope as the stage is rotated.

The number of color bands in uniaxial interference figures varies with the thickness of the section and the double refraction of the mineral. For example, thick sections of a uniaxial mineral may give a number of orders of colors, while a thin section of the same mineral may not yield bands of color above the first order. On the other hand, if two plates are made of different minerals, both of identical orientation and having the same thickness, the mineral with the greater double refraction will develop the greater number of color bands. The relation between uniaxial figures due to mineral plates of the same thickness but differing in double refraction is shown in Fig. 69.

Vibration Directions in Uniaxial Crystals.—Convergent polarized light on emerging from a uniaxial mineral in the direction of the optic axis has specific vibration directions. One significant ray vibrates parallel to a plane which includes the *c*-axis of the crystal; another vibrates parallel to a plane at right angles. The two are refracted differently and consequently travel different distances in passing through the mineral plate.

In the upper nicol, resolution occurs into the plane of vibration of the nicol. When the rays vibrate parallel to the nicols, resolution is zero, and darkness occurs—hence the axial cross. At the 45° position of stage rotation the greatest intensity occurs, and the interference colors are most brilliant.



Weak Double Refraction Strong Double Refraction

Fig. 69.—The comparative effect of strong and weak double refraction on the color bands of a uniaxial interference figure.

When two sets of rays are formed by the passage of light through a uniaxial crystal, one set travels with uniform velocity in all directions and is known as the *ordinary ray;* the other varies in velocity with direction and is called the *extraordinary ray.* If light were to radiate out from the center of a solid mass of such an anisotropic medium, at a given instant the wave front produced by the ordinary ray would be a spheroid, while in the case of the extraordinary ray it would be an ellipsoid. Sections of such systems are illustrated in Fig. 70. Sections of the wave fronts consist of an ellipse and a circle. When the ellipse lies within the circle, the mineral is said to be optically positive. When it lies outside the circle, the mineral is said to be negative.

The indices of refraction of the two rays at right angles to the c-axis are represented by n_ϵ and n_ω. n_ϵ is the index of the extraordinary ray, n_ω the index of the ordinary ray. In the case for positive minerals n_ϵ is greater, while for negative minerals n_ϵ is less. The velocities represented in the diagram Fig. 70 are the reciprocals of the indices of refraction. The ray velocities have equal values in the direction of the c-axis, where the circle and ellipse coincide, and have their maximum difference in a direction at right angles to the c-axis. The greatest and least indices of refraction occur at right angles to the c-axis, and in these directions (only) the indices of refraction are the reciprocals of the ray velocities.

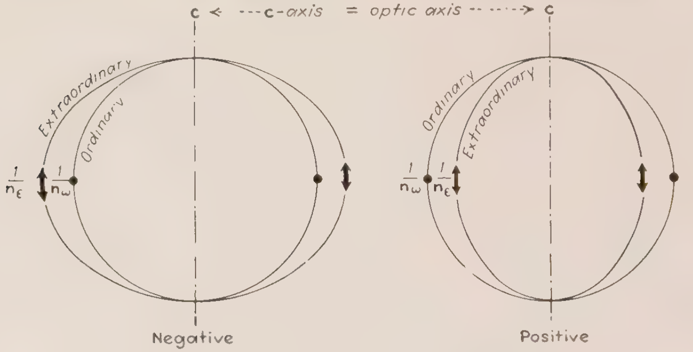


FIG. 70.—Sections of wave surfaces for uniaxial minerals.

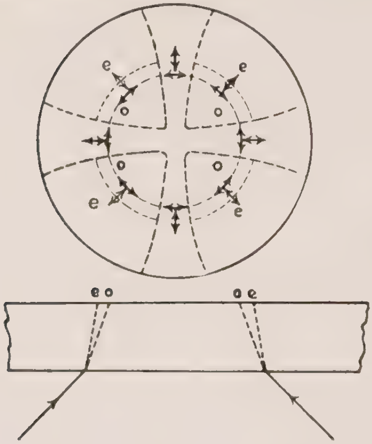


FIG. 71.—Vibration directions in a uniaxial positive interference figure. o = fast ray (least refracted); e = slow ray (most refracted). Velocity of $o = \frac{1}{n\omega}$; velocity of $e = \frac{1}{n\epsilon}$.

In Fig. 71 convergent light is shown striking the surface of a mineral plate such as quartz, cut normal to the c-axis. The convergent beam is refracted and broken into two rays. One of the rays, the extraordinary ray e, is more refracted and has the lesser velocity. The other ray, the ordinary ray o, is less refracted and has the greater velocity. Although the diagram is simplified by using two lines to represent the e and o rays, actually there are many multiples of each of the two rays. The radial arrangement, however, obtains throughout.

Positive and Negative Character of Uniaxial Crystals. As already stated, doubly refracted rays of the uniaxial interference figure are arranged radially as shown in Fig. 71. The extraordinary ray vibrates in the *principal plane* parallel to the *c*-axis; the other vibrates at right angles. In some minerals the ray vibrating in the principal plane is the slow ray of the crystal; in others it is fast. If it is the slow ray, the mineral is positive; if fast, it is negative. The mineral in the case of Fig. 71 would be optically positive since the slow ray *e* vibrates parallel to the *c*-axis.

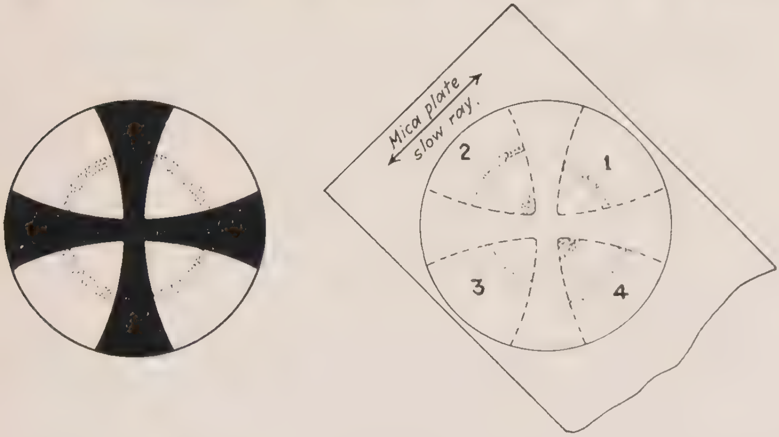


FIG. 72.—Determination of the optic character or sign for a uniaxial positive mineral.

The position of the slow ray with reference to the *c*-axis may be determined with an accessory plate. If a mica plate, gypsum plate, or quartz wedge is inserted with the slow ray in coincidence with the slow ray of the interference figure, the color bands will change position sufficiently to indicate the optical character of the figure. If the retardation is increased parallel to the slow ray of the interference figure, the mineral is positive. If decreased, the mineral is negative. The movement of the color bands, showing the increase and decrease in retardation when a mica plate is inserted, is illustrated in Fig. 72. The color bands in quadrants 1 and 3 move toward the center, while the corresponding color bands in quadrants 2 and 4 move away from the center. The movement in quadrants 1 and 3 represents increase in retardation, while that in quadrants 2 and 4 represents decrease in retardation. In the illustration retardation increases parallel to the slow ray since the vibration direction of the slow ray of the mica plate is parallel to quadrants 1 and 3. A figure of this sort is positive.

Examination of Fig. 73 will show that in the four parts of the circle at 45° to the planes of the nicols the extraordinary and ordinary rays lie in 45° planes or normal to 45° planes. The arrangement is also alternate and opposite.

The direction of vibration of the slow ray should be marked on each accessory. If a mica plate is inserted with the slow ray in the (1–3) position, the retardation along the extraordinary ray in the (1–3) quadrants will in effect be reinforced. At the same time, an effect of subtraction will occur in the (2–4) quadrants. The color bands of the interference figure will be displaced by this superposition. Where reinforcement occurs, the bands will move toward the center of the circle. Where subtraction occurs, the bands will move in the opposite direction.

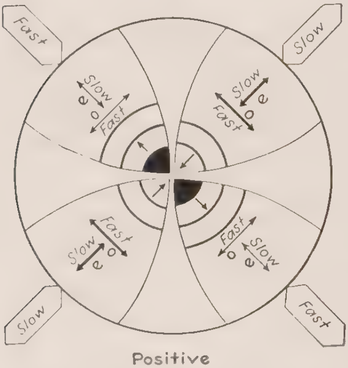


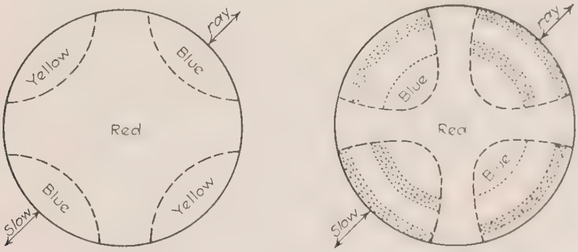
FIG. 73.—The vibration directions in both accessory plate and mineral for a uniaxial positive figure.

In optically positive minerals subtraction occurs at right angles to the direction of the slow ray in the accessory. In negative minerals the subtraction is in the quadrants lying along the slow-ray direction.

The significant directions are shown in Fig. 73. The diagram indicates the direction of vibration for each of the four quadrants of a uniaxial positive interference figure in the 45° position. Corresponding slow- and fast-ray vibration directions for an accessory plate are indicated along the margins of the interference figure. The ordinary ray *o* is less refracted in the mineral and travels with greatest velocity. The extraordinary ray *e* is more refracted and travels with the least velocity.

In uniaxial negative minerals the situation is reversed. The extraordinary ray will be the fast ray, while the ordinary ray will be the slow one. The radial arrangement of vibration directions, however, will remain the same. As a result, increase in retardation will occur parallel to the slow ray. When a mica plate is inserted, decrease in retardation produces two black dots in alternate quadrants at the center of an interference figure. The direction of the two dots forms a plus with the vibration direction of the slow ray of the mica plate in positive uniaxial minerals, and a minus when the minerals are negative. This relationship serves to keep in mind the fast- and slow-ray vibration directions in uniaxial crystals.

The gypsum plate is frequently more useful for determining the optical character of a uniaxial mineral than is the mica plate. Two bright blue areas form in opposite quadrants of the interference figures of many uniaxial minerals. These stand out particularly in figures given by minerals of moderate or intermediate double refraction. When the optical character is positive as in the case of quartz, the two blue areas occur in opposite quadrants parallel to the slow-ray vibration direction of the gypsum plate (see Fig. 74*a*). When the optical character is negative as in the case of calcite, the two blue areas occur in opposite quadrants at right angles to the slow-ray vibration direction of the gypsum plate (see Fig. 74*b*).



(*a*) (*b*)

Fig. 74—(*a*). Uniaxial positive. Quartz cut perpendicular to an optic axis as viewed in the interference figure with a gypsum plate. (*b*) Uniaxial negative. Calcite cut perpendicular to an optic axis as viewed in an interference figure with a gypsum plate.

Biaxial Interference Figures. *Introduction.* Under normal conditions minerals crystallizing in the orthorhombic, monoclinic, and triclinic crystal systems give biaxial interference figures. Rarely, due to crystallization under strain, hexagonal or tetragonal minerals, normally uniaxial, are anomalous and produce biaxial figures. The latter, however, are exceptions to the general rule.

Double refraction, orientation, and thickness of section govern the character of biaxial interference figures as rigidly as in the case of uniaxial interference figures. Biaxial interference figures are also produced by the same optical arrangement of the microscope employed in the case of uniaxial figures. Unlike uniaxial figures, curves of biaxial figures assume different relative forms as the stage is rotated. The difference between uniaxial and biaxial minerals is fundamental and is due to the arrangement of the atoms set up in crystallization.

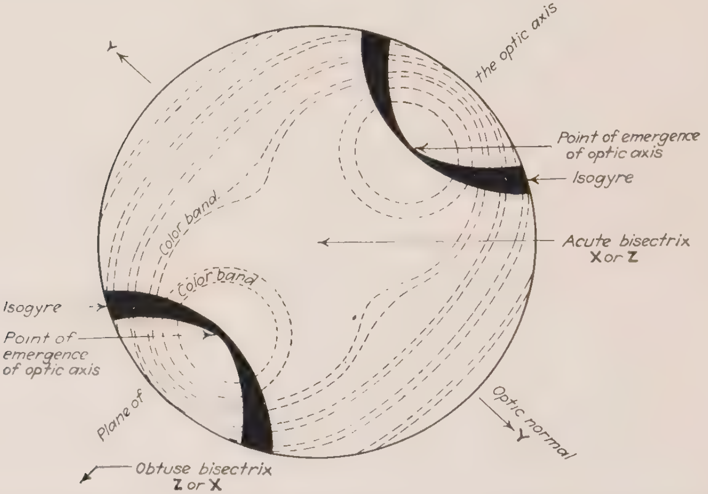


FIG. 75.—The parts of a biaxial interference figure perpendicular to the acute bisectrix in the 45° position.

Figure 67 illustrates the two different forms of a biaxial interference figure given by a mineral at 90° and 45° intervals of rotation of the microscope stage. The 45° position is the most useful for ordinary optical determinations and is ordinarily employed in the study of biaxial minerals. The figure in this position is described as an *acute bisectrix* figure at 45°.

The 45° Acute Bisectrix Figure.—Figure 75 indicates the nomenclature of the parts of an acute bisectrix figure at 45°. The different features may be described as follows:

Isogyres.—The two broad black curves, or brushes, are known as isogyres. The points of tangency on the convex side of these curves mark the positions of the optic axes in the interference figure and are known as the *points of emergence*. In minerals with strong dispersion the curves are not so black or so sharp as in the case of minerals with weak dispersion. Strong dispersion produces red and blue fringes on the margins of the isogyres. By noting the distribution of the colored fringes in the interference figure one determines the character of the dispersion.

Points of Emergence of the Optic Axes.—As just stated, the points of tangency of the two crescent-like curves mark the points of emergence of the optic axes. The amount of separation of these points differs with different minerals but is a constant for an individual mineral. The line between the two points of emergence subtends the optic axial angle. Color bands are distributed symmetrically around the two optic axes.

Johannsen has suggested the word *melatope* for the point of emergence.

Plane of the Optic Axes.—The plane of the optic axes, or axial plane, includes the two points of emergence of the optic axes, the acute bisectrix direction, and the obtuse bisectrix direction.

Color Bands.—Interference color bands representing positions of equal retardation are distributed in symmetrical curves around the points of emergence of the optic axes and are called *isochromatic curves.*

X, Y, and Z Directions:

(X) Light vibrating parallel to X has the maximum velocity.

(Z) Light vibrating parallel to Z has the minimum velocity.

(Y) Indicates the direction at right angles to the plane of X and Z.

The three axes of ease of vibration X, Y, and Z are distributed in the interference figure as shown in the diagram. Y is normal to the plane of the optic axes. If X is the acute bisectrix, the mineral is optically negative. If Z, the mineral is positive. If the acute bisectrix is X, the obtuse bisectrix is Z, and *vice versa.*

Optic Normal.—The direction at right angles to the plane of the optic axes is referred to as the optic normal. It is the axis Y.

Eccentric Biaxial Figures. Biaxial interference figures may be encountered in a number of different positions. Frequently a single isogyre swings across the field of the microscope in a curved path. The most useful figures for all ordinary work are either acute bisectrix or optic-axis figures. In optic-axis figures the convex side of the isogyre in the 45° position indicates the direction of the acute bisectrix.

Optic-axis figures and most acute bisectrix figures are given by mineral sections showing comparatively low-order colors between crossed nicols in parallel light. Examination of a number of crystals of miscellaneous orientation between crossed nicols will often quickly reveal those most likely to give interference figures of useful orientation in convergent light.

Optical Directions in Biaxial Minerals.—Within certain limits the axes X, Y, and Z have positions in minerals which are dependent upon the system of crystallization. In orthorhombic minerals X, Y, and Z are fixed with respect to the crystallographic axes *a*, *b*, and *c*. In the monoclinic system one of the three axes (often Y) coincides with the crystallographic axis *b*. In

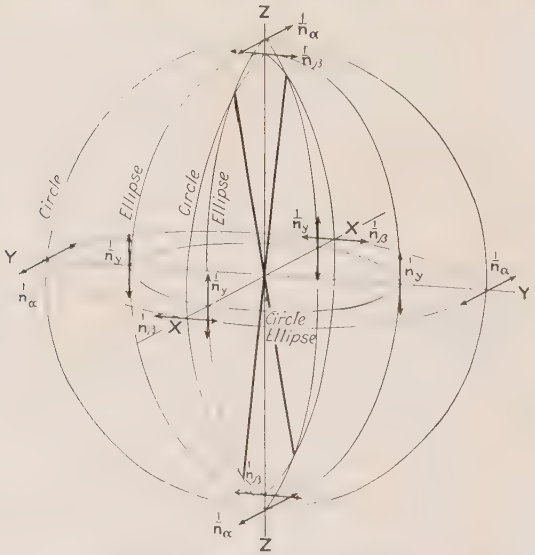


Fig. 76.—Biaxial wave surface.

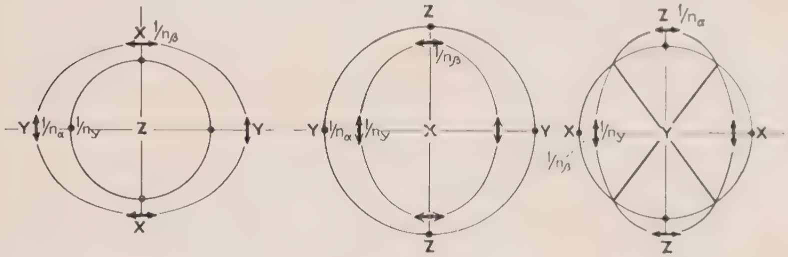
the triclinic system there are no limitations of position according to the crystallographic axes.

Fresnel's wave surface for biaxial crystals is illustrated by Fig. 76. The optic axes lie in the plane of X and Z and the acute angle (2V) between the optic axes varies between 0 and 90°.

If the axis Z is the bisectrix of the acute angle between the optic axes, the mineral is said to be optically positive. If the axis X is the acute bisectrix, the mineral is said to be optically negative.

Let us assume a single crystalline mass of a biaxial crystal of sufficient size to allow examination of light variation in the system. If light were to radiate out from the center of a solid mass of such an anisotropic medium, at a given instant the wave front produced would be a double-sheeted surface with sections as illustrated in Fig. 76.

Two wave fronts appear in each section—one a circle, the other an ellipse. The size of each circle is determined by the velocity of the light ray vibrating parallel to the axis around which it is generated. Around X the radius of the circle is $1/n_\alpha$; around Y the radius is $1/n_\beta$; and around Z it is $1/n_\gamma$. Since n_α is the least index of refraction and $1/n_\alpha$ indicates the greatest velocity for the system, the circle around X is the greatest. Since $1/n_\beta$ is intermediate in velocity, the circle around Y will have intermediate size. Since $1/n_\gamma$ represents the least velocity, the circle around Z will be smaller than the circles around the two other axes. Three combinations of ellipses and circles are represented. In the section perpendicular to Y and along XZ the circle with radius $1/n_\beta$ intersects an ellipse with major and minor axes $1/n_\alpha$ and $1/n_\gamma$, respectively. In the section perpendicular to Z and along XY the smallest circle, radius $1/n_\gamma$, lies within the ellipse with major and minor axes $1/n_\alpha$ and $1/n_\beta$, respectively. In the section perpendicular to X the largest circle, radius $1/n_\alpha$, lies outside the ellipse with major and minor axes $1/n_\beta$ and $1/n_\gamma$, respectively.



(a) (b) (c)

FIG. 77.—Sections of biaxial wave surface. (a) Section perpendicular to Z. (b) Section perpendicular to X. (c) Section perpendicular to Y.

Light vibrating parallel to Z will radiate outward from the center in the plane XY. The wave front will be circular, and the velocity will be $1/n_\gamma$. Similarly, light vibrating parallel to X will travel outward in the plane YZ with a circular wave front, and the velocity will be $1/n_\alpha$. Likewise, light vibrating parallel to Y will travel in the plane XZ with a circular wave front and a velocity $1/n_\beta$. In each of these instances n_α, n_β, and n_γ represent, respectively, the least, intermediate, and greatest indices of refraction of the mineral.

The planes XY, YZ, and XZ require special examination. Sections along each of these planes are illustrated in Fig. 77*a*, *b* and *c*.

In the plane XZ the ellipse and circle will cross at four points. At these four points no difference in wave velocity exists. These points of intersection mark the positions of the *secondary optic axes*, or *biradials*. In most crystals these secondary optic axes lie very near the *primary optic axes* but are not identical with them.

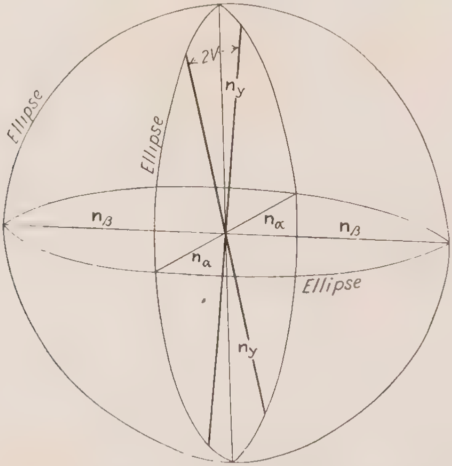


Fig. 78.—The optical indicatrix for biaxial crystals.

Optical Indicatrix.—It is often found more convenient to represent the optical relations of crystals by means of a figure called the optical indicatrix (Fig. 78) than by the biaxial wave surface (Fig. 76). The optical indicatrix is also a three-dimensional figure but differs materially in the surface developed. The biaxial wave surface consists of two intersecting surfaces, whereas the exterior of the optical indicatrix is a single surface. The major, minor, and intermediate axes upon which the two are based also differ materially. The biaxial wave surface is based upon axes which are proportional to the reciprocals of the refractive indices. The optical indicatrix, on the other hand, is based upon axes directly proportional to the refractive indices.

COMPARISON OF THE BIAXIAL WAVE SURFACE AND THE OPTICAL INDICATRIX

Comparative features	Distance from center to surface	
	Biaxial wave surface	Optical indicatrix
Major axis	$1/n_\alpha$ and $1/n_\beta$	n_γ
Intermediate axis	$1/n_\alpha$ and $1/n_\gamma$	n_β
Minor axis	$1/n_\gamma$ and $1/n_\beta$	n_α
Optic axes	Secondary optic axes or biradials	Primary optic axes or normals
Surface	Double	Single

The optical indicatrix for biaxial crystals may be described as a triaxial ellipsoid. In common with all triaxial ellipsoids the surface is symmetric in the origin, and in the coordinate axes and coordinate planes. The origin is the *center* of the ellipsoid, the coordinate axes are the *axes* of the ellipsoid, and coordinate planes are the *principal planes* of the ellipsoid.

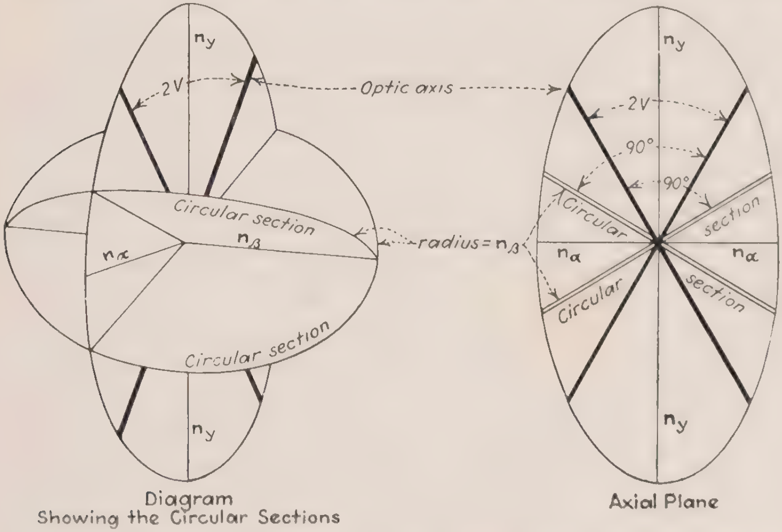


FIG. 79.—The relationship between the two circular sections, the optic axes and ellipsoidal axes (n_α, n_β, and n_γ) in the optical indicatrix.

The diameters of the optical indicatrix measured along the axes are $2n_\alpha$, $2n_\beta$, $2n_\gamma$. These values correspond in order to the minor, intermediate, and major axes of the ellipsoid. The sections cut by the principal planes are the *principal sections* of the ellipsoid. These sections are ellipses and have as major and minor diameters combinations of $2n_\alpha$, $2n_\beta$, and $2n_\gamma$.

All except two of the plane sections of the biaxial indicatrix that are cut through the center are ellipses. These are circles (Fig. 79). The two circular sections include the semi-axis with length n_β, and thus the length of the radius of each circular section equals n_β. The directions perpendicular to the two circular sections are called the *optic* axes, or *binormals.* These are sometimes called the primary optic axes and differ slightly from the secondary optic axes (biradials) of the biaxial wave surface.

The indicatrix for uniaxial crystals provides a special case of the ellipsoid. In such crystals two of the diameters have the same value, $2n_\omega$. As a result, the principal section containing the two diameters, each having the value $2n_\omega$, is a circle. The surface of this indicatrix is an ellipsoid of revolution.

The indicatrix for isometric crystals is another special case. The three diameters of the indicatrix have equal values, $2n$, and the surface developed is a sphere.

The optical properties of light rays may be determined in any given direction in a triaxial ellipsoid. Let us suppose Fig. 80 to represent the ellipsoid. The semi-axes are n_γ, n_β, and n_α, respectively, and $S'S$ represents the direction of propagation of light along a given line. If the direction of $S'S$ has been determined or is known, the following three pairs of optical properties become known by construction:

1. The vibration directions of the two rays traveling along $S'S$.
2. The two corresponding indices of refraction, n_2 and n_1.
3. The directions of the two wave normals.

If the direction of the diameter $S'S$ is known, the position of the planes tangent to $S'S$ at the two ends of the diameter also becomes known. It is then possible to pass a parallel diametral plane through the ellipsoid intersecting the center and equidistant between the two tangent planes. The diametral plane through the center will cut an elliptical section in all but two possible positions of $S'S$. These two exceptional positions are the optic axes, and here the sections cut are circular (Fig. 80). The elliptical section furnishes measurements from which the optical properties can be determined. The diametral plane will have major and minor axes. These axes mark the vibration directions of the two rays traveling along $S'S$. The major and minor radii represent the refractive indices of the waves associated with the two rays, equaling n_2 and n_1. The wave normal corresponding to the ray propagated along $S'S$ and vibrating along the major axis lies in a plane through $S'S$ and the major axis and is normal to the axis. Similarly, the wave normal corresponding to the ray propagated along $S'S$ and vibrating along the minor axis lies in a plane through $S'S$ and the minor axis and is normal to the axis.

Drop perpendiculars from the intersection of the axes with the circumference of the ellipse (Figs. 80 and 81) upon $S'OS$; these perpendiculars are P_2Q_2 and P_1Q_1. Then $1/P_2Q_2$ is the velocity of the ray propagated along $S'OS$ and vibrating along the major axis, and $1/P_1Q_1$ is the velocity of the ray propagated along $S'OS$ and vibrating along the minor axis. P_1Q_1 lies in a plane at right angles to the plane of the drawing in Fig. 81[1].

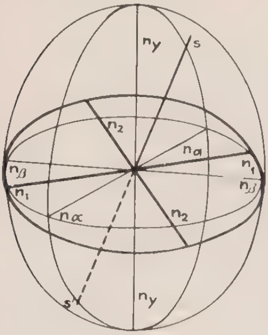


Fig. 80.—A ray OS in an optical indicatrix with a conjugate plane through O and parallel to tangent planes at S and S'.

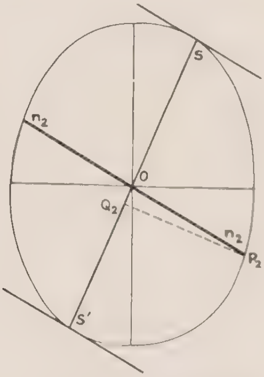


Fig. 81.—Section through an ellipsoid showing the ray OS together with traces of tangent and diametral planes

The Axial Angles 2E and 2V.—The observed axial angle is always greater than the true axial angle within the mineral. This is due to the refraction of the oblique rays as illustrated in Fig. 82. The angle 2E is the angle in air, while 2V is the internal angle.

Mallard's equation ($D = K \sin E$) may be used to determine the approximate axial angle with the microscope. In the equa-

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[1] The above discussion is largely based upon a paper, The Ray Surface, the Optical Indicatrix, and Their Interrelation, by Dr. George Tunell (*Wash. Acad. Sci.*, 1933). An advance copy of the manuscript was kindly furnished by Dr. Tunell prior to publication.

tion K is a constant for a particular microscope, D is one-half the distance between the points of emergence, and E is one-half the axial angle in air. 2E having been determined the next step is to compute 2V.

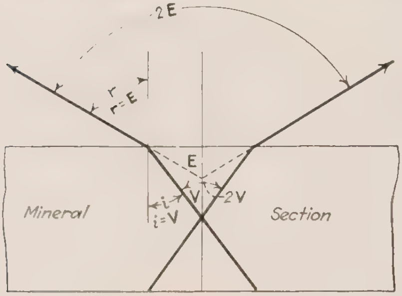


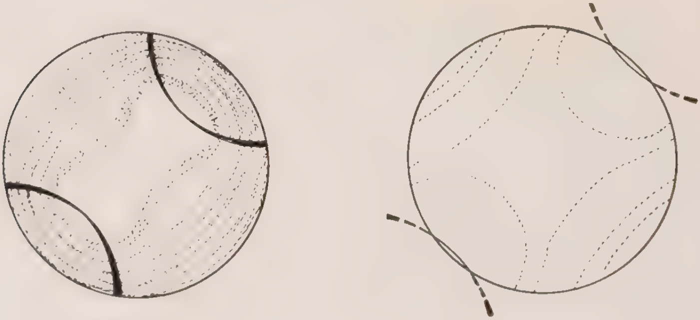
FIG. 82.—The relation between the observed angle $2E$ and the angle $2V$ in biaxial minerals.

The computation of the axial angle in a mineral from the observed axial angle in air depends upon the formula:

$$\sin E = n_\beta \sin V.$$

When $n \sin V$ is equal to 1, the angle 2E becomes 180° and the axial angle in air cannot be measured. Angles greater than 180° likewise cannot be measured in air. The value of the observed angle may be reduced to measurable dimensions by immersing the objective in oil of known refractive index.

Large axial angles need to be measured with a rotation device. Such devices for rotating crystals in a vertical circle may be adapted to the stage of the microscope; otherwise special apparatus must be employed.



(*a*) Aragonite
$2V = 19°$
$N_\gamma - N_\alpha = 0.155$

(*b*) Barite
$2V = 37°30'$
$N_\gamma - N_\alpha = 0.012$

FIG. 83.—Comparison of axial angles.

Variation in Axial Angle.—Figure 83 illustrates two biaxial interference figures in the 45° position. The figures represent two different minerals—aragonite on the left and barite on the right. The two sections from which the interference figures are derived have been cut normal to the acute bisectrix in each instance, and the sections are also of approximately the same thickness. As a result of these conditions, only two variables remain to produce differences in the diagram: variation in the axial angle 2V, and variation in the double refraction $n_2 - n_1$.

The isogyres in the figure on the left represent the approximate position of the two curves in relation to the field of the microscope for an axial angle 2V = 19° (aragonite). The figure on the right represents barite drawn to the same scale. In this instance the angle 2V = 37°30′ places the isogyres at the edge of the field of view.

The dotted lines in the figures indicate the distribution of the color bands. Aragonite has a double refraction of 0.155, which is considerably larger than the double refraction of barite, which is 0.012. In consequence, for the same thickness of section, aragonite has many more color bands than barite.

The student should study the interference figures of a number of different mineral sections of the same thickness, and cut normal to the acute bisectrix, until he becomes familiar with the variation of the isogyres with the axial angle. In fact, it is worth while to record in a notebook the relative positions of the isogyres for angles in the neighborhood of 5, 10, 15, 20, 25, 30, 35, and 40°. A record of this sort will be of considerable assistance in determining the approximate axial angle of an unknown mineral.

It should also be remembered that if the thickness remains the same, the color bands of the interference figures will either increase or decrease with increase or decrease in the double refraction.

Determination of the Optical Character of a Biaxial Mineral. — The optic sign is best determined with the mineral in the 45° position. The quartz wedge is employed for most determinations. In some cases, however, a mica plate or gypsum plate may be preferred. The same principles utilized when the quartz wedge is employed apply equally in determinations with the other accessory plates.

As stated before, X, Y, and Z are the axes of ease of vibration. Light traveling through a crystal normal to X has the maximum velocity for all directions in the crystal. Light traveling normal to Z has the least velocity. The direction Y is normal to the plane of X and Z. When the direction X is the acute bisectrix, the mineral is optically negative. If Z is the acute bisectrix, the mineral is positive.

A biaxial negative crystal in the acute bisectrix position at 45° will be used to illustrate the method of determining the optic sign (see Fig. 84). A biaxial figure of this type is first observed carefully in order to note the position of the color bands, both in the central area and within the two small areas inclosed by the concave portions of the isogyres. A quartz wedge is then inserted in the accessory slot with the slow ray parallel to the axial plane. Movement of the color bands occurs as the wedge is inserted.

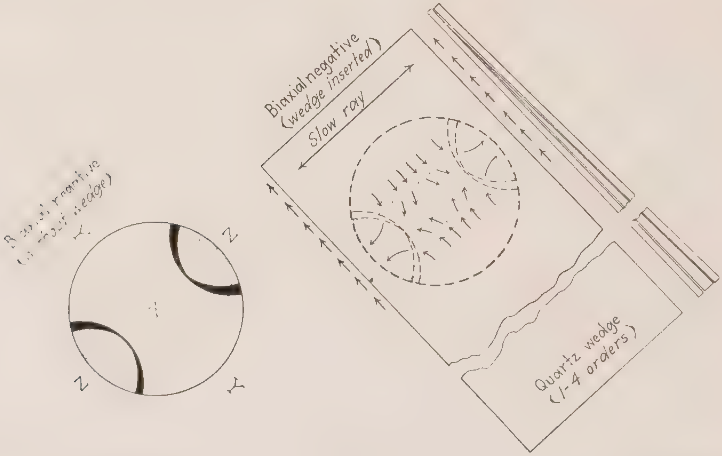


Fig. 84.—The determination of the optic sign with a biaxial negative interference figure.

The movement of the color bands in a negative crystal is indicated by the arrows in Fig. 84. As the wedge is moved in *i.e.*, as the thickness increases the color bands in the central area move toward the two "eyes," or melatopes, of the interference figure. At the same time the bands on the opposite sides of the isogyres within the two small areas move away from the melatopes. As the wedge is withdrawn, the movement of the color bands is reversed. If a positive crystal is substituted, the movement of the color bands is also reversed.

In the biaxial negative crystal illustrated the axis Z lies in the axial plane along the direction of the obtuse bisectrix. The axis X is perpendicular to Z and is the direction of the acute bisectrix. The axis Y is the optic normal. Two rays travel along X with vibration directions at right angles to each other, the vibration directions being parallel, respectively, to Z and Y. The ray vibrating parallel to Z is the slow ray for the crystal (velocity $1/n_\gamma$), while that parallel to Y is intermediate in velocity, having the value $1/n_\beta$. Thus in the central area of the interference figure at X we have a slow ray, velocity $1/n_\gamma$, and an intermediate but faster ray, velocity $1/n_\beta$. Consequently, if the slow ray of the quartz wedge is parallel to the direction Z, increase in retardation occurs as the wedge thickness increases. This results in a movement of the color bands toward the melatopes in the central portion of the figure as the wedge is inserted. At the same time the color bands in the outer portions will move in the opposite direction, since here the slower ray and faster ray relations are reversed. If the quartz wedge is always inserted as indicated in Fig. 84, an acute bisectrix biaxial negative interference figure in the 45° position will always show movement of the color bands toward the melatopes in the central area. Conversely, a biaxial positive figure treated in the same way will show movement in the opposite direction. Since the slow-ray vibration direction in the quartz wedge is marked, the slow-ray vibration direction in the interference figure is easily determined by comparison. Examples of both positive and negative biaxial figures in monochromatic light with the slow-ray vibration direction of an accessory plate superimposed are shown in Fig. 85.

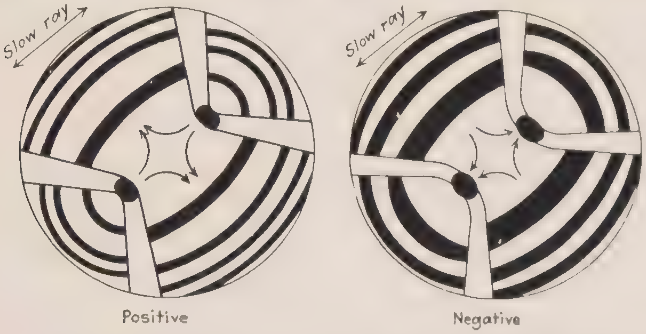


FIG. 85.—Positive and negative biaxial crystals (indicating their appearance with a mica plate in monochromatic light).

The Optic-axis Figure. Interference figures produced by sections cut normal or nearly normal to one of the two optic axes of a biaxial mineral are useful for determinations of optic sign. Such sections yield interference figures having a single isogyre in the field of view. The melatope, or point of emergence, may coincide with the axis of the microscope or may be slightly inclined.

As the stage is rotated, the isogyre swings around the field, remaining centered or nearly centered, depending upon the eccentricity of the section. The color bands are arranged almost circularly around the melatope and vary in retardation with the double refraction of the mineral.

The curvature of the isogyre decreases with an increase in 2V. When the axial angle is large—*i.e.*, near 90°—the isogyre is straight and the acute bisectrix side of the interference figure becomes indistinguishable from the obtuse bisectrix side. When the angle is small, however, the isogyre is definitely curved in a crescent-like form. The convex side of the curve in the 45° position points toward the acute bisectrix, while the obtuse bisectrix is on the concave side.

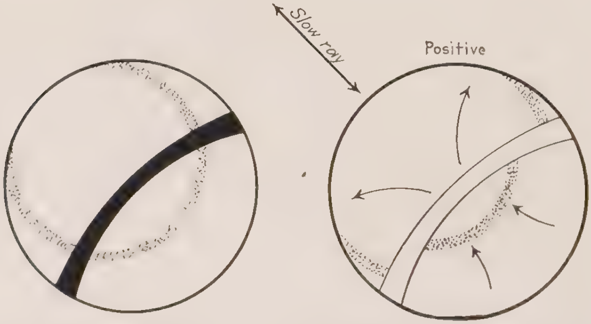


Fig. 86.—The optic sign for a biaxial positive optic-axis figure.

Optic-axis figures showing even slight curvature are useful for determinations of the optic sign. The mica plate, gypsum plate, or quartz wedge may be employed depending upon the double refraction of the mineral. The effect of the quartz wedge upon a biaxial positive optic-axis interference figure is shown in Fig. 86. An optic-axis figure without a plate inserted is shown on one side of the diagram, while the movement of the color bands caused by insertion of a gypsum plate is shown on the opposite side.

Dispersion in Biaxial Interference Figures. The optic angle for light of one wave length is frequently greater or less than for light of another wave length. In the normal interference figure produced by white light this is usually detected by a peculiar arrangement of the color bands or by the development of blue and red fringes on the isogyres.

The dispersion recorded in most tables of optical mineralogy is that of the optic axes. The two extreme rays of the spectrum are used to designate the character of the dispersion. Thus, if the axial angle for red r is greater than that for violet v, the dispersion is expressed $r > v$. In case the reverse is true, the formula is $r < v$.

FIG. 87.—Dispersion $r < v$.

In many instances the dispersion can be determined by direct observation of the biaxial interference figure (Fig. 87). If the isogyres of the interference figure ($r > v$) have a distinct red fringe on the convex edges, the angle for red is greater than for violet. Both isogyres should be observed before reaching a conclusion. On the concave side of the isogyre, as illustrated in the figure, red light is extinguished and consequently the concave fringe is blue in color. Blue is extinguished on the convex side, and the fringe is red.

It should be emphasized that the symmetry of the interference figure is always governed by the symmetry of the mineral. Dispersion varies according to the symmetry of the crystal system. The various types, arranged according to crystal system, are as follows:

- Orthorhombic crystals:
  - Dispersion of the optic axes.
  - Crossed axial plane dispersion.
- Monoclinic crystals:
  - Inclined dispersion (both bisectrices).
  - Horizontal dispersion (acute bisectrix).
  - Crossed dispersion (obtuse bisectrix).
- Triclinic crystals:
  - Unsymmetrical dispersion.

These types are best distinguished by the use of light of various wave lengths. Red and blue color filters to be placed in front of the mirror of the microscope are convenient.

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CHAPTER VII

COLOR, FORM OR AGGREGATION, CLEAVAGE, AND ORIENTATION

Color and Pleochroism.—The color of minerals in the hand specimen is not always a good index of the appearance of the mineral in a thin section. Minerals are faintly colored in thin sections in contrast to deep colors in hand specimens, and frequently minerals having definite and pronounced hues when viewed with the unaided eye are colorless beneath the microscope. Since sections that are not properly ground and are too thick will often retain the hand-specimen color, it is particularly desirable to have thin sections of deeply colored minerals ground as thin as possible. It is obvious that deeply colored minerals are more apt to be colored in thin section than are pale minerals.

Isotropic colored minerals show no color change as the mineral is rotated in plane-polarized light. Anisotropic colored minerals, on the other hand, exhibit a change in color in varying degree as the stage is rotated. Since the same mineral frequently produces a number of colors the change in color produced is known as *pleochroism*. Occasionally light vibrating in one plane through a crystal is colorless, while in another plane at right angles a definite hue is observed; or the condition may obtain in which two vibration directions produce colors, while a third may be colorless. Three different pleochroic colors may be produced by a single biaxial crystal, or two pleochroic colors by a uniaxial crystal.

Hexagonal or tetragonal colored minerals are *dichroic—i.e.*, the pleochroic coloring of minerals in these two systems as exhibited with the microscope is twofold.

Orthorhombic, monoclinic, and triclinic minerals, when colored in thin section, exhibit three different colors and are *trichroic*. The pleochroic colors are normally orientated with the axes of elasticity X, Y, and Z of the crystal. When the directions of the axes of elasticity in a mineral are known from the presence of important cleavages, crystal boundaries, twin planes, or from an interference figure, the colors of light vibrating parallel to the axes X, Y, and Z may be ascertained. Since X, Y, and Z are the vibration axes, a definite relationship exists with n_α, n_β, and n_γ and also the optic axes. The correlation of the relationships is best accomplished by study of the interference figure in order to determine the directions of the axes. As soon as the acute bisectrix Z (if the mineral is positive) or X (if the mineral is negative) is known, the Bertrand lens and analyzer should be removed from the microscope tube and the corresponding natural color ascertained. The color produced by light vibrating in a plane at right angles to the axial plane is Y. The third color will be due to light vibrating parallel to the direction of the obtuse bisectrix. This will be X if the mineral is positive or Z if the mineral is negative.

In pleochroic uniaxial minerals light vibrating parallel to the optic axis is one color, while light at right angles is another.

Biaxial minerals exhibit varying degrees of absorption of color. In common hornblende, for instance, light vibrating parallel to Z usually shows the most absorption, Y is less absorbed, and X is the least. This is recorded by means of the *absorption formula*

$$X < Y < Z$$

It is customary to record the absorption in terms of vibration parallel to the ease of vibration axes.

Form or Aggregation.—Minerals assume many varying forms beneath the microscope, depending upon the chemical nature of the material and the conditions of crystallization. A considerable number of the designs produced by groups of crystals observed in thin sections and cross sections of individual minerals are so unusual that the mental picture produced is of decided aid in identification.

This tendency is useful on account of the frequency with which many minerals assume a peculiar development. Such a tendency in the case of individual crystals may be described as *habit*. *Aggregation* refers to the nature of grouping of either a few or numerous small crystals. The pattern which a mineral group assumes may be described as its *mode of aggregation*. Both form and aggregation are discussed in the following paragraphs.

Incipient Crystallization.—Natural glass frequently forms from a viscous liquor which upon solidifying lacks crystallization and is isotropic. The material, however, contains constituents capable of producing a number of different minerals. Development of these minerals is hindered by the viscosity of the inclosing liquor during the period of crystallization, owing largely to quick release of pressure and rapid cooling of the material. As a result, definite crystals may not develop, but instead needle-like aggregates, fernlike growths, and various odd designs may be formed representing the sudden arrest of the process of crystallization. *Crystallites*, *margarites*, *trichites*, *microlites*, *globulites*, and *longulites* are names that have been applied to various forms of incipient crystallization. Trichites are circular streaks of embryonic crystals in glass. Margarites are long streaks of globular forms resembling portions of strings of seed pearls in curved or straight lines. Longulites are small rodlike forms composed of the grouping of globulites. Crystallites are the minute nuclei of crystallization existing suspended in volcanic glass. Microlites are small needle-like, almost crystalline forms. Incipient crystals in glass are illustrated in Fig. 88.

Non-crystalline Isotropic Minerals.—Minerals lacking directional qualities capable of producing double refraction are dark between crossed nicols. Such minerals are chiefly identified by means of their structure in thin section, combined with a determination of their indices of refraction.

Glass, opal, cliachite (bauxite), and collophane are illustrations of common non-crystalline or amorphous minerals.[1] In addition to incipient crystals, glass frequently exhibits flow lines, cracks, or concentric fractures of distinctive character. Opal is usually banded and in addition may exhibit a play of colors. Shatter cracks are distinctive features in minerals of colloidal origin (Fig. 89).

Cliachite, the amorphous mineral making up a considerable portion of bauxite, occurs in pisolitic or rounded forms frequently cracked and fractured at random. The interstices between the pisolitic forms may be filled with finely crystalline gibbsite forming a fine-grained gray and white mosaic of small crystals between crossed nicols or may be transparent without crossed nicols. A thin section of cliachite and gibbsite in bauxite rock from Arkansas is illustrated in Fig. 90.

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[1] The term *amorphous* is used here although X-ray studies have shown these materials to have directional properties sensitive to short wave lengths.

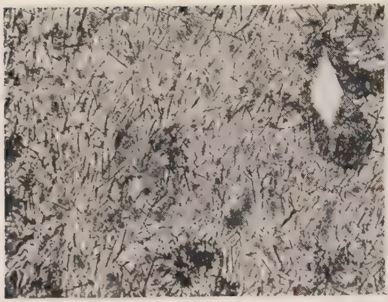

FIG. 88.—Incipient crystals of rod-like aggregates in a ground-mass of volcanic glass.

FIG. 89.—Shatter cracks in halloysite (crossed nicols).

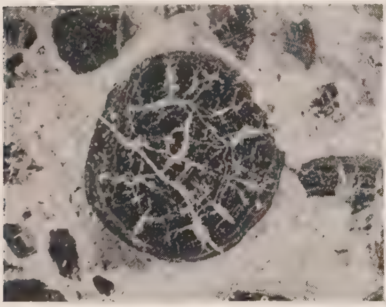

FIG. 90.—Rounded sections of pisolitic bauxite made up of the mineral cliachite. Interstices (around holes in the section) with gibbsite.

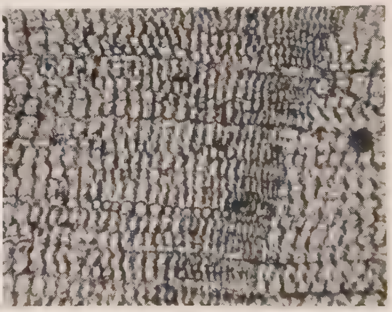

FIG. 91.—Cellular structure of wood preserved in opal.

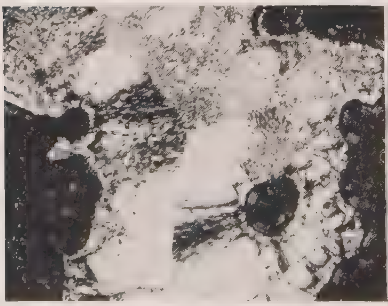

FIG. 92.—Chalcedony between crossed nicols showing both radial aggregates and banded structure.

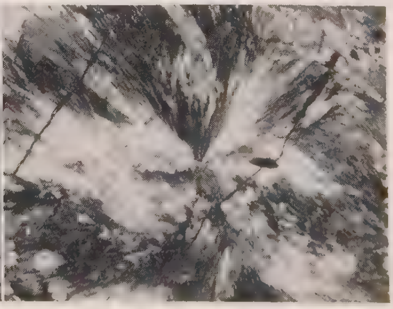

FIG. 93.—A flamboyant radial aggregate of sillimanite between crossed nicols.

The rounded, more or less spherical forms assumed by amorphous and metacolloidal minerals in open spaces are frequently described as *colloform* (Table III, No. 24).

Materials of Organic Origin.—In the study of thin sections, structures are occasionally encountered that are residual from organic life. Diatomaceous, radiolarian, or foraminiferal organisms have distinctive structures frequently preserved in minerals. Fossil diatoms and other microscopic remains are usually opal and have the optical properties of that mineral. The original structures of the microorganisms, however, are on many occasions well preserved (Fig. 94). "Forams" are apt to yield calcite usually finely crystalline in nature and difficult to distinguish from aragonite unless the structure is sufficiently coarse to permit the rhombohedral cleavage to develop (Fig. 95).

Fragments of former vegetable matter preserved as carbonaceous material—lignite, etc.—are usually black or brown in thin section. Cellular structures of wood as preserved in lignite are quite distinctive in thin section. Opal formed by the replacement of wood frequently exhibits cellular structure (Fig. 91).

Collophane, the mineral constituent of fossil bone, usually retains the structure of the bone that has been replaced (Fig. 159).

Fine Aggregates.—Minerals frequently form fine aggregates of distinctive pattern. Aggregate structure is emphasized between crossed nicols either by radial groups or by a fine-grained mosaic-like groundmass of small crystals.

The radial structures and also fine-grained mosaics (Fig. 96) furnish excellent illustrations of this feature. In radial groups the small crystals converge as the spokes of a wheel. Radial uniformity of orientation produces with crossed nicols a dark cross parallel to the positions of extinction. This cross should not be confused with the axial cross of a uniaxial interference figure produced by conoscopic observation of a single crystal and having an entirely different significance.

An illustration of a mineral aggregate is furnished at times by sillimanite (Fig. 93). The needles of sillimanite, however, are not so regularly arranged as is the case of chalcedony.

Crosses due to radial arrangement of fine crystal groups in polarized light are frequently formed in microfossils replaced by calcite. Figure 97 illustrates fossil forams in shale, the outer portions of the two large structures showing parts of an aggregate polarization cross.

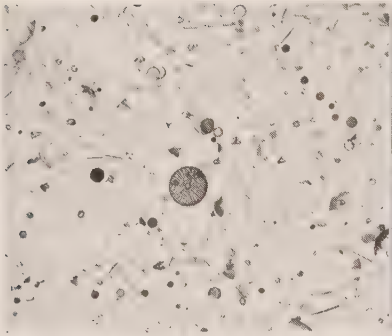

FIG. 94.—The fine microorganic structures preserved in opal-forming fossil diatoms. Diatomaceous earth from Lompoc, California.

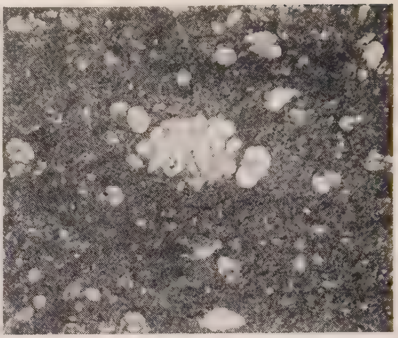

FIG. 95.—Calcite in sections of fossil forams scattered through carbonaceous shale.

FIG. 96.—Mosaic structure in chalcedony. A "salt and pepper" aggregate of small crystals photographed between crossed nicols.

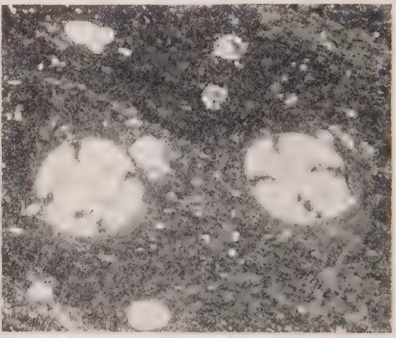

FIG. 97.—A polarization cross in fossil forams of calcite arranged in concentric bands of radial fiber-like crystals.

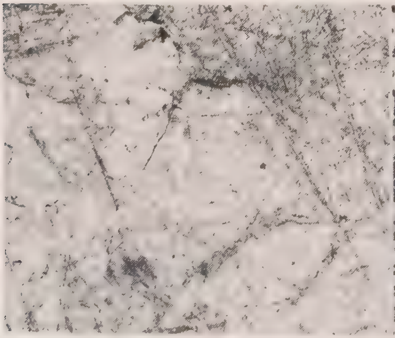

FIG. 98.—Needle-like crystals of sillimanite in quartz.

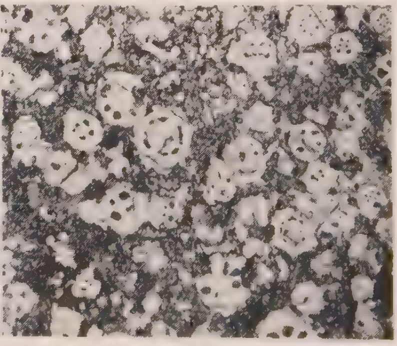

FIG. 99.—Euhedral crystals of leucite containing inclusions of glass.

Spherulitic crystallization in glassy flow rocks is strikingly illustrated between crossed nicols. Figure 131 represents a thin section containing spherulites photographed between crossed nicols. Spherulites of the feldspars or other minerals are often found suspended in volcanic glass of one form or another.

Parallel orientation of fibrous aggregates is illustrated by a thin section of chrysotile in serpentine (Fig. 100). Veinlets of cross-fibers arranged in parallel fashion perpendicular to the walls of the vein are common in serpentine. The fibers are moderately anisotropic, while the serpentine is almost dark between crossed nicols.

Inclusions.—At many times during the process of crystallization small areas of foreign substances are caught within what are otherwise clear crystals. In the crystallization of leucite, for example, small areas of volcanic glass are often distributed symmetrically as small isolated spheres suspended in the crystal. Leucite of this type is illustrated in Fig. 99.

Hypersthene (Fig. 102) also contains areas of brown flakelike inclusions frequently accompanied by a fine transverse system of lines. This is usually described as *schiller structure.*

Occasionally the substances retained within the crystal during formation may be radioactive and during the long progress of geologic time will continue to give off emanations until they finally lose their strength. Such inclusions when trapped in colored minerals such as biotite produce dark brown circular patches, frequently pleochroic. Figure 103 illustrates halos produced by radioactivity in biotite from western Connecticut.

Needle-like Crystals.—A few minerals form fine hairlike masses of crystals usually penetrating some other mineral, such as mica or quartz. Sillimanite, for example, may be found in minute needles penetrating quartz in all directions (Fig. 98). Dumortierite occurs in a similar manner. The dumortierite, however, is usually pink and may impart to the quartz in the hand specimen a color resembling rose quartz, although deeper in color. Rutile forms red or brown needles that may penetrate either quartz or mica. Tourmaline may also occur in similar fashion. The radiating crystals of tourmaline in quartz illustrated in Fig. 101 are characteristic of luxillianite, a rock.

Although these occurrences are quite striking when observed, it should be remembered that the same minerals may occur in large crystals having an entirely different habit.

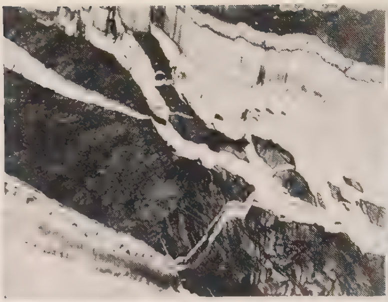

FIG. 100.—Bands of asbestos fibers in serpentine (crossed nicols).

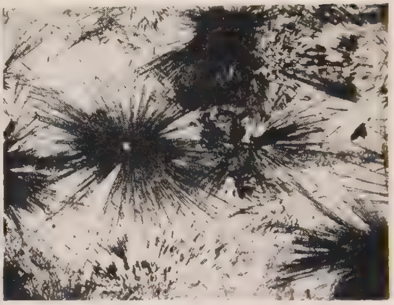

FIG. 101.—Needle-like crystals of tourmaline arranged in radial groups.

FIG. 102.—Schiller structure in hypersthene.

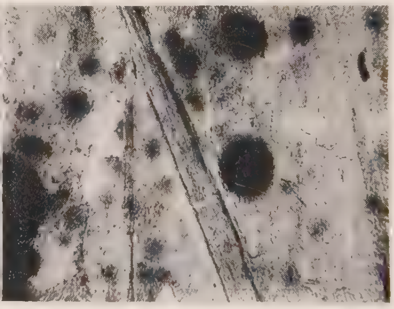

FIG. 103.—Pleochroic halos in biotite.

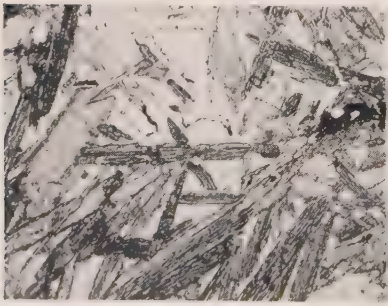

FIG. 104.—Bladed crystals of kyanite.

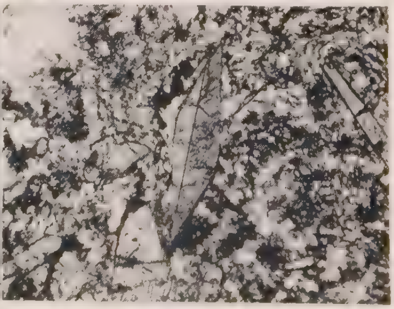

FIG. 105.—Titanite twinned parallel to the length of the section.

Bladed Crystals.—Crystal groups may be composed of larger, coarser individuals causing lathlike sections under the microscope. Also, intermediate sizes of different form and development may occur. One illustration of a coarse-bladed type of development is furnished by kyanite as illustrated in Fig. 104.

Twin Crystals.—The feldspars provide the most outstanding illustration of twinning. Twin lamellae stand out particularly between crossed nicols. The twinning is for the most part polysynthetic, comprising multitudinous lathlike individuals orientated according to either the albite or the pericline law or perhaps both (Fig. 173). Orthoclase provides good illustrations of twinning according to the Carlsbad law and occasionally according to the Baveno and Manebach laws. Plagioclase also twins according to the Carlsbad law. A most outstanding illustration of twinning is the grid structure of microcline between crossed nicols as shown in Fig. 169.

Other minerals besides feldspars provide good illustrations of twinning. Calcite nearly always twins parallel to the long diagonal of the cleavage rhombohedron, while dolomite twins parallel to both the long and the short diagonal of the cleavage rhombohedron. Cassiterite, corundum, pyroxene, aragonite, amphibole, lazulite, and gibbsite are frequently found in twin crystals, the twinning being easily recognized by the different extinction of the various twin individuals between crossed nicols. The crystal of titanite in Fig. 105 is twinned into individuals separated by a plane parallel to the length of the crystal.

Natural Crystal Form in Thin Section. There is a pronounced tendency among crystallized minerals of a given species to follow the same habit of growth. In such instances outlines viewed in thin section, due to natural crystal form, are significant. These outlines often suggest the identity of a mineral at a glance. Apatite, for example, frequently appears in small lathlike elongated crystals with hexagonal cross sections (Fig. 109).

Corundum in mica schist may form skeleton crystals characterized by rounded elongate outlines (Fig. 110).

Pyrite is often found in square areas in thin sections. Although triangular and other shapes also occur, opaque sections of cubes having a brass-yellow color in reflected light distinctly identify the mineral.

FIG. 106.—Anhedral crystals of hornblende associated with quartz.

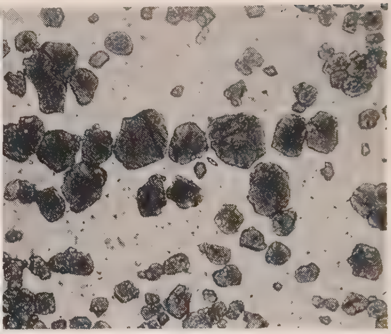

FIG. 107.—Subhedral garnet in quartz.

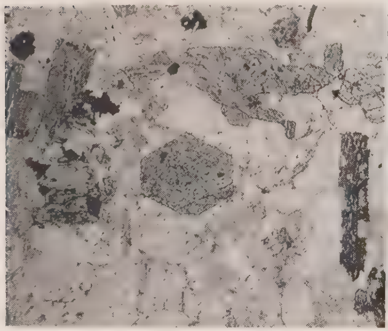

FIG. 108.—Euhedral hornblende associated with biotite in thin section.

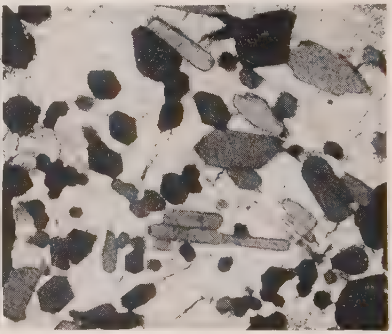

FIG. 109.—Apatite crystals in thin section (crossed nicols).

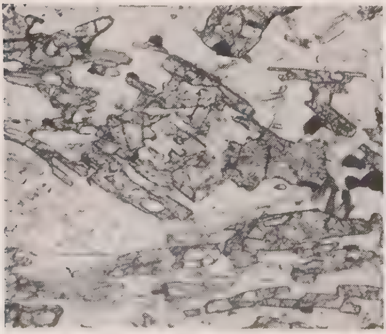

FIG. 110.—Skeleton crystals of corundum in mica schist.

FIG. 111.—Andalusite containing symmetrically arranged carbonaceous inclusions.

Crystals of the type just described occurring in thin sections with well-developed crystal boundaries are called *euhedral*.[1] *Anhedral*[2] crystals are crystals with rounded or irregular boundaries. Partially developed crystals may be called *subhedral*.

Anhedral, subhedral, and euhedral crystals are illustrated in Figs. 106, 107, and 108, respectively. Subhedral garnet (Fig. 107) should be compared with euhedral garnet (Fig. 211).

Isometric Crystals.—Euhedral crystals of common isometric minerals encountered in thin sections frequently exhibit cross sections of such common isometric forms as the cube, octahedron, dodecahedron, and trapezohedron.

Leucite and analcite are illustrated in Figs. 99 and 112. The outline of the analcite crystal and also of the leucite crystals follows the trapezohedron.

Occasionally isometric crystals are twinned, and in some cases weak anisotropism exists, although isometric minerals are normally isotropic. Pseudo-isometric minerals such as leucite exhibit low first-order interference colors. Garnet from contact-metamorphic deposits in limestone may be strongly anisotropic at times. An illustration of garnet of this type is given in Fig. 113.

Tetragonal Crystals.—Few tetragonal minerals having euhedral development are encountered in the routine examination of thin sections. Cross sections of tetragonal minerals are usually the normal section to be expected from a tetragonal prism terminated with a bipyramid as in the case of zircon or a combination of two prisms and two bipyramids as in the case of vesuvianite. The crystals are uniaxial, and sections cut normal to the *c*-axis give optic-axis interference figures. Twinning and cleavage are arranged in accord with tetragonal symmetry. Crystals are anisotropic and extinguish parallel to the crystallographic axes.

Hexagonal Crystals.—A number of common minerals encountered in thin section are hexagonal in crystallization. The crystals follow two principal types of development: Either the crystallization is in accord with the hexagonal subsystem or the rhombohedral subsystem is favored. The hexagonal subsystem is usually represented by elongated crystals of

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[1] Also called *idiomorphic* or *automorphic*.

[2] Also called *allotriomorphic* or *xenomorphic*.

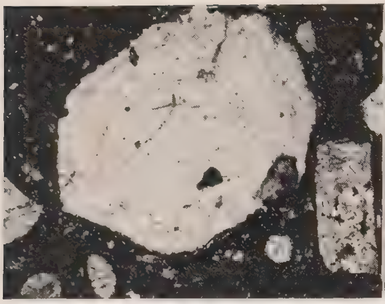

Fig. 112.—A euhedral crystal of analcite.

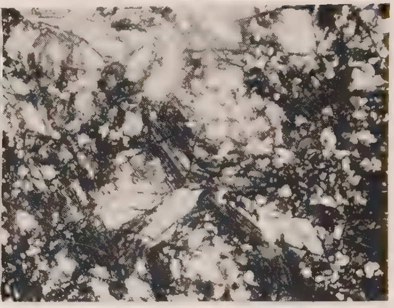

Fig. 113.—Isometric crystals of garnet showing anomalous anisotropism and banding between crossed nicols.

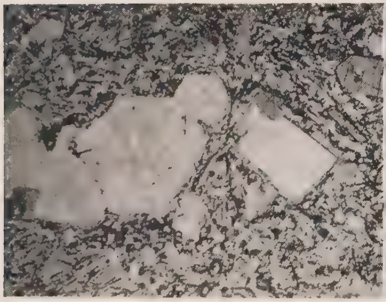

Fig. 114.—Nepheline crystals showing both hexagonal and rectangular outlines.

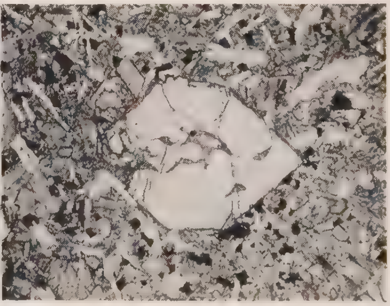

Fig. 115.—A euhedral crystal of olivine.

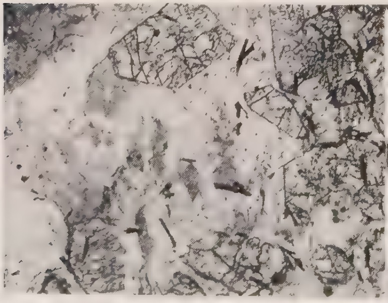

Fig. 116.—Euhedral staurolite crystals in a groundmass of muscovite and other minerals.

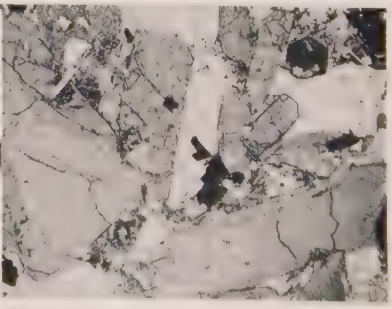

Fig. 117.—Euhedral crystals of pyroxene.

hexagonal cross section, while sections of the rhombohedral division are nearly always rhombic and only occasionally hexagonal.

Quartz, tourmaline, apatite, beryl, and nepheline are frequently encountered hexagonal crystals. The sections of these minerals may be hexagonal, or triangular if normal to the c-axis, and rectangular or modified rectangular where cut along the c-axis. The crystals are commonly elongated parallel to the c-axis and exhibit parallel extinction with positive or negative elongation, depending upon the sign of the mineral. The hexagonal sections are either nearly or completely isotropic and yield uniaxial interference figures. Nepheline (Fig. 114) frequently exhibits both hexagonal and rectangular sections. Apatite (Fig. 109) furnishes both hexagonal and elongated sections.

Rhombohedral crystals include the group of rhombohedral carbonates, and although these minerals are ordinarily found in matted masses of anhedral crystals, occasionally euhedral crystals occur. The euhedral crystals are rhombic in section and frequently exhibit cleavage lines parallel to the sides. The section of the rhombohedron normal to the c-axis may appear hexagonal.

Orthorhombic Crystals.—A number of orthorhombic minerals encountered in thin section form euhedral crystals. Olivine natrolite, barite, zoisite, andalusite, dumortierite, and topaz are among the most common. Euhedral olivine crystals (Fig. 115) are frequently seen in thin sections of basic igneous rocks. The crystals are symmetrical with respect to the crystallographic axes and become extinct when the axes are parallel to the plane of vibration of the nicols. Long square crystals of natrolite with excellent parallel extinction mentioned in the discussion of the adjustments of the microscope are occasionally found in thin sections. Barite crystals may be square, rectangular, or elongated with parallel or symmetrical extinction.

Staurolite crystals are illustrated in Fig. 116. Quartz inclusions are common in crystals of this type. Andalusite contains carbonaceous inclusions arranged in a symmetrical orthorhombic pattern (Fig. 111).

Monoclinic Crystals.—The pyroxenes, amphiboles, monoclinic feldspars, titanite, mica, epidote, and a number of other less common monoclinic minerals are frequently found in euhedral crystals in thin sections. The crystals exhibit inclined extinction when sections are cut either parallel to or near the plane of the *a*- and *c*-axes. Certain sections, however, are frequently so orientated as to furnish either symmetrical or parallel extinction. More crystals are necessary for a proper identification and study of monoclinic minerals in thin section than are needed for minerals in the other systems just described. Each monoclinic crystal is an individual problem in optical orientation and should be considered by itself.

Figures 108 and 117 furnish comparative examples of euhedral amphibole and euhedral pyroxene. The views demonstrate both crystal boundaries and cleavage.

Triclinic Crystals.—The plagioclase group, microcline, kyanite, and rhodonite constitute the ordinary triclinic minerals found in thin section. The extinction is ordinarily inclined in all sections, and the extinction angles are frequently high. The plagioclase group and microcline exhibit striking twinning in addition, the nature of the twinning helping considerably in differentiation.

Cleavage, Parting, and Fracture as an Aid in Distinguishing Minerals.—Cleavage may be defined as the ever present ability of a mineral to break into smaller and smaller particles, with smooth surfaces along planes parallel to the directions of the faces of certain common forms. Cleavage is frequently of assistance in distinguishing minerals. Unfortunately, many minerals show little or no cleavage. When cleavage is well developed, however, a mineral may be often easily identified by means of this property. In the grinding of thin sections, cleavage planes are usually developed and appear in the finished section as lines of varying width.

Some minerals separate only occasionally or break along planes of twinning. Since this ability to cleave is not always present and may not continue to finer and finer particles, it is usually described as *parting*. In an individual specimen, in so far as the effect produced is concerned, cleavage may be indistinguishable from parting.

Several types of cleavage may be observed in minerals. These are often seen in the examination of both thin sections and mounts of crushed fragments. The same type of cleavage often appears considerably different in fragments than it would appear in thin section. This is due to the fact that fragments normally fall with cleavage surfaces flat or almost flat on the surface of the slide, while in thin sections a large number of random orientations are rigidly fixed in the plane of the section. Knowledge of cleavage in fragments is necessary when using the immersion method for determining refractive indices. Cleavage fragments are illustrated in Fig. 118.

FIG. 118.—Cleavage and fracture fragments. (*a*) One direction—irregular plates (not illustrated). (*b*) Two directions—orthoclase, augite, and hornblende. (*c*) Three directions—kyanite, anhydrite (rectangular), calcite (rhombohedral). (*d*) Four directions—fluorite (octahedral). (*e*) Prismatic sillimanite. (*f*) Acicular—natrolite.

In the appended tables for identifying common minerals encountered in the study of thin sections, cleavage planes, fracture planes, or the tendency to break parallel to certain definite directions are indicated for each of the minerals included.

Cleavage in One Direction. A considerable number of minerals have a single plane of cleavage. Muscovite and topaz are examples (Fig. 119). In thin section, crystals showing one direction of cleavage usually exhibit systems of parallel lines, the lines being either closely spaced or spaced at considerable distances. Occasionally, a cleavage plane may be almost parallel to the section, in which instance practically no cleavage lines will appear.

In the case of fragments, minerals with one direction of cleavage usually lie flat upon the microscope slide and have irregular boundaries. The interference color is nearly always uniform for the area of the fragment except on the outer edge, where a number of color bands will be observed, increasing in number in the case of minerals having higher double refraction. Frequently similar orientation of interference figures occurs in the fragments since many fragments lie in the same position.

FIG. 119.—Anhedral topaz crystals with broadly spaced cleavage in one direction with penetrating muscovite having closely spaced cleavage in one direction.

FIG. 120.—Anhedral hornblende with cleavage at 56° and 124° in a groundmass of feldspar.

Cleavage in Two Directions.—Several common minerals develop prominent cleavage in two directions. The pyroxenes, amphiboles, and feldspars are outstanding illustrations.

Common hornblende of the amphibole group is distinguished from pyroxene by a difference in cleavage angle. The cleavage of hornblende (Fig. 120) parallel to the rhombic prism {110} is in two directions at 56° and 124°. The cleavage of the rhombic prism in the case of pyroxene (Fig. 121), however, is approximately 87° and 93°.

The two directions of cleavage may be at 90° in orthorhombic or tetragonal minerals. Figure 122 illustrates andalusite (orthorhombic) with two directions of cleavage at about 90° (89°12′).

Cleavage in Three Directions.—The types of cleavage produced due to cleavage in three directions vary considerably. One of the simplest types is that produced by cleavage parallel to the faces of the cube. In thin sections cleavage of this type produces square or triangular patterns. In fragments the boundaries tend to be square or rectangular. Cubic cleavage is restricted to the isometric system, and both sections and fragments are easily confirmed by the isotropic character of the material.

Fig. 121.—Euhedral pyroxene crystals showing two directions of cleavage in a groundmass of feldspar.

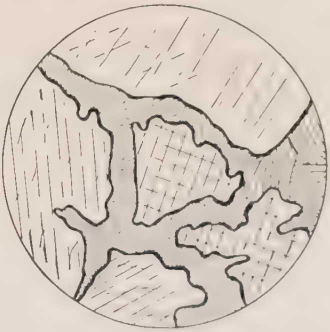

Fig. 122.—Andalusite with cleavage in two directions at about 90°, cut by veinlets of fine muscovite with cleavage in one direction.

Fig. 123.—Anhydrite (rectangular cleavage) and fluorite (octahedral cleavage) in the same thin section. The octahedral cleavage of fluorite produces a triangular pattern.

Rectangular cleavage is similar to cubic cleavage in its appearance in both thin sections and fragments (Fig. 123). Minerals having rectangular cleavage, however, may be easily distinguished from those with cubic cleavage, owing to their anisotropism between crossed nicols.

Rhombohedral cleavage is one of the most common types found within minerals both in thin sections and in fragments. The common carbonate minerals have cleavage of this type. The pattern produced in thin section is crisscross in design, and the crystals usually show inclined cleavage planes penetrating the section. In addition there is frequently a set of twin lines parallel to the long diagonal of the rhombohedron. Occasionally, twinning may appear parallel to both the long and the short diagonal, as in the case of dolomite. In fragments, minerals with rhombohedral cleavage are usually flat lying, with a fairly well-developed rhombic section, and vary in relief with direction. The edges usually show wedgelike or inclined surface boundaries.

Cleavage in three directions is frequently produced by breaking parallel to various directions in crystals of the orthorhombic, monoclinic, and triclinic systems. In most instances the part of the mineral under examination presents a special case. As a rule, however, cleavage of this type produces a crisscross of almost rectangular pattern in thin section, and in fragments the boundaries are either almost rectangular or may be flat lying with wedgelike edges.

Cleavage in Four Directions.—One common mineral, fluorite, has cleavage in four directions parallel to the faces of an octahedron (Fig. 123). Cleavages of fluorite in thin section tend to develop triangular or rhombic patterns. In fragments the outlines of individual fragments are triangular or irregular with pointed edges. These fragments are easily detected between crossed nicols on account of the isotropic character of the mineral. Occasionally spinel is found with an octahedral parting imperfectly developed but somewhat resembling octahedral cleavage. The diamond has octahedral cleavage but needless to say is not retained in grinding thin sections.

Cleavage in Six Directions.—Sphalerite is one of the few minerals with cleavage parallel to the six different directions of a dodecahedron. The outlines of this figure may occasionally be detected in pieces of sphalerite within sections due to the intersections of inclined cleavage planes. In fragments sometimes almost perfect dodecahedrons may be observed.

Tendency to Break on Elongate Directions.—Some minerals exhibit a decided fibrous structure, being made up of numerous small needles visible as parallel crystals beneath the microscope. These may vary in size from small elongated blades to minute capillary fibres. Coarser minerals of this sort change from fibrous to bladed shapes.

Orientation.—The optical orientation of a mineral involves the correlation of the positions of the optical directions with crystallographic directions. In the case of biaxial minerals the problem is usually resolved into locating the position of the acute bisectrix, optic normal, and axial plane with respect to the axes *a*, *b*, and *c* of a crystal. The orientation of uniaxial minerals is less difficult, involving only the relation of the optical system to the *c*-axis. In order to make such a correlation it is necessary to take into account the usual conventions concerning the crystallographic axes of reference. In the following discussion it is assumed that the reader is familiar with the simple rules of description of crystals in the various systems and the conventions of orientation; otherwise a text on geometrical crystallography should be consulted.

Isometric System. Optical orientation in isometric crystals is simplified since isometric crystals are isotropic, hence becoming non-directional as far as light is concerned. Thus all directions in isometric crystals are optically the same.

Tetragonal and Hexagonal Systems.—The optic axis of uniaxial minerals is always parallel to the *c*-axis of tetragonal or hexagonal minerals. The direction may be either the fast or the slow ray of the mineral, depending upon the optic sign, but other variation does not exist in tetragonal or hexagonal crystals.

Orthorhombic System.—The crystallographic axes *a*, *b*, and *c* of orthorhombic minerals correspond with the vibration axes X, Y, and Z but not necessarily in the order named. The crystallographic axis *a*, for instance, may be X, Y, or Z, and the same substitutions are possible for the crystallographic axes *b* and *c*. If two vibration axes are fixed, however, the third becomes known. Thus, if $a = Z$ and $b = Y$, it naturally follows that $c = X$. It is also evident that X and Z define the position of the axial plane; thus, if $a = Z$ and $c = X$, the axial plane includes *a* and *c*. The axial angle 2V may vary in amount in the axial plane.

Orthorhombic crystals are detected in a number of ways with the microscope. In the first place the extinction between crossed nicols is always parallel to *a*, *b*, or *c*. Thus if *a*, *b*, and *c* can be ascertained from some prominent cleavage or a section of a crystal, the nature of the extinction becomes known. Cleavage and crystal faces are particularly important in optical orientation. Orthorhombic crystals with good dispersion are also useful.

When the positions of the axes *a*, *b*, and *c* are once ascertained, the interference figure will furnish criteria for the proper location of X, Y, and Z with respect to the crystallographic axes. The position of the optic axes will also be ascertained at the same time. In practice each mineral presents a special problem in orientation, and it is possible only to outline the general procedure in advance.

Barite furnishes a fairly good illustration of the problem involved in the optical orientation of an orthorhombic mineral. An idealized cleavage of barite is shown in Fig. 124, together with a diagram of a thin section and three orientated sections. In thin section the barite grains exhibit cleavage in three directions, the cleavage parallel to {001} being more pronounced. The grain marked *R* in the thin section happens to be in a position in which the angles of cleavage measure 78°22′. The *c*-axis is perpendicular to this section. The planes {110} and {110} are parallel to the *c*-axis. In this grain the *a*-axis would bisect the obtuse angle of cleavage, and the *b*-axis would bisect the acute angle of cleavage. Between crossed nicols the extinction will be parallel to *a* and *b*, or symmetrical with respect to the cleavage. Grain *S* would have parallel extinction but might be normal to the *b*-axis and not in a position to give an interference figure of the acute bisectrix type. An interference figure is orientated with respect to the cleavage as shown in grain Q. A test with the quartz wedge will determine the fact that the mineral is positive; hence Bx_a = Z. The optic normal is Y, and Bx_o = X. If one refers

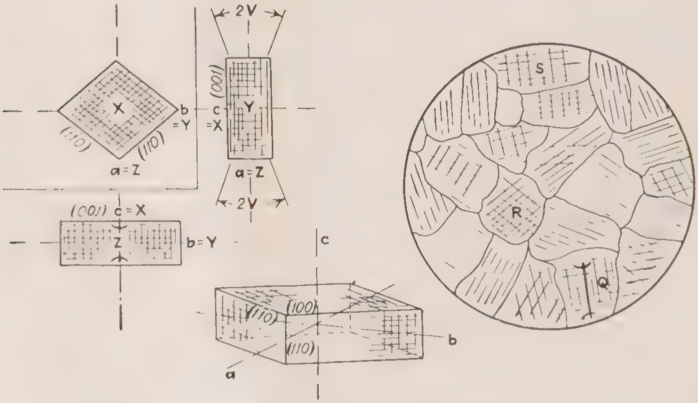

FIG. 124.—Thin-section and orientation diagrams of barite.

again to the figures illustrating the cleavage form, the following orientation is apparent:

$$
\begin{aligned}
a &= Z \\
b &= Y \\
c &= X
\end{aligned}
$$

The angle 2V is estimated with the microscope as approximately equal to the recorded angle 37°30′. Therefore the optic axes make an angle of 18°45′ with the *a*-axis.

The orientation in the case of orthorhombic crystals is not always so simple as in the case of barite. The principles and procedure, however, are essentially the same, and it is always fundamental to be able to fix the position of X, Y, and Z with respect to *a*, *b*, and *c*.

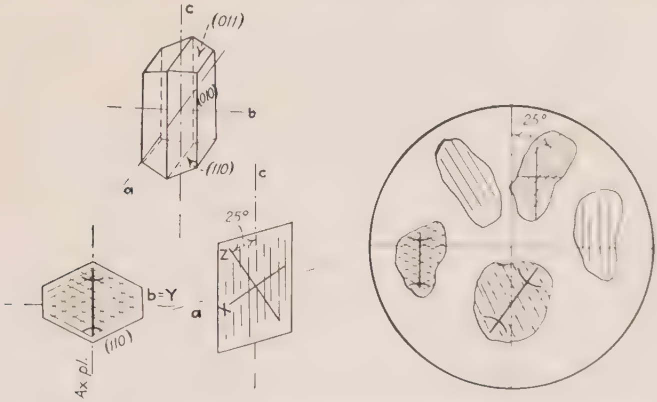

FIG. 125.—Thin-section and orientation diagrams of hornblende.

Monoclinic System.—In monoclinic crystals X, Y, or Z corresponds to the *b*-axis. If Y corresponds to *b*, which is often the case, X and Z will occupy any position at 90° to each other in the plane of *a* and *c*.

Hornblende furnishes a good illustration of the problem of orientation of a monoclinic crystal. The mineral has two prominent directions of cleavage parallel to the rhombic prism $\{110\}$. The *c*-axis is parallel to the edge between the cleavages, and the *b*-axis bisects the angle between (110) and $(1\bar{1}0)$ (Fig. 125). In thin sections either one or two sets of cleavage lines appear, depending upon the orientation. Grains with two cleavage directions are symmetrical in extinction and yield biaxial negative interference figures. The axial plane bisects the obtuse angle of the cleavage, and Y bisects the acute angle. The position of Z may be obtained from a section parallel to the plane of the axes *a* and *c*. Light vibrating parallel to Z is the slow ray; the angle of maximum extinction for the slow ray may be determined with the mica plate. The maximum extinction angle for the single cleavage trace is the angle between Z and the *c*-axis. In hornblende this angle is about 25°. When Z is determined, the angle of X is known since it lies at 90° to Z. Y is perpendicular to the plane of Z and X.

Triclinic System.—Each triclinic crystal constitutes an individual case in optical orientation. The center of the optical system must coincide with the center of the crystallographic system; otherwise there is no agreement.

Suggested References

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CHAPTER VIII

PROCEDURE FOR THE IDENTIFICATION OF MINERALS IN THIN SECTIONS

Summary of a Scheme for Identification.—The following steps are outlined to assist in rapid identification. It is essential in identifying minerals with the microscope to follow some system that is not too involved, and at the same time effort should not be wasted on a large number of tests having no application in identification.

A mineral is seldom identified by means of one simple test. Usually a number of observations become necessary before the identification is complete. Each identification is based upon a number of characteristics determined by study and tabulation of results. The conclusion reached is always based upon a systematic analysis of the observations.

Tables are included to assist in the analysis of observations. The tables are arranged as far as possible to permit a direct interpretation in terms of possible minerals after making a few definite tests with the microscope. The tables merely offer suggestions, however, and final decision in each case should be withheld until the text has been consulted.

Opaque Minerals.—A few common opaque minerals are listed in Table I. If the mineral is transparent, follow the sequence of tables under transparent minerals as shown in the Key to Mineral Tables (page 131).

Color.—If the mineral is colored, consult Table II for colored minerals. Note also whether the mineral is pleochroic or nonpleochroic and the colors of the pleochroism if pleochroic.

Shape or Form.—If the mineral occurs in some suggestive or significant shape, consult Table III. A number of common forms or shapes are illustrated in the table.

Cleavage.—If traces of cleavage are observed, consult Table IV. Various types of cleavage and their examples among minerals are listed in this table.

Index of Refraction.—Since the thin sections are mounted in balsam, comparison of the index with balsam is possible whenever the mineral is in contact with balsam on the edge of the section or bordering a hole in the slice (balsam, $n = 1.537$). The comparative indices of adjacent minerals should also be observed.

The intensity of the boundaries and irregularities of surface for minerals in thin sections varies through wide limits. This property, known as *relief*, should be estimated when the index of refraction is compared with balsam. In most instances by comparison with minerals of known relief the relief of an unknown mineral may be estimated as low, moderate, high, or extreme.

The identification of minerals studied in thin sections is frequently greatly facilitated and the certainty of identification increased by isolating a small portion of a puzzling mineral from the original specimen and determining the indices of refraction by the immersion method. Additional data concerning cleavage and orientation are also occasionally obtained in this way.

In order to be of assistance for such determinations, the indices of refraction of the minerals included in the text are recorded in Table V.

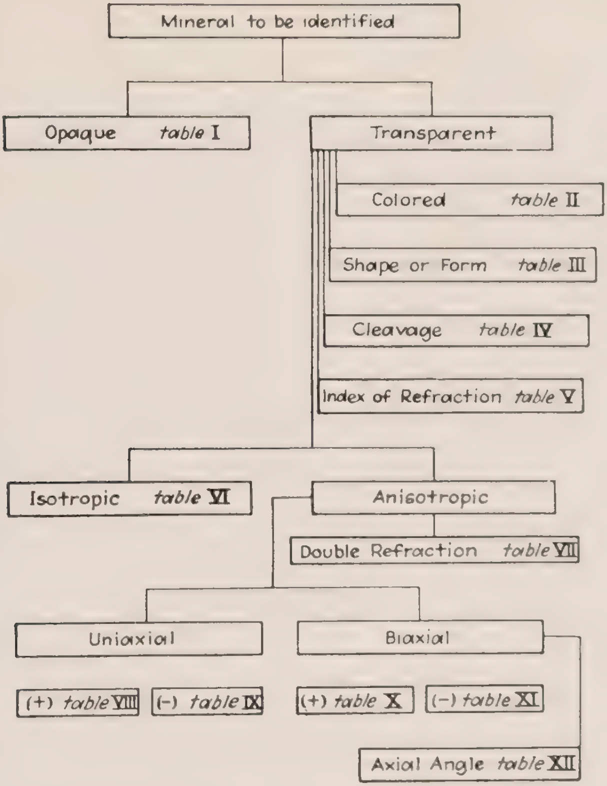
Isotropic or Anisotropic.—The group of isotropic minerals is small, and perhaps the mineral may be recognized directly if color, cleavage, and the relative index of refraction are taken into account. Isotropic minerals are listed in Table VI.

Double Refraction or Birefringence.—Anisotropic minerals vary in double refraction through wide limits. In general, however, the order of the highest observed interference color for an unknown mineral can be determined within limits of accuracy sufficient to be of considerable assistance in determining a mineral. Since properly ground thin sections are about 0.03 to 0.035 mm. in thickness, the double refraction may be estimated from the interference colors and reference to the interference color chart (Table VII).

When a mineral shows cleavage or occurs in such a form that definite knowledge of orientation is possible, the angle of extinction may be utilized in identification. Elongated crystals may also be tested for either positive or negative elongation.

Optic Sign or Optical Character.—The optical classification of anisotropic minerals as uniaxial or biaxial, positive or negative, may conveniently be applied with the aid of interference figures. Since each of the four groups contains a large number of minerals, other properties as outlined in the other tables must be relied upon in addition before the identification is restricted to an individual mineral. Uniaxial positive minerals are listed in Table VIII, and uniaxial negative minerals in Table IX. Biaxial positive and negative minerals are listed in Tables X and XI.

KEY TO MINERAL TABLES



Biaxial Minerals.—In addition to the determination of optic sign it is possible in the case of biaxial minerals to utilize the optic angle 2V or the observed angle 2E in identification. A considerable number of biaxial minerals also exhibit dispersion of the optic axes, and the dispersion formula $r > v$ or $r < v$ may be used in such cases.

Suggested Outline.—It is suggested that the following systematic outline should be followed in the identification of each mineral. It is not necessary to apply each specific test for every mineral. Often a mineral may be identified by means of a comparatively few observations. The procedure should be of value, however, in cases of doubt.

OUTLINE FOR IDENTIFICATION

Description of the mineral to be identified

....

....

Associated minerals...

1. Opaque........................Color (if opaque).................

Transparent...

Properties if transparent:

2. Color...

Pleochroism...

3. Shape or form..

....

4. Cleavage..

....

5. Indices of refraction...

....

6. Isotropic...............or Anisotropic.....................

7. If anisotropic:

Birefringence or double refraction..........................

Twinning (if present)..

Elongation (if any)..

Optical classification:

Uniaxial

Positive.......................Negative.......................

Biaxial

Positive.......................Negative.......................

2V.......................(or 2E).......................

Dispersion..

Optical orientation

Conclusion.

TABLE I.—OPAQUE MINERALS

Color with reflected light	Mineral	Comment
Black	Graphite, C	Frequently occurs in thin flakes or scattered specks with micaceous cleavage. Carbonaceous matter may occur as fine black inclusions
Brass yellow........	Pyrite, FeS_2	Euhedral crystals are common with square, triangular, or rectangular sections. Cleavage indistinct or absent. High relief due to hardness
Bronze to copper red	Pyrrhotite, $FeS(S)_x$	Found in masses or bladed crystals. Basal parting ‖ to {0001}. Darker color than pyrite
Strong brass yellow..	Chalcopyrite, $CuFeS_2$	Found in masses and occasionally in euhedral crystals. Deeper yellow than pyrite, and lower relief
Steel blue, red, or gray black.	Hematite, Fe_2O_3	Blood red on translucent edges. Occasionally shows parting. Found in euhedral crystals and masses
Violet black........	Ilmenite, $FeTiO_3$	More violet or purple than hematite. Basal parting and flake-like crystals common. Often found with magnetite
Steel blue black.....	Magnetite, $Fe^{II}Fe_2^{III}O_4$	Octahedral (occasionally dodecahedral) crystals are common. The mineral may have octahedral parting. Frequently a primary mineral
Iron black to brownish black.	Chromite, $(Fe,Mg)(Cr,Al,Fe)_2O_4$	Usually brown on thin edges. Octahedral parting common. Frequently found with serpentine
Yellow brown.......	Limonite, $H_2Fe_2O_4(H_2O)_x$	Colloform, pisolitic, porous and massive aggregates common. Thin transparent edges are dark between crossed nicols
White	Leucoxene, TiO_2 etc.	A white, fine-grained opaque alteration product of primary titanium minerals

TABLE II.—COL

	Red	Pink-rose	Orange	Brown	Yellow
ISOTROPIC NON-PLEOCHROIC		(Sodalite)			(Sodalite)
	(Sphalerite)			SPHALERITE	SPHALERITE
		(Fluorite)		(Fluorite)	(Fluorite)
	(Spinel)			SPINEL	(Spinel)
				COLLOPHANE	COLLOPHANE
	CLIACHITE			CLIACHITE	
	PEROVSKITE	PEROVSKITE	PEROVSKITE	PEROVSKITE	
		GARNET		GARNET	(Garnet)
ANISOTROPIC PLEOCHROIC[1]				ZIRCON	ZIRCON
				CASSITERITE	(Cassiterite)
	RUTILE			RUTILE	Rutile
					[*Chloritoid*]
				[*Biotite*]	[*Biotite*]
				DRAVITE	DRAVITE
					SCHORLITE
		(Tourmaline)		TOURMALINE	(Tourmaline)
		(Corundum)			
				(Apatite)	
					JAROSITE
	PIEDMONTITE	Piedmontite	Piedmontite		PIEDMONTITE
		TITANITE		(Titanite)	TITANITE
		Staurolite	Staurolite		STAUROLITE
				(Monazite)	MONAZITE
					CHLORITOID
		(Clinochlore)			Clinochlore
				AEGIRINE-AUGITE	AEGIRINE-AUGITE
				CHONDRODITE	CHONDRODITE
	PEROVSKITE	PEROVSKITE	PEROVSKITE	PEROVSKITE	
	IDDINGSITE			IDDINGSITE	
				BIOTITE	BIOTITE
					EPIDOTE
					(Glaucophane)
	(Allanite)			ALLANITE	ALLANITE
				PHLOGOPITE	PHLOGOPITE
				BASALTIC HORNBLENDE	
				(Aegirine)	
		HYPERSTHENE		(Hypersthene)	
					ACTINOLITE
					Glauconite
		ANDALUSITE			
		DUMORTIERITE			
				HORNBLENDE	

---

[1] Colored minerals, although normally pleochroic, may fail to vary in color with rotation under exceptional

ORED MINERALS

Green	Blue	Violet	Gray	Black	
	SODALITE		Sodalite		ISOMETRIC
FLUORITE	FLUORITE	FLUORITE			
SPINEL	SPINEL			SPINEL	
			Cliachite		
(Perovskite)		(Perovskite)	(Perovskite)		
(Garnet)				(Garnet)	
	LAZURITE				
			Zircon		UNIAXIAL (+)
			Cassiterite		
(Rutile)	(Rutile)	(Rutile)	(Rutile)		
[*Chloritoid*]	[*Chloritoid*]				
[*Chlorite*]	[*Chlorite*]				
[*Biotite*]					(−)
SCHORLITE	SCHORLITE	SCHORLITE	SCHORLITE	SCHORLITE	
(Tourmaline)					
	CORUNDUM	CORUNDUM			
(Apatite)	(Apatite)		APATITE		
		PIEDMONTITE			BIAXIAL (+)
(Titanite)			TITANITE	(Titanite)	
CHLORITOID	CHLORITOID				
CHLORITE					
AEGIRINE-AUGITE					
(Perovskite)		(Perovskite)	(Perovskite)		
CROCIDOLITE	CROCIDOLITE	Crocidolite			(±)
CHLORITE	CHLORITE				
RIEBECKITE	RIEBECKITE				
BIOTITE					(−)
EPIDOTE	(Epidote)				
	GLAUCOPHANE	GLAUCOPHANE	(Glaucophane)		
BASALTIC HORNBLENDE					
AEGIRINE				(Aegirine)	
HYPERSTHENE					
ACTINOLITE					
GLAUCONITE				(Glauconite)	
	DUMORTIERITE	DUMORTIERITE			
HORNBLENDE					
	(Cordierite)				
	LAZULITE				

circumstances.

AGGREGATES AND STRUCTURES

See Table III for corresponding numbers.

TABLE III.—SHAPE OR FORM

A. Aggregates and structures (see opposite page for corresponding numbers):

1. Bladed crystals
KYANITE TREMOLITE DIASPORE CLINOZOISITE EPIDOTE DIOPSIDE
Dumortierite Zoisite Hornblende Piedmontite Anhydrite (Actinolite)

2. Prismatic aggregates
TREMOLITE (ACTINOLITE) WOLLASTONITE SILLIMANITE, THOMSONITE JADEITE
Hornblende Anthophyllite Dumortierite Pyrophyllite Glaucophane Zoisite
Gypsum Kyanite Brucite

3. Fibrous
Chrysotile (serpentine asbestos) Crocidolite Tremolite

4. Flakelike
MUSCOVITE CHLORITE BIOTITE PYROPHYLLITE TALC
Chloritoid Phlogopite Lepidolite

5. Scalelike
SERICITE TALC PYROPHYLLITE BRUCITE GIBBSITE Dickite
Kaolinite Dahllite

6. Amygdaloidal
CHALCEDONY QUARTZ OPAL Zeolites (Chlorite) (Calcite)

7. Rosettes
THOMSONITE TOURMALINE ARAGONITE Stilbite, Dumortierite

8. Radial aggregates
CHALCEDONY Gibbsite

9. Oolitic Collophane Siderite
CALCITE Dolomite (Chalcedony)

10. Pisolitic
CLIACHITE GIBBSITE (Calcite) (Dolomite)

11. Shatter cracks
ALLOPHANE HALLOYSITE OPAL Glass

12. Beam structure
ANTIGORITE

13. Mesh structure
ANTIGORITE

14. Matted needles
TOURMALINE AEGIRINE
Sillimanite Stilbite

15. Capillary crystals
RUTILE TOURMALINE

16. Acicular crystals
(ACTINOLITE) ARAGONITE NATROLITE

17. Bent Needle-like crystals
SILLIMANITE Tourmaline Wollastonite Tremolite Dumortierite

18. Foliated mass
TALC PYROPHYLLITE Chlorite Chloritoid Pennine Anthophyllite
Muscovite Biotite Iddingsite

19. Mosaic
CHALCEDONY Quartz Diaspore Kaolinite Dickite Gibbsite Alunite
Cristobalite Antigorite Dahllite

20. Veinlets (21. Cementing minerals)
QUARTZ CALCITE Albite Adularia Fluorite Barite Opal Chalcedony Dahllite

22, 23. Graphic structures, etc.
QUARTZ-FELDSPAR Nepheline-feldspar Corundum-andalusite
Quartz-staurolite Quartz-actinolite Glass-leucite

24. Colloform
COLLOPHANE Opal Allophane

25. Banded
CHALCEDONY OPAL Calcite Aragonite Barite Fluorite

26. Flow structure
GLASS

Phenocrysts
Quartz feldspar olivine augite
Diopside leucite nepheline

27. Shards
GLASS MONTMORILLONITE

28. Perlitic cracks
GLASS

29–32. Incipient crystals
GLASS, CRISTOBALITE, FELDSPAR

33. Spherulites
FELDSPAR Cristobalite (Wollastonite) (Tremolite) (Chalcedony)

34. Lithophysae
TRIDYMITE ORTHOCLASE (Topaz) (Garnet) (Cristobalite) (Quartz)

Structures of organic origin:

35. Bone structure
COLLOPHANE

36. Cellular structure
LIGNITE Chalcedony Opal Quartz

37. Fossil diatoms
OPAL

38. Microfossils (calcareous)
CALCITE Aragonite Dolomite
Collophane

B. Minerals found in euhedral crystals:

Isometric
GARNET
LEUCITE
Analcite
Sodalite
(Spinel)
(Fluorite)

Tetragonal
Vesuvianite
SCAPOLITE
Rutile
Cassiterite
Melilite

Hexagonal
Calcite
Dolomite
SIDERITE
NEPHELINE
QUARTZ
TOURMALINE
APATITE
CORUNDUM

Orthorhombic
OLIVINE
Andalusite
Dumortierite
STAUROLITE
ZOISITE
Lawsonite

Monoclinic
TITANITE
PYROXENE
AMPHIBOLE
ORTHOCLASE
Epidote
ADULARIA
Gypsum
Dickite
Monazite
Aegirine-augite
Basaltic hornblende

Triclinic
PLAGIOCLASE
Microcline

TABLE IV.—CLEAVAGE

E = eminent *P* = perfect *D* = distinct

Minerals with Cleavage in One Direction

Index	Relief	Double refraction 0.01 or less	Double refraction 0.01 to 0.03	Double refraction 0.03 or greater
$n <$ balsam	Low	Stilbite (010)*P* Heulandite (010)*P* Thomsonite (010)*D* Gypsum (010)*E*	Montmorillonite (001)*D*	
$n >$ balsam	Low	Kaolinite (001)*D* Dickite (001)*D* Chlorite (001)*P*	Cordierite (010)*D* Gibbsite (001)*E* Alunite (0001)*D* Brucite (0001)*E*	
	Low or moderate			Prehnite (001)*D* Pyrophyllite (001)*E* Talc (001)*E* Muscovite (001)*E* Lepidolite (001)*E*
	Moderate or high	Topaz (001)*P* Zoisite (010)*P* Clinozoisite (010)*P* Staurolite (010)*D* Chloritoid (001)*E* Corundum (0001) parting	Prehnite (001)*D* Glauconite (001)*P* Sillimanite (100)*P* (Mullite) (100)*D* Dumortierite (100)*D*	Phlogopite (001)*E* Biotite (001)*E* Chondrodite (001)*P* Epidote (001)*P* (Piedmontite) Jarosite (0001)*D* Monazite (001) (parting)

Minerals with Cleavage in Two Directions

$n <$ balsam	Low	Mesolite (110)*P*(1$\bar{1}$0)*P* Scolecite (110)*D* Orthoclase (010)(001)*P* (Sanidine)(Anorthoclase) Microcline (010)(001)*P* Albite (001)*P*(010)*D*	Natrolite (110)*P*	
$n >$ balsam	Low	Plagioclase (001)*P*(010)*D*	Scapolite (110)*D*	
	Moderate to high	Enstatite (110)*P* Andalusite (110)*D* Riebeckite (110)*P*	Tremolite (110)*P* Anthophyllite (110) Actinolite (110)*P* Glaucophane (110)*P* Wollastonite (100)*P*(001)*D* Hornblende (110)*P* Jadeite (110)*P* Hedenbergite (110)*P* Augite (110)*P* Enstatite (110)*P* Hypersthene (110)*P* Aegirine-augite (110)*P* Crocidolite (110)*P* Augite (110)*P*	Pectolite (100)(001)*P* Diopside (110)*P* Aegirine (110)*P* Basaltic hornblende (110)*P* Rutile (110)*D* Titanite (parting)

TABLE IV.—(*Continued*)

Minerals with Cleavage in Three or More Directions

Index	Relief	Double refraction 0.01 or less	Double refraction 0.01 to 0.03	Double refraction 0.03 or greater
THREE DIRECTIONS (MISCELLANEOUS TYPES)				
$n >$ balsam	Low relief	Halite (100)*P* (isotropic)	Scapolite (100)*P*(110)*D* Ext. parallel or sym. Celestite (001)*P*(110)*D*	Anhydrite (001)(010)(100)*P* Ext. parallel
	Moderate to high relief	Axinite (001)(130)(010)*D* Inclined Ext. Corundum (1011) (parting)	Barite (001)(110)*P* Ext. parallel or sym. Lawsonite (010)*P*(110)*D* Kyanite (100)(010)*P*(001) parting Inclined ext.	Diaspore (010)*E*(210)*P* Ext. parallel or sym. Iddingsite (100)(010)(001)*D* Ext. parallel
	Extreme relief	Periclase (100)*P*(isotropic)		Rutile (100)(110)*D* Ext. parallel or sym.
THREE DIRECTIONS (RHOMBOHEDRAL CARBONATES)				
	Calcite Dolomite Magnesite Siderite	All minerals in this group exhibit the following: Variation in relief with direction moderate to high. Very high double refraction. 0.172 (calcite) to 0.234 (siderite). Usually twinned. Uniaxial negative. Cleavage rhombohedral		
SPECIAL CASES				
Isotropic	$n <$ balsam $n >$ balsam		Fluorite (111) octahedral (Spinel (111) octahedral parting) Sphalerite (110)*P* dodecahedral cleavage	
Anisotropic	$n >$ balsam	Relief low	Nepheline (10$\bar{1}$0)*D* (hexagonal)	
		Relief extreme or high		

TABLE V

Indices of Refraction $n = 1.400$ to $n = 1.530$

1.400			
1.410			
1.420			
1.430			
	Fluorite $n = 1.434$		
1.440			
	Opal $n = 1.44$–1.46		
1.450			
	Lechatelierite $n = 1.459$		
1.460			
		Tridymite $\alpha = 1.469$	
1.470			
	Natrolite $\alpha = 1.473$–1.480	Tridymite $\gamma = 1.473$	
	Chabazite $\omega = 1.478$–1.485		
1.480			
	Cristobalite $\alpha = 1.484$		
	Analcite $n = 1.487$	Calcite $\epsilon = 1.486$	Sodalite $n = 1.483$–1.487
	Cristobalite $\gamma = 1.487$		
1.490	Chabazite $\epsilon = 1.480$–1.490		
		Montmorillonite $\alpha = 1.492$	
	Natrolite $\gamma = 1.485$–1.493		
		Stilbite $\alpha = 1.494$	
	Heulandite $\alpha = 1.498$		
1.500		Stilbite $\gamma = 1.500$	Lazurite $n = 1.500$
	Dolomite $\epsilon = 1.502$		
	Heulandite $\gamma = 1.505$	Mesolite $\alpha = 1.505$ $\gamma = 1.506$	
	Leucite $n = 1.508$–1.509	Magnesite $\epsilon = 1.509$	
1.510			
	Scolecite $\alpha = 1.512$		Thomsonite $\alpha = 1.512$–1.530
		Montmorillonite $\gamma = 1.513$	
	Scolecite $\gamma = 1.519$	Orthoclase $\alpha = 1.518$.	
1.520		Gypsum $\alpha = 1.520$	Sanidine $\alpha = 1.520$
	Anorthoclase $\alpha = 1.523$		Microcline $\alpha = 1.522$
	Albite $\alpha = 1.525$–1.532		Sanidine $\gamma = 1.525$
		Orthoclase $\gamma = 1.526$	

Indices of refraction exceeding 1.750

Siderite $(\epsilon = 1.634)\omega = 1.872$
Jarosite $(\epsilon = 1.715)\omega = 1.820$
Iddingsite $\gamma = 1.718$–1.768
Spinel $n = 1.72$–1.78
Chloritoid $n = 1.73$–1.77
Epidote $\gamma = 1.734$–1.779
Grossularite $n = 1.744$–1.757
Aegirine $\alpha = 1.745$–1.777 $\gamma = 1.782$–1.836
Hedenbergite $\gamma = 1.750$–1.757
Allanite $\gamma = 1.751$
Basaltic hornblende $\gamma = 1.752$
Staurolite $\gamma = 1.756$

Piedmontite $\alpha = 1.758$ $\gamma = 1.819$
Corundum $\epsilon = 1.759$ $\omega = 1.767$
Monazite $\alpha = 1.795$ $\gamma = 1.841$
Almandite $n = 1.802$–1.811
Andradite $n = 1.856$–1.889
Titanite $\alpha = 1.887$–1.913 $\gamma = 1.979$–2.054
Zircon $\omega = 1.925$–1.931 $\epsilon = 1.985$–1.993
Cassiterite $\omega = 1.996$ $\epsilon = 2.093$
Perovskite $n = 2.34$–2.38
Rutile $\omega = 2.616$ $\epsilon = 2.903$

TABLE V.—(*Continued*)

Indices of Refraction $n = 1.530$ to $n = 1.650$

1.530 Anorthoclase $\gamma = 1.529$ Gypsum $\gamma = 1.529$
Chalcedony $\omega = 1.531$ Aragonite $\alpha = 1.530$ Microcline $\gamma = 1.530$
Oligoclase $\alpha = 1.532–1.545$ Cordierite $\alpha = 1.532–1.552$ Nepheline $\epsilon = 1.533$
Gibbsite $\alpha = 1.535$
Chalcedony $\epsilon = 1.539$ Talc $\alpha = 1.539$ Nepheline $\omega = 1.537$
1.540 Albite $\gamma = 1.536–1.541$ Scapolite $\epsilon = 1.540–1.571$
Chrysotile $\alpha = 1.542$ Thomsonite $\gamma = 1.518–1.542$
Andesine $\alpha = 1.545–1.555$ Halite $n = 1.544$ Quartz $\omega = 1.544$
Polyhalite $\alpha = 1.548$
1.550 Halloysite $n = 1.551$
Oligoclase $\gamma = 1.541–1.552$ Pyrophyllite $\alpha = 1.552$
Quartz $\epsilon = 1.553$
Chrysotile $\gamma = 1.555$ Labradorite $\alpha = 1.555–1.563$
Lepidolite $\alpha = 1.560$ Muscovite $\alpha = 1.556–1.570$
1.560 Antigorite $\alpha = 1.560$ Dickite $\alpha = 1.560$ Kaolinite $\alpha = 1.561$

Andesine $\gamma = 1.552–1.562$ Chlorite $\alpha = 1.562–1.605$ Phlogopite $\alpha = 1.562$
Beryl $\omega = 1.564–1.590$ Bytownite $\alpha = 1.563–1.571$
Polyhalite $\gamma = 1.567$ Dickite $\gamma = 1.566$ Kaolinite $\gamma = 1.566$ Brucite $\omega = 1.566$
Antigorite $\gamma = 1.571$ Cordierite $\gamma = 1.539–1.570$
1.570 Alunite $\omega = 1.572$ Anhydrite $\alpha = 1.570$ Anorthite $\alpha = 1.571–1.575$
Labradorite $\gamma = 1.562–1.571$
1.580

Bytownite $\gamma = 1.571–1.582$
Brucite $\epsilon = 1.585$
1.590 Talc $\gamma = 1.589$ Anorthite $\gamma = 1.582–1.588$
Alunite $\epsilon = 1.592$ Collophane $n = 1.57–1.62$

1.600 Beryl $\epsilon = 1.568–1.598$
Pyrophyllite $\gamma = 1.600$
Chondrodite $\alpha = 1.601–1.643$ Tremolite $\alpha = 1.602–1.623$
Gibbsite $\gamma = 1.604$ Glauconite $\alpha = 1.603–1.615$
Lepidolite $\gamma = 1.605$ Topaz $\alpha = 1.607–1.629$ Phlogopite $\gamma = 1.606$
1.610 Scapolite $\epsilon = 1.550–1.607$
Chlorite $\gamma = 1.577–1.610$ Muscovite $\gamma = 1.593–1.611$
Hornblende $\alpha = 1.614–1.675$ Wollastonite $\alpha = 1.614–1.621$
Prehnite $\alpha = 1.615$ Anhydrite $\gamma = 1.614$ Tourmaline $\omega = 1.615–1.675$
1.620 Anthophyllite $\alpha = 1.619–1.633$
Dahllite $\epsilon = 1.619–1.626$ Celestite $\alpha = 1.622$ Glaucophane $\alpha = 1.621$
Melilite $\epsilon = 1.626–1.629$
Dahllite $\omega = 1.623–1.635$
1.630
Andalusite $\alpha = 1.632$ Celestite $\gamma = 1.631$
Siderite $\omega = 1.634$ Melilite $\omega = 1.632–1.634$
Apatite $\epsilon = 1.635$ Wollastonite $\gamma = 1.631–1.635$ Forsterite $\alpha = 1.635–1.640$
Barite $\alpha = 1.636$
1.640 Apatite $\omega = 1.639$ Topaz $\gamma = 1.617–1.638$ Glaucophane $\gamma = 1.639$
Andalusite $\gamma = 1.643$ Mullite $\alpha = 1.642$
Prehnite $\gamma = 1.646$ Glauconite $\gamma = 1.623–1.645$
Barite $\gamma = 1.648$

TABLE V.—(*Continued*)

Indices of Refraction $n = 1.650$ to $n = 1.750$

1.650 Diopside $\alpha = 1.650$–1.698 Enstatite $\alpha = 1.650$–1.658

Olivine $\alpha = 1.651$–1.672 Tremolite $\gamma = 1.624$–1.650

Jadeite $\alpha = 1.655$ Mullite $\gamma = 1.654$

Anthophyllite $\gamma = 1.640$–1.657

Calcite $\omega = 1.658$

1.660 Sillimanite $\alpha = 1.659$

Lawsonite $\alpha = 1.665$

Jadeite $\gamma = 1.667$

1.670

Chondrodite $\gamma = 1.636$–1.670 Enstatite $\gamma = 1.661$–1.671

Dumortierite $\alpha = 1.675$ Iddingsite $\alpha = 1.674$–1.730

Axinite $\alpha = 1.678$

1.680 Aegirine-augite $\alpha = 1.680$ Basaltic Hornblende $\alpha = 1.680$ Forsterite

$\gamma = 1.670$–1.680

Dolomite $\omega = 1.681$ Sillimanite

Lawsonite $\gamma = 1.684$

Aragonite $\gamma = 1.686$ Tourmaline $\epsilon = 1.633$–1.685

1.690 Augite $\alpha = 1.688$–1.712 Axinite $\gamma = 1.688$

Dumortierite $\gamma = 1.690$

Riebeckite $\alpha = 1.693$ Hypersthene $\alpha = 1.692$–1.716

Riebeckite $\gamma = 1.697$ Zoisite $\alpha = 1.696$–1.700

1.700 Hornblende $\gamma = 1.633$–1.701 Magnesite $\epsilon = 1.700$

Diaspore $\alpha = 1.702$ Vesuvianite $\omega = 1.701$–1.726

Olivine $\gamma = 1.685$–1.709

1.710 Aegirine-augite $\gamma = 1.709$

Clinozoisite $\alpha = 1.710$–1.723

Kyanite $\alpha = 1.712$

Jarosite $\epsilon = 1.715$

Iddingsite $\gamma = 1.718$–1.768 Zoisite $\gamma = 1.702$–1.718

1.720 Epidote $\alpha = 1.720$–1.734

Spinel $n = 1.72$–1.78

Allanite $\alpha = 1.727$ Diopside $\gamma = 1.631$–1.727

Kyanite $\gamma = 1.728$ Hypersthene $\gamma = 1.700$–1.727

1.730 Chloritoid $n = 1.73$–1.77

Hedenbergite $\alpha = 1.732$–1.739 Vesuvianite $\epsilon = 1.705$–1.732

Clinozoisite $\gamma = 1.719$–1.734 Epidote $\gamma = 1.734$–1.779

Augite $\gamma = 1.713$–1.737

1.740 Periclase $n = 1.738$

Staurolite $\alpha = 1.744$ Aegirine $\alpha = 1.745$–1.777

Pyrope $n = 1.741$–1.750

1.750 Allanite $\gamma = 1.751$ Diaspore $\gamma = 1.750$ Grossularite $n = 1.744$–1.757

For minerals with indices exceeding 1.750 see top of page 140.

NOTE.—For convenience, the indices of refraction n_α, n_β, n_γ, n_ϵ, and n_ω are abbreviated α, β, γ, ϵ, and ω in Table V.

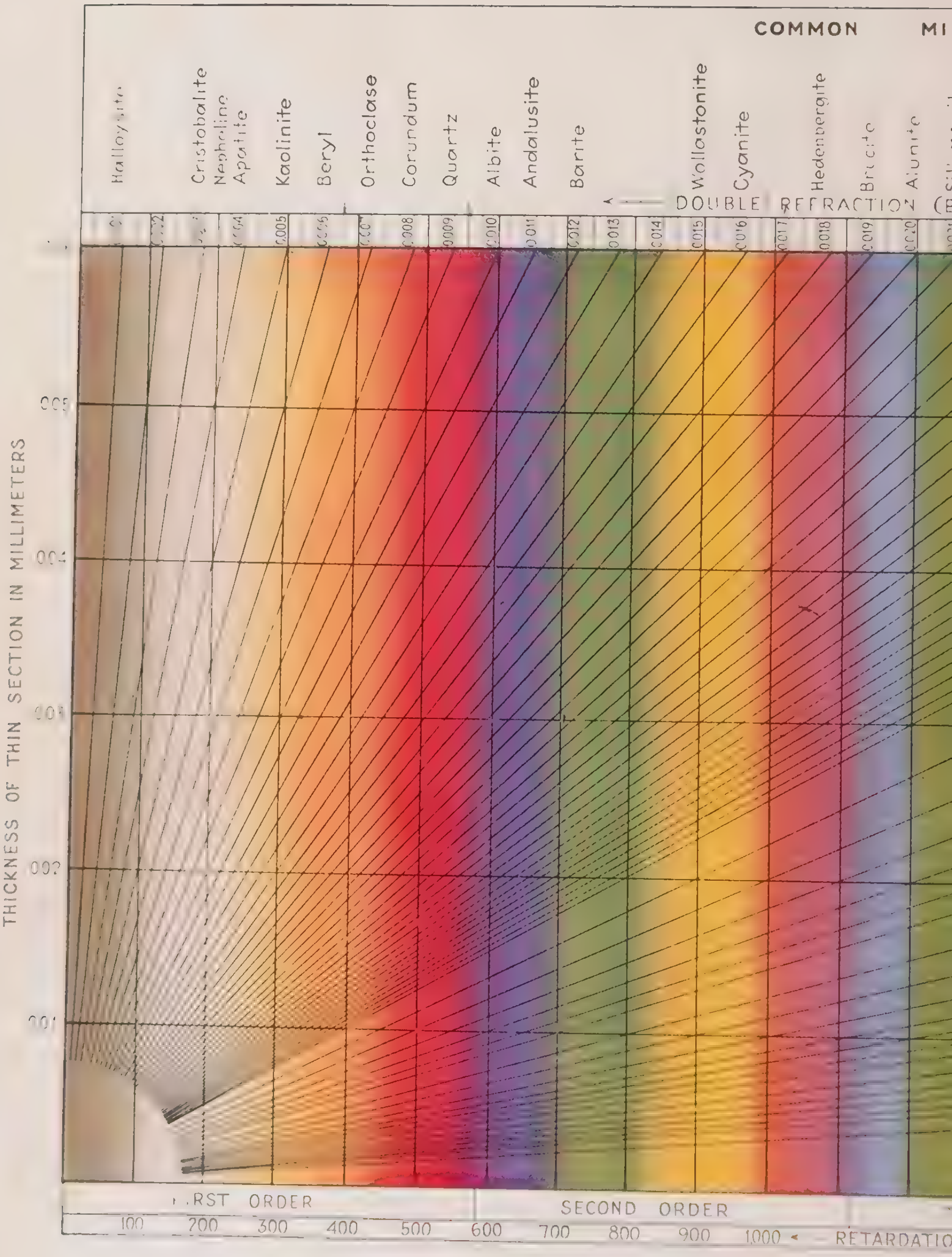
TABLE VI.—ISOTROPIC MINERALS

		Index	Mineral	Composition
Index < balsam	Moderate to strong relief	1.44–1.46	Opal	$SiO_2(H_2O)_x$
		1.434	Fluorite	CaF_2
		1.459	Lechatelierite	SiO_2
		1.483–1.487	Sodalite	$3NaAlSiO_4.NaCl$
		1.484–1.487	Cristobalite	SiO_2
		1.487	Analcite	$NaAl(SiO_3)_2.H_2O$
	Low relief	1.47–1.538	Halloysite	$Al_2O_3.2SiO_2.(2H_2O \pm)$
		1.50	Lazurite	$3NaAlSiO_4Na_2S$
		1.508–1.509	Leucite	$KAl(SiO_3)_2$
Balsam $n = 1.537$				
Index > balsam	Moderate to strong relief	1.544	Halite	$NaCl$
		1.57 ±	Cliachite	$Al_2O_3(H_2O)x$
		1.57–1.62	Collophane	$3Ca_3(PO_4)_2.nCa(CO_3,F_2,O)(H_2O)_x$
		1.741–1.889	Garnet group	$R_3{}^{II}R_2{}^{III}(SiO_4)_3$
		1.738	Periclase	MgO
		1.72–1.78	Spinel	$(Mg,Fe)(Al,Cr)_2O_4$
	Extreme high relief	2.37	Sphalerite	ZnS

Mineraloid—Glass, $n = 1.48 - 1.61$, variable composition.
Palagonite, $n = 1.47 - 1.63$, variable composition.

TABLE VII.—DOUBLE REFRACTION OR BIREFRINGENCE TABLE

Birefringence	Mineral (birefringence constant)	Mineral (birefringence variable)	Birefringence
0.001	(Halloysite)	Analcite	0.000–0.002
	Leucite	Perovskite	0.000–0.002
	Mesolite		
0.002			
0.003	Cristobalite	Collophane	0.000–0.005
0.004	Nepheline	Vesuvianite	0.001–0.006
	Apatite	Chabazite	0.002–0.005
	Riebeckite		
	Tridymite		
0.005	(Kaolinite)		
	Sanidine		
0.006	(Dickite)	Beryl	0.004–0.008
	Anorthoclase	Melilite	0.005–0.007
	Stilbite		
0.007	Andesine	Dahllite	0.004–0.009
	Orthoclase		
	Heulandite		
	Scolecite		
0.008	Microcline	Clinozoisite	0.005–0.010
	Chalcedony	Oligoclase	0.007–0.009
	Corundum	Labradorite	0.007–0.008
0.009	Quartz	Chlorite	0.003–0.015
	Gypsum	Cordierite	0.007–0.011
	Celestite	Topaz	0.008–0.010
0.010	Axinite	Bytownite	0.008–0.011
		Enstatite	0.008–0.011
		Hypersthene	0.008–0.011
		Albite	0.009–0.011
0.011	Antigorite	Chloritoid	0.007–0.015
	Andalusite		
0.012	Jadeite	Zoisite	0.005–0.018
	Mullite	Anorthite	0.011–0.013
	Barite	Natrolite	0.011–0.013
	Staurolite		
0.013	Chrysotile	Thomsonite	0.006–0.020
0.014			
0.015	....	Wollastonite	0.014–0.015
0.016	Kyanite		
0.017			
0.018	Hedenbergite		
	Glaucophane		
0.019	Lawsonite		
	Brucite		
	Polyhalite		
0.020	Alunite		
0.021	(Montmorillonite)		
	Sillimanite		
0.022			
0.023	....	Hornblende	0.019–0.026
		Anthophyllite	0.021–0.024


COMMON MI
Halloysite
Cristobalite
Nepheline
Apatite
Kaolinite
Beryl
Orthoclase
Corundum
Quartz
Albite
Andalusite
Barite
Wollastonite
Cyanite
Hedenbergite
Brucite
Alunite
DOUBLE REFRACTION (B
0.005
0.008
0.009
0.010
0.011
0.012
0.013
0.014
0.015
0.016
0.017
0.018
0.019
0.020
THICKNESS OF THIN SECTION IN MILLIMETERS
.005
.004
.003
.002
.001
FIRST ORDER
SECOND ORDER
100
200
300
400
500
600
700
800
900
1000
RETARDATIO

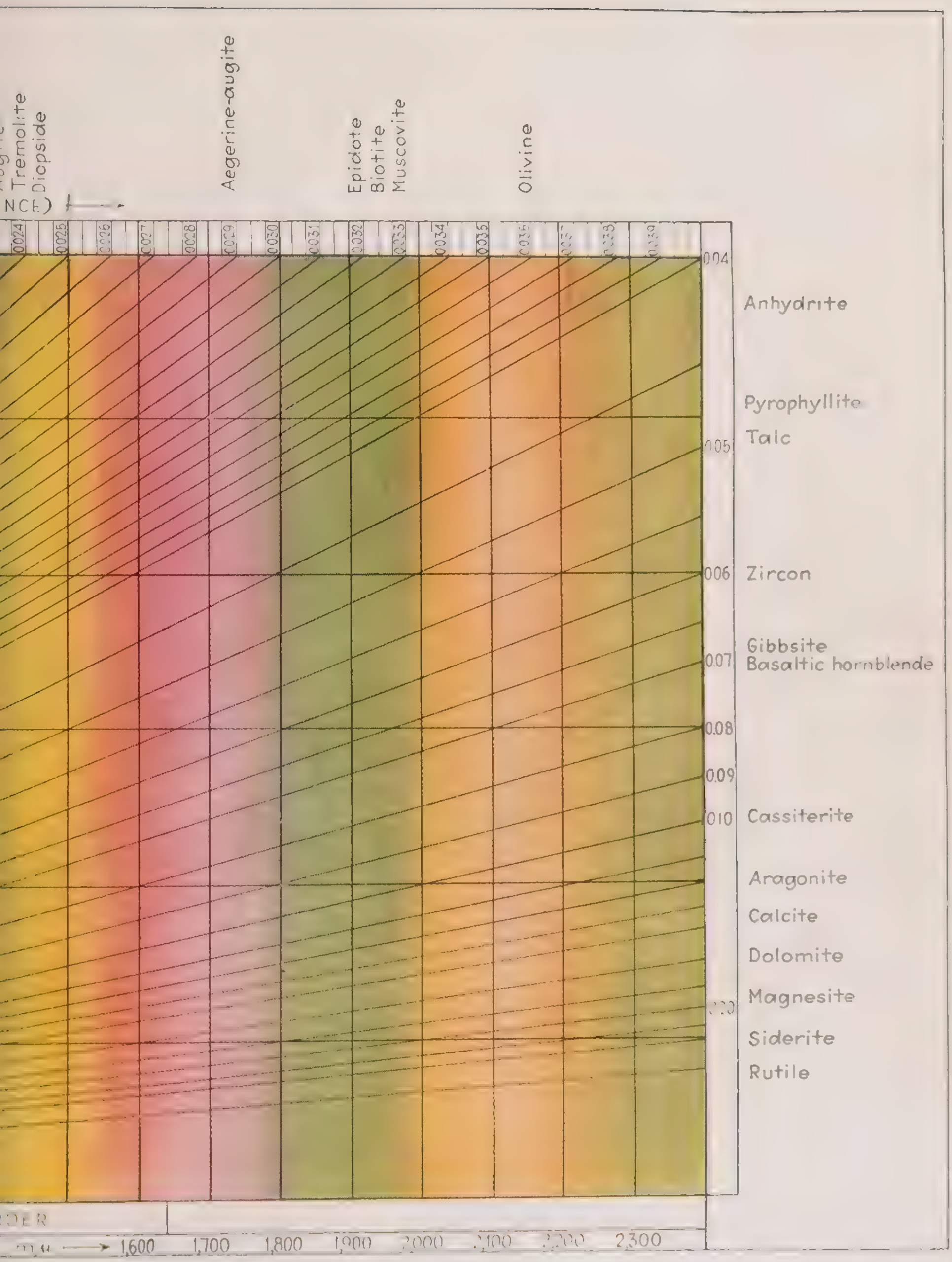


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TABLE VII.—*(Continued)*

Birefringence	Mineral (birefringence constant)	Mineral (birefringence variable)	Birefringence
0.024	Allanite	Scapolite Augite	0.010–0.038 0.021–0.026
0.025	....	Tremolite (Glauconite)	0.023–0.027 0.018–0.032
0.026			
0.027	....	Diopside	0.022–0.031
0.028			
0.029	Aegirine-augite		
0.030	....	Chondrodite	0.025–0.034
0.031	Prehnite		
0.032	....	Epidote	0.014–0.050
0.033	Biotite Muscovite		
0.034			
0.035			
0.036	....	Olivine	0.035–0.037
0.043	....	Iddingsite	0.035–0.050
0.044	Anhydrite Phlogopite		
0.045	Lepidolite		
0.046	Monazite		
0.048	Pyrophyllite (Diaspore)	Aegirine	0.037–0.059
0.050	Talc		
0.061	Piedmontite	Zircon	0.060–0.062
0.069	Gibbsite		
0.072	Basaltic hornblende		
0.097	Cassiterite		
0.105	Jarosite		
0.117	....	Titanite	0.092–0.141
0.156	Aragonite		
0.172	Calcite		
0.179	Dolomite		
0.191	Magnesite		
0.238	Siderite		
0.287	Rutile		

TABLE VIII.—ANISOTROPIC MINERALS

Uniaxial Positive

		Indices		Mineral	Birefringence	
		n_ω	n_ϵ			
n < balsam	Low relief	1.478–1.485	1.480–1.490	Chabazite	0.002–0.005	Low
		1.508	1.509	Leucite	0.001	Low
Balsam n = 1.537						
n > balsam	Low relief	1.544	1.553	Quartz	0.009	Low
		1.566	1.585	Brucite	0.019	Moderate
		1.572	1.592	Alunite	0.020	Moderate
	Extreme high relief	1.925–1.931	1.985–1.993	Zircon	0.060–0.062	High
		1.996	2.093	Cassiterite	0.097	High
		2.616	2.903	Rutile	0.287	High

TABLE IX.—ANISOTROPIC MINERALS

Uniaxial Negative

		Indices		Mineral	Birefringence	
		n_ϵ	n_ω			
n < balsam	Low to moderate relief	1.484	1.487	Cristobalite	0.003	Low
n > balsam	Low relief	1.533	1.537	Nepheline	0.004	Low
		1.564	1.568	Beryl	0.004–0.008	Low
		1.540–1.571	1.550–1.607	Scapolite	0.010–0.038	High
		1.562–1.605	1.575–1.605	Chlorite (Pseudo-hexagonal)	0.003–0.015	Low
	Moderate to strong relief	1.619–1.626	1.623–1.635	Dahllite	0.004–0.009	Low
		1.626–1.629	1.632–1.634	Melilite	0.005–0.007	Low
		1.635	1.639	Apatite	0.004	Low
		1.615–1.675	1.633–1.685	Tourmaline	0.025	Moderate
		1.701–1.726	1.705–1.732	Vesuvianite	0.001–0.006	Low
		1.759	1.767	Corundum	0.008	Low
		1.715	1.820	Jarosite	0.105	High
	Variable relief	Rhombohedral carbonate minerals; rhombohedral cleavage, strong variations in relief, strong birefringence Separated best by chemical tests for Ca, Mg, and Fe, applied to selected portions of the hand specimen				
		1.486	1.658	Calcite	0.172	Very high
		1.502	1.681	Dolomite	0.179	Very high
		1.509	1.700	Magnesite	0.191	Very high
		1.634	1.872	Siderite	0.238	Very high

TABLE X.—ANISOTROPIC MINERALS

Biaxial Positive

		Indices			Mineral
		n_α	n_β	n_γ	
Index < balsam	High relief	1.469	1.469	1.473	Tridymite
		1.473–1.480	1.476–1.482	1.485–1.493	Natrolite
	Low or moderate relief	1.498	1.499	1.505	Heulandite
		1.505	1.505	1.506	Mesolite
		1.508	....	1.509	Leucite
		1.520	1.522	1.529	Gypsum
		1.512–1.530	1.513–1.532	1.518–1.542	Thomsonite
		1.525–1.532	1.529–1.536	1.536–1.541	Albite
		1.535	1.535	1.604	Gibbsite
		1.532–1.545	1.536–1.548	1.541–1.552	Oligoclase
		n balsam = 1.537			
Index > balsam	Low to moderate relief	1.525–1.532	1.529–1.536	1.536–1.541	Albite
		1.512–1.530	1.513–1.532	1.518–1.542	Thomsonite
		1.545–1.555	1.548–1.558	1.552–1.562	Andesine
		1.542	....	1.555	Chrysotile
		1.532–1.545	1.536–1.548	1.541–1.552	Oligoclase
		1.560	1.562	1.566	Dickite
		1.555–1.563	1.558–1.567	1.562–1.571	Labradorite
		1.570	1.576	1.614	Anhydrite
	Moderate to high relief	1.562–1.605	1.575–1.605	1.577–1.610	Chlorite
		1.535	1.535	1.604	Gibbsite
		1.607–1.629	1.610–1.631	1.617–1.638	Topaz
		1.622	1.624	1.631	Celestite
		1.615	1.625	1.646	Prehnite
		1.619–1.633	1.630–1.642	1.640–1.657	Anthophyllite
		1.601–1.643	1.616–1.655	1.636–1.670	Chondrodite
		1.636	1.637	1.648	Barite
		1.642	1.644	1.654	Mullite
		1.655	1.659	1.667	Jadeite
		1.659	1.661	1.680	Sillimanite
		1.665	1.674	1.684	Lawsonite
		1.651–1.672	1.667–1.690	1.685–1.709	Olivine
		1.650–1.698	1.657–1.706	1.681–1.727	Diopside
		1.680	1.687	1.709	Aegirine-augite
		1.696–1.700	1.696–1.703	1.702–1.718	Zoisite
		1.688–1.712	1.701–1.717	1.713–1.737	Augite
		1.710–1.723	1.715–1.729	1.719–1.734	Clinozoisite
		1.702	1.722	1.750	Diaspore
		1.674–1.730	1.715–1.763	1.718–1.768	Iddingsite
		1.732–1.739	1.737–1.745	1.750–1.757	Hedenbergite
		1.744	1.749	1.756	Staurolite
		....	1.75–1.77	....	Chloritoid
	Extreme high relief	1.758	1.771	1.819	Piedmontite
		1.795	1.796	1.841	Monazite
		1.887–1.913	1.894–1.921	1.979–2.054	Titanite

TABLE XI.—ANISOTROPIC MINERALS
Biaxial Negative

		Indices			Mineral
		n_α	n_β	n_γ	
Index < balsam	Low relief		1.487	....	Analcite
		1.494	1.498	1.500	Stilbite
		1.560	1.570	1.571	Antigorite
		1.492	....	1.513	Montmorillonite
		1.512	1.519	1.519	Scolecite
		1.518	1.524	1.526	Orthoclase
		1.520	1.525	1.525	Sanidine
		1.522	1.526	1.530	Microcline
		1.523	1.528	1.529	Anorthoclase
		1.532–1.545	1.536–1.548	1.541–1.552	Oligoclase
		1.532–1.555	1.536–1.562	1.539–1.570	Cordierite
			n balsam = 1.537		
Index > balsam	Low relief	1.532–1.545	1.536–1.548	1.541–1.552	Oligoclase
		1.545–1.555	1.548–1.558	1.552–1.562	Andesine
		1.548	1.562	1.567	Polyhalite
		1.561	1.565	1.566	Kaolinite
		1.532–1.555	1.536–1.562	1.539–1.570	Cordierite
	Low or moderate relief	1.563–1.571	1.567–1.577	1.571–1.582	Bytownite
		1.541–1.579	1.574–1.638	1.574–1.638	Biotite
		1.571–1.575	1.577–1.583	1.582–1.588	Anorthite
		1.562–1.605	1.575–1.605	1.577–1.610	Chlorite
		1.552	1.588	1.600	Pyrophyllite
		1.539	1.589	1.589	Talc
		1.556–1.570	1.587–1.607	1.593–1.611	Muscovite
		1.560	1.598	1.605	Lepidolite
	Moderate or high relief	1.562	1.606	1.606	Phlogopite
		1.602–1.623	1.613–1.638	1.624–1.650	Tremolite
		1.603–1.615	nearly γ	1.623–1.645	Glauconite
		1.614–1.621	1.629–1.633	1.631–1.635	Wollastonite
		1.619–1.633	1.630–1.642	1.640–1.657	Anthophyllite
		1.621	1.638	1.639	Glaucophane
		1.632	1.638	1.643	Andalusite
		1.614–1.675	1.618–1.691	1.633–1.701	Hornblende
		1.635–1.640	1.651–1.660	1.670–1.680	Forsterite
		1.650–1.658	1.656–1.665	1.661–1.671	Enstatite
		1.530	1.682	1.686	Aragonite
		1.678	1.685	1.688	Axinite
		1.675	1.685	1.690	Dumortierite
		1.693	1.695	1.697	Riebeckite
		1.692–1.716	1.695–1.720	1.700–1.727	Hypersthene
		1.712	1.720	1.728	Kyanite
		1.680	1.725	1.752	Basaltic hornblende
		1.674–1.730	1.715–1.763	1.718–1.768	Iddingsite
		1.727	1.739	1.751	Allanite
		1.720–1.734	1.724–1.763	1.734–1.779	Epidote
		1.745–1.777	1.770–1.823	1.782–1.836	Aegirine

TABLE XII.—AXIAL ANGLES

Positive	Angle 2V	Negative	Angle 2V
Leucite	Small	Staurolite	88°
Chrysotile	Small	Biotite	Small
		Phlogopite	0–10°
		Sanidine	0–12°
		Glauconite	0–20°
Monazite	14°		
		Montmorillonite	7–25°
		Talc	6–30°
		Aragonite	18°
Gibbsite	0–40°		
Sillimanite	20° ±		
		Beidellite	18–31°
		Stilbite	33° ±
Heulandite	34° ±	Dumortierite	30–40°
Tridymite	35° ±	Scolecite	36° ±
Barite	36°		
Titanite	23–50°	Wollastonite	39–40°
		Lepidolite	40° ±
		Muscovite	40° ±
Anhydrite	42°	Glaucophane	45°
Zoisite	30–60°		
Mullite	45–50°	Anorthoclase	47–52°
Chloritoid	36–60°		
Celestite	51°		
Thomsonite	54° ±	Pyrophyllite	53–60°
Topaz	48–65°		
Gypsum	58°	Cordierite	40–80°
Diopside	58–60°		
Augite	58–62°	Kaolinite	60°
Aegirine-augite	60 ± °		
Hedenbergite	60°	Aegirine	60–66°
Natrolite	60–63°	Nacrite	68°(?)
		Hornblende	52–85°
Piedmontite	55–80°	Adularia	70°
		Polyhalite	70 ± °
		Allanite	70 ± °
		Orthoclase	69–72°
Jadeite	70°	Axinite	70–75°
		Hypersthene	60–90°
Albite	74°	Anorthite	77–78°
		Epidote	69–89°
Clinozoisite	66–90°	Basaltic hornblende	79–80°
		Microcline	77–84°
Olivine	70–90°	Tremolite	79–85°
Mesolite	80° ±	Kyanite	82°
Chondrodite	72–90°	Bytownite	78–90°
		Andalusite	84°
Labradorite	75–89°	Hornblende	84°
Diaspore	84°	Forsterite	85–90°
Lawsonite	84°		
Clinozoisite	85°	Riebeckite	Large
Minerals Showing Wide Angular Variations			
Prehnite	Varies	Analcite	Var.
		Antigorite	20–90°
		Enstatite	31–80°

Minerals with Variable Sign (±)

Chabazite	0–32°
Chlorite group	0–50°
Iddingsite	25–60°
Anthophyllite	70–89°
Andesine	76–90°
Oligoclase	81–90°

PART II

DESCRIPTIONS OF INDIVIDUAL MINERALS

INTRODUCTION TO PART II

Of the 1200 to 1500 known minerals comparatively few are important rock-forming constituents. In the following pages descriptions of individual minerals and mineral groups are given. The list of minerals and mineraloids included in the descriptions and presented on page 154 includes practically all the common and important minerals found in igneous, sedimentary, or metamorphic rocks, together with a few important vein minerals. Other minerals may be important locally. Minerals other than those listed may occasionally be encountered; then the larger reference books should be consulted. A selected list of these may be found on the opposite page.

For convenience of reference the microscopic and optical characteristics of the minerals are given under appropriate headings. *Color* refers to the color of the mineral in thin sections. Pleochroism and absorption are included along with color, for ordinarily the lower nicol is in place during the entire examination of the slide. *Relief* refers to the ordinary thin section mounted in balsam. The interference colors listed are usually the maximum colors for thin sections of about 0.03 mm. thickness. If sections are thicker or thinner than this value, allowance must be made. The thickness may usually be determined fairly accurately if a known mineral such as quartz is present in the slide. Clockwise extinction angles are considered positive; and counter-clockwise ones, negative. *Orientation* refers especially to the position of the faster and slower rays in characteristic sections. The optical orientation is given in the tabulation just below the name of the mineral at the top of the page. The size of the axial angle for biaxial crystals is indicated in a general way in the text. Exact values of this angle are given in the tabulation just referred to. Approximate measurements of the axial angle can be made in favorable cases by the use of a micrometer ocular which has been calibrated by means of several biaxial crystals of known axial angles. Under the heading *Distinguishing Features* resemblances to, and differences from, similar minerals are pointed out as an aid in the determination.

Orientation diagrams for nearly all the biaxial minerals are given, and for most of the monoclinic minerals both plans and side elevations are inserted in order to facilitate an understanding of their optical properties.

It is to be hoped that the photographs of typical thin sections will aid in the identification of minerals.

References for Part II

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CLASSIFICATION OF THE MINERALS DESCRIBED

ELEMENTS
- GRAPHITE

SULFIDS AND SULFOSALTS
- Sphalerite
- PYRITE
- Pyrrhotite
- Chalcopyrite

HALOIDS
- Halite
- Fluorite

OXIDS
- SILICA MINERALS
  - α-QUARTZ
  - β-QUARTZ
  - CHALCEDONY
  - OPAL
  - Tridymite
  - Cristobalite
  - Lechatelierite
- Periclase
- Corundum
- Hematite
- ILMENITE
- Rutile
- Cassiterite

ALUMINATES, etc.
- Spinel
- MAGNETITE
- Chromite

HYDROUS OXIDS
- Diaspore
- Gibbsite
- Cliachite
- Brucite
- Limonite

CARBONATES
- CALCITE
- DOLOMITE
- Magnesite

CARBONATES *(Continued)*
- Siderite
- Aragonite

SULFATES
- Barite
- Celestite
- Anhydrite
- GYPSUM
- Polyhalite
- Alunite
- Jarosite

PHOSPHATES
- Monazite
- APATITE
- Dahllite
- COLLOPHANE
- Lazulite

TITANATES and TITANO-SILICATES
- Perovskite
- Titanite

SILICATES
- THE FELDSPARS
  - ORTHOCLASE
  - Adularia
  - SANIDINE
  - MICROCLINE
  - Anorthoclase
  - ALBITE
  - OLIGOCLASE
  - ANDESINE
  - LABRADORITE
  - Bytownite
  - Anorthite
- THE FELDSPATHOIDS
  - Leucite
  - Nepheline
  - Sodalite
  - Lazurite
  - Melilite

CLASSIFICATION OF THE MINERALS DESCRIBED

(*Continued*)

SILICATES (*Continued*)
- PYROXENE GROUP
  - Enstatite
  - Hypersthene
  - DIOPSIDE
  - AUGITE
  - Hedenbergite
  - Aegirine-augite
  - Aegirine
  - Jadeite
- AMPHIBOLE GROUP
  - Anthophyllite
  - TREMOLITE
  - HORNBLENDE
  - BASALTIC HORNBLENDE
  - Riebeckite
  - Glaucophane
- Forsterite
- OLIVINE
- Chondrodite
- GARNET GROUP
- Wollastonite
- Beryl
- Scapolite Group
- Vesuvianite
- Zircon
- Topaz
- Andalusite
- Sillimanite
- Kyanite
- Mullite
- Dumortierite
- TOURMALINE GROUP
- Axinite
- EPIDOTE GROUP
  - Zoisite
  - Clinozoisite

SILICATES (*Continued*)
  - EPIDOTE
  - Piedmontite
  - Allanite
- Staurolite
- Cordierite
- Prehnite
- Lawsonite
- MICA GROUP
  - MUSCOVITE
  - Lepidolite
  - PHLOGOPITE
  - BIOTITE
- CHLORITE GROUP
- Chloritoid
- TALC
- Pyrophyllite
- CLAY MINERALS
  - KAOLINITE
  - Dickite
  - Halloysite
  - MONTMORILLONITE
- ANTIGORITE
- Chrysotile
- Iddingsite
- Glauconite
- ZEOLITE GROUP
  - Analcite
  - Heulandite
  - Stilbite
  - Chabazite
  - Natrolite
  - Mesolite
  - Thomsonite
  - Scolecite

MINERALOIDS
  - VOLCANIC GLASS
  - Palagonite

GRAPHITE

C Opaque Hexagonal

Color.—Black with metallic luster in reflected light. It is opaque even in the thinnest sections.

Form.—The characteristic occurrence of graphite is in thin flakes and disseminated scales. The crystals are tabular in habit.

Fig. 126.—(×20) Graphite in schist.

Distinguishing Features.—In thin sections graphite resembles magnetite, but its flaky appearance is distinctive for an opaque mineral.

Occurrence.—Graphite is characteristic of metamorphic rocks such as schists, gneisses, slates, and metamorphic limestones. It gives the gray color to many metamorphic limestones and in some cases is the only mineral present in addition to calcite.

Carbonaceous Matter

It is very common to find, in some rocks, finely divided opaque particles which cannot be referred to any definite mineral. This material is usually carbonaceous matter which has not been subjected to a temperature high enough to produce graphite.

Sphalerite

(Zn,Fe)S Isometric

$n = 2.37$

Color.—Gray to yellow or brown; the color is not always uniform.

Form.—Sphalerite is usually found in anhedral crystals.

Cleavage.—More or less prominent parallel to $\{110\}$.

Relief.—Very high, $n >$ balsam; adamantine luster by reflected light.

Birefringence nil. Dark between crossed nicols, but it may be difficult to recognize the isotropic character on account of total reflection.

Distinguishing Features.—The very high relief, isotropic character, and cleavage are characteristic.

Occurrence.—Sphalerite is a common and widely distributed mineral in veins and replacement deposits. The common associates are pyrite, galena, marcasite, and the gangue minerals, quartz, calcite, dolomite, and siderite. It occurs in a few sedimentary rocks but is very rare as a rock-forming mineral.

PYRITE

FeS_2 Opaque Isometric

Color.—Brass colored with metallic luster in reflected light. Opaque even in the thinnest sections.

Form.—Pyrite is common in euhedral crystals, which are usually cubes, showing in thin sections square, rectangular, or triangular outlines. It also occurs in irregular grains, masses, and veinlets.

Distinguishing Features.—Pyrite resembles pyrrhotite and chalcopyrite but is distinguished by color differences in reflected light. Chalcopyrite is deeper yellow. Pyrrhotite is bronze colored. Pyrite is even more like marcasite, and it may be necessary to use polished surfaces to differentiate the two minerals.

Alteration.—Pyrite is often more or less altered to limonite, occasionally to turyite.

Occurrence.—Pyrite is a very common and widely distributed mineral in veins and a secondary mineral in igneous rocks. It is also found in many sedimentary and metamorphic rocks.

Pyrrhotite

$FeS(S)_x$ Opaque Hexagonal

Color.—Bronze colored with metallic luster in reflected light. Opaque even in the thinnest sections.

Form.—Pyrrhotite usually occurs in grains and irregular masses. Euhedral crystals are exceedingly rare.

Distinguishing Features.—Pyrrhotite resembles pyrite but is bronze rather than brass colored. It is scratched by a knife blade while pyrite is not. Pentlandite, a rare nickel-iron sulfid, is a common associate of pyrrhotite and very much resembles it, but pentlandite has a characteristic octahedral parting. This does not always show, and it may be necessary to use polished surfaces to distinguish the two minerals.

Occurrence.—Pyrrhotite occurs in igneous rocks as a late magmatic mineral. It is also found in veins and in some metamorphic rocks. Compared with pyrite it is a high-temperature mineral.

Chalcopyrite

$CuFeS_2$ Opaque Tetragonal

Color.—Brass colored with metallic luster in reflected light. Opaque even in the thinnest sections.

Form.—Chalcopyrite rarely occurs in euhedral crystals. It is found in anhedra and in veinlets.

Distinguishing Features.—Chalcopyrite resembles pyrite but is a deeper yellow. It is scratched by a knife; pyrite is not.

Occurrence.—Chalcopyrite is a very common mineral in veins and ore deposits. It is occasionally found in igneous, sedimentary, and metamorphic rocks.

Halite

NaCl Isometric

$n = 1.544$

Color.—Colorless but may contain inclusions.

Form.—Halite is not found in thin sections prepared in the ordinary way, but the sections may be ground in petroleum or oil. The halite usually appears in anhedral crystals.

Cleavage perfect cubic.

Relief very low, n being about the same as balsam or clove oil.

Birefringence nil. Dark between crossed nicols.

Distinguishing Features.—The very low relief, cubic cleavage, and solubility are characteristic. About the only mineral that is likely to be mistaken for halite is sylvite, but the latter has appreciable relief and n less than balsam (for sylvite $n = 1.49$).

Occurrence.—Halite occurs in sedimentary beds of rock salt which are accompanied by anhydrite and gypsum. Sylvite and polyhalite are characteristic associates.

Fluorite

CaF_2 Isometric

$n = 1.434$

Color.—Colorless or purple in bands or spots.

Form.—Fluorite is sometimes found in euhedral crystals with square outline, but it is usually anhedral and often fills the spaces between other minerals.

Cleavage perfect octahedral {111}. The cleavage usually appears as two intersecting lines at oblique angles of 70 and 110°, occasionally at three intersecting lines of 60 and 120°.

Relief fairly high, $n <$ balsam. The index of refraction is remarkably constant, 1.4338 for sodium light. Dispersion is very low, hence the use of fluorite for apochromatic objectives.

Birefringence nil. Dark between crossed nicols.

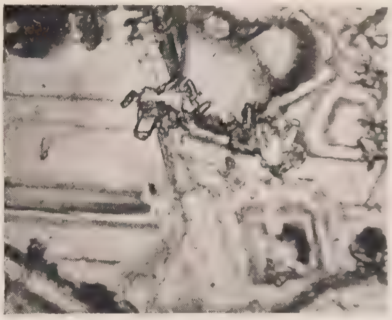


Fig. 127.—(×9) Fluorite showing zonal structure.

Distinguishing Features.—The rather high relief, perfect cleavage, and isotropic character distinguish fluorite from practically all other minerals. The purple spots or bands (see Fig. 127) are very characteristic.

Occurrence.—Fluorite is a common vein mineral, but it is rather rare in rocks in general. It is found in some granites, occasionally in sandstones, limestones, and phosphorites.

THE SILICA MINERALS

Silica occurs in nature in the six distinct minerals listed on page 160. Of these the first three are very common. Lechatelierite (silica glass) is exceedingly rare. The other two, tridymite and cristobalite, are widely distributed in volcanic rocks and can hardly be called rare minerals. They have frequently been overlooked.

In respect to physical properties the silica minerals may be placed in two groups. Quartz and chalcedony have refractive

The Silica Minerals

Mineral	Crystal system	Indices of refraction
QUARTZ	Hexagonal	$n_\omega = 1.544$, $n_\epsilon = 1.553$, $n_\epsilon - n_\omega = 0.009$
CHALCEDONY	Aggregates	$n_\alpha = 1.531$, $n_\gamma = 1.539$, $n_\gamma - n_\alpha = 0.008$
OPAL	Amorphous	$n = 1.44 - 1.46$
Tridymite	Pseudo-hexagonal	$n_\alpha = 1.469$, $n_\gamma = 1.473$, $n_\gamma - n_\alpha = 0.004$
Cristobalite	Pseudo-isometric	$n_\alpha = 1.484$, $n_\gamma = 1.487$, $n_\gamma - n_\alpha = 0.003$
Lechatelierite	Amorphous	$n = 1.459$

indices near that of balsam and birefringence of about 0.009; the other four have lower indices of refraction and weaker birefringence, which reaches nil in lechatelierite and usually in opal.

Chalcedony always occurs in aggregates of some sort, and consequently the optical properties are not completely known.

On heating quartz there is a sudden change in the properties at 573° C. The symmetry changes from $A_3.3A_2$ to $A_6.6A_2$. The low-temperature form is called *α-quartz* or *low-quartz* and the high-temperature form, *β-quartz* or *high-quartz*. The quartz of igneous rocks was β-quartz at the time of its formation but on cooling inverted to α-quartz. Similar changes take place on heating tridymite and cristobalite. The stability range of the various silica minerals is shown in the diagram of Fig. 128.

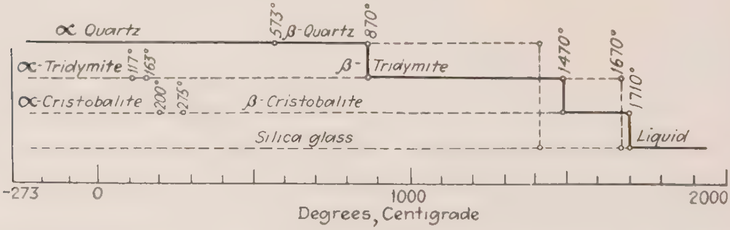


Fig. 128.—Diagram to show the relations between the various forms of silica. (*After Sosman.*)

Chalcedony and opal are low-temperature minerals. Quartz has a considerable temperature range. Tridymite and cristobalite are comparatively high-temperature minerals. They occur almost exclusively in volcanic igneous rocks and in all probability have been formed by hot gases at the close of the magmatic period.

α-QUARTZ

SiO_2 (Low Quartz) Hexagonal
($A_3.3A_2$)

$n_\omega = 1.544$
$n_\epsilon = 1.553$
Opt. (+); $c = Z$
Fig. 129, Page 164

Color.—Colorless, often contains inclusions.

Form.—Quartz occurs in euhedral prismatic crystals, in veinlets, disseminated grains, and as replacement anhedra. It may be intergrown with orthoclase or microcline (graphic granite) and with plagioclase in vermicular forms (myrmekite). It often occurs as a late interstitial mineral.

Cleavage usually absent, but it sometimes shows on the edge of the slide. The cleavage is imperfect rhombohedral {10$\bar{1}$1}, almost rectangular in favorable sections, $rr' = 85°46'$.

Relief very low, $n >$ balsam.

Birefringence weak, $n_\epsilon - n_\omega = 0.009$; thin sections 0.03 mm. thick show as a maximum, first-order white interference color with a tinge of yellow. Quartz is very useful in determining the thickness of any slide in which it occurs.

Extinction parallel in euhedral crystals and symmetrical to cleavage traces. Basal sections are dark in all positions. Irregular and wavy extinction due to strain is common. Vein quartz often shows peculiar structures such as flamboyant, feathered, lamellar, etc. (see Fig. 129, page 164). Secondary enlargements of quartz grains are common.

Orientation.—The position of the slower ray marks the trace of the *c*-axis. Euhedral crystals are therefore length-slow.

Twinning is rarely seen in thin sections.

Interference Figure.—Basal sections of ordinary thickness give a uniaxial positive figure without any rings. The interference figure of thick sections (greater than 1 mm.) has a hollow center on account of rotary polarization. Occasionally quartz gives a biaxial figure.

Distinguishing Features. Quartz is easy to determine on account of its lack of alteration, absence of cleavage except perhaps on the edge of the section, and absence of twinning. Cordierite may be mistaken for it, but cordierite is biaxial. Beryl resembles quartz in thin sections but is length-fast and optically negative. Some varieties of scapolite also resemble quartz, but they are optically negative, length-fast, and have cleavage. Chalcedony has aggregate structure.

Alteration.—Quartz is less affected by alteration than almost any other mineral, but it sometimes shows slight replacement by sericite.

Occurrence.—Quartz is a ubiquitous mineral. It is found in many rock types as an essential, accessory, or secondary mineral. It is especially abundant in sandstones, arkoses, sands, quartzites, granites, and gneisses. In many igneous rocks it is a secondary mineral in seams and cavities. It occurs as a replacement of other minerals and as a replacement of wood and calcareous fossils.

β-QUARTZ

SiO_2 (High Quartz) Hexagonal
Fig. 130, Page 164 ($A_6.6A_2$)

The quartz of rhyolites and quartz porphyries is the high-temperature form known as β-quartz. It has formed above 573° C.; and the low-temperature form called α-quartz, below 573° C. On cooling, the β-quartz inverts to the α-form, so that all quartz examined in thin sections is now α-quartz. The habit of β-quartz is usually different from that of the α-form. A hexagonal bipyramid (the symmetry is $A_6.6A_2$) predominates and the prism face is subordinate, while in the α-form the prism predominates.

The twinning laws of β-quartz are different from those of α-quartz, but twinning rarely shows in thin sections.

CHALCEDONY

SiO_2

Aggregates
[Crystal System (?)]

$$n_\alpha = 1.531$$
$$n_\gamma = 1.539$$

Fig. 131, Page 164

Color.—Colorless to pale brown and often bluish white by reflected light.

Form.—Chalcedony usually occurs as a cavity filling or lining which is often spherulitic (see Fig. 131, page 164), as a replacement of fossils, as cementing material, and in massive form.

Relief low, n about the same as that of balsam, either slightly lower or slightly greater.

Birefringence weak, $n_\gamma - n_\alpha = 0.008$, practically the same as that of quartz. Chalcedony always shows aggregate structure between crossed nicols. This often takes on a spherulitic form with the spherulitic cross prominent in many cases.

Extinction parallel to the length of the fibers.

Orientation.—The fibers are usually length-fast, but in many cases they are length-slow. The fibers of concentric zones are often alternately slow and fast. No explanation has ever been made of this variation.

Distinguishing Features.—The aggregate structure with optical properties very close to those of quartz is distinctive for chalcedony. The minerals most likely to be mistaken for chalcedony are probably gibbsite and dahllite, but in both of these the relief is distinctly higher.

Occurrence.—Chalcedony is a secondary mineral in the cavities of igneous rocks and is often associated with quartz, opal, and the zeolites. It also occurs in sedimentary limestone in nodules and bands and as a replacement of calcareous fossils. Chalcedony is the principal constituent of cherts and jaspers. It occurs in diatomite as a replacement of opal. The temperature range of chalcedony seems to be lower than that of quartz.

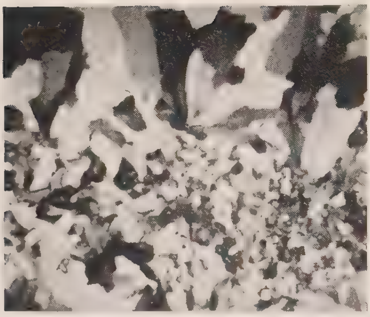


FIG. 129.—(×9) Vein quartz (α-quartz). (× nicols.)

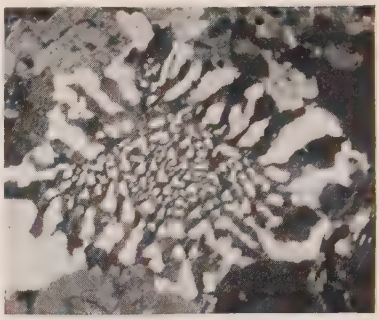


FIG. 130.—(×12) Graphic intergrowth of β-quartz and feldspar. (× nicols.)

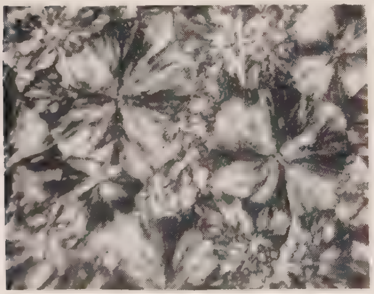


FIG. 131.—(×45) Spherulitic chalcedony. (× nicols.)

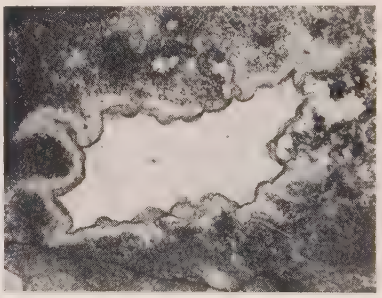


FIG. 132.—(×34) Colloform opal with infilled chalcedony.

FIG. 133.—(×50) Twinned tridymite in cavity of altered rhyolitic glass. (× nicols.)

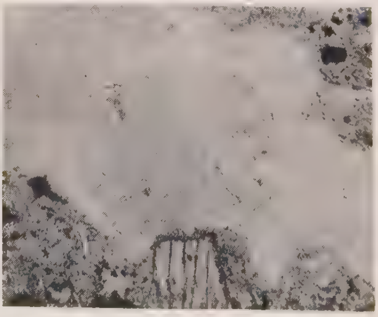


FIG. 134.—(×20) Cristobalite in cavity of auganite.

PHOTOMICROGRAPHS OF THIN SECTIONS OF SILICA MINERALS

OPAL

$SiO_2(H_2O)_x$ Amorphous

$n = 1.44$ to 1.46

Fig. 132, Page 164

Color.—Colorless to pale gray or brown.

Form.—Opal is often found in colloform crusts, in veinlets, and as a cavity filling or lining. More often it is massive without any particular structure. It often occurs as a replacement of wood and other organic materials. It is common as a replacement of feldspar and as the cementing material in sandstone.

Cleavage absent, but irregular fractures are found on the edges of thin sections.

Relief rather high, but $n <$ balsam.

Birefringence usually nil, but some varieties, especially hyalite, may show weak double refraction which is due to strain. Interference colors caused by exceedingly thin films show in sections of precious opal, especially in reflected light.

Distinguishing Features.—The high relief and low index of refraction are distinctive. Lechatelierite (silica glass) is very similar, and it may be necessary to try the closed-tube test for water in order to distinguish them.

Occurrence.—Opal is a secondary mineral in volcanic igneous rocks. It appears in cavities or seams and as a replacement of feldspars or other silicates. The more common associates are quartz, chalcedony, and tridymite. It is the principal constituent of diatomite and geyserite and occasionally occurs as the cementing material in sandstone.

LUSSATITE

A fibrous variety of silica with a low index of refraction known as lussatite has been considered to be a variety of tridymite or even a distinct silica mineral, but it is probably a mixture of fibrous chalcedony and opal.

Tridymite

SiO_2

Orthorhombic
(Hexagonal above 117° C.)

$$n_\alpha = 1.469$$
$$n_\beta = 1.469$$
$$n_\gamma = 1.473$$
$$2V = 35°$$

Fig. 133, Page 164

Color.—Colorless.

Form.—Tridymite usually occurs in minute euhedral crystals as a cavity lining. The crystals are six sided, thin tabular, and are often twinned. It also occurs as a porous crystalline aggregate.

Relief moderate, but $n <$ balsam.

Birefringence very weak, $n_\gamma - n_\alpha = 0.004$; best seen with a sensitive violet test plate.

Twinning.—Wedge-shaped twins made up of two or three individuals are characteristic (see Fig. 133, page 164). The twin-plane is $\{10\bar{1}6\}$.

Distinguishing Features.—Tridymite very much resembles cristobalite, not only in its general appearance but also in its geologic occurrence. The twinning of tridymite and the wedge-shaped sections are characteristic; in their absence it may be necessary to determine the refractive index of isolated grains. For tridymite $n < 1.480$; for cristobalite $n > 1.480$.

Alteration.—Pseudomorphs of cristobalite after tridymite have been found at several localities by Rogers. Pseudomorphs of quartz after tridymite (the pseudo-tridymite of Mallard) are known from a number of localities.

Occurrence.—The characteristic occurrence of tridymite is in the cavities of volcanic igneous rocks such as obsidian, rhyolite, andesite, etc. It is a late mineral formed by hot gases. Tridymite is not very abundant, but it is common and widely distributed. A tridymite-feldspar rock formed by the action of hot gases upon rhyolitic obsidian has been found by Rogers in Imperial County, California. In Texas tridymite occurs in a rhyolitic tuff (Gueydan formation of the southwestern Gulf Coastal Plain).

ARTIFICIAL TRIDYMITE

The principal constituent of silica brick is tridymite with cristobalite as an associate. The silica bricks are made by heating ground-up quartzites of low iron content.

Cristobalite

SiO_2 Pseudo-isometric
(Isometric above 230° C.)

$$n_\alpha = 1.484$$
$$n_\gamma = 1.487$$

Fig. 134, Page 164

Color.—Colorless.

Form.—Cristobalite is found in minute square crystals or aggregates in the cavities of volcanic igneous rocks; it also occurs intergrown with the feldspar fibers of spherulites.

Cleavage.—Cristobalite has a peculiar curved fracture which is highly characteristic.

Relief moderate, $n <$ balsam.

Birefringence very weak, $n_\gamma - n_\alpha = 0.003$; best detected with a sensitive violet test plate. Between crossed nicols it often shows mosaic structure which is due in part to twinning.

Distinguishing Features.—Cristobalite closely resembles tridymite, but the curved fracture usually distinguishes it. It may be necessary to determine the refractive index of detached fragments. For cristobalite $n > 1.480$; for tridymite $n < 1.480$.

Occurrence.—Cristobalite is found in volcanic igneous rocks such as obsidian, rhyolite, andesite, auganite, and basalt. The fact that it usually occurs in cavities is evidence that it has been formed by hot gases at a late stage. Tridymite is a common associate, and at several localities pseudomorphs of cristobalite after tridymite have been noted.

ARTIFICIAL CRISTOBALITE

Cristobalite and tridymite are the constituents of silica bricks which are made by heating ground-up quartzites of low iron content.

Lechatelierite

SiO_2 (Silica Glass) Amorphous

$n = 1.459$

Color.—Colorless. The tendency toward opacity is due to minute bubbles.

Form.—Lechatelierite is amorphous silica glass. It is usually vesicular and may also be banded and show flow structure.

Relief low, $n <$ balsam.

Birefringence nil. Dark between crossed nicols.

Distinguishing Features.—From other glasses lechatelierite may be distinguished by its very low refractive index. It very much resembles opal except in its geologic occurrence. A closed-tube test may be necessary to make certain that the mineral is not opal.

Occurrence.—Lechatelierite is the main constituent of fulgurites, which are hollow tubes of glass produced by the action of lightning upon quartzose sand.

A unique occurrence of lechatelierite is that of Meteor Crater, Arizona. Here a highly vesicular silica glass has been produced from sandstone by the heat generated as a result of the impact of a huge meteorite or meteorite swarm (Cañon Diablo meteorite).

ARTIFICIAL LECHATELIERITE

Silica glass is now made artificially on a large scale for various kinds of chemical apparatus, lenses, and window panes to transmit ultra-violet light. It has a remarkably low coefficient of thermal expansion.

Periclase

MgO Isometric

$n = 1.738$

Color.—Colorless.

Form.—Periclase occurs in equant crystals or anhedral crystal aggregates. Individual anhedra may be recognized by cleavage traces.

Cleavage cubic. Parting, dodecahedral. Crushed fragments are square or rectangular.

Relief high, $n >$ balsam.

Birefringence nil. Dark between crossed nicols.

Distinguishing Features.—The cubic cleavage, high relief, and isotropic character taken together are distinctive.

Occurrence.—The most common occurrence of periclase is in metamorphic limestones. It is found as cores within brucite spots (see Fig. 135), which are formed by hydration of the periclase.

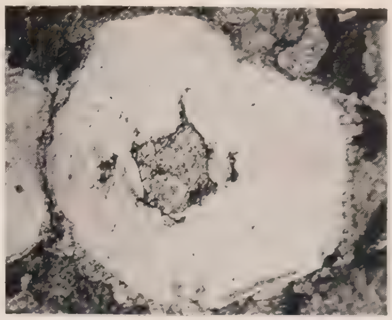


FIG. 135.—(×13) Core of periclase surrounded by brucite in metamorphic limestone.

ARTIFICIAL PERICLASE

Artificial periclase, now prepared on a commercial scale from selected magnesite, is more familiar than the natural mineral. It is used as a high-grade electric insulator.

Corundum

Al_2O_3 Hexagonal
(Rhombohedral Subsystem)

$$n_\epsilon = 1.759$$
$$n_\omega = 1.767$$
$$\text{Opt. } (-);\ c = X$$

Color.—Usually colorless, sometimes with blue or pink areas which are not uniformly colored. In thick sections corundum may be pleochroic.

Form.—Euhedral crystals are common. The habit varies from tabular to prismatic; cross sections are six sided and may show zonal structure.

Cleavage.—Parting often parallel to the unit rhombohedron $\{10\bar{1}1\}$ or the pinacoid $\{0001\}$ or both.

Relief very high, $n >$ balsam.

Birefringence weak, $n_\omega - n_\epsilon = 0.008$. Sections are usually thicker than normal on account of the extreme hardness of the corundum. For this reason the maximum interference color runs up into the second order.

Extinction parallel to the crystal outlines or symmetrical to the rhombohedral parting.

Orientation.—Sections of tabular crystals are length-slow, and sections of prismatic crystals are length-fast, since $c = X$.

Twinning.—Twinning lamellae or twin seams with $\{10\bar{1}1\}$ as the twin-plane are rather common.

Interference Figure.—The figure obtained in basal sections is uniaxial negative usually with one ring.

Distinguishing Features.—The combination of very high relief with weak birefringence, parting, and twinning lamellae is distinctive.

Occurrence.—Corundum is especially characteristic of corundum syenites, contact-metamorphic limestones, and metamorphosed shales. It may also be found in schists and as a sporadic detrital mineral. It is one of the principal constituents of emery. In igneous rocks it never occurs with original quartz.

FIG. 136.—(×22) Corundum crystal in syenite.

Hematite

Fe_2O_3 Hexagonal

(Rhombohedral Subsystem)

(Usually opaque)

Color.—Black with metallic luster in reflected light. Usually opaque, but some varieties are translucent red.

Form.—Hematite occurs in anhedral crystals, grains, masses, and occasionally minute scales. It is found as inclusions in other minerals.

Birefringence.—The translucent red scales are dark between crossed nicols since they are parallel to (0001).

Distinguishing Features.—Generally speaking, hematite resembles magnetite but is a somewhat different color by reflected light. It is non-magnetic and is often translucent red.

Occurrence.—Hematite is rare as an original constituent of igneous rocks, but it is rather common as a secondary mineral in many types of rocks. It occurs as the main constituent of hematite schist.

ILMENITE

$FeTiO_3$ Opaque Hexagonal
(Rhombohedral Subsystem)

Color.—Black with metallic luster. It is opaque even in the thinnest sections.

Form.—Ilmenite occurs in disseminated tabular crystals, which usually appear as elongate sections, in irregular grains, and sometimes in masses. It may also appear as an intergrowth with magnetite, but polished surfaces are usually necessary to reveal it.

Distinguishing Features.—Ilmenite is easily mistaken for magnetite or hematite but may as a rule be recognized by the tendency to form skeleton crystals (see Fig. 137), and by the white alteration product (leucoxene).

FIG. 137.—(×12) Skeleton crystal of ilmenite.

Alteration.—Ilmenite is usually more or less altered to an opaque white material called *leucoxene*. According to a recent investigation leucoxene is amorphous hydrous titanium dioxid.

Occurrence.—Ilmenite is a widely distributed mineral in some types of igneous rocks, more especially diabases and dolerites. It also occurs in some kinds of refractory iron ore. Ilmenite is an important constituent of many "black sands."

Rutile

TiO_2 Tetragonal

$$n_\omega = 2.616$$
$$n_\epsilon = 2.903$$
$$\text{Opt. } (+);\ c = Z$$

Color yellowish to reddish brown.

Form.—Rutile usually occurs in small prismatic to acicular crystals and in grains. Knee-shaped twins with {101} as the twin-plane are characteristic. Capillary crystals are common, especially in quartz.

Cleavage parallel to the length of the crystals {110}.

Relief very high, $n >$ balsam. Adamantine luster by reflected light.

Birefringence extreme, $n_\epsilon - n_\omega = 0.287$; interference colors are very high but do not show well on account of total reflection.

Extinction parallel.

Twinning common (see under Form).

Distinguishing Features.—The color, together with very high relief, is distinctive.

Occurrence.—A rather widely distributed accessory mineral in various metamorphic rocks. It also occurs as a detrital mineral. Titanite is a common associate.

Cassiterite

SnO_2 Tetragonal

$$n_\omega = 1.996$$
$$n_\epsilon = 2.093$$
$$\text{Opt. } (+);\ c = Z$$

Color.—Colorless to gray, yellowish, reddish, or brown. It often shows zones of varying color.

Form.—Cassiterite is usually found in subhedral crystals. Veinlets are rather common.

Cleavage prismatic, parallel to the length.

Relief very high, $n >$ balsam. Adamantine luster in reflected light.

Birefringence extreme, $n_\epsilon - n_\omega = 0.097$; the interference colors are high order but are usually masked by the color of the mineral.

Extinction parallel to the cleavage, oblique to the twin-plane.

Twinning.—Twinned crystals are common; the twin-plane is $\{101\}$.

Distinguishing Features.—Cassiterite resembles sphalerite, but the latter is isotropic.

Occurrence.—Cassiterite occurs in granite pegmatites, in greisen, and in high-temperature veins. The usual associates are quartz, muscovite, tourmaline, and topaz.

Spinel

$(Mg,Fe)(Al,Cr)_2O_4$ Isometric

$n = 1.72$ to 1.78

Color.—Colorless to green (pleonaste), olive green, or brown (picotite).

Form.—Spinel practically always occurs in euhedral or subhedral crystals or in equant grains. Crystals are octahedra, and the most common sections are rhombic in outline.

Cleavage imperfect octahedral, but it may not show.

Relief high, $n >$ balsam.

Birefringence nil.—It is one of the few isometric minerals that is invariably isotropic.

Twinning.—Twinning according to the spinel law with $\{111\}$ as twin-plane is rather common, but it does not always show in the slide.

Distinguishing Features.—Picotite, a variety intermediate between spinel and chromite, resembles chromite but is more transparent.

Pleonaste, the iron-bearing variety, is much like hercynite, $FeAl_2O_4$, a mineral of the spinel group. Spinel is distinguished from garnet by its octahedral form.

Occurrence.—Spinel occurs in metamorphic limestone with phlogopite and chondrodite, in other metamorphic rocks, and also in various igneous rocks. It is rare as a detrital mineral. Picotite is common in peridotites, dunites, and derived serpentines.

A related mineral, hercynite $FeAl_2O_4$, is a prominent constituent of certain types of emery.

MAGNETITE

$Fe^{II}Fe_2^{III}O_4$ Opaque Isometric

Color.—Black with metallic luster in reflected light. Opaque even in the thinnest sections. Strongly magnetic with an ordinary magnet.

Form.—Magnetite is found in distinct crystals, irregular grains, and masses. The common crystal form is the octahedron, sections of which are triangles, squares, and rhombs. Skeleton crystals are sometimes encountered. Magnetite may occur as an intergrowth with ilmenite.

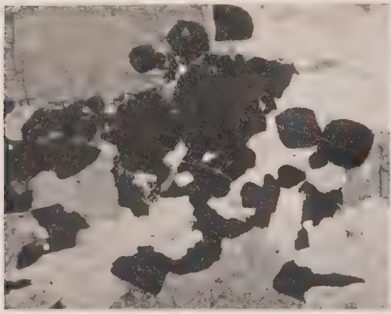


FIG. 138.—(×9) Euhedral to anhedral magnetite in norite.

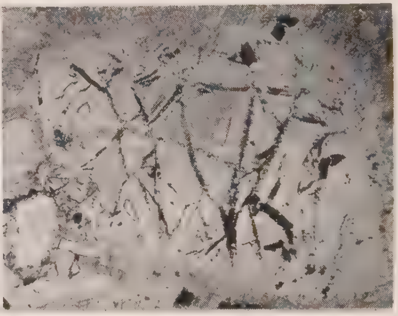


FIG. 139.—(×12) Secondary magnetite in antigorite formed at the expense of olivine.

Cleavage.—Octahedral parting is sometimes present.

Distinguishing Features.—The minerals most likely to be mistaken for magnetite are ilmenite, hematite, and chromite. Ilmenite usually occurs in skeleton crystals and often has an opaque white alteration product on its surface or borders. Hematite is a different color from magnetite and is non-magnetic. Chromite is translucent brown on thin edges.

Occurrence.—Magnetite is a very common and widely distributed mineral in nearly all igneous and metamorphic rocks. In igneous rocks it is usually a late magmatic mineral but sometimes occurs as a secondary one. It is one of the most common detrital minerals and is the chief constituent of most "black sands."

Chromite

$(Fe,Mg)(Cr,Al,Fe)_2O_4$ Isometric

$$n = 2.07 \text{ to } 2.16$$

Color.—Black with submetallic luster in reflected light. Opaque in general, but thin edges show translucent brown.

Form.—Chromite usually occurs in subhedral crystals, grains, or aggregates. Occasionally it is found in minute octahedra.

Birefringence nil. The translucent brown edges are dark between crossed nicols.

Distinguishing Features.—Chromite is easily mistaken for magnetite, but the thin edges are translucent brown. If the section is a thick one, it may be well to crush some of the rock and make a rough concentrate. Very small particles of the chromite will appear translucent brown and isotropic.

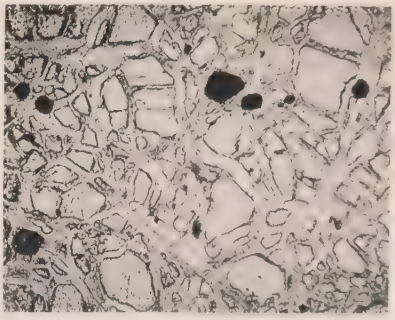


FIG. 140.—(×39) Chromite in altered dunite.

Occurrence.—Chromite occurs for the most part in peridotites, pyroxenites, dunites, and derived serpentines. In the igneous rocks it is probably a late magmatic mineral. In most serpentines it is a relict mineral but may at times be formed during serpentinization at the expense of picotite.

Diaspore

$Al_2O_3.H_2O$ Orthorhombic

$$n_\alpha = 1.702$$
$$n_\beta = 1.722$$
$$n_\gamma = 1.750$$
$$2V = 84°; \text{Opt. } (+)$$
$$a = Z, b = Y, c = X$$

Color.—Colorless to pale blue. Sometimes pleochroic in thick sections.

Form.—Diaspore occurs in tabular crystals. The crystals may be rather large to very minute.

Cleavage perfect in one direction {010}.

Relief high, $n >$ balsam.

Birefringence very strong, $n_\gamma - n_\alpha = 0.048$, so the maximum interference color is about upper third order.

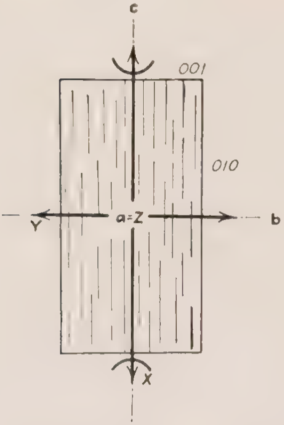


FIG. 141.—Orientation diagram of diaspore. Section parallel to (100).

Extinction parallel.

Orientation.—The crystals are length-fast.

Interference Figure.—The figure is biaxial positive with a very large axial angle. The axial plane is {010}. Dispersion, $r < v$ weak.

Distinguishing Features.—Diaspore resembles andalusite and sillimanite but has much stronger birefringence.

Occurrence.—Diaspore occurs in metamorphic rocks such as schists and emery. It occurs in a few altered igneous rocks associated with alunite. It is also a prominent constituent of some highly aluminous clays.

Gibbsite

$Al(OH)_3$ (Hydrargillite) Monoclinic

$$n_\alpha = 1.567$$
$$n_\beta = 1.567$$
$$n_\gamma = 1.589$$
$$2V = 0 \text{ to } 40°; \text{Opt. } (+)$$
$$b = X, c \wedge Y = +21°$$

Color.—Colorless to pale brown.

Form.—Gibbsite (called hydrargillite by some mineralogists) occurs in minute euhedral crystals in cavities and in fine crystalline aggregates which are often pseudomorphs after feldspars. Reticulate structure is common.

Cleavage in one direction parallel to {001}.

Relief moderate, $n >$ balsam.

Birefringence extreme, $n_\gamma - n_\alpha = 0.022$. The maximum interference colors are bright upper first-order colors.

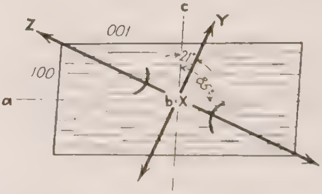


FIG. 142.—Orientation diagram of gibbsite. Section parallel to (010).

Extinction.—Oblique extinction angles, up to a maximum of 21° in sections parallel to {010}.

Orientation. Since the crystals are tabular parallel to {001}, elongate sections with twinning are length-slow.

Twinning.—Polysynthetic twinning with {001} as twin-plane is often sharp and well defined.

Interference Figure.—The crystals are usually too small to give an interference figure.

Distinguishing Features.—On account of the aggregate structure gibbsite resembles chalcedony, but the relief is higher and the birefringence much stronger. It also resembles dahllite, but the latter mineral has weak birefringence.

Occurrence.—Some bauxites (bauxite is used as a rock name) are made up largely of gibbsite, others largely of amorphous cliachite with crystalline gibbsite in cavities.

Cliachite

$Al_2O_3(H_2O)_x$ Amorphous

$n = 1.57$ to 1.61

Fig. 90, Page 110

Color.—Colorless to deep brown. Translucent to nearly opaque.

Form.—Cliachite is pisolitic or massive without any indication of crystalline structure.

Relief moderate, $n >$ balsam. It is difficult to test the relief and refractive index unless the mineral is powdered.

Birefringence nil. In favorable spots or in a powdered form the mineral is isotropic.

Distinguishing Features. The pisolitic structure and association with gibbsite are distinctive.

Occurrence.—Cliachite is the main constituent of many bauxites. (Bauxite is here used as a rock name.) Common associates are gibbsite and siderite. There may also be relict minerals such as ilmenite and titanite, for in many cases bauxites are derived from syenites.

Brucite

$Mg(OH)_2$ Hexagonal
(Rhombohedral Subsystem)

$$n_\omega = 1.566$$
$$n_\epsilon = 1.585$$
$$\text{Opt. } (+);\ c = Z$$

Fig. 135, Page 169

Color.—Colorless.

Form. Brucite usually occurs in plates or scaly aggregates which appear fibrous in sections.

Cleavage perfect in one direction {0001} but may not show in thin sections.

Relief fair, $n >$ balsam.

Birefringence moderate, $n_\epsilon - n_\omega = 0.019$. Some of the interference colors are anomalous; a peculiar reddish brown takes the place of the yellow and orange of the first order. If the section is too thin, the anomalous colors do not show.

Extinction parallel.

Orientation.—The scaly aggregates, which are apparently fibrous, are length-fast.

Interference Figure.—The interference figure is uniaxial positive with the first ring anomalous (see under Birefringence). At times the figure is biaxial.

Alteration.—Brucite is often altered to hydromagnesite, $Mg_4(OH)_2(CO_3)_3.3H_2O$.

Occurrence.—The most common occurrence of brucite is in calcite-brucite rocks (predazzite) as an alteration of periclase, MgO (see Fig. 135, page 169). It is sometimes found in serpentine.

Limonite

$H_2Fe_2O_4(H_2O)_x$ Amorphous

$n = 2.0$ to 2.1

Although limonite may not be a distinct mineral in the sense that hematite and magnetite are, it is a convenient term for the hydrous non-crystalline iron oxid with a yellow-brown streak.

Color.—Brown, translucent to opaque.

Form.—Limonite usually occurs as a stain or border around other minerals. Apparent crystals are pseudomorphs after pyrite.

Relief very high, $n >$ balsam.

Occurrence.—Limonite is practically always a secondary mineral. It usually appears as an indefinite stain or coating but is sometimes a pseudomorph after other minerals, especially pyrite.

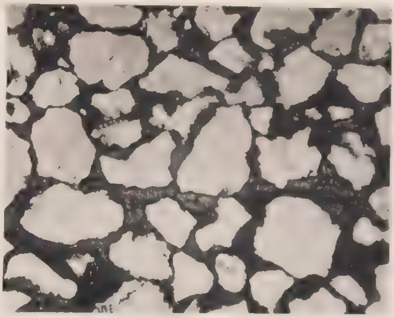


Fig. 143.—(×12) Limonite cementing quartz.

THE CALCITE GROUP

The calcite group of rhombohedral carbonates consists of the minerals listed below. They are hexagonal with perfect rhombohedral cleavage and a cleavage angle of 73 to 75°. They are uniaxial and optically negative. All show change of relief when rotated; the higher relief is obtained when the long diagonal of the rhomb is parallel to the vibration plane of the lower nicol. The birefringence is extreme and the maximum interference colors are high-order white.

Calcite Group

Mineral	Chemical composition	n_ϵ	n_ω	$n_\omega - n_\epsilon$
CALCITE	$CaCO_3$	1.486	1.658	0.172
DOLOMITE	$Ca(Mg,Fe)(CO_3)_2$	1.502	1.681	0.179
Magnesite	$MgCO_3$	1.509	1.700	0.191
Siderite	$FeCO_3$	1.634	1.872	0.238

Dolomite and magnesite may contain iron carbonate in isomorphous mixture and this increases the value of the refractive indices.

Another member of the calcite group is rhodochrosite, $MnCO_3$. It is very similar to the other minerals in its optical properties. Rhodochrosite occurs in veins but is very rare as a rock-forming mineral.

CALCITE

$CaCO_3$ Hexagonal
(Rhombohedral Subsystem)

$$n_\epsilon = 1.486$$
$$n_\omega = 1.658$$
$$\text{Opt. } (-);\ c = X$$

Color.—Colorless but often cloudy.

Form.—Fine to coarse aggregates usually anhedral. Euhedral crystals are rare. It often shows organic structure of some kind. Frequently oölitic or spherulitic.

Cleavage perfect rhombohedral $\{10\bar{1}1\}$, usually shows at two intersecting lines at oblique angles (75° if section is cut normal to the cleavage traces). In very fine aggregates cleavage may not show.

Relief varies with the direction. It is high when the long diagonal of the rhomb is parallel to the vibration plane of the lower nicol and low when the short diagonal is in this position. Occasional sections parallel to $\{0001\}$ have high relief in all positions since n for all Z directions is 1.658.

Birefringence extreme, $n_\omega - n_\epsilon = 0.172$. The maximum interference color is pearl gray (or white of the higher orders). Thin edges of the slide usually show bright interference colors.

Extinction symmetrical to the cleavage traces. When a section is in one of the extinction positions, fine birefringent calcite dust formed by grinding is prominent.

Orientation is difficult to determine on account of the extreme birefringence.

Twinning. Polysynthetic twinning with $\{0112\}$ as twin-plane is very common, especially in the calcite of metamorphic limestone. The twin lamellae are mostly parallel to the long diagonal, but they also intersect at oblique angles depending upon how the section is cut. The twin lamellae are usually so thin that they show first-order interference colors.

Interference Figure. The interference figure is uniaxial negative with many rings. Cleavage flakes give a very eccentric figure. Occasionally calcite gives a biaxial figure with a small axial angle.

Distinguishing Features. Dolomite, magnesite, and siderite may all be mistaken for calcite. Dolomite is usually subhedral to euhedral and often has twin lamellae parallel to the short diagonal as well as to the long diagonal. Siderite usually has iron stains around the borders of the grains, and the relief is not low in any position. Since there is no distinctive feature for magnesite, it may be necessary to make chemical tests. Aragonite is also similar to calcite but lacks the rhombohedral cleavage, and in no section is the refractive index less than balsam. Aragonite is also biaxial.

Occurrence.—Calcite is the principal constituent of both sedimentary and metamorphic limestones, but it is found in many other rock types. It is a very common secondary mineral in cavities of igneous rocks, where it is often associated with zeolites. Next to quartz, calcite is the most common vein mineral.

DOLOMITE

$Ca(Mg,Fe)(CO_3)_2$ Hexagonal
(Rhombohedral Subsystem)

$$n_\epsilon = 1.502$$
$$n_\omega = 1.681$$
$$\text{Opt. } (-);\ c = X$$

Color.—Colorless to gray.

Form. Fine to coarse grained and usually subhedral. Euhedral crystals of the unit rhombohedron $\{10\bar{1}1\}$ are rather common. Crystals are often curved. Zonal structure frequent.

Cleavage perfect rhombohedral parallel to {1011}, which usually shows as two intersecting sets of lines at oblique angles.

Relief varies with the direction. It is high when the long diagonal of the rhomb is parallel to the vibration plane of the lower nicol and low when the short diagonal is in this position. An occasional section parallel to {0001} has high relief in all positions.

Birefringence extreme, $n_\omega - n_\epsilon = 0.179$; interference colors are pearl gray or white of the high order. Bright colors of the fourth and fifth orders may show on the edge of the slide.

Extinction symmetrical to outlines of crystals and to the cleavage traces. Curved crystals show wavy extinction.

Twinning.—The dolomite of metamorphic rocks usually shows polysynthetic twinning with $\{02\bar{2}1\}$ as twin-plane. The twinning lamellae are parallel to both short and long diagonals of the rhombs. The twin lamellae are usually so thin that they show first-order interference colors.

Interference Figure.—The interference figure is uniaxial negative with many rings.

Distinguishing Features.—Dolomite closely resembles calcite, but in many cases it may be distinguished by its tendency to euhedral crystals, by zonal structure, and by twinning lamellae parallel to the short diagonal. It is even more like magnesite, and thus it may be necessary to rely on chemical tests.

Occurrence.—Dolomite is a very common mineral. It occurs in veins and replacement deposits, in sedimentary dolomite rocks and limestones, and in metamorphic dolomite rocks.

Magnesite

$MgCO_3$ Hexagonal
(Rhombohedral Subsystem)

$$n_\epsilon = 1.509$$
$$n_\omega = 1.700$$
$$\text{Opt. } (-);\ c = X$$

Color.—Colorless.

Form.—Magnesite usually occurs in anhedral crystal aggregates. One variety has a fine microcrystalline structure. Euhedral crystals are rare.

Cleavage perfect rhombohedral $\{10\bar{1}1\}$ as in calcite, dolomite, and siderite.

Relief changes on rotation like calcite and dolomite. It has high relief when the long diagonal of the rhomb is parallel to the vibration plane of the lower nicol and low relief when the short diagonal is in this position. An occasional section parallel to $\{0001\}$ has high relief in all positions.

Birefringence extreme, $n_\omega - n_\epsilon = 0.191$; interference colors are pearl gray (white of the high order).

Extinction symmetrical with respect to cleavage traces.

Twinning absent.

Interference Figure.—The interference figure is uniaxial negative with many rings.

Distinguishing Features.—Magnesite is very similar to dolomite and calcite but has no distinctive optical properties of its own. Chemical tests may be necessary to distinguish it.

Occurrence.—Metamorphic magnesite rocks are found in Stevens County, Washington. Magnesite veinlets are sometimes found in altered serpentine. Microcrystalline porcelain-like magnesite occurs in California in serpentine.

Siderite

$FeCO_3$ Hexagonal
(Rhombohedral Subsystem)

$$n_\epsilon = 1.634$$
$$n_\omega = 1.872$$
$$\text{Opt. } (-);\ c = X$$

Color.—Colorless to gray or yellowish or brown in spots. The brown spots are due to alteration.

Form. Siderite occurs in fine to coarse aggregates of anhedral crystals and is sometimes oölitic or spherulitic.

Cleavage perfect rhombohedral $\{1011\}$ as in calcite, dolomite, and magnesite.

Relief varies somewhat on rotation. The relief is high when the long diagonal is parallel to the vibration plane of the lower nicol and moderate when the short diagonal is in this position. In both positions the index of refraction is greater than balsam.

Birefringence extreme, $n_\omega - n_\epsilon = 0.238$. Interference colors are pearl gray (white of high order). Bright colors may show on the edge of the slide.

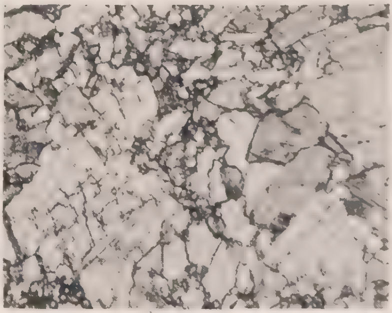


Fig. 144.—(×12) Siderite with alteration of limonite (dark stain).

Extinction symmetrical to cleavage traces.

Twinning. Twin lamellae parallel to the long diagonal [twin-plane = $\{01\bar{1}2\}$] are occasionally observed.

Interference Figure. The interference figure is uniaxial negative with numerous rings.

Distinguishing Features. Siderite very much resembles the other rhombohedral carbonates but may often be distinguished by the brown stain around the borders of the grains and along cleavage cracks. The index of refraction in all positions is greater than balsam, while in calcite, dolomite, and magnesite the index of refraction for X is less than balsam.

Occurrence.—The chief occurrence of siderite is in veins with quartz as a common associate. Siderite also occurs in some bauxites and is the principal mineral of septarian concretions. It is a secondary mineral in the cavities of some basalts.

Aragonite

$CaCO_3$ Orthorhombic

$$n_\alpha = 1.530$$
$$n_\beta = 1.682$$
$$n_\gamma = 1.686$$
$$2V = 18°;\ \text{Opt. } (-)$$
$$a = Y,\ b = Z,\ c = X$$

Color.—Colorless.

Form.—Aragonite usually shows a columnar structure. Cross sections are six sided.

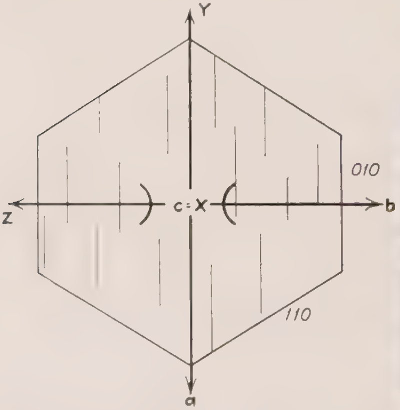


FIG. 145.—Orientation diagram of aragonite. Section parallel to (001).

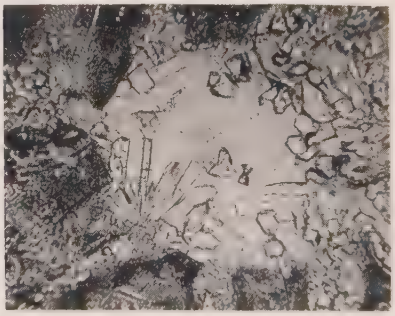


FIG. 146.—(×45) Aragonite in palagonite tuff.

Cleavage imperfect parallel to the length of the crystals.

Relief varies with the direction; the relief is low when the columns are parallel to the vibration plane of the lower nicol and high when these are perpendicular to this direction. Basal sections show no change of relief as n_β is about the same as n_γ.

Birefringence extreme, $n_\gamma - n_\alpha = 0.156$. Interference colors pearl gray (white of the high order). Bright colors may show on thin edges and along cracks.

Extinction parallel to crystals or columns.

Twinning fairly common [twin-plane = {110}] both as twin lamellae and as contact and penetration twins.

Interference Figure.—Basal {001} sections of aragonite give a negative biaxial interference figure with a small axial angle. The axial plane is {100}. Dispersion, $r < v$ weak.

Distinguishing Features.—Aragonite greatly resembles calcite but lacks the rhombohedral cleavage. It is biaxial, while calcite is uniaxial.

Alteration.—Aragonite alters easily to calcite, which is the stable form of calcium carbonate.

Occurrence.—The most common occurrence of aragonite is probably as a secondary mineral in cavities of basalts and andesites. It also occurs in seams of limestones, sandstones, and occasionally in veins. It was probably a widespread original constituent of sediments but has since been altered to calcite.

Barite

$BaSO_4$ Orthorhombic

$$n_\alpha = 1.636$$
$$n_\beta = 1.637$$
$$n_\gamma = 1.648$$
$$2V = 36°; \text{Opt. } (+)$$
$$a = Z, b = Y, c = X$$

Color.—Colorless.

Form.—Usually in granular aggregates, but the individual crystals may be elongate.

Cleavage in three directions, parallel to {001} and {110} and therefore at angles of 90 and 78°.

Relief fairly high, $n >$ balsam.

Birefringence rather weak, $n_\gamma - n_\alpha = 0.012$, a little greater than that of quartz. The maximum interference color is rarely above first-order yellow or orange. The interference colors are frequently mottled.

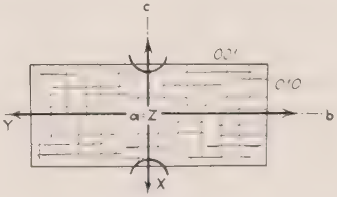


Fig. 147.—Orientation diagram of barite. Section parallel to (100).

Extinction parallel to the best cleavage {001}. The extinction in {001} sections is symmetrical.

Orientation.—The direction of the best cleavage is the slower ray.

Twinning.—Polysynthetic twinning with {110} as the twin-plane is occasionally found.

Interference Figure.—Sections cut parallel to {100} give a positive biaxial interference figure with a moderate axial angle. The axial plane is {010}. Dispersion, $r < v$ weak.

FIG. 148. (×30) Barite (bladed) in calcite.

Distinguishing Features. Barite greatly resembles celestite but the axial angle is smaller. It may be necessary to determine refractive indices carefully or to make chemical tests in order to distinguish them.

Occurrence.—Barite is a prominent vein mineral; the common associates are quartz and calcite. It also occurs in limestones and sandstones and is prominent in some concretions but it is rare as a strictly rock-forming mineral.

Celestite

$SrSO_4$ Orthorhombic

$$n_\alpha = 1.622$$
$$n_\beta = 1.624$$
$$n_\gamma = 1.631$$
$$2V = 51°; \text{Opt. } (+)$$
$$a = Z, b = Y, c = X$$

Color.—Colorless.

Form. Euhedral to anhedral crystals, sometimes fine granular. Euhedral crystals are mostly tabular parallel to {001} and elongated in the direction of the *b*-axis [010].

Cleavage perfect parallel to {001}, imperfect parallel to {110}.

Relief fair, $n >$ balsam.

Birefringence weak, $n_\gamma - n_\alpha = 0.009$, the same as that of quartz, so that the highest interference color is white or straw yellow.

Extinction parallel to the outlines and to the cleavage.

Orientation. The elongation of tabular crystals is parallel to the slower ray.

Interference Figure.—Sections cut parallel to {100} give a positive biaxial interference figure with moderate axial angle. The axial plane is {010}. Dispersion, $r > v$.

Distinguishing Features.—Celestite very much resembles barite, but the axial angle is larger.

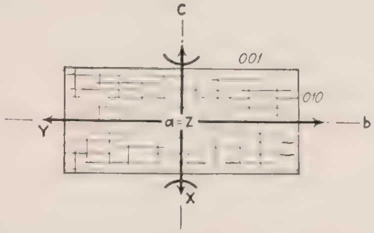


Fig. 149.—Orientation diagram of celestite. Section parallel to (100).

Occurrence.—Celestite usually occurs in sedimentary limestones, where it is more common than barite.

Anhydrite

$CaSO_4$ Orthorhombic

$$n_\alpha = 1.570$$
$$n_\beta = 1.576$$
$$n_\gamma = 1.614$$
$$2V = 42°;\ \text{Opt. } (+)$$
$$a = Z,\ b = Y,\ c = X$$

Color.—Colorless.

Form. Usually fine to medium-grained aggregates or annedral to subhedral crystals, which are sometimes elongate. Euhedral crystals are rare. It also occurs as inclusions in halite.

Cleavage in three directions at right angles {100}, {010}, and {001}.

Relief moderate, $n >$ balsam. Some sections show a slight change of relief when the stage is rotated.

Birefringence very strong, $n_\gamma - n_\alpha = 0.044$. The interference colors range up to about fourth-order red.

Extinction parallel to the cleavage traces.

Twinning.—Polysynthetic twinning with {101} as twin-plane is common. The twinning lamellae show best on the (010) face and make an angle of 42 and 48° with the cleavage traces. There may be two sets of twin lamellae (101) and (101) intersecting at angles of $83\frac{1}{2}$ and $96\frac{1}{2}°$.

Interference Figure. Cleavage fragments or sections parallel to {100} give a biaxial positive interference figure with a moderate axial angle. The axial plane is {010}. Dispersion, $r < v$.

Distinguishing Features.—Anhydrite is distinguished from gypsum by higher relief and stronger birefringence. The pseudo-cubic cleavage is distinctive.

Alteration.—Between grains and along veinlets anhydrite is often altered to gypsum, and anhydrite may be found as remnants within gypsum.

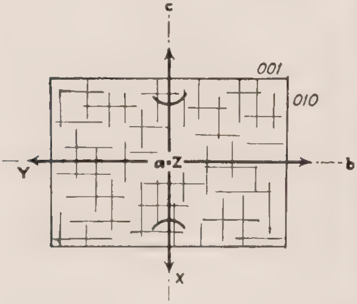


FIG. 150.—Orientation diagram of anhydrite. Section parallel to (100).

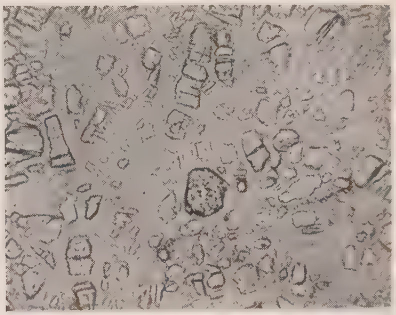


FIG. 151.—(×20) Anhydrite partially altered to gypsum. The crystal in the center with high relief is dolomite.

Occurrence.—Anhydrite occurs in sedimentary beds. It is often encountered in deep drilling but near the surface is usually altered to gypsum. It often occurs with halite and is common in salt mines. Metamorphic anhydrite is found at the Nevada-Douglas mine, Lyon County, Nevada.

GYPSUM

$CaSO_4.2H_2O$ Monoclinic

$$n_\alpha = 1.520$$
$$n_\beta = 1.522$$
$$n_\gamma = 1.529$$
$$2V = 58°; \text{Opt. } (+)$$
$$b = Y,\ c \wedge X = +37°28'$$

Color.—Colorless.

Form.—Gypsum usually occurs in anhedral to subhedral aggregates and is often uneven grained. It sometimes shows a fibrous structure.

Cleavage perfect in one direction $\{010\}$, imperfect parallel to $\{100\}$ and $\{\bar{1}01\}$. $(\bar{1}00) \wedge (\bar{1}01) = 66°10'$.

Relief low, n slightly $<$ balsam.

Birefringence weak, $n_\gamma - n_\alpha = 0.009$ (the same as quartz).

The highest interference color is white or straw yellow. Sections with the highest interference color do not usually show any cleavage.

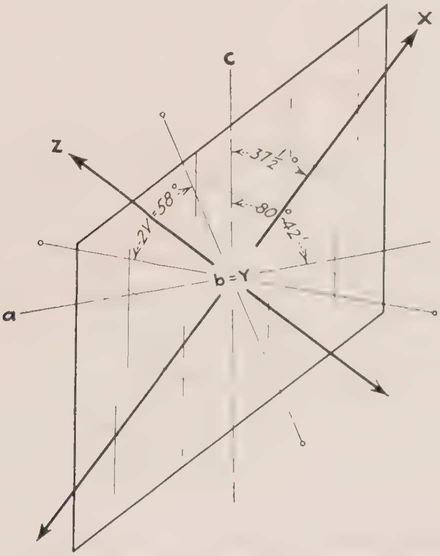


FIG. 152.—Orientation diagram of gypsum. Section parallel to (010).

Extinction parallel to the best cleavage.

Orientation.—Cleavage traces are parallel to both slower and faster rays since *b* = Y.

Twinning.—The polysynthetic twinning often found in thin sections of gypsum is produced by heating the section. The twinning is evidence that it has been partially transformed into anhydrous calcium sulfate.

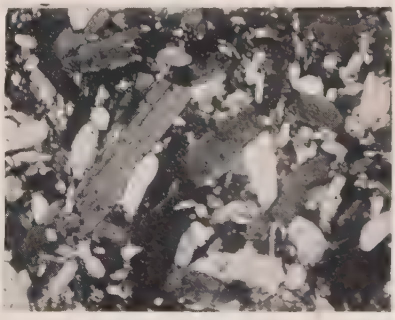


FIG. 153.—(×12) Gypsum rock. (× nicols.)

Interference Figure.—The interference figure is biaxial positive with a moderate axial angle. The axial plane is {010}. Dispersion, $r > v$.

Distinguishing Features. Gypsum is easily distinguished from anhydrite by lower relief and weaker birefringence.

Occurrence.—Gypsum is the chief constituent of gypsum rock, which in most cases has been formed by the hydration of anhydrite. Anhydrite may occur in the gypsum as a relict mineral. Gypsum occurs in veinlets and between grains of anhydrite. Other associated minerals are calcite, dolomite, and halite.

Polyhalite

$K_2MgCa_2(SO_4)_4.2H_2O$ Triclinic

$$n_\alpha = 1.548$$
$$n_\beta = 1.562$$
$$n_\gamma = 1.567$$
$$2V = ca.\ 70°;\ \text{Opt.}\ (-)$$

(Optical orientation unknown)

Color.—Colorless to reddish.

Form.—Polyhalite shows granular or fibrous structure.

Relief low, $n >$ balsam.

Birefringence moderate, $n_\gamma - n_\alpha = 0.019$. The interference colors range up to second-order blue.

FIG. 154.—(×9) Polyhalite. (× nicols.)

Extinction oblique.

Twinning.—Polysynthetic twinning is very common.

Interference Figure.—The interference figure is biaxial negative with a rather large axial angle but may be difficult to obtain on account of the small size of the crystals.

Distinguishing Features. Polyhalite may resemble gypsum, but its refractive indices and birefringence are higher. It is decomposed by water with the separation of microchemical gypsum.

Occurrence.—Polyhalite occurs in saline beds; the common associates are halite, sylvite, magnesite, and anhydrite. In the West Texas–New Mexico Permian basin it is an alteration product of anhydrite.

Alunite

$KAl_3(OH)_6(SO_4)_2$ Hexagonal
(Rhombohedral Subsystem)

$$n_\omega = 1.572$$
$$n_\epsilon = 1.592$$
$$\text{Opt. } (+);\ c = Z$$

Color.—Colorless.

Form. Alunite usually shows fine to coarse aggregates. Crystals vary from tabular to pseudo-cubic rhombohedral.

Cleavage.—Fair cleavage in one direction {0001}.

Relief fair, $n >$ balsam. When the stage is rotated there is a slight change of relief.

Birefringence rather strong, $n_\epsilon - n_\omega = 0.020$; the interference colors range up to second-order blue.

Extinction parallel or symmetrical in most sections. Basal sections are dark in all positions.

Orientation.—Crystals and cleavage traces are length-fast.

Interference Figure.—Basal sections give a positive uniaxial interference figure.

Occurrence.—Alunite occurs as a hydrothermal alteration product and as a vein mineral.

Jarosite

$KFe_2^{III}(OH)_6(SO_4)_2$ Hexagonal
(Rhombohedral Subsystem)

$$n_\epsilon = 1.715$$
$$n_\omega = 1.820$$
$$\text{Opt. } (-);\ c = X$$

Color.—Colorless to brown.

Form.—Jarosite occurs in crystal aggregates and occasionally in crystals, which are similar to those of alunite, for these two minerals are isomorphous.

Relief very high, $n >$ balsam.

Birefringence extreme, $n_\omega - n_\epsilon = 0.105$.

Extinction parallel or symmetrical. Basal sections are dark in all positions.

Orientation difficult to test on account of the extreme birefringence.

Interference Figure. Tabular crystals give a positive uniaxial figure with many rings.

Alteration.—Jarosite alters readily to limonite.

Occurrence.—Jarosite is usually found in the lower oxidized zone of ore deposits. It is occasionally found in igneous rocks, perhaps as a late hydrothermal mineral.

Monazite

$(Ce,La,Nd,Pr)PO_4$ Monoclinic

$$n_\alpha = 1.795$$
$$n_\beta = 1.796$$
$$n_\gamma = 1.841$$
$$2V = 14°;\ \text{Opt. } (+)$$
$$b = X,\ c \wedge Z = -2 \text{ to } -4°$$

Color.—Nearly colorless to neutral colors.

Form.—Monazite occurs in euhedral crystals, which are usually small.

Cleavage.—Parting parallel to {001} is often prominent.

Relief very high, $n >$ balsam.

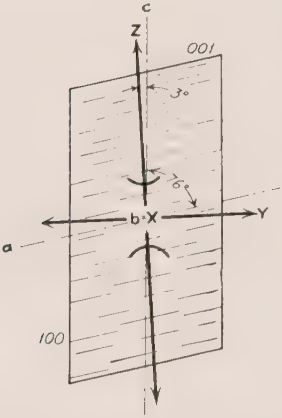


FIG. 155.—Orientation diagram of monazite. Section parallel to (010).

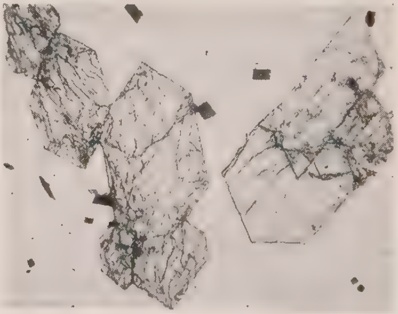


FIG. 156.—(×10) Monazite crystals in quartz matrix.

Birefringence very strong, $n_\gamma - n_\alpha = 0.046$. The maximum interference color is upper fourth or lower fifth order. Cross sections of crystals have very weak birefringence since $n_\beta - n_\alpha = 0.001$.

Extinction.—Longitudinal sections have a small extinction angle (2 to 4°). Sections parallel to {001} do not show complete extinction.

Orientation.—Crystals are length-slow.

Interference Figure. The interference figure is biaxial positive with a small axial angle. The axial plane is normal to {010}. Dispersion strong, $r < v$.

Distinguishing Features.—Monazite is more like titanite than any common mineral, but its birefringence is not so high.

Occurrence.—Monazite occurs in some granite pegmatites. It is a characteristic detrital mineral but is rare except in certain sands where there has been a concentration of the mineral.

APATITE

$3Ca_3(PO_4)_2.CaF_2$ Hexagonal
(Hexagonal Subsystem)

$$n_\epsilon = 1.635$$
$$n_\omega = 1.639$$
$$\text{Opt. } (-);\ c = X$$

Color.—Colorless.

Form. Apatite is usually found as minute six-sided prismatic crystals. It is a common and widely distributed mineral but usually occurs in small amounts.

Cleavage, imperfect basal {0001} shown as cross fractures. Larger crystals may show imperfect cleavage parallel to the length.

Relief moderate, $n >$ balsam.

Birefringence very weak, $n_\omega - n_\epsilon = 0.004$. The interference colors are first-order gray. Cross sections are dark between crossed nicols.

Extinction parallel.

Orientation.—The crystals are length-fast.

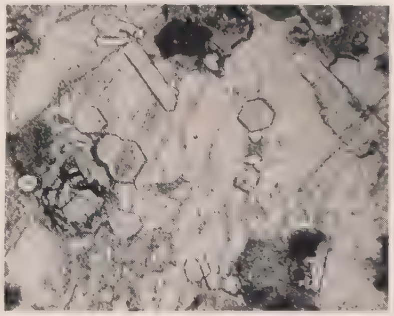


FIG. 157.—(×20) Apatite crystals in an igneous rock.

Interference Figure.—Basal sections are usually too small to give good interference figures.

Distinguishing Features.—Apatite is distinctive. The only minerals that closely resemble it are dahllite, which occurs as a secondary mineral in cavities and seams associated with collophane; and wilkeite, a rare mineral of the apatite group, which gives a sulphate as well as a phosphate test.

Occurrence.—Apatite is a common minor accessory mineral of practically all igneous rocks. It also occurs in pegmatites, in some high-temperature veins, and in metamorphic limestones, and is also prominent in some iron ores.

Dahllite

$3Ca_3(PO_4)_2.CaCO_3$ Hexagonal

$$n_\epsilon = 1.619 \text{ to } 1.626$$
$$n_\omega = 1.623 \text{ to } 1.635$$
$$\text{Opt. } (-);\ c = X$$

Color.—Colorless to pale brown or gray.

Form.—Dahllite occurs in minute hexagonal crystals, in crusts with banded subradiating structure, in spherulites, and in fine-grained aggregates.

Relief moderate, $n >$ balsam.

Birefringence very weak, $n_\omega - n_\epsilon = 0.004$ to 0.009. Interference colors are bluish gray of the first order.

Extinction parallel. Cross sections are dark.

Orientation.—Prismatic crystals are length-fast like apatite. The columns of crusts are also length-fast. Sections of tabular crystals are length-slow.

Distinguishing Features.—Dahllite is much like apatite but is always a secondary mineral. To make certain of its identity it may be necessary to try the solubility of isolated particles of the mineral.

Occurrence.—Dahllite occurs as a secondary mineral in phosphorite or so-called phosphate rock. The usual associate is collophane. The dahllite has probably been formed by the gradual crystallization of the collophane and by the migration of some of the calcium phosphate.

COLLOPHANE

$3\ Ca_3(PO_4)_2.nCa(CO_3,F_2,O)(H_2O)_x$ Amorphous

$n = 1.57$ to 1.62

Color. Usually light to dark brown, yellowish brown, gray, etc., but occasionally colorless.

Form. Collophane is usually massive but may be oölitic or colloform, in grains and fragments. It often shows the organic structure of bones, molluscs, brachiopods, crinoids, bryozoans, or corals.

Cleavage absent. Irregular fracture may show on edges of the slide.

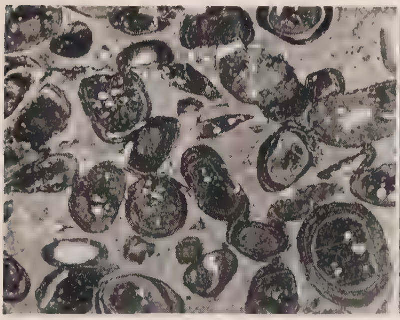


FIG. 158.—(×12) Collophane in oölitic phosphorite.

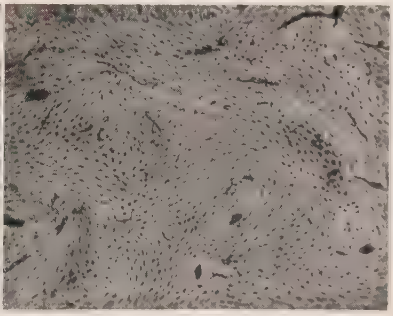


FIG. 159.—(×12) Collophane (fossil bone).

Relief moderate, $n >$ balsam. The index of refraction is usually 1.60 to 1.61.

Birefringence.—Usually isotropic but may show weak birefringence (up to 0.005) due to strain. Pseudo-spherulitic structure (concentric instead of fibrous elements) sometimes shows.

Orientation.—Birefringent areas may be length-slow or length-fast.

Distinguishing Features.—Collophane sometimes resembles opal, but the refractive index of the latter is always less than balsam.

Alteration.—Collophane is often more or less replaced by calcite. Replacement by quartz, chalcedony, or opal is very rare.

Occurrence.—In sedimentary phosphatic limestones, in phosphorites or so-called phosphate rocks as the chief constituent, and in phosphate nodules. It is the dominant mineral of fossil bone, in which the microstructure of the original bone is usually preserved. It also occurs as a detrital mineral in beach sands of the South Atlantic states.

NOTE

Amorphous calcium phosphate is often considered to be a massive form of apatite, but it is really a distinctive mineral.

Lazulite

$Al_2(Mg,Fe)(OH)_2(PO_4)_2$ Monoclinic

$$n_\alpha = 1.603$$
$$n_\beta = 1.632$$
$$n_\gamma = 1.639$$
$$2V = 69° \pm ;\ \text{Opt. } (-)$$
$$b = Y,\ c \wedge X = +9°$$

Color.—Blue to colorless. Some sections are pleochroic from blue to colorless.

Form. Lazulite is occasionally found in euhedral crystals of bipyramidal habit but usually occurs in anhedra.

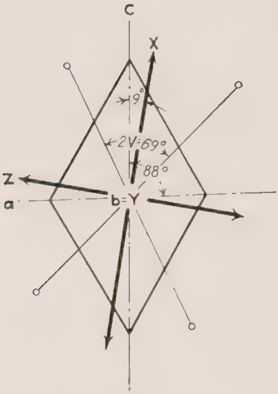


FIG. 160.—Orientation diagram of lazulite. Section parallel to (010).

Cleávage indistinct.

Relief fairly high, $n >$ balsam.

Birefringence strong, $n_\gamma - n_\alpha = 0.036$, so that the maximum interference color is about upper second order.

Extinction oblique.

Orientation.—The long diagonal of the crystal sections is the faster ray.

Twinning.—Polysynthetic twinning is common.

Interference Figure.—The figure is biaxial negative with a large axial angle. The axial plane is {010}. Dispersion, $r < v$ strong.

Distinguishing Features.—Lazulite is practically the only blue pleochroic mineral with strong birefringence.

Occurrence.—As far as known, lazulite is confined to metamorphic rocks. It occurs in quartzites either disseminated or in veins. Usual associates are quartz, rutile, corundum, pyrophyllite, kyanite, and andalusite.

Perovskite

$CaTiO_3$ Isometric

$$n = 2.34 \text{ to } 2.38$$

Color.—Yellow to brown.

Form. Perovskite is usually found in small cubic crystals.

Cleavage cubic, noticed only in large crystals.

Relief very high, $n >$ balsam. It is difficult to make the Becke test on account of total reflection. In reflected light it shows adamantine luster.

Birefringence nil to 0.002. Minute crystals are dark between crossed nicols; larger crystals have weak birefringence.

Twinning.—The larger crystals show complicated polysynthetic twinning.

Distinguishing Features.—Perovskite resembles melanite (garnet) and picotite (spinel) but has a much higher refractive index than these.

Occurrence.—Perovskite is a rare, but widely distributed, mineral in basic igneous rocks, especially melilite basalts and peridotites. There are some other rare isometric minerals that resemble it; so, if possible, chemical tests should be made on isolated crystals.

Titanite

$CaTiSiO_5$ (Sphene) Monoclinic

$$n_\alpha = 1.887 \text{ to } 1.913$$
$$n_\beta = 1.894 \text{ to } 1.921$$
$$n_\gamma = 1.979 \text{ to } 2.054$$
$$2V = 23 \text{ to } 50°;\ \text{Opt. } (+)$$
$$b = Y,\ c \wedge X = +39°$$

Color.—Neutral.

Form.—Titanite usually occurs in euhedral crystals which have an acute rhombic cross section, or in irregular grains.

Cleavage.—Titanite often has prominent parting which is not parallel to the crystal outlines.

Relief very high, $n >$ balsam.

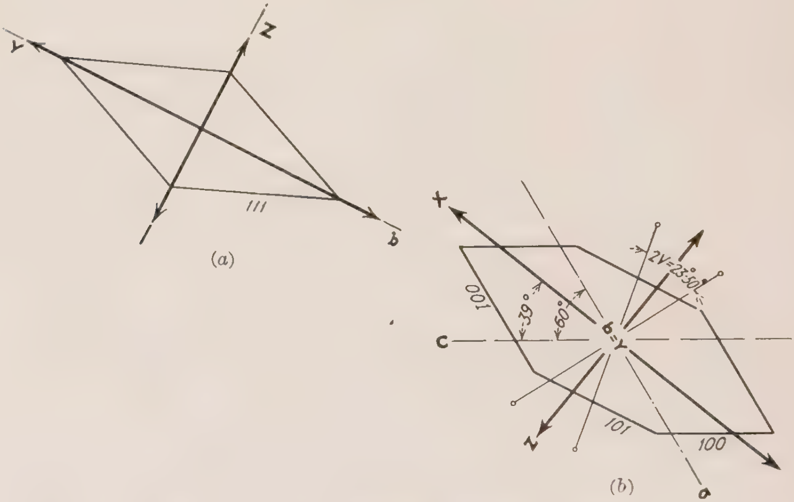
Birefringence extreme, $n_\gamma - n_\alpha = 0.092$ to 0.141; the interference colors are high-order white but are usually obscured by total reflection.

Extinction.—On account of strong dispersion titanite does not always show complete extinction. Rhombic sections have symmetrical extinction.

Twinning.—Twins with {100} as twin-plane are sometimes present (Fig. 105, page 114).

Interference Figure.—The figure is biaxial positive with a moderate axial angle. The axial plane is {010}. Dispersion, $r > v$ strong.

Distinguishing Features.—Monazite is somewhat like titanite but has lower birefringence and weaker dispersion. The rhombic cross sections of titanite are very characteristic.



(a)

(b)

Figs. 161 *a*, *b*.—Orientation diagrams of titanite.

Occurrence.—Titanite, or sphene, is a widely distributed accessory mineral in igneous and metamorphic rocks. It has probably formed at a late stage in igneous rocks. It is not common as a detrital mineral except locally.

THE FELDSPARS

Of all the silicates the feldspars are the most important rock-forming minerals since they constitute about 60 per cent of the earth's crust or outer shell. The classification of igneous rocks depends to a large extent on the character of the feldspar.

There are three well-marked groups of feldspars. The first group consists of the monoclinic potassium feldspar, orthoclase, and its dimorph, sanidine. The rare barium feldspar, celsian, $BaAl_2Si_2O_8$, also is monoclinic.

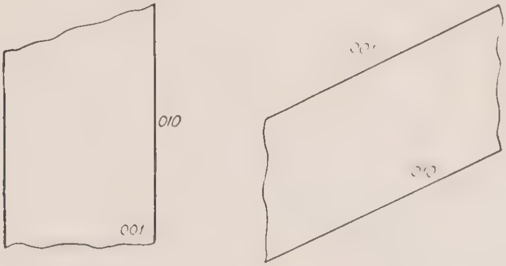
The microcline group is triclinic with microcline and the closely related anorthoclase, sometimes called soda microcline.

Next we have the triclinic group of plagioclases which are isomorphous mixtures of two end members, albite and anorthite. The plagioclase group will be discussed in detail later on.

The Feldspars

Mineral		Chemical composition	n_α	n_β	n_γ	2V
ORTHOCLASE		$(K,Na)AlSi_3O_8$	1.519	1.524	1.526	69-72°
SANIDINE		$(K,Na)AlSi_3O_8$	1.520	1.525	1.525	0-12°
MICROCLINE		$KAlSi_3O_8$	1.522	1.526	1.530	77-84°
Anorthoclase		$(Na,K)AlSi_3O_8$	1.522	1.528	1.529	43-54°
PLAGIOCLASE	ALBITE	$NaAlSi_3O_8$	1.525	1.529	1.536	82°
	ANORTHITE	$CaAl_2Si_2O_8$	1.575	1.583	1.588	77°

The feldspars are monoclinic or triclinic pseudo-monoclinic. There is perfect cleavage in two directions {001} and {010} at 90 or nearly 90° (about 86 to 87°). Cleavage fragments appear as in Figs. 162*a*, *b*. The feldspars have low relief in balsam and birefringence varying from 0.006 to 0.013. They are all biaxial with a very small axial angle for sanidine, a moderate one for anorthoclase, and a large to very large one for orthoclase, microcline, and the plagioclases.



(*a*) (*b*)

Figs. 162 *a*, *b*.—Cleavage fragments of feldspar.

Twinning is common in all the feldspars and is almost universal in microcline and the plagioclases. The extinction angles in twinned crystals constitute one of the chief methods of distinguishing the individual members of these groups.

ORTHOCLASE

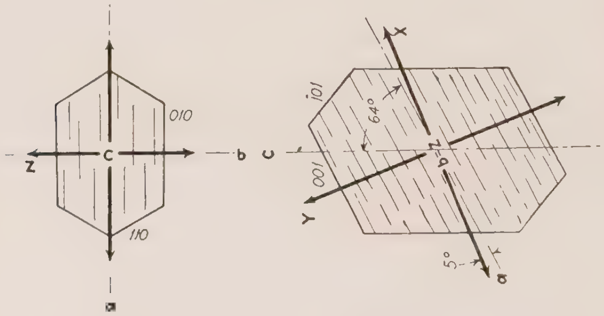
$(K,Na)AlSi_3O_8$ Monoclinic

$$n_\alpha = 1.519$$
$$n_\beta = 1.524$$
$$n_\gamma = 1.526$$
$$2V = 69 \text{ to } 72°; \text{Opt. } (-)$$
$$b = Z, a \wedge X = +5 \text{ to } +12°, c \wedge Y = -14 \text{ to } -21°$$

Figs. 168–170, Page 206

Color.—Colorless but may be cloudy on account of incipient alteration in contrast with quartz, which is clear.

Form.—Orthoclase occurs in phenocrysts, in subhedral and anhedral crystals, and in spherulites.



(a) (b)

Figs. 163 *a*, *b*.—Orientation diagrams of orthoclase. Sections (*a*) normal to the *c*-axis and (*b*) parallel to (010).

Cleavage. Perfect cleavage parallel to {001}, less perfect parallel to {010}, imperfect parallel to {110}.

Relief low, $n <$ balsam.

Birefringence weak, $n_\gamma - n_\alpha = 0.007$, so interference colors are gray and white of the first order and the maximum a little lower than that of quartz in the same slide.

Extinction on {001} parallel, on {010} from 5 to 12°, increasing with the soda content.

Orientation. Cleavage traces on {010} make a small angle with the faster ray.

Twinning. Twinning according to the Carlsbad law (*c*-axis or [001] = twin-axis). These are simple twins consisting of two individuals and are practically never polysynthetic.

Interference Figure.—The interference figure is biaxial negative with a large axial angle. The axial plane is normal to {010}. Dispersion, $r > v$.

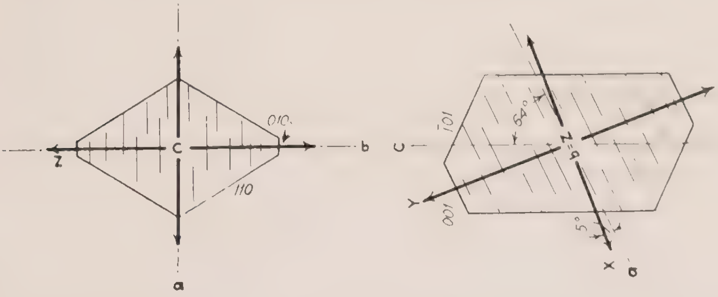
Distinguishing Features.—Orthoclase is distinguished from its dimorph sanidine by its large axial angle. Sanidine practically always occurs in phenocrysts.

Occurrence.—Orthoclase is a widely distributed mineral in persilicic igneous rocks such as granites and syenites. In spherulites of obsidian and rhyolite it is often intergrown with cristobalite or quartz. The potassium feldspar of metamorphic rocks is usually microcline. It is also common in detrital deposits and in sandstones and arkoses.

Adularia

$KAlSi_3O_8$ Monoclinic

Although adularia is probably a variety of orthoclase and not a distinctive mineral, it may well be treated separately.



(a) (b)

FIGS. 164 *a*, *b*.—Orientation diagrams of adularia. Sections (*a*) normal to the *c*-axis and (*b*) parallel to (010).

The optical properties of adularia are the same as those of orthoclase, but there is a distinction in crystal habit. Adularia is pseudo-orthorhombic with a rhombic cross section ($110 \wedge 1\bar{1}0 = 61°13'$). The (010) face is very narrow or absent.

Adularia is a rather low-temperature feldspar found in veins and replacement deposits. It occurs especially with gold and silver ores. The crystals are commonly minute and can be identified only with a rather high-power objective (8 mm).

SANIDINE

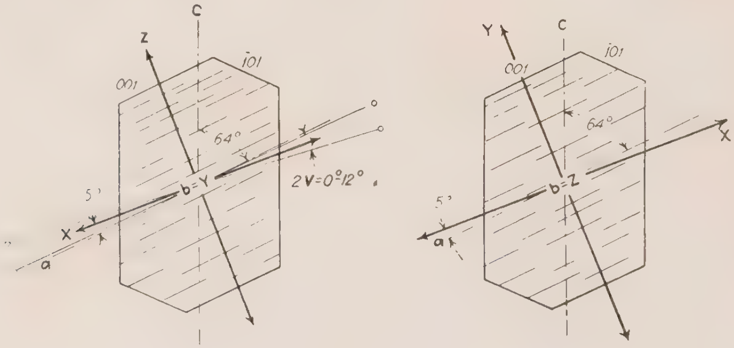
$(K,Na)AlSi_3O_8$ Monoclinic

$$n_\alpha = 1.520$$
$$n_\beta = 1.525$$
$$n_\gamma = 1.525$$
$$2V = 0 \text{ to } 12°;\ \text{Opt. } (-)$$

Orientation: (1) Ax. pl. $\{010\}$, $b = Y$,
$a \wedge X = +5°$ or (2) Ax. pl. $\perp \{010\}$,
$b = Z$, $a \wedge X = +5°$

Color.—Colorless.

Form.—Sanidine usually occurs in distinct euhedral crystals as phenocrysts.



(a) (b)

FIGS. 165 *a*, *b*.—Orientation diagrams of sanidine. Sections parallel to (010).

Cleavage perfect parallel to $\{001\}$, less perfect parallel to $\{010\}$. There may also be a parting parallel to $\{100\}$.

Relief low, $n <$ balsam.

Birefringence weak, $n_\gamma - n_\alpha = 0.005$, so the interference colors are gray and grayish white of the first order.

Extinction on (001) parallel, on (010) +5°. Sections normal to an optic axis remain dark since the axial angle is often very small.

Twinning.—Usually according to the Carlsbad law (*c*-axis or [001] = twin-axis). Twins are simple twins of two individuals and are rarely, if ever, polysynthetic.

Interference Figure. Some sections give a negative biaxial interference figure with a small axial angle, but the angle may be so small that the figure is almost uniaxial. Dispersion, (1) $r < v$, (2) $r > v$.

Distinguishing Features. Sanidine is distinguished from orthoclase by the small axial angle and in some cases by a difference of orientation. Orthoclase is usually cloudy on account of incipient alteration; sanidine, on the other hand, is clear.

Occurrence. Sanidine is practically confined to persilicic volcanic rocks such as rhyolites and trachytes and the corresponding tuffs.

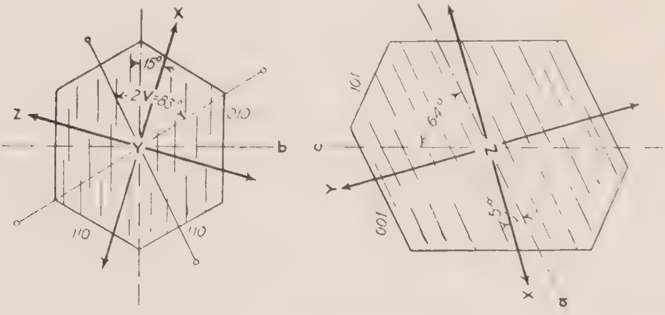
MICROCLINE

$KAlSi_3O_8$ Triclinic

$n_\alpha = 1.522$
$n_\beta = 1.526$
$n_\gamma = 1.530$
2V = 77 to 84°; Opt. (−).
Ax. pl. and Z are nearly $\perp$ (010). Angle
between trace of ax. pl. and edge (001) : (010) = +5°
Fig. 169, Page 206

Color. Colorless but may be cloudy on account of incipient alteration.

Form. Microcline is usually found in subhedral to anhedral crystals. Euhedral crystals are rarely seen in rock sections.



(*a*) (*b*)

FIGS. 166 *a*, *b*.—Orientation diagrams of microcline. Sections (*a*) normal to the *c*-axis and (*b*) parallel to (010).

Cleavage perfect parallel to {001}, less perfect parallel to {010}, imperfect parallel to {110} and $\{1\bar{1}0\}$.

Relief low, $n <$ balsam.

Birefringence weak, $n_\gamma - n_\alpha = 0.008$, so interference colors are gray and white of the first order.

Extinction. Extinction angle on (001) = +15°, on (010) = +5°.

Orientation.—Cleavage traces on (010) are about parallel to the faster ray.

Twinning.—Polysynthetic twinning is almost universal in microcline. The twinning is in two directions, one according to the albite law ({010} = twin-plane) and the other according to the pericline law (*b*-axis or [010] = twin-axis). This usually gives the so-called "gridiron" or "quadrille" structure, the two sets of lamellae being at right angles. The twin lamellae are spindle shaped and the extinction is usually wavy.

Intergrowth.—Albite is commonly intergrown with microcline so that the (010) directions are parallel. This intergrowth is known as *perthite.*

Interference Figure.—On account of the twinning it is usually difficult to obtain good interference figures. Dispersion, $r > v$.

Distinguishing Features.—Microcline is distinguished from orthoclase by the polysynthetic twinning and from albite by extinction angles and spindle-shaped twin lamellae.

Occurrence.—Microcline occurs in some granites, syenites, and gneisses. In the intergrowth known as perthite it is the principal feldspar of granite pegmatites. It is also a common mineral in sandstones, arkoses, etc.

Anorthoclase

$(Na,K)AlSi_3O_8$ (Soda Microcline) Triclinic

$$n_\alpha = 1.522$$
$$n_\beta = 1.528$$
$$n_\gamma = 1.529$$
$$2V = 43 \text{ to } 54°;\ \text{Opt. } (-).$$
Ax. pl. nearly ⊥ to {010}

Color.—Colorless.

Form.—Anorthoclase occurs in phenocrysts and in anhedral crystals, also in large cleavage masses.

Cleavage perfect parallel to {001}, less perfect parallel to {010}, as in the other feldspars.

Relief low, $n <$ balsam.

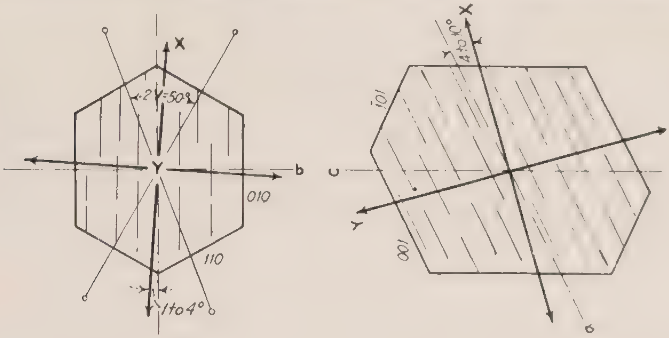
Birefringence weak, $n_\gamma - n_\alpha = 0.007$; the interference colors are gray and white of the first order.

Extinction on (001) = +1 to +4°, on (010) = +4 to +10°.

Twinning.—Polysynthetic twinning in two directions like that of microcline, but the lamellae are finer. It may be necessary to have a very thin section in order to detect the twinning.

Interference Figure.—The figure is biaxial negative with a moderate axial angle. Dispersion, $r > v$.

Distinguishing Features.—Anorthoclase may be distinguished from practically all other feldspars by the axial angle of about 50° (sanidine is lower and the others are higher). The small extinction angle on (001) distinguishes it from microcline and all the plagioclases except albite.



(a) (b)

Figs. 167 *a*, *b*.—Orientation diagram of anorthoclase. Sections (*a*) normal to the *c*-axis and (*b*) parallel to (010).

Occurrence.—The characteristic occurrence of anorthoclase is in soda-rich igneous rocks. It is sometimes found in pegmatites. It is a comparatively rare mineral.

PLAGIOCLASE GROUP

The minerals of this group consist of isomorphous mixtures of the two end members: albite, $NaAlSi_3O_8$, abbreviated Ab, and anorthite, $CaAl_2Si_2O_8$, abbreviated An. The following is

Ab_{10}
Albite
Ab_9An_1
Oligoclase
Ab_7An_3
Andesine
Ab_5An_5
Labradorite
Ab_3An_7
Bytownite
Ab_1An_9
Anorthite
An_{10}

the decimal classification of Calkins now generally used by petrographers.

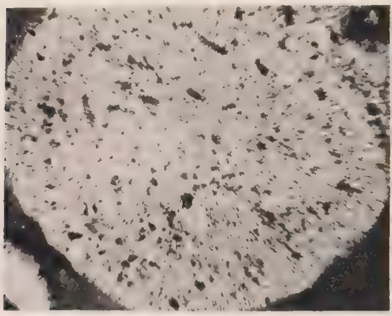


FIG. 168.—(×80) Orthoclase-cristobalite spherulite in volcanic glass.

FIG. 169.—(×9) Microcline section oriented parallel to (001). There are several albite inclusions. (× nicols.)

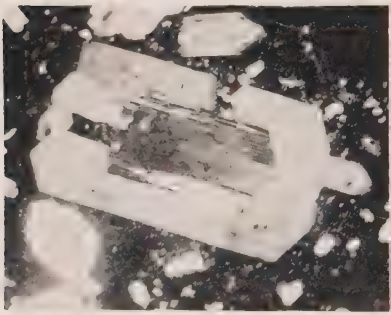


FIG. 170.—(×9) Orthoclase overgrowth on plagioclase in trachyte porphyry. (× nicols.)

FIG. 171.—(×20) Zonal structure in plagioclase. Section parallel to (010). (× nicols.)

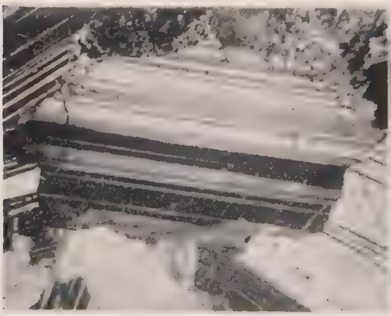


FIG. 172.—(×9) Combined Carlsbad-albite twinning in plagioclase. (× nicols.)

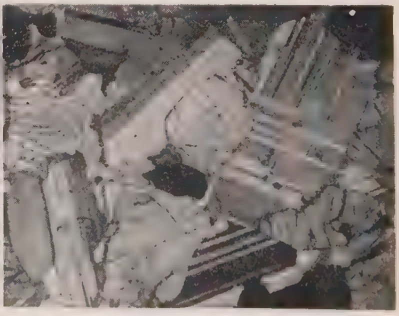


FIG. 173.—(×12) Albite, Carlsbad, and pericline twinning in plagioclase. (× nicols.)

The plagioclases crystallize in the triclinic system with angles much like those of orthoclase. The interfacial angle (001:010) varies from 86°6′ for Ab to 85°48′ for An. The angle between the *a*-axis and *b*-axis varies from 87°5′ for Ab to 91°34′ for An, with $\gamma = 90°$ for $Ab_{58}An_{42}$.

The cleavage of the plagioclases is perfect parallel to {001}, less perfect parallel to {010}, and imperfect parallel to {110} and {1$\bar{1}$0}.

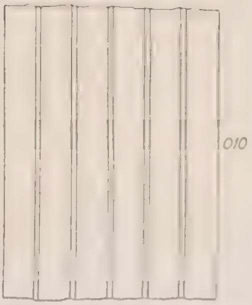


Fig. 174.—Plagioclase cleavage parallel to (001) showing albite twin-lamellae.

Twinning is almost universal in the plagioclases. There are numerous twin-laws known for plagioclase, but the three most important are:

Albite law: {010} = twin-plane, (010) = composition face, Fig. 174.

Pericline law: [010] = twin-axis, rhombic section = composition face, Fig. 175, below.

Carlsbad law: [001] = twin-axis, (010) = composition face, Fig. 176, below.

The axial angle of the plagioclase varies from about 74 to 90°. The optical character is positive, negative, or neutral (2V = 90°) for a few in passing from positive to negative.

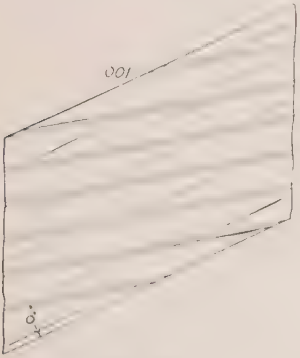


Fig. 175.

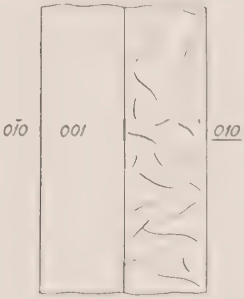


Fig. 176.

Fig. 175.—Plagioclase cleavage parallel to (010) showing pericline twin-lamellae. The angle σ is the "angle of the rhombic section."

Fig. 176.—Sketch showing Carlsbad twinning.

In specimens twinned according to the albite law, the lamellae appear on the (001) cleavage face and are always parallel to the (001: 010) edge as shown in Fig. 174, above.

ANGLE OF THE RHOMBIC SECTION

With pericline twinning the lamellae appear on the (010) cleavage face and make an angle with the (001 : 010) edge which varies with the character of the plagioclase. This is illustrated in Fig. 175, page 207, where σ is the angle in question. This angle is known as the angle of the rhombic section. Two individuals in a pericline twin are united in a plane, the intersection of which with faces (110),$(1\bar{1}0)$,$(\bar{1}\bar{1}0)$, and $(\bar{1}10)$ is a rhombus; hence the term *rhombic section*. The curve of Fig. 177, above, shows the variation of this angle with the relative proportions of the albite and anorthite molecules. This method is about the only method of determining the kind of plagioclase by simple non-optical tests, but unfortunately pericline twinning is not always present. Here as in all curves for plagioclase, positive angles are clockwise, and negative angles are counterclockwise. For plagioclase with the composition $Ab_{58}An_{42}$ the lamellae are exactly parallel to the edge.

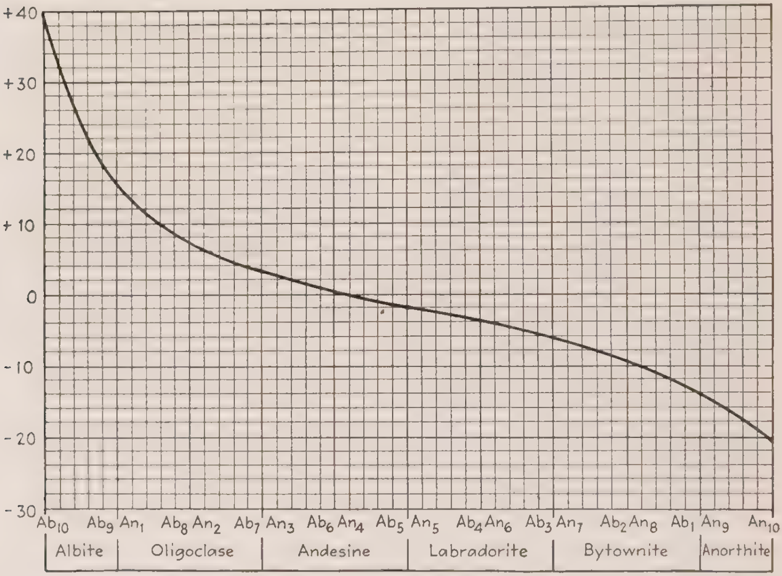


FIG. 177.—Curve showing the "angle of the rhombic section" for pericline twins of the plagioclase feldspars. (*After E. Schmidt.*)

Extinction Angles in Oriented Sections

Cleavage flakes of plagioclase are parallel to either (001) or (010). The former are more frequent than the latter since they are parallel to the better cleavage. Albite twin lamellae are usually present on these flakes. Flakes parallel to (010) usually show no twinning but occasionally have pericline twinning. They usually have the shape of Fig. 162b, page 199, with a fairly straight edge parallel to the *c*-axis, which is due to imperfect cleavage parallel to {110} and $\{1\bar{1}0\}$. Extinction angles for sections parallel to (001) and (010) are given in the curves of Fig. 178, above. More accurate determinations for the sodic plagioclases can be made on (010) sections as may be seen on inspection of the curves.

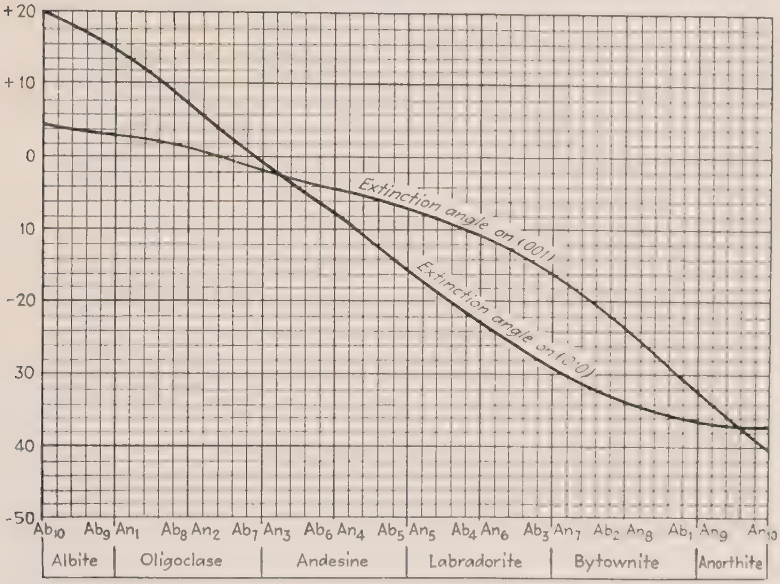


Fig. 178.—Curves showing the extinction angles of oriented sections of the plagioclase feldspars parallel to (001) and (010).

Maximum Extinction Angles of Albite Twins in Sections Normal to {010}

Figs. 179, 180, Page 210

This, the statistical method of Michel-Lévy (1877), is perhaps the most useful single method of determining the character of the plagioclase. Sections normal to {010} may be recognized (1) by the sharpness of the lines separating the twin-lamellae, (2) by the equal illumination when the lamellae are parallel to the vibration planes of the nicols, and (3) by the equality of the extinction angles on both sides of the twin lines. Figure 179 shows the procedure. Many different sections cut normal to {010} can usually be found. The angles given on the curves (Fig. 180, above) are the maximum angles for the various kinds

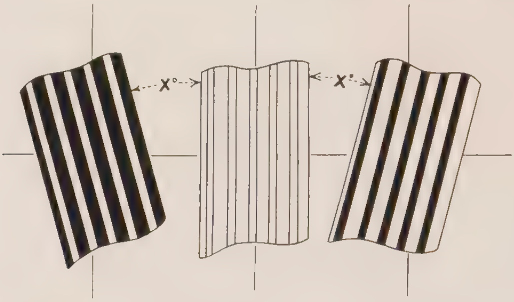


FIG. 179.—Diagram showing the method of determining the extinction angles in albite twins cut normal to (010) for the plagioclase feldspars.

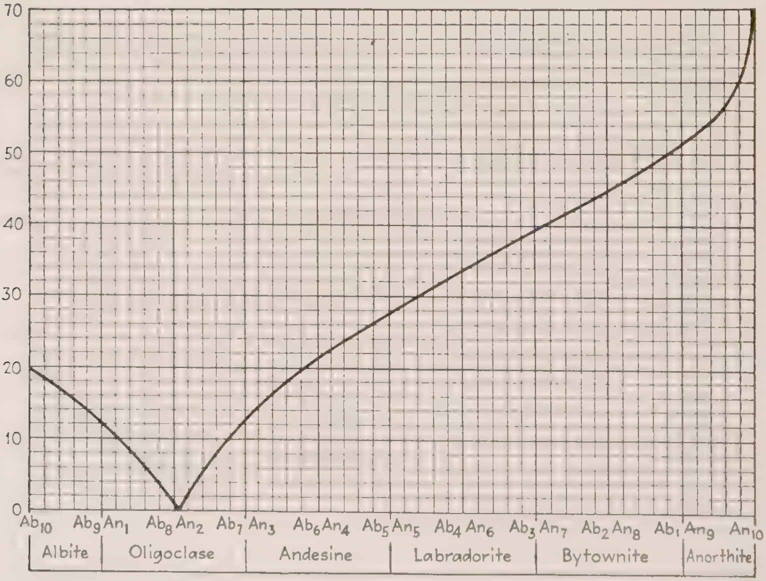


FIG. 180.—Curve showing the maximum extinction angle of albite twins cut normal to (010) for the plagioclase feldspars.

of plagioclase. It is necessary to determine the extinction angle in eight or ten different (or more if greater accuracy is desired) sections in the slide and use the maximum one. It is not necessary to have the extinction angles on each side exactly equal. The two angles may differ by as much as 5 or 6° and in this case the average of the two readings is used. In recording the extinction angle the direction of the faster ray is used; otherwise no angle greater than 45° would ever be obtained. It will be noted that angles of 19½° or less appear twice on the curve. From Ab_{100} to $Ab_{79}An_{21}$ the angle is negative and for those above $Ab_{79}An_{21}$ it is positive. In the absence of the (001 : 100) edge, and this is rarely present, positive and negative angles cannot be distinguished. In order to distinguish plagioclase between Ab_{100} and $Ab_{79}An_{21}$ from plagioclase between $Ab_{79}An_{21}$ and $Ab_{62}An_{38}$, indices of refraction or optical character must be used. Most of the first group have indices of refraction less than balsam and are optically positive. The others have indices of refraction greater than balsam and are optically negative.

Extinction Angles of Combined Carlsbad and Albite Twins in Sections Normal to {010}

Fig. 182, Page 212

If both Carlsbad and albite twinning are present, a single section normal to (010) will suffice for the determination. Sections twinned according to both the Carlsbad and albite laws will in general appear as in Fig. 172, page 206, where four different extinction positions for the crystal may be found. Now sections normal to (010), the composition face for both kinds of twins, may be recognized by the fact that in the 45° position the albite

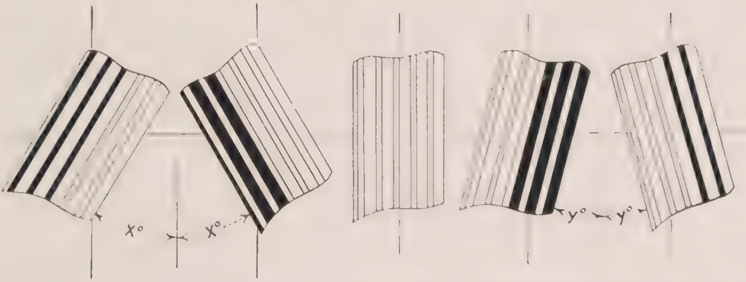


FIG. 181.—Diagram showing the method of determining the two sets of extinction angles ($x°$ and $y°$) in sections of combined Carlsbad-albite twins cut normal to (010).

twinning disappears and the crystal appears to be a simple Carlsbad twin. In the 0° position both the albite and Carlsbad twinning practically disappear. The extinction angles of the albite twins in each half of the section are measured. The procedure is shown in Fig. 181, page 211. The average of the two smaller is given on the horizontal lines of Fig. 182, and the average of the two larger on the curves. The intersection of these two lines gives a point which indicates the relative amounts of the albite and anorthite molecules.

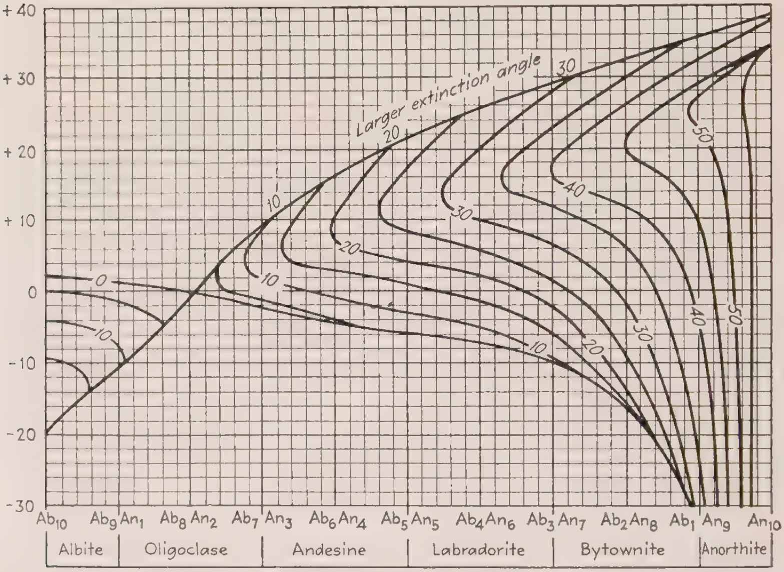


FIG. 182.—Curves showing extinction angles of combined Carlsbad-albite twins normal to (010) for the plagioclase feldspars. (*After F. E. Wright.*)

For a plagioclase with the composition of about $Ab_{80}An_{20}$, Carlsbad twinning cannot be detected in thin sections. In this case the maximum extinction angle for albite twins in sections normal to (010) is 0° (see Fig. 180, page 210).

In general the two sets of extinction angles will indicate two kinds of plagioclase and it will be necessary to use some method to distinguish them.

INDICES OF REFRACTION OF CLEAVAGE FLAKES

Fig. 183, Page 213

The indices of refraction for plagioclase vary from $n_\beta = 1.529$ for pure albite to $n_\beta = 1.583$ for pure anorthite. The relief in balsam then is low to rather low. The principal indices for the various plagioclases are listed under the individual descriptions.

It is rather difficult to determine the maximum and minimum indices unless special precautions are taken. Since these minerals are triclinic the ellipsoid axes are not in general parallel to the cleavages. In ordinary cleavage flakes special values of the indices of refraction n_1 and n_2 are obtained for the two orientations {001} and {010}. Curves for the indices are given in Fig. 183, above; the dotted lines are values for {001} and the solid lines for {010}. For these curves we are indebted to Tsuboi.

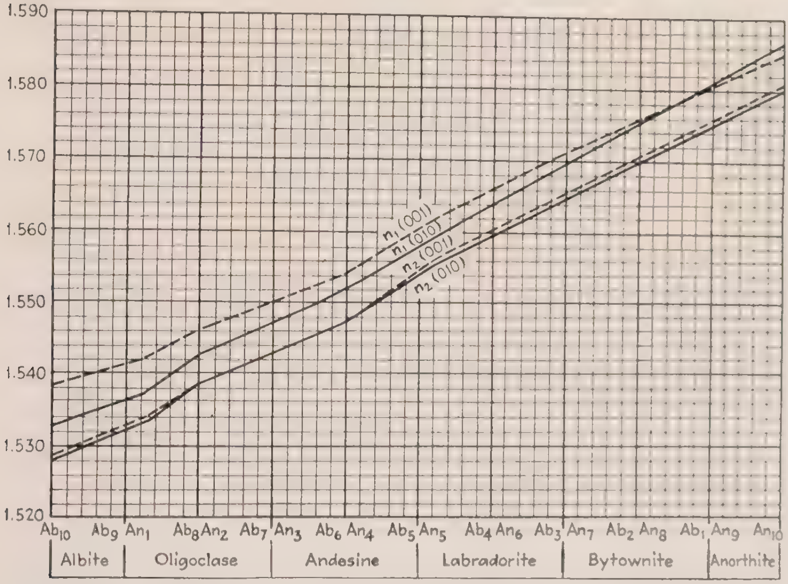


FIG. 183.—Curves showing the indices of refraction n_1 and n_2 of cleavage flakes of the plagioclase feldspars. (*After Tsuboi.*)

ALBITE

Ab_{10} to Ab_9An_1 Triclinic

$$n_\alpha = 1.525 \text{ to } 1.532$$
$$n_\beta = 1.529 \text{ to } 1.536$$
$$n_\gamma = 1.536 \text{ to } 1.541$$
$$2V = 77 \text{ to } 82°;\ \text{Opt.}\ (+)$$

Color.—Colorless.

Form.—Albite occurs in plates or lath-shaped sections, rarely in phenocrysts. It may be intergrown with microcline.

Cleavage $\{001\}$ perfect, $\{010\}$ less perfect, $\{110\}$ and $\{1\bar{1}0\}$ imperfect.

Relief low, $n <$ balsam. (For indices of cleavage flakes see page 213.)

Birefringence rather weak, $n_\gamma - n_\alpha = 0.009$ to 0.011; interference colors are pale yellow of the first order, about the same as quartz in the same section.

Extinction.—The maximum extinction angle in albite twins (*i.e.*, twins according to the albite law) varies from 12 to 19°. In cleavage flakes parallel to (001) the extinction angle is 3° ±; on those parallel to (010), from 15 to 20°.

Twinning.—Polysynthetic twinning according to the albite law ($\{010\}$ = twin-plane) is rarely absent. There may also be twinning according to the Carlsbad law (*c*-axis or [001] = twin-axis) either alone or combined with albite twinning. Pericline twinning (*b*-axis or [010] = twin-axis) is sometimes present.

Interference Figure.—The interference figure is biaxial positive with a large axial angle. Dispersion, $r < v$ weak.

Distinguishing Features.—Albite is distinguished from the other plagioclases by lower indices of refraction and by the various extinction angles.

Occurrence.—Albite occurs in some granites, in granite pegmatites, in veins, and in some metamorphic rocks. It is the only plagioclase that is at all common as a vein mineral. In some altered subsilicic igneous rocks it is formed at the expense of calcic plagioclase.

OLIGOCLASE

Ab_9An_1 to Ab_7An_3 Triclinic

$$n_\alpha = 1.532 \text{ to } 1.545$$
$$n_\beta = 1.536 \text{ to } 1.548$$
$$n_\gamma = 1.541 \text{ to } 1.552$$
$$2V = 82 \text{ to } 90°; \text{ Opt. } (+) \text{ or } (-)$$

Color.—Colorless in thin sections.

Form.—Oligoclase occurs in euhedral, subhedral, and anhedral crystals. The appearance is the same as for the other feldspars.

Cleavage $\{001\}$ perfect, $\{010\}$ less perfect, $\{110\}$ and $\{1\bar{1}0\}$ imperfect.

Relief low, n either less than, greater than, or about equal to that of balsam. (For indices of cleavage flakes see page 213.)

Birefringence weak, $n_\gamma - n_\alpha = 0.007$ to 0.009; interference colors are gray or white of the first order.

Extinction.—The maximum extinction angle in albite twins (twinning according to the albite law) varies from 0 to 12°. The extinction angle on a (001) cleavage flake varies from 0 to 3°; on $\{010\}$ flakes, 0 to +15°.

Interference Figure.—The figure is biaxial, either positive or negative with a very large axial angle, or neutral ($2V = 90°$) for $Ab_{83}An_{17}$. Dispersion, $r > v$ weak.

Distinguishing Features.—Oligoclase is distinguished from the other plagioclases by extinction angles in twinned crystals and by the index of refraction.

Occurrence.—Oligoclase is very common in persilicic igneous rocks such as granites and rhyolites, also in syenites, trachytes, and other igneous rocks. It is occasionally found in granite pegmatites.

ANDESINE

Ab_7An_3 to Ab_5An_5 Triclinic

$$n_\alpha = 1.545 \text{ to } 1.555$$
$$n_\beta = 1.548 \text{ to } 1.558$$
$$n_\gamma = 1.552 \text{ to } 1.562$$
$$2V = 76 \text{ to } 90°; \text{Opt. } (+) \text{ or } (-)$$

Color.—Colorless in thin sections.

Form.—Andesine is found in euhedral to anhedral crystals.

Cleavage $\{001\}$ perfect, $\{010\}$ less perfect, $\{110\}$ and $\{1\bar{1}0\}$ imperfect.

Relief low, n always greater than balsam. (For indices of cleavage flakes see page 213.)

Birefringence weak, $n_\gamma - n_\alpha = 0.007$, so that the interference colors are gray or white of the first order.

Extinction.—The maximum extinction angle in albite twins (twins according to the albite law) varies from 13 to 27½°. On (001) cleavage flakes the extinction angle varies from 0 to 7°; on (010) flakes, from 0 to −16°.

Interference Figure.—The figure is biaxial, either positive or negative with a large axial angle, or neutral ($2V = 90°$) for $Ab_{62}An_{38}$. Dispersion, $r < v$.

Distinguishing Features.—Andesine is distinguished from other plagioclases by maximum extinction angles of twinned crystals and by the indices of refraction.

Occurrence.—Andesine is a common and widely distributed mineral in igneous rocks of various types. It is especially common in diorites and andesites.

LABRADORITE

Ab_5An_5 to Ab_3An_7 Triclinic

$$n_\alpha = 1.555 \text{ to } 1.563$$
$$n_\beta = 1.558 \text{ to } 1.567$$
$$n_\gamma = 1.562 \text{ to } 1.571$$
$$2V = 76 \text{ to } 90°; \text{Opt. } (+)$$

Color.—Colorless, often with regularly arranged inclusions.

Form.—Labradorite occurs in euhedral to anhedral crystals. The anhedral crystals are often large as compared with those of other plagioclases.

Cleavage $\{001\}$ perfect, $\{010\}$ less perfect, $\{110\}$ and $\{110\}$ imperfect.

Relief fairly low, $n >$ balsam. (For indices of cleavage flakes see page 213.)

Birefringence weak, $n_\gamma - n_\alpha = 0.007$ to 0.008; interference colors are gray or white of the first order.

Extinction.—The maximum extinction angle in albite twins (twinning according to the albite law) varies from 27½ to 39°. The extinction angle on (001) cleavage flakes varies from −7 to −16°; on (010) flakes, from −16 to −29°.

Interference Figure.—The figure is usually biaxial positive with a large axial angle but is biaxial negative at times and neutral for $Ab_{32}An_{68}$. Dispersion, $r < v$.

Distinguishing Features.—Labradorite is distinguished from the other plagioclases by the maximum extinction angles of albite twins and by the indices of refraction.

Occurrence.—Labradorite is a very common mineral in subsilicic igneous rocks such as auganites, basalts, gabbros, and olivine gabbros. It is the principal constituent of most anorthosites.

Bytownite

Ab_3An_7 to Ab_1An_9 Triclinic

$$n_\alpha = 1.563 \text{ to } 1.571$$
$$n_\beta = 1.567 \text{ to } 1.577$$
$$n_\gamma = 1.571 \text{ to } 1.582$$
$$2V = 79 \text{ to } 88°;\ \text{Opt. } (-)$$

Color.—Colorless.

Form.—Bytownite occurs in subhedral to anhedral crystals.

Cleavage {001} perfect, {010} less perfect, {110} and {110} imperfect.

Relief moderate, $n >$ balsam. (For indices of cleavage flakes see page 213.)

Birefringence weak, $n_\gamma - n_\alpha = 0.008$ to 0.011. Interference colors are gray, white, or pale yellow of the first order.

Extinction.—The maximum extinction angle in albite twins (twinning according to the albite law) varies from 39 to 51°. The extinction angle on (001) cleavage flakes varies from −16 to −32°; on {010} flakes, from −29 to −36°.

Interference Figure.—The figure is biaxial negative with a very large axial angle. Dispersion, $r > v$.

Distinguishing Features.—Bytownite is distinguished from other plagioclases by extinction angles and refractive indices.

Occurrence.—Bytownite usually occurs in gabbros or basalts, but it is a comparatively rare mineral.

Anorthite

Ab_1An_9 to An_{10} Triclinic

$$n_\alpha = 1.571 \text{ to } 1.575$$
$$n_\beta = 1.577 \text{ to } 1.583$$
$$n_\gamma = 1.582 \text{ to } 1.588$$
$$2V = 77 \text{ to } 79°; \text{ Opt. } (-)$$

Color.—Colorless.

Form.—Anorthite occurs in anhedral to subhedral plates or laths.

Cleavage $\{001\}$ perfect, $\{010\}$ less perfect, $\{110\}$ and $\{1\bar{1}0\}$ imperfect.

Relief fair, $n >$ balsam. (For indices of cleavage flakes see page 213.)

Birefringence rather weak, $n_\gamma - n_\alpha = 0.011$ to 0.013; interference colors are gray, white, or yellow of the first order.

Extinction.—The maximum extinction angle in albite twins (twinning according to the albite law) varies from 51 to 70°. The extinction angle on (001) cleavage flakes varies from −32 to −40°; on (010) it is about −37°.

Interference Figure.—The figure is biaxial negative with a large axial angle. Dispersion, $r > v$.

Distinguishing Features.—Anorthite is distinguished from other plagioclases by the extinction angles and refractive indices.

Occurrence.—Anorthite is rare compared with the other plagioclases. It is found in a few contact-metamorphic deposits and in a few lavas.

THE FELDSPATHOIDS

The feldspathoids play the same role in some igneous rocks that the feldspars do. They may either take the place of the feldspars or occur with them. They are comparatively rare.

Strictly speaking, lazurite is not a feldspathoid since it does not occur in igneous rocks, but it is isomorphous with sodalite. Analcite, though a zeolite, sometimes plays the part of feldspar in some igneous rocks.

THE FELDSPATHOIDS

Mineral	Chemical composition	Crystal system	Indices of refraction
Leucite . . .	KAl	Pseudo-isometric	$n_\alpha = 1.508$, $n_\gamma = 1.509$
Nepheline.	NaAl	Hexagonal	$n_\epsilon = 1.532$–1.542, $n_\omega = 1.536$–1.547
Sodalite. . .	NaAl + Cl	Isometric	$n = 1.483$–1.487
Lazurite. . .	NaAl + S	Isometric	$n = 1.50$
Melilite. . .	Ca, Mg, Al	Tetragonal	$n_\epsilon = 1.626$–1.629, $n_\omega = 1.632$–1.634.

Leucite

$KAl(SiO_3)_2$ Pseudo-isometric

$$n_\alpha = 1.508$$
$$n_\gamma = 1.509$$

Fig. 99, Page 112

Color.—Colorless.

Form.—Leucite practically always occurs in euhedral crystals. The crystal form is the trapezohedron {211}, which has octagonal sections. It often contains inclusions and these may be arranged in a regular manner either radially or concentrically.

Relief fair, $n <$ balsam.

Birefringence very weak, $n_\gamma - n_\alpha = 0.001$; it is best detected by using the sensitive-violet test plate. Minute crystals may not show any birefringence.

Extinction is often wavy.

Twinning.—A characteristic feature of leucite is the complicated polysynthetic twinning in several directions, which often resembles that of microcline. When heated to about 500° C. the twinning disappears, which proves that $KAl(SiO_3)_2$ is dimorphous.

Distinguishing Features. Leucite resembles analcite. The latter shows weak birefringence but does not have definite polysynthetic twinning. Microcline has greater birefringence and lower relief.

Occurrence. Leucite occurs almost exclusively as phenocrysts in lavas (leucite tephrite, leucitite, leucite basalt, etc.) and the corresponding tuffs. Leucite-bearing rocks are common in Italy but rare in most other parts of the world. In the United States leucite occurs in the Leucite Hills, Wyoming.

Nepheline

$(Na,K)AlSiO_4.(SiO_2)_x$ (Eleolite) Hexagonal

(Hexagonal Subsystem)

n_ϵ = 1.532 to 1.542

n_ω = 1.536 to 1.547

Opt. (−); c = X

Fig. 114, Page 118

Color. Colorless to turbid and may also show rows of inclusions.

Form.—Nepheline occurs in short prismatic hexagonal crystals and also in anhedra. The crystals have rectangular and hexagonal sections and sometimes show zonal structure.

Cleavage imperfect parallel to $\{10\bar{1}0\}$, not always apparent.

Relief very low, n about the same as balsam but usually slightly higher.

Birefringence weak, $n_\omega - n_\epsilon$ = 0.004 to 0.005; interference colors are gray of the first order.

Extinction parallel for rectangular sections. Basal sections are dark between crossed nicols.

Orientation.—The rectangular sections are length-fast.

Interference Figure.—Basal sections give a negative uniaxial figure without any rings.

Distinguishing Features.—The mineral most likely to be mistaken for nepheline is orthoclase, but the latter has good cleavage and is biaxial.

Alteration.—Nepheline alters very readily to zeolites, sodalite, muscovite, or cancrinite.

Occurrence.—Nepheline is a rare mineral confined to soda-rich igneous rocks such as nepheline syenites, phonolites, and a few basaltic rocks. Nepheline never occurs with original quartz.

Sodalite

$3NaAlSiO_4.NaCl$ Isometric

$n = 1.483$ to 1.487

Color.—Colorless to gray, often with dark borders.

Form.—Sodalite occurs in six-sided euhedral crystals (cross sections of dodecahedra) and in anhedra.

Cleavage imperfect parallel to {110}, more likely to show on edges of the slide.

Relief fair, $n <$ balsam.

Birefringence nil.

Extinction.—Dark between crossed nicols.

Distinguishing Features.—Sodalite resembles analcite, but the latter is usually secondary. Nosean and haüyne, rare minerals of the sodalite group, are much like sodalite. It may be necessary to make chemical tests to confirm the determination.

Alteration.—Sodalite is readily altered to zeolites.

Occurrence.—Sodalite is practically confined to soda-rich igneous rocks such as syenites and trachytes. It is a common associate of nepheline.

Lazurite

$3NaAlSiO_4.Na_2S$ (Lapis Lazuli) Isometric

$n = 1.50$

Color.—Blue.

Form.—Lazurite occurs in granular aggregates more or less disseminated through the rock.

Cleavage absent.

Relief rather low, $n <$ balsam.

Birefringence nil. Dark between crossed nicols. Apparent birefringent areas are due to overlapping of such minerals as calcite.

Extinction complete in all positions.

Distinguishing Features.—The only minerals likely to be mistaken for lazurite are nosean and haüyne, isometric minerals of the same group. Association with pyrite is highly characteristic of lazurite.

Occurrence.—Lazurite is practically confined to contact-metamorphic limestones. Pyrite is an invariable associate. Other associates are calcite, diopside, muscovite, and plagioclase.

LAPIS LAZULI

Lapis lazuli is the name used for an intimate mixture of lazurite with varying amounts of calcite, diopside, pyrite, and other minerals. This semiprecious or ornamental stone was formerly a source of ultramarine.

Melilite

$m(Ca_2Al_2SiO_7)+$
$n(Ca_2MgSi_2O_7)$

Tetragonal

$$n_\epsilon = 1.626 \text{ to } 1.629$$
$$n_\omega = 1.632 \text{ to } 1.634$$
$$\text{Opt. } (-);\ c = X$$

Color.—Colorless.

Form. The usual forms of melilite are euhedral crystals of tabular habit which show as rectangular sections. It often has "peg-structure" due to lines normal to the length of the sections.

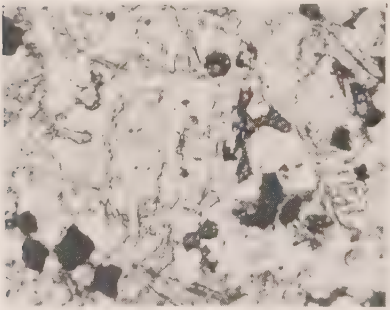


FIG. 184.—(×100) Melilite (fair relief) in nephelinite.

Cleavage indistinct parallel to {001}, which often appears as a single crack in the center of the section.

Relief fairly high, $n >$ balsam.

Birefringence very weak, $n_\omega - n_\epsilon = 0.005$ to 0.006; interference colors are first-order gray, often anomalous Berlin blue.

Extinction parallel.

Orientation. The rectangular sections are length-slow, since the mineral is optically negative and tabular in habit.

Interference Figure.—Basal sections give a uniaxial negative figure without any rings.

Distinguishing Features.—Elongated sections with weak birefringence and peg structure are characteristic.

Alteration. Incipient alteration takes place along lines normal to the length of the crystal. This gives the so-called peg structure. It may also be altered to calcite and zeolites.

Occurrence.—Melilite occurs in subsilicic igneous rocks such as nepheline- and leucite-bearing lavas and in melilite basalts (alnöites). Usual associates are augite, olivine, nepheline, leucite, and perovskite. Melilite is also found in slags.

THE PYROXENE GROUP

The pyroxene group includes some of the most important rock-forming minerals. They are orthorhombic or monoclinic with the cross sections of Fig. 185, below. The angle $(110:1\bar{1}0)$ is about 93°. The cleavage is parallel to {110} as shown in Fig. 185, above. There is sometimes parting parallel to {001} or {100}. Twinning with {100} as twin-plane is rather common. The minerals are all biaxial with rather large axial angles. One of the best means of identifying individual members of the group

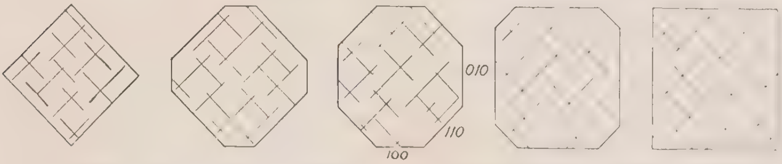


FIG. 185.—Cross sections of minerals of the pyroxene group showing cleavage.

PYROXENE GROUP

	Mineral	Chemical composition	n_α	n_β	n_γ	2V	c : Z
Orthorhombic	Enstatite	Mg	1.650 1.658	1.656 1.665	1.661 1.671	31–80°	0°
	Hypersthene	Mg,Fe	1.692 1.716	1.695 1.720	1.700 1.727	60–90°	0°
Monoclinic	DIOPSIDE	Ca(Mg,Fe)	1.650 1.698	1.657 1.706	1.681 1.727	58–60°	37–44°
	AUGITE	Ca(Mg,Fe) + Al	1.688 1.712	1.701 1.717	1.713 1.737	58–62°	45–54°
	Hedenbergite	CaFe	1.732 1.739	1.737 1.745	1.750 1.757	60°	48°
	Aegirine-augite	NaCaMgFe	1.680	1.687	1.700	60°	52–75°
	Aegirine	NaFe	1.745 1.777	1.770 1.823	1.782 1.836	60–66°	82–88°
	Jadeite	NaAl	1.655	1.659	1.667	70–72°	30–36°

is by use of the maximum extinction angles in longitudinal sections.

Augite is by far the most common mineral of the group. A pale-colored augite with a small axial angle known as pigeonite is also very common. The last three minerals of the above list are known as soda pyroxenes.

Enstatite

$MgSiO_3$ (inc. Bronzite) Orthorhombic

$$n_\alpha = 1.650 \text{ to } 1.658$$
$$n_\beta = 1.656 \text{ to } 1.665$$
$$n_\gamma = 1.661 \text{ to } 1.671$$
$$2V = 31 \text{ to } 80^\circ;\ \text{Opt. } (+)$$
$$a = X,\ b = Y,\ c = Z$$

Color.—Colorless to neutral. Bronzite has faint pleochroism.

Form.—Enstatite is found in prismatic crystals with the characteristic pyroxene cross section. Inclusions are common and produce what is known as *schiller* structure in the ferriferous variety known as *bronzite.*

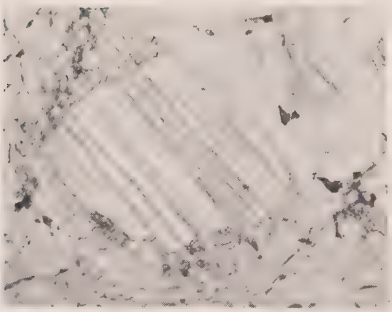


FIG. 186.—(×12) Enstatite in altered peridotite.

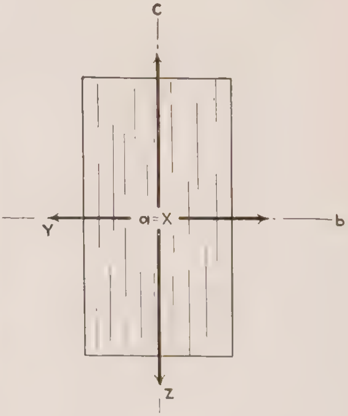


FIG. 187.—Orientation diagram of enstatite. Section parallel to (100).

Cleavage {110} in two directions at nearly right angles (88 and 92°). Cleavage or parting parallel to {010} is also sometimes present. In longitudinal sections the cleavage traces are in one direction parallel to the outlines.

Relief high, $n >$ balsam.

Birefringence rather weak, $n_\gamma - n_\alpha = 0.011$ to 0.013; the maximum interference color is pale yellow of the first order.

Extinction parallel in most sections.

Twinning rarely present.

Orientation.—The crystals and cleavage traces are length-slow.

Interference Figure.—The figure is biaxial positive with a moderate to large axial angle. The axial plane is {100}. Dispersion, $r > v$ weak.

Intergrowth.—The intergrowth of enstatite with a monoclinic pyroxene is rather common. They have their c axes in common and at first glance resemble polysynthetic twins.

Distinguishing Features.—Enstatite is distinguished from hypersthene by lack of pleochroism and from the monoclinic pyroxenes by parallel extinction.

Alteration.—It is common to find enstatite more or less altered to antigorite. Pseudomorphs of antigorite after enstatite are known as *bastite*.

Occurrence.—Enstatite is a characteristic mineral of subsilicic igneous rocks and derived serpentites. It is also found in meteorites.

Hypersthene

$(Mg,Fe)SiO_3$ Orthorhombic

$n_\alpha = 1.692$ to 1.716
$n_\beta = 1.695$ to 1.720
$n_\gamma = 1.700$ to 1.727
2V = 60 to 90°; Opt. (−)
$a = X, b = Y, c = Z$
Figs. 188, 189, Page 226

Color.—Neutral to pale green or pale red. Pleochroic from greenish to pale reddish. Inclusions are common and produce schiller structure.

Form.—Hypersthene usually occurs in subhedral crystals of prismatic habit. The cross sections are nearly square.

Cleavage parallel to {110}; sometimes parallel to {010} and {100}.

Relief high, $n >$ balsam.

Birefringence rather weak, $n_\gamma - n_\alpha = 0.008$ to 0.011; the maximum interference color is pale yellow of the first order.

Extinction parallel in most sections.

Orientation.—The cleavage traces are length-slow.

Interference Figure.—The figure is biaxial negative with a large axial angle. The axial plane is {010}. Dispersion, $r > v$.

Distinguishing Features.—The pleochroism is the most distinctive feature of hypersthene. It resembles some varieties of andalusite but the latter mineral is length-fast, while hypersthene is length-slow.

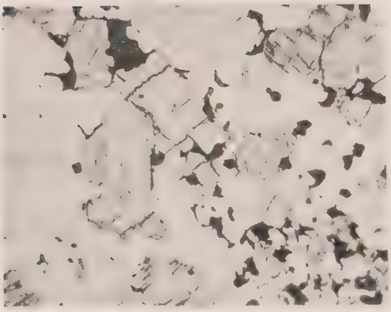


Fig. 188.—(×9) Hypersthene in norite.

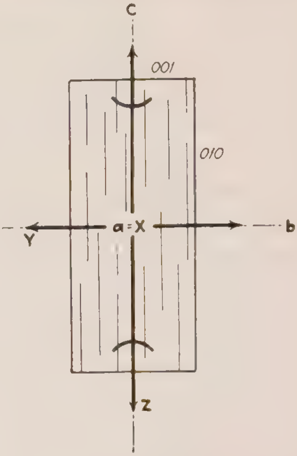


Fig. 189.—Orientation diagram of hypersthene. Section parallel to (100).

Occurrence.—Hypersthene is found in a number of igneous rocks but is especially characteristic of norite, hypersthene gabbro, some andesite, and a peculiar hypersthene granite known as charnockite.

DIOPSIDE

$Ca(Mg,Fe)(SiO_3)_2$ Monoclinic

$n_\alpha = 1.650$ to 1.698
$n_\beta = 1.657$ to 1.706
$n_\gamma = 1.681$ to 1.727
$2V = 58$ to $60°$; Opt. $(+)$
$b = Y$, $c \wedge Z = -37$ to $-44°$.
Fig. 191, Page 228

Color.—Colorless, neutral, pale green to bright green.

Form.—Diopside usually occurs in subhedral crystals of short prismatic habit. Cross sections are four or eight sided.

Cleavage parallel to {110} and so in two directions at angles of 87 and 93°. Parting parallel to {001} is sometimes developed.

Relief fairly high, $n >$ balsam.

Birefringence strong, $n_\gamma - n_\alpha = 0.029$ to 0.031; the maximum interference color is about upper second order.

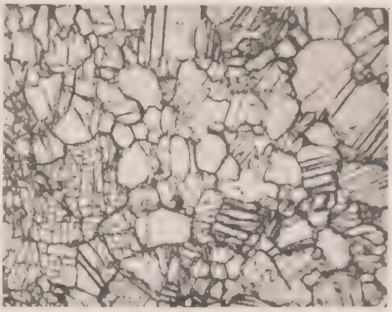


FIG. 190.—(×36) Diopside from contact-metamorphic zone.

Extinction.—The maximum extinction angle in sections cut parallel to the c axis varies from -37 to $-44°$. In cross sections the extinction is symmetrical to the cleavage traces.

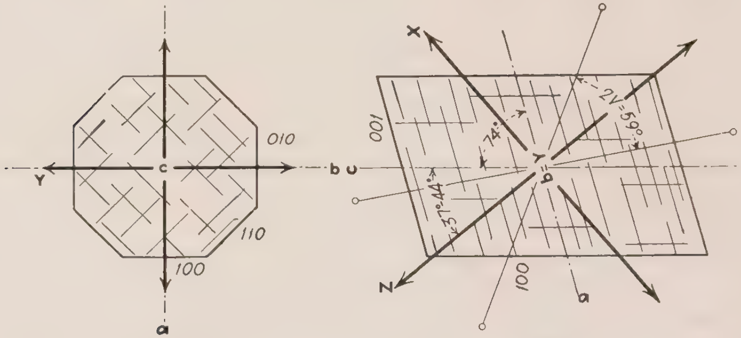
Orientation.—The extinction direction that makes the smaller angle with the cleavage traces in longitudinal sections is the slower ray.

Twinning.—Twins with {100} as twin-plane are rather common. Polysynthetic twinning with {001} as twin-plane is common as secondary twinning.

Interference Figure.—Diopside gives a biaxial positive figure with a rather large axial angle. Dispersion, $r < v$ weak. Chips parallel to the {001} parting give a good optic-axis figure.

Distinguishing Features.—Diopside is distinguished from hedenbergite by lower refractive indices. From tremolite it is distinguished by larger extinction angle. Augite has a little higher extinction angle ($c \wedge Z$) and is usually a darker color.

Alteration.—Diopside is sometimes more or less altered to tremolite or actinolite.



(*a*) (*b*)

FIGS. 191 *a,b*.—Orientation diagrams of diopside. Sections (*a*) normal to the *c*-axis and (*b*) parallel to (010).

Occurrence.—Diopside is especially characteristic of contact-metamorphic zones. It occurs with garnet, wollastonite, vesuvianite, and other silicates. It is also found in some gneisses and schists and in some igneous rocks.

AUGITE

(inc. Pigeonite)

$Ca(Mg,Fe)(SiO_3)_2[(Al,Fe)_2O_3]_x$ Monoclinic

$n_\alpha = 1.688$ to 1.712
$n_\beta = 1.701$ to 1.717
$n_\gamma = 1.713$ to 1.737
$2V = 58$ to $62°$; Opt. (+)
$b = Y, c \wedge Z = -45$ to $-54°$

Color.—Almost colorless, neutral, pale greenish, or pale purplish brown. Pleochroism absent to weak; it is best shown in (100) sections.

Form.—Augite usually occurs in short prismatic crystals with four- or eight-sided cross sections.

Cleavage {110} in two directions at angles of 87 and 93°. Cleavage traces are in one direction in longitudinal sections. Diallage has prominent parting parallel to {100}.

Relief high, $n >$ balsam.

Birefringence rather strong, $n_\gamma - n_\alpha = 0.025$. The maximum interference color is about middle second order. Sections parallel to {100} have low first-order colors.

Extinction.—The maximum extinction angle of longitudinal sections varies from 36 to 45°. These sections have the maximum interference colors for the slide. Some varieties have a peculiar concentric wavy extinction known as the *hourglass* structure. Cross sections have parallel or symmetrical extinction depending upon whether {100} and {010} or {110} predominates.

Orientation.—The extinction direction that makes the smaller angle with the cleavage traces is the faster ray.

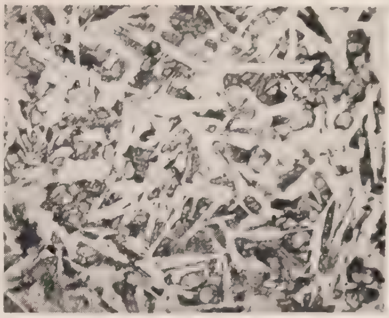
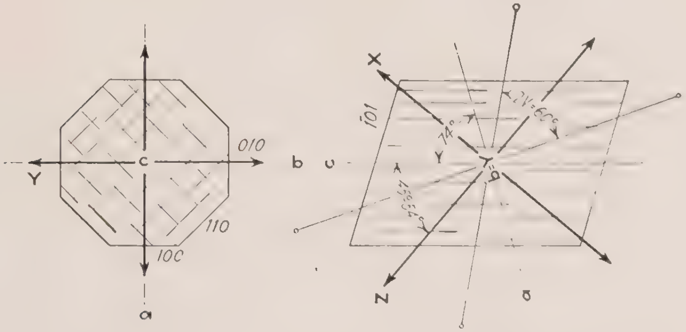


FIG. 192.—(×12) Augite with plagioclase in basalt.

Twinning.—Twins with {100} as twin-plane are common; these often appear as twin seams. Polysynthetic twins with {001} as twin-plane are occasionally found. Combined {100} twins with {001} polysynthetic twins give what is known as *herringbone* structure.



(*a*) (*b*)

FIGS. 193 *a,b*.—Orientation diagrams of augite. Sections (*a*) normal to the *c*-axis and (*b*) parallel to (010).

Interference Figure.—The figure is biaxial positive with a rather large axial angle. The axial plane is {010}. Dispersion, $r > v$.

Distinguishing Features.—Augite is often difficult to distinguish from diopside. The extinction angle $c \wedge Z$ is a little smaller and the color lighter in diopside.

Alteration.—There are two common alteration products of augite: (1) hornblende formed at a late magmatic stage and in parallel position on the augite (see Fig. 203, page 239); (2) uralite or secondary tremolite (or actinolite) formed by hydrothermal alteration.

Occurrence.—Augite is a very common mineral in subsilicic igneous rocks such as auganites, gabbros, basalts, olivine gabbros, limburgites, and peridotites. Locally it is found in gneisses and granulites. Augite is also a common detrital mineral.

PIGEONITE

A pale-colored monoclinic pyroxene related to augite and known as pigeonite is a very common and widely distributed mineral according to Barth. It may be distinguished from augite by its small axial angle.

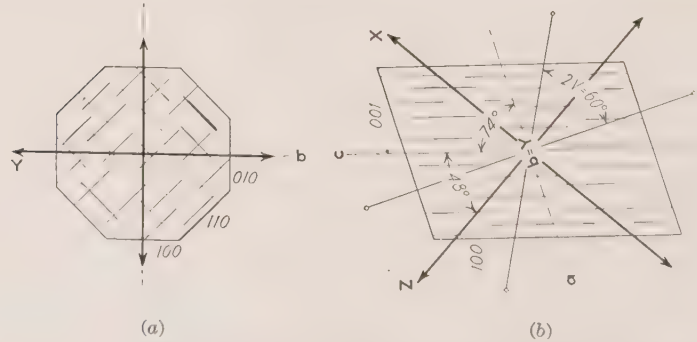
Hedenbergite

$Ca(Fe,Mg)(SiO_3)_2$ Monoclinic

$$n_\alpha = 1.732 \text{ to } 1.739$$
$$n_\beta = 1.737 \text{ to } 1.745$$
$$n_\gamma = 1.750 \text{ to } 1.757$$
$$2V = 60°; \text{ Opt. } (+)$$
$$b = Y,\ c \wedge Z = -48°$$

Color.—Neutral to greenish.

Form.—Hedenbergite usually occurs in columnar aggregates.



(a) (b)

FIGS. 194 *a,b*.—Orientation diagrams of hedenbergite. Sections (*a*) normal to the *c*-axis and (*b*) parallel to (010).

Cleavage {110} in two directions at angles of 87 and 93° (like the other pyroxenes).

Relief very high, $n >$ balsam.

Birefringence moderate, $n_\gamma - n_\alpha = 0.016 - 0.018$; the maximum interference color is about first-order violet.

Extinction.—The maximum extinction angle in longitudinal sections is about 42° ($c \wedge X$).

Orientation.—The extinction direction that makes the smaller angle with the cleavage traces is the faster ray.

Interference Figure.—The figure is biaxial positive with a rather large axial angle. The axial plane is {010}. Dispersion, $r > v$ weak.

Distinguishing Features.—Hedenbergite is distinguished from diopside and augite by higher indices of refraction.

Occurrence.—The characteristic occurrence of hedenbergite is in contact-metamorphic zones. It is often associated with ores.

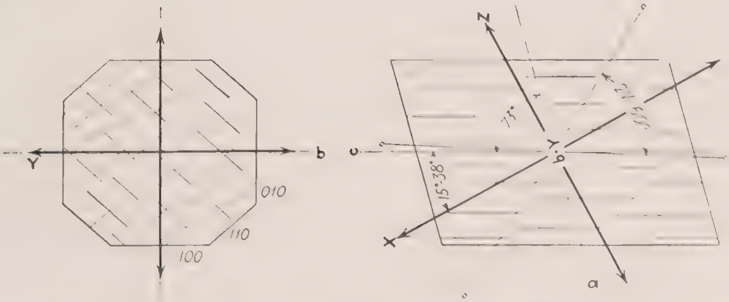
Aegirine-Augite

Intermediate between
aegirine and augite
in chemical composition

Monoclinic

$$n_\alpha = 1.680$$
$$n_\beta = 1.687$$
$$n_\gamma = 1.709$$
$$2V = 60°; \text{Opt. } (+)$$
$$b = Y,\ c \wedge X = -15 \text{ to } -38°$$

Color.—Green. Pleochroic from yellow green (Y) to greenish (X, Z).



(a) (b)

Figs. 195 a,b.—Orientation diagrams of aegirine-augite. Sections (a) normal to the c-axis and (b) parallel to (010).

Form.—Aegirine-augite usually occurs in euhedral crystals of short prismatic habit with {100} as the dominant form.

Cleavage in two directions {110} at angles of 87 and 93°.

Relief high, $n >$ balsam.

Birefringence strong, $n_\gamma - n_\alpha = 0.029$; interference colors range up to the middle of the second order.

Extinction.—The maximum extinction in longitudinal sections varies from −15 to −38°.

Orientation.—In sections with the maximum extinction angle the extinction direction nearest the *c*-axis is the faster ray.

Twinning.—Twins with {100} as twin-plane are common.

Interference figure is biaxial negative with a rather large axial angle. The axial plane is {010}. Dispersion, $r > v$.

Distinguishing Features.—Aegirine-augite resembles aegirine but may be distinguished by the larger extinction angles. It is most easily distinguished from the green varieties of hornblende by pyroxene cross sections and cleavage.

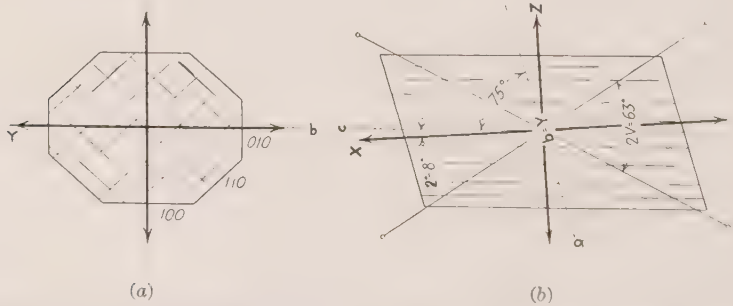
Occurrence.—Aegirine-augite occurs in soda-rich igneous rocks such as syenites, trachytes, nepheline syenites, phonolites, etc.

Aegirine

$NaFe(SiO_3)_2$ (inc. Acmite) Monoclinic

$$n_\alpha = 1.745 \text{ to } 1.777$$
$$n_\beta = 1.770 \text{ to } 1.823$$
$$n_\gamma = 1.782 \text{ to } 1.836$$
$$2V = 60 \text{ to } 66°; \text{Opt. } (-)$$
$$b = Y, c \wedge X = -2 \text{ to } -8°$$

Color.—Green or brown. Pleochroic from green to yellow green or brown to greenish yellow.



(*a*) (*b*)

FIGS. 196 *a,b*.—Orientation diagrams of aegirine. Sections (*a*) normal to the *c*-axis and (*b*) parallel to (010).

Form.—Aegirine is usually found in long prismatic crystals with the typical four- to eight-sided cross section of the pyroxenes.

Cleavage {110} in two directions at angles of 87 and 93°.

Relief high, $n >$ balsam.

Birefringence strong to very strong, $n_\gamma - n_\alpha = 0.037$ to 0.059; the interference colors should be third or fourth order but may be difficult to determine because of the color of the mineral which may mask the interference colors.

Extinction.—The maximum extinction angle in longitudinal sections is very small (from 2 to 8°).

Orientation.—The crystals are always length-fast.

Interference Figure.—The figure is biaxial negative with a rather large axial angle. The axial plane is {010}. Dispersion, $r > v$.

Distinguishing Features.—Aegirine resembles some of the amphiboles but is distinguished by the small maximum extinction angle and negative elongation. All the other monoclinic pyroxenes have larger extinction angles.

Occurrence.—Aegirine, although a rather rare mineral, is characteristic of soda-rich igneous rocks such as nepheline syenite, phonolite, syenite, trachyte, soda granite, soda aplite, etc.

Jadeite

$NaAl(SiO_3)_2$ (Jade in part) Monoclinic

$$n_\alpha = 1.655$$
$$n_\beta = 1.659$$
$$n_\gamma = 1.667$$
$$2V = 70 \text{ to } 72°;\ \text{Opt. } (+)$$
$$b = Y,\ c \wedge Z = -30 \text{ to } -36°$$

Color.—Colorless.

Form.—Jadeite usually appears in interlocking columnar aggregates. Euhedral crystals are exceedingly rare.

Cleavage {110} in two directions at angles of about 87 and 93°.

Relief rather high, $n >$ balsam.

Birefringence moderate, $n_\gamma - n_\alpha = 0.012$; the maximum interference colors are second order.

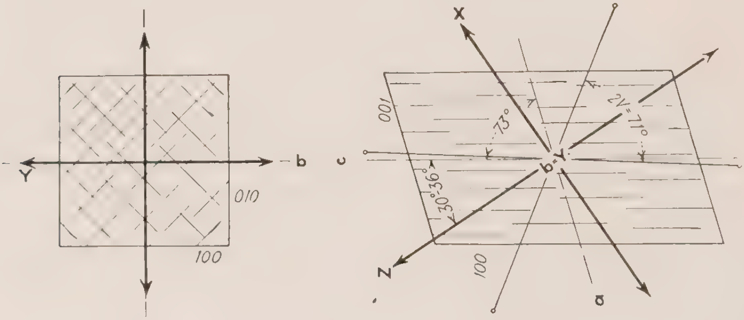
Extinction.—The maximum extinction angle in longitudinal sections varies from 30 to 36°.

Orientation.—The extinction direction nearest the c-axis is the slower ray.

Twinning.—Twins with {100} as twin-plane are occasionally found.

Interference Figure.—The figure is biaxial positive with a large axial angle. The axial plane is {010}. Dispersion, $r < v$.

Distinguishing Features.—Jadeite is distinguished from nephrite (variety of actinolite) by larger extinction angle and higher refractive indices. From diopside it is distinguished by smaller maximum extinction angles and columnar habit.



(*a*) (*b*)

Figs. 197 *a*,*b*.—Orientation diagrams of jadeite. Sections (*a*) normal to the *c*-axis and (*b*) parallel to (010).

Alteration.—Jadeite is sometimes found more or less altered to tremolite.

Occurrence.—Jadeite occurs exclusively in metamorphic rocks of obscure origin restricted to certain localities in Burma, Tibet, and Central America.

JADE

The name jade is a general name for jadeite (soda pyroxene) and nephrite (variety of actinolite). Jade-like minerals are californite (mixture of vesuvianite, diopside, etc.) and South African "jade" (massive green grossularite), williamsite (antigorite), and agalmatolite (variety of halloysite).

THE AMPHIBOLE GROUP

The amphiboles have rhombic to pseudo-hexagonal cross sections and perfect cleavage parallel to {110} at angles of about 56 and 124° as shown in Fig. 198, below. Twinning parallel to {100} is fairly common.

AMPHIBOLE GROUP

	Mineral	Chemical composition	$n\alpha$	$n\beta$	$n\gamma$	2V	$c:Z$
Ortho-rhombic	Anthophyllite	MgFe	1.619 1.633	1.630 1.642	1.640 1.657	70–90°	0°
Monoclinic	TREMOLITE	CaMgFe	1.602 1.623	1.613 1.638	1.624 1.650	79–85°	10–20°
	HORNBLENDE	CaMgFeAl	1.614 1.675	1.618 1.691	1.633 1.701	52–85°	12–30°
	BASALTIC HORNBLENDE	CaMgFeAl	1.680	1.725	1.752	79–80°	0–10°
	Riebeckite	NaFe	1.693	1.695	1.697	Large	85°
	Glaucophane	NaAlFe	1.621	1.638	1.639	45°	4– 6°

The amphibole group is parallel to the pyroxene group. Corresponding members of the two groups, however, are not dimorphous. Hornblende is by far the most common mineral of the group. Cummingtonite is a pale brown monoclinic amphibole with the composition of anthophyllite. It is very rare. Actinolite, often listed as a distinct mineral, is here considered a ferriferous variety of tremolite. Basaltic hornblende is considered a distinctive mineral and not a variety of hornblende. Riebeckite, glaucophane, and a few rarer minerals are known as soda amphiboles. Crossite is a soda amphibole intermediate between riebeckite and glaucophane.

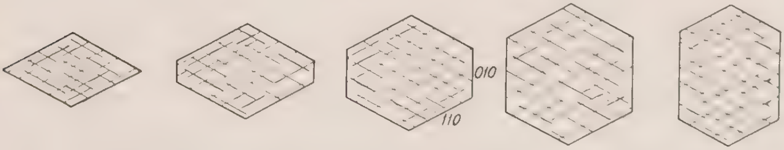


FIG. 198.—Cross sections of minerals of the amphibole group showing cleavage.

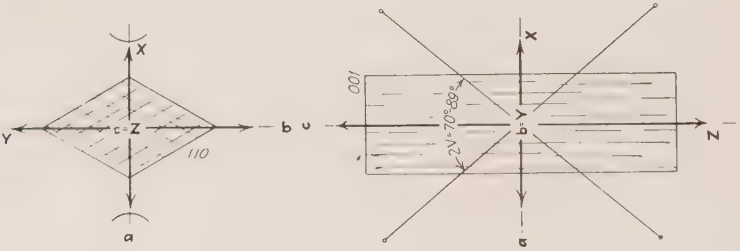
Anthophyllite

$(Mg,Fe)SiO_3$ (inc. Gedrite) Orthorhombic

$$n_\alpha = 1.619 \text{ to } 1.633$$
$$n_\beta = 1.630 \text{ to } 1.642$$
$$n_\gamma = 1.640 \text{ to } 1.657$$
$$2V = 70 \text{ to } 90°; \text{ Opt. } (+) \text{ or } (-)$$
$$a = X, b = Y, c = Z$$

Color.—Colorless or pale colored. Some of the colored varieties show pleochroism.

Form. Long prismatic crystals and columnar to fibrous aggregates are characteristic of anthophyllite. It is sometimes asbestiform.



(a) (b)

FIGS. 199 *a,b*.—Orientation diagrams of anthophyllite. Sections (*a*) normal to the *c*-axis and (*b*) parallel to (010).

Cleavage in two directions {110} at angles of 54 and 126°. Cross fractures are common.

Relief high, $n >$ balsam.

Birefringence rather strong, $n_\gamma - n_\alpha = 0.021$ to 0.024; interference colors range up to low second order.

Extinction parallel in longitudinal sections, in cross sections symmetrical to outline or cleavage.

Orientation length-slow.

Interference Figure.—The figure is biaxial and positive, neutral ($2V = 90°$), or negative with a very large axial angle. The axial plane is {010}. Dispersion, $r > v$ or $r < v$.

Distinguishing Features.—Anthophyllite resembles tremolite but may be distinguished by its parallel extinction.

Alteration.—Anthophyllite is often altered to talc. The partially altered mineral was formerly called *hydrous anthophyllite*.

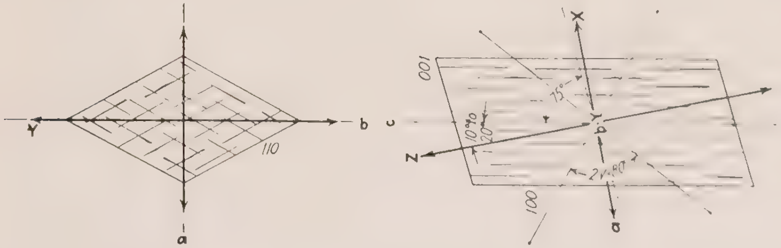
Occurrence.—Anthophyllite is characteristic of metamorphic rocks. It is the main constituent of anthophyllite schist and is also a secondary mineral in peridotites and dunites.

TREMOLITE

$H_2Ca_2(Mg,Fe)_5(SiO_3)_8$ (inc. Actinolite) Monoclinic

$$n_\alpha = 1.602 \text{ to } 1.623$$
$$n_\beta = 1.613 \text{ to } 1.638$$
$$n_\gamma = 1.624 \text{ to } 1.650$$
$$2V = 79 \text{ to } 85°;\ \text{Opt. } (-)$$
$$b = Y,\ c \wedge Z = -10 \text{ to } -20°$$

Color.—Colorless to pale green. The green varieties show faint pleochroism. Green ferriferous tremolite is known as *actinolite.*



(*a*) (*b*)

FIGS. 200 *a,b*.—Orientation diagrams of tremolite. Sections (*a*) normal to the *c*-axis and (*b*) parallel to (010).

Form.—Tremolite occurs in long prismatic crystals and columnar to fibrous aggregates. Asbestiform varieties are common. The typical cross section is rhombic with $(110 \wedge 1\bar{1}0) = 56°$.

Cleavage {110} in two directions at angles of about 56 and 124°. Longitudinal sections show cleavage traces parallel to the length.

Relief fairly high, $n >$ balsam.

Birefringence moderate, $n_\gamma - n_\alpha = 0.022$ to 0.027, so the interference colors range up to low or middle second order. Narrow longitudinal sections show the highest colors. Cross sections have white to yellow interference colors.

Extinction.—The maximum extinction in longitudinal sections varies from 10 to 20°. A few longitudinal sections have parallel or nearly parallel extinction. Cross sections have symmetrical extinction.

Orientation.—Elongate sections are length-slow. In cross sections the long diagonal is the slower ray.

Twinning.—Twins with {100} as twin-plane are frequent. Fine polysynthetic twinning with {001} as twin-plane is occasionally encountered.

Interference Figure.—Tremolite gives a biaxial negative figure with very large axial angle. The axial plane is {010}. Dispersion, $r < v$ weak. Broad elongate sections with low interference colors give the best figure.

Distinguishing Features.—The extinction angle and amphibole cross sections are characteristic. Wollastonite has the same general appearance as tremolite, but the trace of the optic axial plane is normal to the cleavage instead of parallel to it as in tremolite.

Alteration.—Tremolite is sometimes found altered to talc.

Occurrence.—Tremolite occurs in contact-metamorphic deposits, in schists and gneisses, and in metamorphic limestones. It is also found as a replacement of pyroxene in igneous rocks.

HORNBLENDE

Ca,Mg,Fe,Al silicate Monoclinic

$$n_\alpha = 1.614 \text{ to } 1.675$$
$$n_\beta = 1.618 \text{ to } 1.691$$
$$n_\gamma = 1.633 \text{ to } 1.701$$
$$2V = 52 \text{ to } 85°; \text{ Opt. } (-)$$
$$b = Y,\ c \wedge Z = -12 \text{ to } -30°$$

Color.—Green or brown of various tones. Pleochroism as follows:

X	Y	Z
Yellow green	Olive green	Dark green
Pale green	Green	Dark green
Pale brown	Greenish	Dark green
Yellow green	Yellow	Brown
Greenish brown	Reddish brown	Red brown

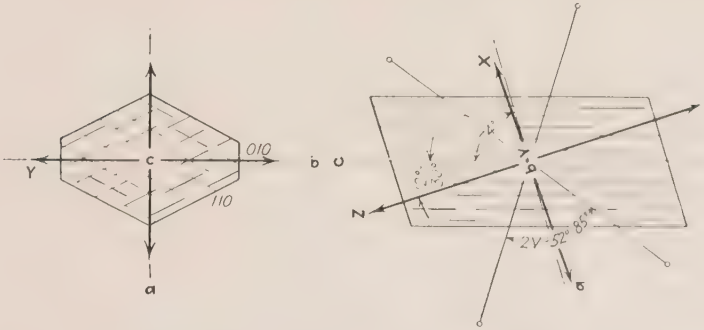
Absorption scheme, Z > Y > X.

Form.—Crystals are prismatic in habit with pseudo-hexagonal cross sections (110 ∧ 110 = 55°49′).

Cleavage {110} in two directions at angles of 56 and 124°.

Relief rather high, $n >$ balsam.

Birefringence rather strong, $n_\gamma - n_\alpha = 0.019$ to 0.026. The maximum interference colors are about middle second order, but in many varieties the color of the mineral modifies or even masks the interference colors.



(a) (b)

Figs. 201 *a*,*b*.—Orientation diagrams of hornblende. Sections (*a*) normal to the *c*-axis and (*b*) parallel to (010).

Extinction.—The maximum extinction angle in longitudinal sections varies from about 12 to about 30°. In cross sections the extinction is symmetrical to the outlines or to cleavage traces.

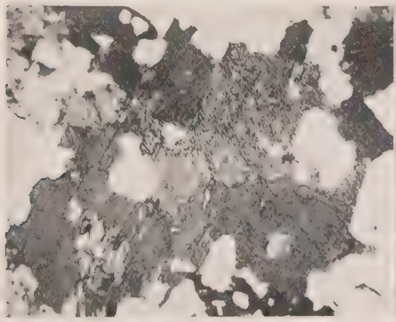


Fig. 202.

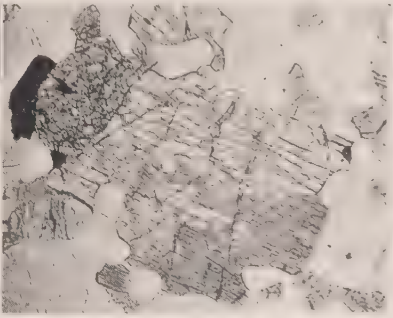


Fig. 203.

Fig. 202.—(×13) Hornblende in norite.
Fig. 203.—(×12) Late magmatic hornblende (dark) formed at the expense of pyroxene.

Twinning.—Twins with {100} as the twin-plane are rather common. Twinning is often manifest as twin-seams.

Interference Figure.—The figure is biaxial negative with a large axial angle. The axial plane is {010}. Dispersion, $r < v$ weak.

Distinguishing Features.—Hornblende differs from augite in cleavage, pleochroism, and maximum extinction angle. Brown hornblende resembles biotite, but the latter has better cleavage (in one direction only) and parallel or almost parallel extinction. Basaltic hornblende has a smaller extinction angle and stronger birefringence.

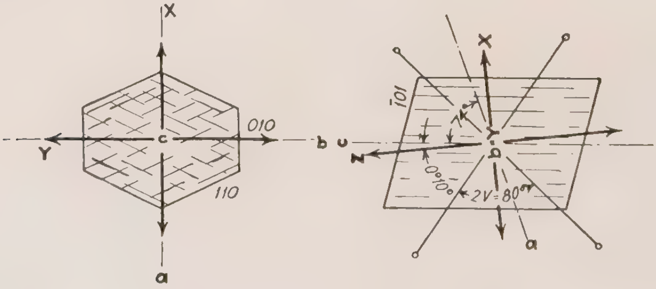
Occurrence.—Hornblende is a very common and widely distributed mineral in many types of igneous rocks. It also occurs in schists, gneisses, and amphibolites. It is a prominent constituent of many detrital sediments.

BASALTIC HORNBLENDE

Ca,Mg,Fe,Al silicate Monoclinic

$$n_\alpha = 1.680$$
$$n_\beta = 1.725$$
$$n_\gamma = 1.752$$
$$2V = 79 \text{ to } 80°;\ \text{Opt. } (-)$$
$$b = Y,\ c \wedge Z = 0 \text{ to } -10°$$

Basaltic hornblende is not, as the name implies, a variety of hornblende. It is an independent mineral of the amphibole group.



(a) (b)

FIGS. 204 *a*,*b*.—Orientation diagrams of basaltic hornblende. Sections (*a*) normal to the *c*-axis and (*b*) parallel to (010).

Color.—Yellow to brown, often with opaque borders. Pleochroism rather strong: X, light yellow; Y, brown; Z, dark brown.

Form.—Basaltic hornblende occurs almost invariably in euhedral crystals with the pseudo-hexagonal cross section of the amphiboles. The habit is short prismatic.

Cleavage {110} in two directions at angles of 56 and 124° as in the other amphiboles.

Relief high, $n >$ balsam.

Birefringence extreme, $n_\gamma - n_\alpha = 0.072$. The interference colors should be high order, but they are usually masked by the color of the mineral.

Extinction.—The maximum extinction angle is very small, from almost parallel up to as much as 10° in some varieties.

Orientation.—The crystals are length-slow. Cross sections have symmetrical extinction.

Twinning.—Twins with {100} as twin-plane are found but are not conspicuous on account of the small size of the extinction angle.

Interference Figure.—The figure is biaxial negative with a large axial angle. The axial plane is {010}. Dispersion, $r < v$.

Distinguishing Features.—Basaltic hornblende is distinguished from ordinary brown hornblende by the smaller extinction angle and the stronger birefringence. Biotite shows no cleavage in six-sided sections.

Occurrence.—Basaltic hornblende occurs in volcanic rocks such as andesites, auganites, basalts, and the corresponding tuffs. It is also common as a detrital mineral.

It seems likely that basaltic hornblende has been produced from ordinary hornblende by the oxidation of the iron, possibly by hot gases at the end of the magmatic stage.

Riebeckite

(inc. Crocidolite)

$NaFe^{III}(SiO_3)_2.Fe^{II}SiO_3$ Monoclinic

$$n_\alpha = 1.693$$
$$n_\beta = 1.695$$
$$n_\gamma = 1.697$$
$$2V \text{ large; Opt. } (-)$$
$$b = Y,\ c \wedge X = +5°$$

Color.—Dark blue. Pleochroism strong: X, deep blue; Y, lighter blue; Z, greenish. Absorption, X > Y > Z.

Form.—Riebeckite occurs in subhedral prismatic crystals and in fibrous and asbestiform aggregates. According to recent investigations crocidolite is a fibrous variety of riebeckite.

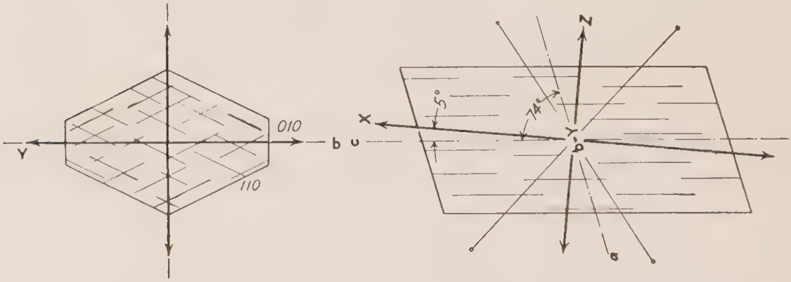
Cleavage {110} in two directions at angles of about 56 and 124°.

Relief high, $n >$ balsam.

Birefringence very weak; $n_\gamma - n_\alpha = 0.004$; the interference colors are masked by the deep color of the mineral.

Extinction.—The maximum extinction angle in elongate sections is about 5°, but the fibrous variety, crocidolite, has parallel extinction.

Orientation.—The crystals are length-fast.



(*a*) (*b*)

FIGS. 205 *a,b*.—Orientation diagrams of riebeckite. Sections (*a*) normal to the *c*-axis and (*b*) parallel to (010).

Interference Figure.—The figure is biaxial negative with a large axial angle. The axial plane is {010}. Dispersion, $r > v$ strong.

Distinguishing Features.—The color, pleochroism, and small extinction angle are distinctive.

Occurrence.—Riebeckite is characteristic of soda-rich granites, microgranites, granite pegmatites, syenites, and trachytes. Crocidolite is found in certain highly siliceous metamorphic rocks such as the "ironstones" of Griqualand West, South Africa.

Glaucophane

$Na(Al,Fe)(SiO_3)_2$ Monoclinic

$$n_\alpha = 1.621$$
$$n_\beta = 1.638$$
$$n_\gamma = 1.639$$
$$2V = 45°;\ \text{Opt.}\ (-)$$
$$b = Y;\ c \wedge Z = -4 \text{ to } -6°$$

Color.—Blue to violet. Pleochroism: X, neutral; Y, violet; Z, blue.

Form.—Glaucophane occurs in prismatic crystals or columnar aggregates. The cross sections are pseudo-hexagonal.

Cleavage {110} in two directions at angles of 56 and 124°.

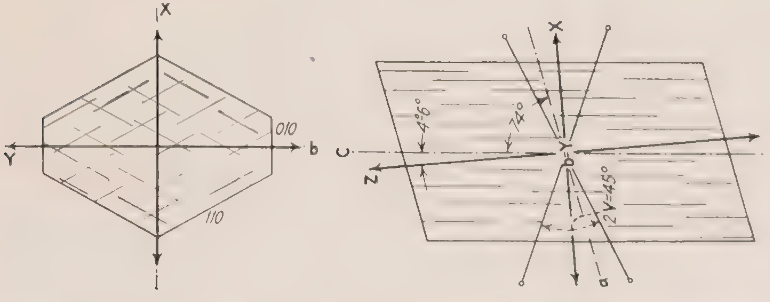
Relief fairly high, $n >$ balsam.

Birefringence moderate, $n_\gamma - n_\alpha = 0.018$; the maximum interference color is about sensitive violet, but the color of the mineral may modify or even mask the interference colors.

Extinction.—The maximum extinction angle in longitudinal sections is very small (4 to 6°). Cross sections have symmetrical extinction.

Orientation.—The crystals are length-slow.

Interference Figure.—The figure is biaxial negative with a moderate axial angle. The axial plane is {010}. Dispersion, $r < v$ strong.



(*a*) (*b*)

Figs. 206 *a*,*b*.—Orientation diagrams of glaucophane. Sections (*a*) normal to the *c*-axis and (*b*) parallel to (010).

Distinguishing Features.—The axial colors, together with the small extinction angle and amphibole cross section and cleavage, distinguish glaucophane from all other minerals.

Occurrence.—Glaucophane is found in certain schists and gneisses. The usual associates are muscovite, quartz, garnet, titanite, lawsonite, and clinozoisite. Glaucophane schists are abundant in the Coast Ranges of California and are also found in Syra (Greece), Italy, and Japan, but are rare taken the world over.

THE OLIVINE GROUP

The olivine group consists of the two end members, forsterite and fayalite, and the intermediate isomorphous mixture, olivine. There are also tephroite, Mn_2SiO_4; larnite, Ca_2SiO_4; and the double salt, monticellite, $CaMgSiO_4$, but these are rare minerals. The crystal system is orthorhombic.

THE OLIVINE GROUP

Mineral	Chemical composition	n_α	n_β	n_γ	2V
Forsterite	Mg_2SiO_4	1.635 1.640	1.651 1.660	1.670 1.680	85–90°
OLIVINE	$(Mg,Fe)_2SiO_4$	1.651 1.672	1.667 1.690	1.685 1.709	70–90°
Fayalite	Fe_2SiO_4	1.835	1.877	1.886	47–50°

Minerals of the olivine group are characterized by rather high refractive indices and strong birefringence. The axial angle is very large.

Olivine is exceedingly abundant as a rock-forming mineral in subsilicic igneous rocks. Forsterite is practically limited to metamorphic limestones. Fayalite is found in granite pegmatites, in lithophysae of rhyolitic obsidians, and in some ores, but it is rather rare.

Forsterite

Mg_2SiO_4 Orthorhombic

$$n_\alpha = 1.635 \text{ to } 1.640$$
$$n_\beta = 1.651 \text{ to } 1.660$$
$$n_\gamma = 1.670 \text{ to } 1.680$$
$$2V = 85 \text{ to } 90°; \text{Opt. } (+)$$
$$a = Z,\ b = X,\ c = Y$$

Color.—Colorless.

Form.—Forsterite usually occurs in euhedral to subhedral crystals.

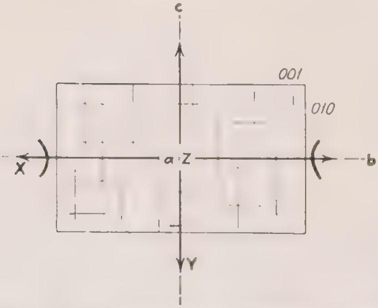


FIG. 207.—Orientation diagram of forsterite. Section parallel to (100).

Relief fairly high, $n >$ balsam. The indices increase with increasing iron content.

Cleavage {010} imperfect. Irregular fractures common.

Birefringence strong, $n_\gamma - n_\alpha = 0.035$ to 0.040. The maximum interference color is upper second order.

Extinction parallel to crystal outlines and cleavage traces.

Orientation.—Crystals showing cleavage are length-slow.

Interference Figure.—The interference figure is biaxial positive with a very large axial angle. The axial plane is {001}. Dispersion, $r < v$.

Distinguishing Features.—Forsterite is an iron-free olivine and so resembles ordinary olivine but has somewhat lower indices of refraction. (See also under Alteration.)

Alteration.—Forsterite is often altered to antigorite, but the secondary magnetite so common with altered olivine is absent.

Occurrence.—Forsterite occurs for the most part in metamorphic limestones. Phlogopite is a common associate.

OLIVINE

$(Mg,Fe)_2SiO_4$ (Chrysolite) Orthorhombic

$$n_\alpha = 1.651 \text{ to } 1.672$$
$$n_\beta = 1.667 \text{ to } 1.690$$
$$n_\gamma = 1.685 \text{ to } 1.709$$
$$2V = 70 \text{ to } 90°\text{; Opt. } (+)$$
$$a = Z,\ b = X,\ c = Y$$

Color.—Colorless.

Form.—Olivine, also known as chrysolite, occurs in anhedra with polygonal outlines and in phenocrysts with the characteristic outline of Fig. 115, page 118, which is a section parallel to {100}.

Cleavage imperfect parallel to {010}, irregular fractures common.

Relief fairly high, $n >$ balsam.

Birefringence strong, $n_\gamma - n_\alpha = 0.034$ to 0.037; the maximum interference color is upper second order.

Extinction parallel to crystal outlines and cleavage traces.

Orientation.—Crystals showing cleavage are length-slow.

Twinning is sometimes found, but the lamellae are broad and not well defined.

Interference Figure.—The interference figure is biaxial positive with a large axial angle. Olivine high in iron is optically negative. The axial plane is {001}. Dispersion, $r < v$.

Distinguishing Features.—The mineral most apt to be mistaken for olivine is diopside, but diopside has better cleavage, oblique extinction, and somewhat weaker birefringence.

Alteration.—Olivine commonly shows alteration to antigorite and secondary magnetite along irregular fractures (see Fig. 139, page 174). In basaltic rocks the alteration to brownish red iddingsite is fairly common (see Fig. 252, page 291).

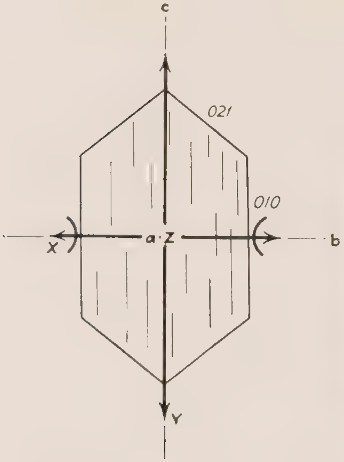


FIG. 208.—Orientation diagram of olivine. Section parallel to (100).

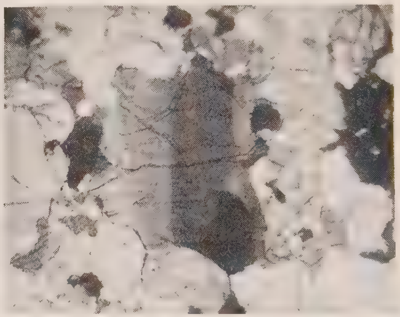


FIG. 209.—(×9) Twinned olivine in dunite. (× nicols.)

Occurrence.—Olivine is an exceedingly common mineral in subsilicic igneous rocks such as basalts, olivine gabbros, and peridotites. In the rock dunite it is the dominant mineral. It is a relict mineral in many serpentines (see Fig. 115, page 118). Locally, olivine may be important as a detrital mineral.

Chondrodite

$2\ Mg_2SiO_4.Mg(OH,F)_2$ Monoclinic

$$n_\alpha = 1.601 \text{ to } 1.643$$
$$n_\beta = 1.616 \text{ to } 1.655$$
$$n_\gamma = 1.636 \text{ to } 1.670$$
$$2V = 72 \text{ to } 90°; \text{ Opt. } (+)$$
$$b = Z,\ a \wedge X = -26 \text{ to } -31°$$

Color.—Colorless to yellowish or brownish. The deeper colored varieties are pleochroic from neutral to brown or pale brown to red brown, etc.

Form.—Chondrodite is commonly found in subhedral crystals which are often rounded and in large anhedra. Although the mineral is monoclinic, the angle β between the a- and c-axes is 90°.

Cleavage practically absent.

Relief fairly high, $n >$ balsam.

Birefringence strong, $n_\gamma - n_\alpha = 0.027$ to 0.035; the maximum interference color varies from green to red of the second order for different varieties.

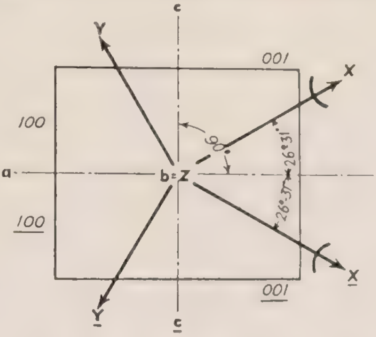


Fig. 210.—Orientation diagram of chondrodite. Twin-crystal with (001) as twin-plane. Section parallel to (010).

Extinction.—The maximum extinction angle measured from the trace of the twin-plane {001} varies from −26 to −31°.

Orientation.—The extinction direction nearest the trace of the twin-plane is the faster ray.

Twinning.—Twinning, which may appear as simple twins, twin seams, or polysynthetic twins, is rather common. The twin-plane is {001}. Without twinning it is very difficult to orient chondrodite.

Interference Figure.—The figure is biaxial positive with a large axial angle. The axial plane is normal to {010}. Dispersion, $r > v$ weak.

Distinguishing Features.—Three other minerals of the chondrodite group, *viz.*, norbergite, humite, and clinohumite, are similar to chondrodite. The distinction is based upon extinction angles and refractive indices.

Occurrence.—Chondrodite is one of the characteristic minerals of metamorphic limestone. It is often associated with phlogopite and spinel.

GARNET GROUP

Grossularite,	$Ca_3Al_2(SiO_4)_3$	$n = 1.744–1.757$	Isometric
Pyrope,	$Mg_3Al_2(SiO_4)_3$	$n = 1.741–1.750$	
Almandite,	$Fe_3Al_2(SiO_4)_3$	$n = 1.802–1.811$	
Andradite,	$Ca_3Fe_2(SiO_4)_3$	$n = 1.856–1.889$	

Color.—Colorless, pale reddish, pale to dark brown, greenish gray, etc.

Form.—Euhedral dodecahedral crystals in six-sided sections and trapezohedral crystals in eight-sided sections are common. Garnet also occurs in polygonal grains, aggregates, and masses. Inclusions are frequent.

Cleavage absent but may have parting parallel to {110}. Irregular fractures characteristic.

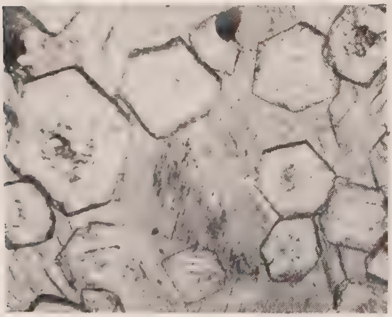


Fig. 211.—(×20) Euhedral garnet crystals in schist.

Relief very high, surface rough; $n >$ balsam.

Birefringence.—Most varieties are dark between crossed nicols but some have weak double refraction. The birefringent areas are often arranged in zones or sectors.

Distinguishing Features.—Garnet resembles spinel, but the latter occurs in octahedra. The different kinds of garnet may be determined by indices of refraction.

Occurrence.—Garnet is especially characteristic of metamorphic rocks. It is also a very common detrital mineral. Almandite is the common garnet of schists and gneisses. Pyrope is practically confined to peridotites and derived serpentines. Grossularite and andradite are common in contact-metamorphic zones. Melanite, a deep brown variety of andradite, occurs in soda-rich igneous rocks such as nepheline syenites, phonolites, etc.

Wollastonite

$CaSiO_3$ Monoclinic

$$n_\alpha = 1.614 \text{ to } 1.621$$
$$n_\beta = 1.629 \text{ to } 1.633$$
$$n_\gamma = 1.631 \text{ to } 1.635$$
$$2V = 39 \text{ to } 40^\circ;\ \text{Opt.}\ (-)$$
$$b = Y,\ c \wedge X = +32^\circ$$

Color.—Colorless.

Form.—Wollastonite usually appears in columnar or fibrous aggregates. The cross sections are nearly rectangular.

Cleavage in two directions {100} and {001} at angles of about 84½ and 95½°.

Relief fairly high, $n >$ balsam.

Birefringence moderate, $n_\gamma - n_\alpha = 0.014$ to 0.017; the maximum interference color is about orange of the first order. Longitudinal sections show gray or white interference colors.

Extinction parallel in longitudinal sections, oblique in cross sections.

Orientation.—Longitudinal sections are either length-slow or length-fast since the elongation is in the direction of the b-axis and $b = Y$.

Twinning.—Twins with {100} as twin-plane are known.

Interference Figure.—The figure is biaxial negative with a moderate axial angle. Since the axial plane is {010}, the figure lies normal to the length of the crystals. Dispersion, $r > v$.

Distinguishing Features. — Tremolite very much resembles wollastonite not only in thin sections but in hand specimens as well. Tremolite, however, has oblique extinction and the typical amphibole cross section and cleavage. In tremolite the interference figure lies along the length of the crystal; in wollastonite it lies normal to the length.

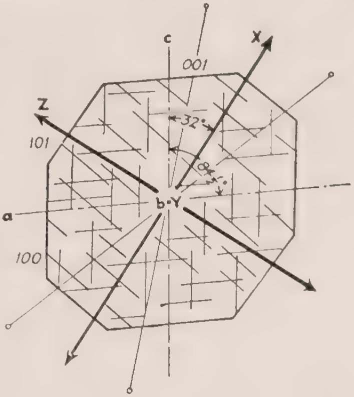


Fig. 212.—Orientation diagram of wollastonite. Section parallel to (010).

Occurrence. Wollastonite occurs in contact-metamorphic zones, in limestone inclusions in volcanic rocks, and in some schists and gneisses.

Beryl

$Be_3Al_2(SiO_3)_6$ Hexagonal
(Hexagonal Subsystem)

$$n_\epsilon = 1.564 \text{ to } 1.590$$
$$n_\omega = 1.568 \text{ to } 1.598$$
$$\text{Opt. } (-);\ c = X$$

Color.—Colorless.

Form.—Beryl usually occurs in rather large crystals of prismatic habit and in massive form. Liquid inclusions with gas bubbles in six-sided negative crystals are common.

Cleavage imperfect parallel to (0001), not usually seen in thin sections.

Relief moderate, $n >$ balsam.

Birefringence weak, $n_\omega - n_\epsilon = 0.004$ to 0.008; interference colors are gray, white, or straw of the first order.

Extinction.—Longitudinal sections have parallel extinction. Basal sections are dark in all positions.

Orientation.—Crystal sections are length-fast.

Interference Figure.—Basal sections give a negative uniaxial figure without any rings. The cross may show a slight opening in certain areas.

Distinguishing Features.—Beryl resembles apatite, but the latter has higher indices of refraction. From quartz it is distinguished by its length-fast character.

Occurrence.—The principal occurrence of beryl is in granite pegmatites. It is also found in mica schists and in veins in limestone.

Scapolite Group

(Wernerite)

$m[3NaAlSi_3O_8.Na(Cl,SO_4,CO_3)]$ Tetragonal
$n[3CaAl_2Si_2O_8.Ca(O,CO_3,SO_4)]$

$$n_\epsilon = 1.540 \text{ to } 1.571$$
$$n_\omega = 1.550 \text{ to } 1.607$$
$$\text{Opt. } (-);\ c = X$$

Scapolite is an isomorphous mixture of the two end members given above. The sodium end member is called *marialite*, and the calcium end member, *meionite*.

Color.—Colorless.

Form.—Minerals of the scapolite group usually occur in columnar aggregates. Crystals are usually rather large.

Relief low to fair, $n >$ balsam.

Cleavage distinct parallel to {100}, less distinct parallel to {110}. In most sections the cleavage traces are parallel to the length; in cross sections the cleavage shows in two directions at right angles.

Birefringence moderate to strong, $n_\omega - n_\epsilon = 0.010$ to 0.036. The maximum interference color varies from yellow of the first order up to second-order violet depending upon the chemical composition. The birefringence increases with calcium content.

Extinction parallel in most sections. Basal sections remain dark between crossed nicols.

Orientation.—The cleavage traces and main crystal outlines are parallel to the faster ray.

Interference Figure.—Basal sections give a uniaxial negative figure with a few rings. Longitudinal sections give a "flash figure."

Distinguishing Features.—Scapolite is similar to plagioclase but lacks twinning, has parallel extinction, and has stronger birefringence. Without chemical analyses it is difficult to determine the various kinds of scapolite, but the birefringence increases with the calcium content.

Alteration.—Scapolite is often altered to ill-defined fibrous aggregates.

Occurrence.—The characteristic occurrence of scapolite is contact-metamorphic limestones. It also occurs in certain gneisses and in some gabbros as a high-temperature alteration of plagioclase. It will be noted that the chemical composition is similar to the plagioclases but with added NaCl, $CaCO_3$, etc.

Vesuvianite

$Ca_2Al_2(OH,F)Si_2O_7$ Tetragonal

$$n_\epsilon = 1.701 \text{ to } 1.726$$
$$n_\omega = 1.705 \text{ to } 1.732$$
$$\text{Opt. } (-);\ c = X$$

Color.—Colorless to neutral. May be pleochroic in thick sections.

Form.—Vesuvianite occurs in euhedral crystals, in columnar aggregates, and in anhedra with polygonal outlines.

Cleavage absent.

Relief high, $n >$ balsam.

Birefringence very weak to weak, $n_\omega - n_\epsilon = 0.004$ to 0.006; interference colors are low first-order gray, sometimes normal, sometimes anomalous gray green or deep blue.

Extinction parallel.

Orientation length-fast in columnar aggregates.

Interference Figure.—The figure is usually uniaxial negative but may be biaxial with a small axial angle.

Distinguishing Features.—Anomalous vesuvianite resembles zoisite and clinozoisite and is often difficult to distinguish from them.

Occurrence.—The principal occurrence of vesuvianite is in contact-metamorphic zones. Associated minerals are garnet, diopside, wollastonite, and calcite. Vesuvianite is also found in association with serpentine as a kind of pseudo-jade (californite).

Zircon

$ZrSiO_4$ Tetragonal

$$n_\omega = 1.925 \text{ to } 1.931$$
$$n_\epsilon = 1.985 \text{ to } 1.993$$
$$\text{Opt. } (+); c = Z$$

Color.—Colorless to pale colors.

Form.—Zircon usually occurs in minute crystals of short prismatic habit. They are often found as inclusions and may be surrounded by pleochroic haloes.

Cleavage absent.

Relief very high, $n >$ balsam.

Birefringence extreme, $n_\epsilon - n_\omega = 0.060$ to 0.062; the maximum interference colors are usually pale tints of the fourth order, but minute crystals have lower interference colors.

Extinction parallel.

Orientation.—Crystals are length-slow.

Interference Figure.—The interference figure is uniaxial but may be difficult to obtain on account of the small size of the crystals.

Distinguishing Features.—Zircon is distinguished from apatite by stronger birefringence and higher relief.

Occurrence.—Zircon is a widely distributed mineral in grained igneous rocks. In some syenites it is prominent enough to furnish the name *zircon syenite.* Zircon also occurs in certain metamorphic rocks. It is one of the most widespread and abundant detrital minerals. Occasionally it is a prominent mineral in sandstone.

Topaz

$Al_2(F,OH)_2SiO_4$ Orthorhombic

$$n_\alpha = 1.607 \text{ to } 1.629$$
$$n_\beta = 1.610 \text{ to } 1.631$$
$$n_\gamma = 1.617 \text{ to } 1.638$$
$$2V = 48 \text{ to } 65°;\ \text{Opt. } (+)$$
$$a = X,\ b = Y,\ c = Z$$

Color.—Colorless.

Form.—Topaz appears in euhedral crystals of short prismatic habit, in anhedral grains, and in columnar aggregates. Negative crystals with fluid inclusions and gas bubbles are not uncommon.

Cleavage perfect in one direction parallel to {001}.

Relief fairly high, $n >$ balsam.

Birefringence rather weak, $n_\gamma - n_\alpha = 0.009$ to 0.010, about the same as quartz. Interference colors are gray, white, or straw yellow of the first order. Cleavage flakes show very weak birefringence since $n_\beta - n_\alpha = 0.003$.

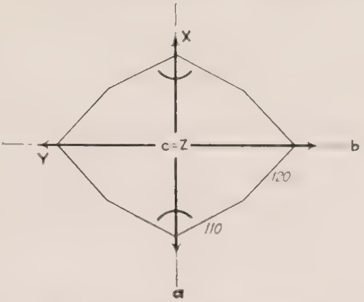


Fig. 213.—Orientation diagram of topaz. Section parallel to (001).

Extinction parallel in longitudinal sections and symmetrical in basal sections.

Orientation.—Cleavage traces are parallel to the faster ray.

Interference Figure.—Cleavage flakes and basal sections give a biaxial positive figure with a rather large axial angle. The axial plane is {010}. Dispersion, $r > v$ distinct.

Distinguishing Features.—Topaz resembles quartz but has higher relief and is biaxial.

Occurrence.—Topaz occurs in high-temperature veins, in granite pegmatites, and occasionally in rhyolites. Associated minerals are tourmaline, fluorite, cassiterite, and muscovite.

Andalusite

Al_2SiO_5 (inc. Chiastolite) Orthorhombic

$$n_\alpha = 1.632$$
$$n_\beta = 1.638$$
$$n_\gamma = 1.643$$
$$2V = 84°;\ \text{Opt. } (-)$$
$$a = Z,\ b = Y,\ c = X$$

Color.—Usually colorless, more rarely reddish. The colored variety is pleochroic from rose (Z) to pale green (Y) and (Z).

Form.—Andalusite usually occurs in euhedral crystals or coarse columnar aggregates. Cross sections are nearly square ($110{:}1\bar{1}0 = 89°12'$). Dark inclusions of carbonaceous matter are often present and arranged symmetrically to form a kind of cross. This variety is known as *chiastolite* (see Fig. 111, page 116).

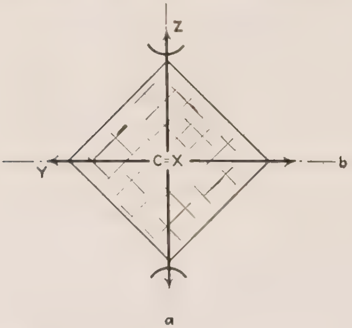


Fig. 214.—Orientation diagram of andalusite. Section parallel to (001).

Cleavage distinct parallel to {110}. In cross sections the cleavage traces are in two directions at approximately right angles.

Relief moderate, $n >$ balsam.

Birefringence moderate, $n_\gamma - n_\alpha = 0.011$, somewhat greater than that of quartz. Interference colors range up to first-order yellow.

Extinction parallel in most sections. Cross sections have symmetrical extinction.

Orientation.—Crystals or columnar aggregates are length-fast.

Interference Figure.—Cross sections give a negative biaxial figure with a very large axial angle. The axial plane is {010}.

Distinguishing Features.—Andalusite is distinguished from sillimanite by its length-fast character, weaker birefringence, and large axial angle. The colored variety resembles hypersthene but the latter is length-slow instead of length-fast.

Alteration.—The variety chiastolite is usually more or less altered to sericite along the lines of included carbonaceous matter.

Occurrence.—Andalusite occurs in granite pegmatites, and in the form of chiastolite it is a characteristic contact-metamorphic mineral in schists and slates. It is a rather common mineral.

Sillimanite

Al_2SiO_5 Orthorhombic

$$n_\alpha = 1.659$$
$$n_\beta = 1.661$$
$$n_\gamma = 1.680$$
$$2V = 20°; \text{Opt. } (+)$$
$$a = X, b = Y, c = Z$$

Color.—Colorless.

Form.—Sillimanite usually occurs in small, often minute, slender prismatic crystals and in a felted mass of fibers.

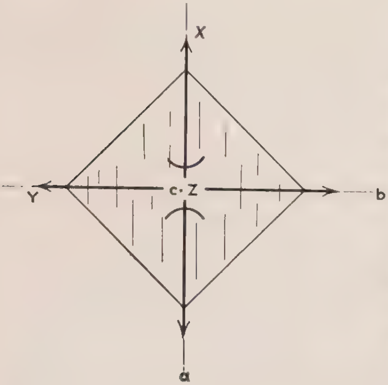


FIG. 215.—Orientation diagram of sillimanite. Section parallel to (001).

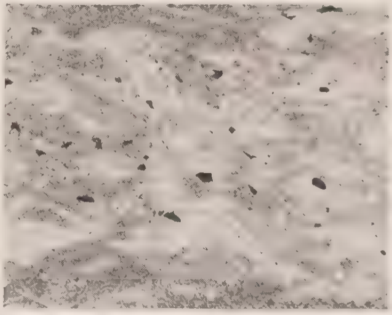


FIG. 216.—(×12) Sillimanite in quartz.

Cleavage parallel to {010} but rarely noticed in sections. Transverse fractures are common.

Relief fairly high, $n >$ balsam.

Birefringence rather strong, $n_\gamma - n_\alpha = 0.021$, so the interference colors range up to second-order blue.

Extinction parallel.

Orientation.—The crystals or fibers are length-slow.

Interference Figure.—On account of the small size of the crystals, good figures are rarely obtained. The axial plane is {010}. Dispersion, $r > v$ strong.

Distinguishing Features. Sillimanite is distinguished from andalusite by its length-slow character, stronger birefringence, and smaller axial angle. At times it resembles apatite but the latter is length-fast and has weaker birefringence.

Occurrence.—Sillimanite is found in gneisses, schists, slates, hornfels, and other metamorphic rocks. The more common associates are corundum, andalusite, kyanite, dumortierite, and cordierite.

Kyanite

Al_2SiO_5 Triclinic

$$n_\alpha = 1.712$$
$$n_\beta = 1.720$$
$$n_\gamma = 1.728$$
$$2V = 82°;\ \text{Opt.}\ (-)$$
$$\text{Ax. pl. } ca. \perp \{100\};\ c \wedge Z\ ca.\ -30°$$

Fig. 104, Page 114

Color.—Colorless to pale blue. Pleochroic in thick sections.

Form.—The characteristic sections of kyanite are broad elongate plates tabular parallel to {100}.

Cleavage perfect parallel to {100}, imperfect parallel to {010}, also cross parting {001} at angles of 85° with the length of the crystals.

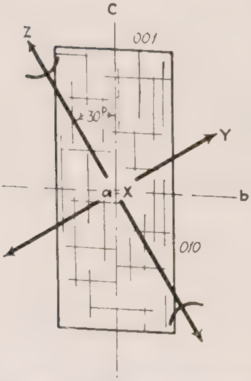


Fig. 217. Orientation diagram of kyanite. Section parallel to (100).

Relief high, $n >$ balsam.

Birefringence moderate, $n_\gamma - n_\alpha = 0.016$; hence interference colors range up to first-order red.

Extinction angle on {100} is about 30° with the length of the crystals. In other sections parallel to the c-axis the extinction angle is small, sometimes practically zero.

Orientation.—The extinction direction nearest the c-axis is the slow ray.

Twinning.—Twinning is frequent; there are two common twin-laws: (1) {100} = twin-plane, (2) {001} = twin-plane.

Interference Figure.—Sections cut parallel to {100} or cleavage flakes give a negative biaxial figure with a large axial angle. The axial plane makes an angle of 30° with the trace of the c-axis. Dispersion, $r > v$.

Distinguishing Features.—The extinction angle of 30° together with the biaxial interference figure obtained from the broad sections is distinctive for kyanite.

Occurrence.—Kyanite occurs in schists and gneisses associated with quartz, muscovite, garnet, staurolite, and rutile. It never occurs in igneous rocks. It is also found as a detrital mineral.

Mullite

$3Al_2O_3.2SiO_2$ Orthorhombic

$$n_\alpha = 1.642$$
$$n_\beta = 1.644$$
$$n_\gamma = 1.654$$
$$2V = 45 \text{ to } 50°; \text{Opt. } (+)$$
$$a = X, b = Y, c = Z$$

Color.—Colorless.

Form.—Mullite occurs in crystals of long prismatic habit with nearly square cross section.

Cleavage {010}, distinct.

Relief rather high, $n >$ balsam.

Birefringence moderate, $n_\gamma - n_\alpha = 0.012$; the maximum interference color is about first-order yellow. Cross sections have dark gray interference colors since $n_\beta - n_\alpha = 0.002$.

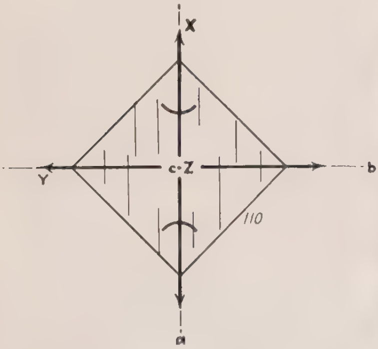


Fig. 218.—Orientation diagram of mullite. Section parallel to (001).

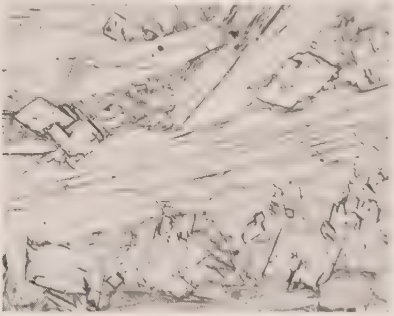


Fig. 219.—(×16) Artificial mullite.

Extinction parallel in longitudinal sections and symmetrical in cross sections.

Orientation.—The crystals are length-slow.

Interference Figure.—The figure is biaxial positive with a moderate axial angle. The axial plane is {010}.

Distinguishing Features.—Mullite is so much like sillimanite in its properties that it was not recognized as a distinct mineral until about a decade ago. The refractive indices of sillimanite are a little higher and the axial angle lower than that of mullite.

Occurrence.—Mullite occurs in fused argillaceous sediments found as inclusions in igneous intrusions. Only one locality is known for this mineral, the original locality in the island of Mull.

ARTIFICIAL MULLITE

Artificial mullite is the substance formed by heating sillimanite, andalusite, or kyanite to a high temperature. It is used in the manufacture of high-grade porcelains such as those used in spark plugs for automobiles. Mullite is also found in ordinary porcelain as minute prismatic crystals.

Dumortierite

$HBAl_8Si_3O_{20}$ Orthorhombic

$$n_\alpha = 1.675$$
$$n_\beta = 1.685$$
$$n_\gamma = 1.690$$
$$2V = 30 \text{ to } 40°;\ \text{Opt.}\ (-)$$
$$a = Z,\ b = Y,\ c = X$$

Color.—Colorless to blue, lavender, pink, or reddish. Pleochroic from colorless to blue or colorless to reddish with the greatest absorption when the length of the crystal is parallel to the vibration plane of the lower nicol.

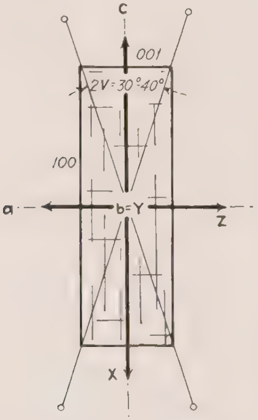


FIG. 220.—Orientation diagram of dumortierite. Section parallel to (010).

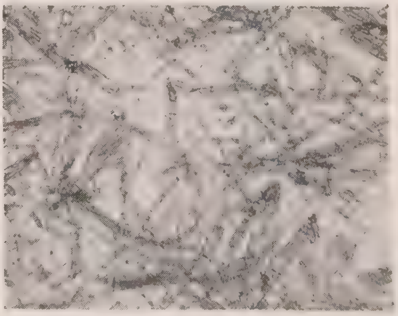


FIG. 221.—(×12) Dumortierite in schist.

Form.—Dumortierite occurs in prismatic to acicular crystals, which often form a felt of fibers. Cross sections are pseudohexagonal on account of twinning.

Cleavage imperfect parallel to the length. There are also cross fractures.

Relief high, $n >$ balsam.

Birefringence moderate, $n_\gamma - n_\alpha = 0.015$, so the maximum interference color is about orange of the first order.

Extinction parallel in most sections.

Orientation.—The crystals are length-fast.

Twinning.—Cross sections are sometimes penetration trillings with {110} as the twin-plane.

Interference Figure.—The interference figure is biaxial negative with a moderate axial angle, but on account of the small size of the crystals it may be difficult to obtain. The axial plane is {010}. Dispersion, $r < v$.

Distinguishing Features.—Dumortierite resembles some varieties of tourmaline, but the greater absorption is manifest when the crystals are parallel to the vibration plane of the lower nicol instead of normal to that direction. Non-pleochroic dumortierite resembles sillimanite but the latter is length-slow.

Alteration.—Dumortierite is sometimes more or less altered to sericite.

Occurrence.—Dumortierite occurs in pegmatites, schists, gneisses, and other metamorphic rocks. The common associates are quartz, muscovite, tourmaline, andalusite, sillimanite, topaz, and rutile.

TOURMALINE GROUP

(SCHORLITE, Elbaite, Dravite)

$R_9^{I}Al_3B_2(OH)_2Si_4O_{19}$ Hexagonal

Where R^{I} = Na,Li,Fe'',Mg (Rhombohedral Subsystem)

$$n_\epsilon = 1.615 \text{ to } 1.675$$
$$n_\omega = 1.633 \text{ to } 1.685$$
$$\text{Opt. } (-);\ c = X$$

Color. Colorless, smoke gray, bluish, pale brown, to almost black. The color is not always uniform, and zonal structure is often present. All colored varieties are pleochroic, with the greater absorption when the length of the crystal is normal to the vibration plane of the lower nicol. Basal sections are sometimes almost dark even with one nicol.

Form. Tourmaline occurs in short to long prismatic crystals and in columnar to fibrous aggregates which are more or less radiating. Cross sections are usually three or six sided.

Cleavage absent but cross fractures are very common. There is sometimes a parting parallel to the length of the crystal.

Relief high, $n >$ balsam.

Birefringence moderate to strong, $n_\omega - n_\epsilon = 0.010$ to 0.018, usually about 0.025. The maximum interference color is usually about middle second order, but the colors may be masked by the color of the mineral.

FIG. 222. (×12) Tourmaline in quartz.

Extinction parallel in most sections. Cross sections are dark in all positions.

Orientation.—The crystals are length-fast, but it is not always possible to make this test on account of the color masking the interference color.

Interference Figure.—Unless they are too dark, basal sections give a negative uniaxial interference figure.

Distinguishing Features.—The absence of cleavage, together with strong absorption when the section is normal to vibration plane of the lower nicol, is distinctive for nearly all varieties of tourmaline. Colorless tourmaline (elbaite) may be difficult to distinguish in thin sections.

Minerals of the Tourmaline Group.—There are three fairly distinct kinds of tourmaline minerals: (1) The common black iron-bearing tourmaline is *schorlite.* (2) The pink, green, or blue alkali tourmaline is called *elbaite.* (3) The brown magnesium tourmaline is known as *dravite.*

Occurrence.—The most characteristic occurrence of tourmaline is in granite pegmatites, but it is also found in granites, high-temperature veins, schists, metamorphic limestones (dravite), and as a detrital mineral (often in much rounded grains).

Axinite

$H(Fe,Mn)Ca_2Al_2B(SiO_4)_4$ Triclinic

$$n_\alpha = 1.678$$
$$n_\beta = 1.685$$
$$n_\gamma = 1.688$$
$$2V = 70 \text{ to } 75°; \text{ Opt. } (-)$$

Color.—Colorless to pale violet. It may show pleochroism in thick sections.

Form.—Axinite usually occurs in anhedral crystals with acute-angled sections. Inclusions are frequent.

Cleavage imperfect.

Relief fairly high, $n >$ balsam.

Birefringence rather weak, $n_\gamma - n_\alpha = 0.010$, about the same as that of quartz.

Extinction oblique to outlines and to cleavage traces.

Interference Figure.—The figure is biaxial negative with a large axial angle. Dispersion, $r < v$ distinct.

Distinguishing Features.—Axinite has no very distinctive features and is difficult to recognize. Its birefringence is like that of quartz, but its refractive indices are considerably higher. It is biaxial while quartz is uniaxial.

Occurrence.—Axinite occurs in contact-metamorphic zones often associated with quartz and calcite. It is a comparatively rare mineral, but in a contact-metamorphic rock known as limurite it forms more than 50 per cent of the rock.

Zoisite

$Ca_2(Al,Fe)_3(OH)(SiO_4)_3$ Orthorhombic

$$n_\alpha = 1.696 \text{ to } 1.700$$
$$n_\beta = 1.696 \text{ to } 1.703$$
$$n_\gamma = 1.702 \text{ to } 1.718$$
$$2V = 30 \text{ to } 60°; \text{ Opt. } (+)$$

Two orientations:

(1) $a = Z, b = Y, c = X$

(2) $a = Z, b = X, c = Y$

Color.—Usually colorless, but a manganese-bearing variety (thulite) is pink and pleochroic.

Form.—Zoisite usually occurs in columnar aggregates.

Cleavage perfect in one direction {010}.

Relief high, $n >$ balsam.

Birefringence weak to moderate, $n_\gamma - n_\alpha = 0.006$ to 0.018; the interference colors in one variety (2) are normal; in the other variety (1) they are anomalous (deep blue).

Extinction parallel in most sections.

Orientation.—In some specimens (1) the crystals are length-fast; in others (2) either length-fast or length-slow.

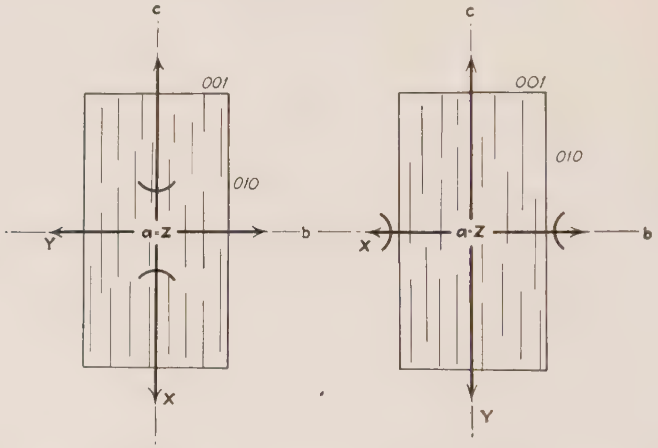


Fig. 223. Fig. 224.

Figs. 223, 224.—Orientation diagrams of zoisite. Sections parallel to (100). Fig. 223.—Orientation (1). Fig. 224—Orientation (2).

Twinning.—Polysynthetic twinning may be present.

Interference Figure.—The interference figure is biaxial positive with a moderate axial angle. The axial plane is either (1) $\{010\}$ or (2) $\{001\}$. Dispersion, (1) $r < v$ distinct or (2) $r > v$ distinct.

Distinguishing Features.—There are two varieties of zoisite: a non-ferriferous variety with orientation (1) and anomalous interference colors, which resembles clinozoisite; and a ferriferous variety with orientation (2) and normal interference colors which is difficult to identify. Clinozoisite is much more common than zoisite.

Occurrence.—Zoisite is a rather rare mineral found in some metamorphic rocks.

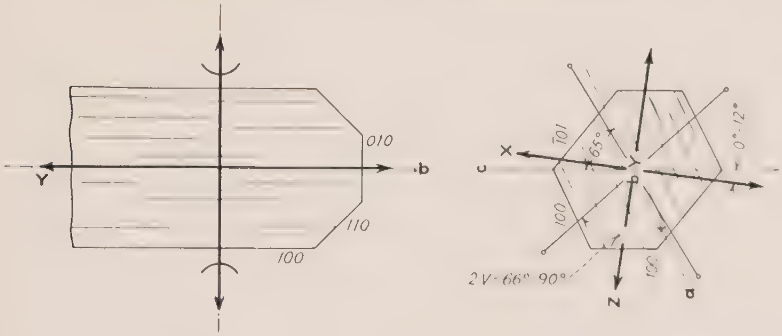
Clinozoisite

$Ca_2Al_3(OH)(SiO_4)_3$ Monoclinic

$$n_\alpha = 1.710 \text{ to } 1.723$$
$$n_\beta = 1.715 \text{ to } 1.729$$
$$n_\gamma = 1.719 \text{ to } 1.734$$
$$2V = 66 \text{ to } 90°; \text{Opt. } (+)$$
$$b = Y, c \wedge X = 0 \text{ to } +12°$$

Color.—Colorless and non-pleochroic.

Form.—Clinozoisite, an iron-free or iron-poor epidote, usually occurs in elongated crystals or columnar aggregates.



(a) (b)

FIGS. 225 *a,b*.—Orientation diagrams of clinozoisite. Sections (*a*) normal to the *c*-axis and (*b*) parallel to (010).

Cleavage perfect in one direction {001}.

Relief high, $n >$ balsam.

Birefringence weak, $n_\gamma - n_\alpha = 0.009$ to 0.011; interference colors are middle first order but anomalous. The gray is somewhat blue, white is absent, and the yellow is greenish yellow. Upper first-order colors of thicker sections are normal.

Extinction.—The extinction is parallel, since the crystals are nearly always elongated in the direction of the *b*-axis.

Orientation.—Some sections are length-slow and some length-fast since $b = Y$.

Twinning.—Polysynthetic twinning with {100} as twin-plane may be found in some specimens.

Interference Figure.—The interference figure is biaxial positive with large to very large axial angle. The axial plane is {010}. Dispersion, $r < v$ strong.

Distinguishing Features.—Clinozoisite is distinguished from epidote by weaker birefringence and lack of pleochroism and from zoisite by the distinctive yellow-green interference color and larger axial angle.

Occurrence.—The occurrence of clinozoisite is practically the same as that of epidote. It is a rather common and widely distributed mineral and has often been identified as zoisite.

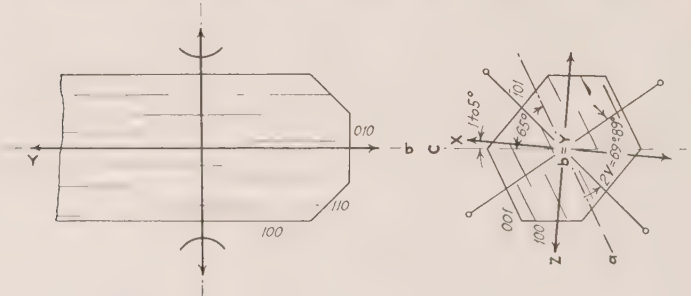
EPIDOTE

$Ca_2(Al,Fe)_3(OH)(SiO_4)_3$ Monoclinic

$$n_\alpha = 1.720 \text{ to } 1.734$$
$$n_\beta = 1.724 \text{ to } 1.763$$
$$n_\gamma = 1.734 \text{ to } 1.779$$
$$2V = 69 \text{ to } 89°; \text{Opt. } (-)$$
$$b = Y, c \wedge X = +1 \text{ to } +5°$$

Color.—Colorless to yellowish green, not usually uniform. The mineral is somewhat pleochroic.

Form.—Epidote occurs in granular to columnar aggregates and in more or less distinct crystals which are elongated in the direction of the b-axis and have a pseudo-hexagonal cross section with the forms {001}, {100}, and {$\bar{1}01$}.



(a) (b)

Figs. 226 *a*,*b*.—Orientation diagram of epidote. Sections (*a*) normal to the *c*-axis and (*b*) parallel to (010).

Cleavage perfect in one direction {001}.

Relief high, $n >$ balsam.

Birefringence moderate to very strong, $n_\gamma - n_\alpha = 0.014$ to 0.045, increasing with increase in iron content. The maximum interference colors range from low second-order to upper third-order colors. The middle first-order colors are anomalous like those of clinozoisite.

Extinction parallel in elongate sections since epidote, unlike most monoclinic crystals, is elongated in the direction of the *b*-axis.

Orientation.—Since $b = Y$, some sections are length-slow and some length-fast.

Twinning.—Twins with {100} as twin-plane are not uncommon.

Interference Figure.—The interference figure is biaxial negative with a large axial angle. Cleavage flakes give an optic-axis figure, since one of the optic axes is almost normal to {001}. The axial plane is {010}. Dispersion, $r > v$.

Distinguishing Features.—Epidote is distinguished from clinozoisite and zoisite by stronger birefringence and from diopside and augite by parallel extinction.

Occurrence.—Epidote is a common and widely distributed mineral in many types of igneous and metamorphic rocks. It seems to be a high-temperature hydrothermal or late magmatic mineral. Epidote is rather common as a detrital mineral.

Piedmontite

$Ca_2(Al,Fe,Mn)_3(OH)(SiO_4)_3$ Monoclinic

$$n_\alpha = 1.758$$
$$n_\beta = 1.771$$
$$n_\gamma = 1.819$$
$$2V = 55 \text{ to } 80°; \text{Opt. } (+)$$
$$b = Y, c \wedge X = -5 \text{ to } -7°$$

Color.—Vivid characteristic colors: yellow, orange, red, violet. Pleochroic: X, yellow to orange; Y, amethyst to violet; Z, carmine to deep red.

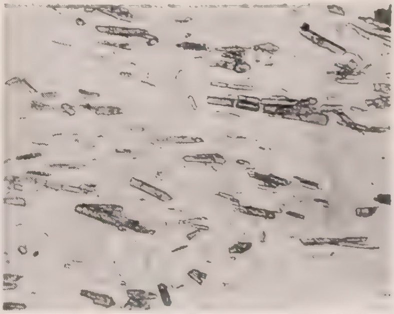


FIG. 227.—(×20) Piedmontite in quartz.

Form.—In form piedmontite is very much like epidote, of which it is a manganese-bearing variety.

Cleavage in one direction {001}.

Relief high, $n >$ balsam.

Birefringence very strong to extreme, $n_\gamma - n_\alpha = 0.061$. The interference colors are high order but are more or less masked by the color of the mineral.

Extinction parallel in elongate sections since the crystals, like those of epidote, are elongated in the direction of the *b*-axis.

Orientation.—The direction of the faster or slower ray is difficult to determine.

Interference Figure.—The figure is biaxial positive with a large axial angle. The axial plane is {010}. Dispersion, $r > v$ strong.

Distinguishing Features.—The color and pleochroism of piedmontite are so distinctive that there is little chance of mistaking it for any other mineral.

Occurrence.—Piedmontite occurs for the most part in schists and gneisses, also in altered quartz porphyries as at South Mountain, Pa.

Allanite

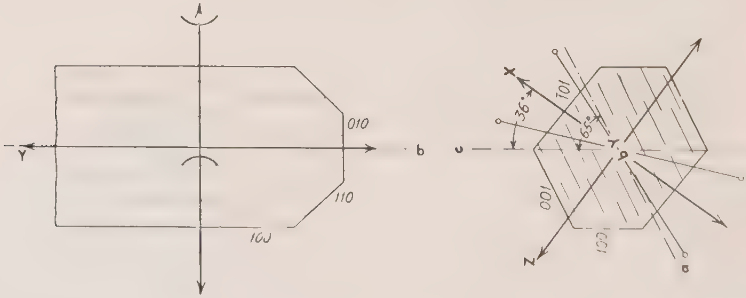
(Orthite)

$(Ca,Fe^{II})_2(Al,Ce,Fe^{III})_3(OH)(SiO_4)_3$ Monoclinic

$$n_\alpha = 1.727$$
$$n_\beta = 1.739$$
$$n_\gamma = 1.751$$
$$2V = \text{large; Opt. } (-)$$
$$b = Y,\ c \wedge X = +36°$$

Color.—Brown and pleochroic from pale brown to dark brown.

Form.—In form allanite is similar to epidote, of which it is a cerium-bearing variety. It often occurs in parallel position with epidote.



(*a*) (*b*)

FIGS. 228 *a*,*b*.—Orientation diagrams of allanite. Sections (*a*) normal to the *c*-axis and (*b*) parallel to (010).

Relief high, $n >$ balsam.

Cleavage imperfect parallel to {001}.

Birefringence rather strong, $n_\gamma - n_\alpha = 0.024$; the interference colors are usually masked by the brown color of the mineral.

Extinction usually parallel, like other members of the epidote group.

Orientation difficult to obtain.

Twinning is like that of epidote.

Distinguishing Features.—Allanite is distinguished from brown hornblende by parallel extinction and cleavage in one direction instead of two.

Alteration.—Allanite is often altered or inverted to an amorphous substance with about the same chemical composition as allanite. Whether this is a distinctive mineral or not is uncertain.

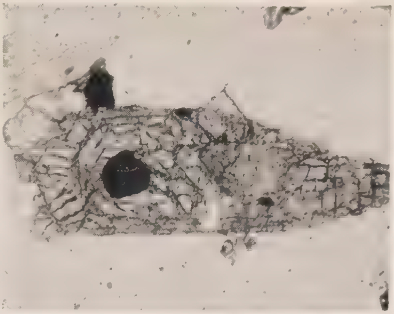


FIG. 229.—(×20) Allanite in granite.

Occurrence.—Allanite is found in granites, syenites, granite pegmatites, and gneisses.

Staurolite

$Fe(OH)_2(Al_2SiO_5)_2$ Orthorhombic

$$n_\alpha = 1.744$$
$$n_\beta = 1.749$$
$$n_\gamma = 1.756$$
$$2V = 88°;\ \text{Opt.}\ (+)$$
$$a = Y,\ b = X,\ c = Z$$

Color.—Pale yellow. Pleochroism distinct from nearly colorless to yellow-brown. Absorption, $Z > Y > X$.

Form.—Staurolite usually occurs in euhedral crystals of short prismatic habit and six-sided cross section with the forms {110} and {010}.

Relief high, $n >$ balsam.

Cleavage inconspicuous.

Inclusions.—Irregularly arranged inclusions of quartz are nearly always prominent.

Birefringence rather weak, $n_\gamma - n_\alpha = 0.012$; the maximum interference color is first-order yellow.

Extinction parallel in most sections.

Orientation.—The crystals are length-slow.

Twinning.—Penetration twins with {023} or {232} as twin-planes are common, but polysynthetic twins are unknown.

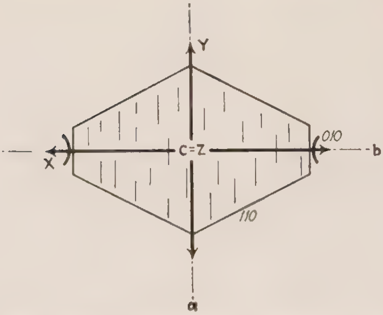


Fig. 230. Orientation diagram of staurolite. Section parallel to (001).

Interference Figure.—The interference figure is biaxial positive with a very large axial angle. The axial plane is {100}. Dispersion, $r > v$ weak.

Distinguishing Features.—The color, pleochroism, and quartz inclusions are distinctive.

Occurrence.—Staurolite is found in metamorphic rocks such as schists, phyllites, and gneisses. Common associates are garnet, kyanite, and sillimanite. It is also a common detrital mineral.

Cordierite

$Mg_2Al_4Si_5O_{18}$ Orthorhombic

$$n_\alpha = 1.532 \text{ to } 1.552$$
$$n_\beta = 1.536 \text{ to } 1.562$$
$$n_\gamma = 1.539 \text{ to } 1.570$$
$$2V = 40 \text{ to } 80°; \text{ Opt. } (-)$$
$$a = Y, b = Z, c = X$$

Color.—Colorless in thin sections. Very thick sections are pleochroic. X, yellow; Y, dark violet or blue; Z, pale blue or violet. Absorption, $Y > Z > X$.

Form.—The characteristic form of cordierite is in pseudohexagonal crystals of short prismatic habit. These crystals are penetration twins. Cordierite also occurs in anhedra and anhedral aggregates. Inclusions are common; these are often surrounded by pleochroic haloes.

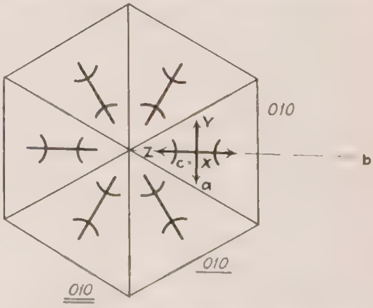


Fig. 231.—Orientation diagram of cordierite. Section of twin-crystal parallel to (001). The twin-plane is {110}.

Cleavage cannot be recognized in sections.

Relief low, n either a little less or a little greater than balsam.

Birefringence weak, $n_\gamma - n_\alpha = 0.007$ to 0.011, about the same as that of quartz; hence maximum interference colors are usually about straw yellow of the first order.

Extinction parallel to crystal outlines.

Twinning.—The pseudo-hexagonal crystals are penetration twins with {110} as twin-plane. Twin-lamellae are also often present.

Interference Figure.—The figure is biaxial negative with a variable axial angle. The axial plane is {100}. Dispersion, $r < v$ weak.

Distinguishing Features.—Cordierite is one of the few minerals that is easily mistaken for quartz. It is biaxial with a moderate or large axial angle and often shows twinning (either penetration or polysynthetic).

Alteration.—Cordierite is usually more or less altered to sericite (pinite), chlorite, talc, or indefinite silicates.

Occurrence.—Cordierite is a typical metamorphic mineral. It is found in gneisses and schists, often at the contact with persilicic igneous rocks. It is a characteristic mineral of hornfels. Rarely is it found in igneous rocks.

Prehnite

$H_2Ca_2Al_2(SiO_4)_3$ Orthorhombic

$$n_\alpha = 1.615$$
$$n_\beta = 1.625$$
$$n_\gamma = 1.646$$

2V variable; Opt. (+)

$a = X,\ b = Y,\ c = Z$

Color.—Colorless.

Form.—Prehnite usually occurs in aggregates which are often sheaf-like and approach spherulites. What may be called *bow-tie* structure is characteristic. Crystals are mostly tabular parallel to {001}.

Cleavage good in one direction {001}.

Relief fairly high, $n >$ balsam.

Birefringence strong, $n_\gamma - n_\alpha = 0.031$; the maximum interference is about yellow of the

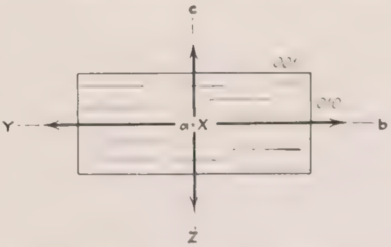


FIG. 232.—Orientation diagram of prehnite. Section parallel to (100).

second order. Anomalous interference colors are found in some varieties.

Extinction parallel to the cleavage. The extinction is often wavy on account of the structure.

FIG. 233.—(×12) Prehnite showing "bow-tie" structure.

Orientation.—The cleavage traces are parallel to the fast ray.

Twinning.—Fine polysynthetic twinning in two directions at right angles is found in some sections.

Interference Figure.—Prehnite gives a positive biaxial figure, but the axial angle is variable even in the same specimen. The axial plane is {010}. Dispersion, $r > v$ weak.

Distinguishing Features.—Lawsonite in some occurrences is like prehnite, but the birefringence of lawsonite is considerably lower and the indices of refraction somewhat higher.

Occurrence.—Prehnite is a secondary mineral in cavities and seams of various igneous rocks. It is sometimes found in veins. Associated minerals are quartz, calcite, datolite, and zeolites.

Lawsonite

$H_4CaAl_2Si_2O_{10}$ Orthorhombic

$$n_\alpha = 1.665$$
$$n_\beta = 1.674$$
$$n_\gamma = 1.684$$
$$2V = 84°;\ \text{Opt. } (+)$$
$$a = X,\ b = Y,\ c = Z$$

Color.—Colorless.

Form.—Lawsonite occurs in euhedral crystals of varying habit. Sections are usually rhombic ($110 \wedge 1\bar{1}0 = 67°$) or rectangular.

Cleavage good parallel to {010}, fair parallel to {110}.

Relief rather high, $n >$ balsam.

Birefringence moderate, $n_\gamma - n_\alpha = 0.019$; so the interference colors range up to second-order blue.

Extinction parallel or symmetrical.

Orientation. The long diagonal of rhombic sections is parallel to the slower ray.

Twinning.—Polysynthetic twinning with {110} as twin-plane is rather common. The lamellae are usually thin and may be in either one or two directions.

Interference Figure.—The figure is biaxial positive with a very large axial angle. The axial plane is {010}. Dispersion, $r > v$ strong.

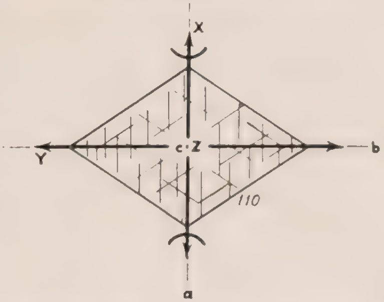


FIG. 234. Orientation diagram of lawsonite. Section parallel to (001).

Distinguishing Features. Clinozoisite somewhat resembles lawsonite, but the anomalous interference colors distinguish it. Prehnite may also be mistaken for lawsonite, but its birefringence is greater.

Occurrence.—The characteristic occurrence of lawsonite is in metamorphic rocks such as glaucophane schists. It is also found in gabbros and diorites as the result of metamorphism. The type locality is Tiburon Peninsula on San Francisco Bay, California, but it has also been found in Italy, Corsica, and New Caledonia. The usual associates of lawsonite are muscovite, glaucophane, garnet, etc.

THE MICA GROUP

The micas constitute a well-defined group of silicates of aluminum together with the alkalies, magnesium, and ferrous iron. They are characterized by a very perfect cleavage in one direction {001} and by very strong birefringence. The extinc-

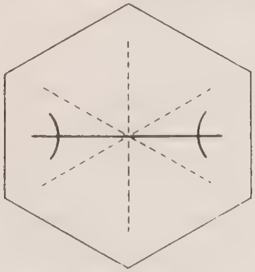


FIG. 235.

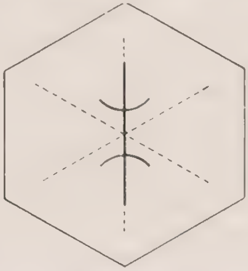


FIG. 236.

FIG. 235.—Mica of the first class. The dotted lines represent the "percussion figure."
FIG. 236.— Mica of the second class.

tion angles are very small or practically zero. The micas are pseudohexagonal monoclinic. They may be divided into two classes depending upon whether the optic axial plane is (1) normal to or (2) parallel to {010} (see Figs. 235, 236, page 271. Muscovite and lepidolite belong to the first class, and phlogopite and biotite to the second. All the micas are optically negative.

THE MICA GROUP

Mineral	Chemical composition	n_α	n_β	n_γ	2 V
MUSCOVITE..............	KAl	1.556 1.570	1.587 1.607	1.593 1.611	40°
Lepidolite...................	KLiAl	1.560	1.598	1.605	40°
PHLOGOPITE.............	KMgAl	1.562	1.606	1.606	0–10°
BIOTITE..................	KMg,FeAl	1.541 1.579	1.574 1.638	1.574 1.638	0–25°

Lepidomelane is the name given to iron-rich biotite. Fuchsite and mariposite are green chromium-bearing varieties of muscovite. Sericite is a secondary muscovite found in minute shreds and aggregates and formed by hydrothermal alteration.

MUSCOVITE

$H_2KAl_3(SiO_4)_3$ (inc. Sericite) Monoclinic

$$n_\alpha = 1.556 \text{ to } 1.570$$
$$n_\beta = 1.587 \text{ to } 1.607$$
$$n_\gamma = 1.593 \text{ to } 1.611$$
$$2V = ca.\ 40°;\ \text{Opt.}\ (-)$$
$$b = Z,\ a \wedge Y, = +1 \text{ to } +3°$$

Color.—Colorless to pale green.

Form.—Muscovite usually occurs in thin tabular crystals or in scaly aggregates or shreds. The minutely crystalline variety is called *sericite.*

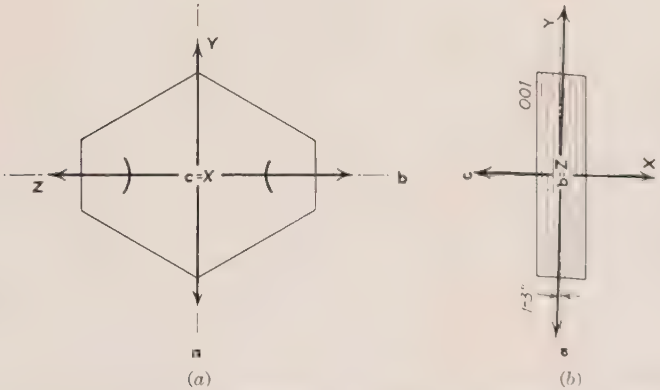
Cleavage in one direction {001} very perfect.

Relief not marked, $n >$ balsam. On rotation there is some change of relief, fair when the cleavage traces are parallel to the vibration plane of the lower nicol and low in a position at right angles to this.

Birefringence strong, $n_\gamma - n_\alpha = 0.037$ to 0.041; hence the highest interference colors are upper second order. Sections parallel to the cleavage give first-order colors since $n_\gamma - n_\beta = 0.004$ to 0.006.

Extinction.—The extinction is as a rule practically parallel to the cleavage traces, but it is often possible to find angles as high as 2 or 3°.

Orientation.—The direction of the cleavage traces is always the slower ray.



FIGS. 237 *a*,*b*.—Orientation diagrams of muscovite. Sections (*a*) parallel to (001) and (*b*) parallel to (010).

Twinning.—Twinning according to the mica law [twin-plane = {110} and composition face = (001)] is fairly common. It may be detected by slight differences in interference colors as well as by extinction angles.

Interference Figure.—Sections parallel to {001} or cleavage flakes give a biaxial negative figure with a moderate axial angle. Dispersion, $r > v$ weak. The axial plane is normal to {010}.

Distinguishing Features.—Talc is so similar to muscovite and pyrophyllite in its optical properties that it is distinguished with difficulty. The axial angle of talc is smaller. It may be necessary to make a microchemical test for magnesium in order to differentiate them.

Occurrence.—Muscovite is very common in metamorphic rocks such as schists and gneisses. It is found in some granites and reaches its maximum development in granite pegmatites. Common as a detrital mineral, especially in arkoses.

SERICITE

Sericite occurs in minute shreds and is a secondary mineral formed by hydrothermal alteration of silicates, especially the feldspars. It is in all probability a late hydrothermal mineral. Sericite also occurs as a constituent of schists, phyllites, and slates.

Lepidolite

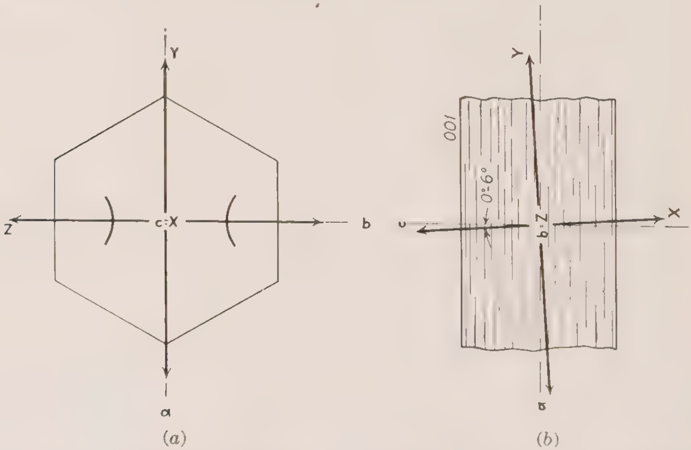
$LiKAl_2(OH,F)_2(SiO_4)_3$ Monoclinic

$$n_\alpha = 1.560$$
$$n_\beta = 1.598$$
$$n_\gamma = 1.605$$
$$2V = 40° \pm;\ \text{Opt. } (-)$$

Color.—Colorless.

Form.—Lepidolite usually occurs in thick tabular or short prismatic pseudohexagonal crystals.

Cleavage perfect in one direction {001}.



(a) (b)

FIGS. 238 *a,b*.—Orientation diagrams of lepidolite. Sections (*a*) parallel to (001) and (*b*) parallel to (010).

Relief fair, $n >$ balsam.

Birefringence strong, $n_\gamma - n_\alpha = 0.045$; hence interference colors range up to the middle of the third order. Sections parallel to the cleavage (including cleavage flakes) have weak double refraction ($n_\gamma - n_\beta = 0.007$).

Extinction. The extinction angle measured against the cleavage traces varies from 0 up to a maximum of 6 or 7°.

Orientation.—The direction of the cleavage trace is always the slower ray.

Twinning.—Twinning is common according to the mica law [twin-plane = {110}], the composition face being {001}. Sometimes there are penetration twins.

Interference Figure.—The figure is biaxial negative with a moderate axial angle, usually about 40°. Dispersion, $r > v$ weak.

Distinguishing Features.—Lepidolite is very similar to muscovite in its optical properties but has a larger extinction angle. It may be necessary to use some non-optical test to distinguish them. Lepidolite is easily fusible and gives a lithium flame.

Occurrence.—Lepidolite occurs in granite pegmatites, in some high-temperature veins, and occasionally in granites. The usual associates are tourmaline (especially elbaite), albite, topaz, beryl, spodumene, and quartz.

PHLOGOPITE

$H_2KMg_3Al(SiO_4)_3$ Monoclinic

$$n_\alpha = 1.562$$
$$n_\beta = 1.606$$
$$n_\gamma = 1.606$$
$$2V = 0 \text{ to } 10°;\ \text{Opt. } (-)$$
$$b = Y$$

Color.—Pale brown to colorless. Slightly pleochroic.

Form.—Phlogopite is found in six-sided thick tabular to short prismatic crystals.

Cleavage in one direction {001} as with the other micas.

Relief fair, $n >$ balsam.

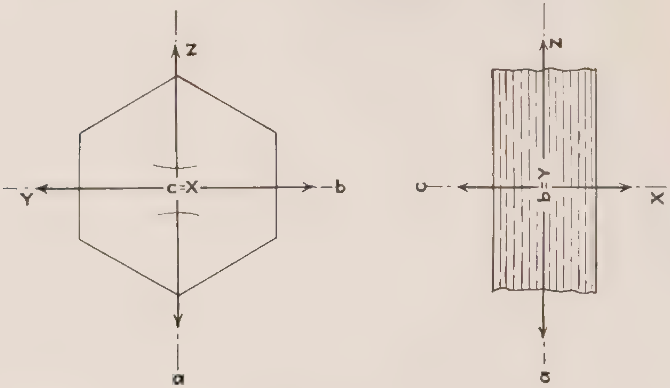
Birefringence very strong, $n_\gamma - n_\alpha = 0.044$; the maximum interference color is about the middle of the third order. Sections parallel to {001}, which include cleavage flakes, have very weak birefringence, since $n_\gamma - n_\beta$ is very small.

Extinction.—Extinction is usually parallel to the cleavage but sometimes the extinction angle is as much as 5°.

Orientation.—The cleavage traces are parallel to the slower ray.

Twinning, though often present, is not conspicuous. It may be recognized by differences in interference colors of adjacent parts of a crystal as well as by extinction angles.

Interference Figure.—Basal sections, which also include cleavage flakes, give a negative interference figure which is either biaxial with a very small angle or practically uniaxial. Dispersion, $r < v$ weak.



(*a*) (*b*)

Figs. 239 *a,b*.—Orientation diagrams of phlogopite.

Distinguishing Features.—Phlogopite is distinguished from biotite by lighter color and weaker absorption. Colorless phlogopite is much like muscovite but may be distinguished by its smaller axial angle.

Occurrence.—The characteristic occurrence of phlogopite is in metamorphic limestones. The common associates are chondrodite, spinel, and forsterite. It is also found in a few igneous rocks such as peridotites, derived serpentines, and leucite-bearing rocks.

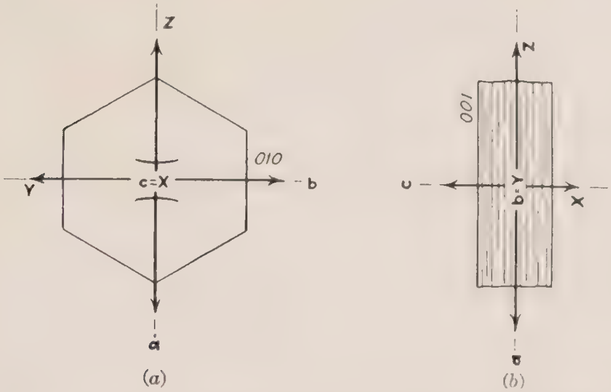
BIOTITE

$(H,K)_2(Mg,Fe)_2Al_2(SiO_4)_3$ Monoclinic
(Pseudo-hexagonal)

$$n_\alpha = 1.541 \text{ to } 1.579$$
$$n_\beta = 1.574 \text{ to } 1.638$$
$$n_\gamma = 1.574 \text{ to } 1.638$$
$$2V = 0 \text{ to } 25°;\ \text{Opt. } (-)$$
$$b = Y,\ c \wedge X = 3° \pm$$

Color.—Brown, yellowish brown, reddish brown, olive-green, green. Pleochroic. The absorption is stronger when the cleavage traces are parallel to the vibration plane of the lower nicol.

Form.—Common in euhedral six-sided crystals which are usually tabular in habit, also in lamellar aggregates. The plates are sometimes bent.



FIGS. 240 *a,b*.—Orientation diagrams of biotite. Sections (*a*) parallel to (001) and (*b*) parallel to (010).

Inclusions.—Inclusions of such minerals as zircon surrounded by pleochroic haloes are fairly common in biotite (Fig. 103, page 114).

Cleavage perfect in one direction {001}. Sections cut parallel to {001} do not show any cleavage. In schistose rocks these sections predominate.

Relief fair, $n >$ balsam.

Birefringence strong, $n_\gamma - n_\alpha = 0.033$ to 0.059; interference colors range up to second-order red, but the color of the mineral may mask the interference color. The birefringence of sections parallel to {001} is practically nil since $n_\gamma - n_\beta = 0.000x$.

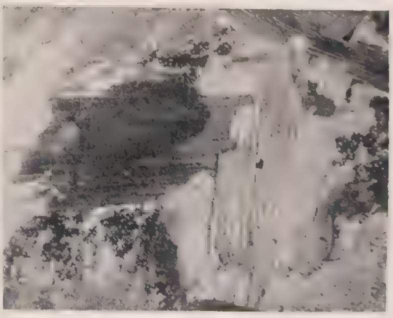


FIG. 241.—(×22) Biotite in gneiss.

Extinction usually parallel to the cleavage traces, but the extinction angle may be as much as 3° in some sections. Bent plates have wavy extinction. Near the extinction position a peculiar crinkly appearance is usually noticed in biotite.

Orientation.—The direction of the cleavage traces is always the slower ray.

Twinning.—Twinning according to the mica law [twin-plane = {110}] may be present.

Interference Figure.—Sections parallel to {001}, including cleavage flakes, give a negative biaxial figure with a very small axial angle. The axial plane is usually parallel to {010} but in one variety (anomite) the axial plane is normal to {010}. Dispersion, $r > v$ or $r < v$ weak.

Distinguishing Features.—Biotite is distinguished from phlogopite by its darker color and stronger absorption. From ordinary brown hornblende it is distinguished by the smaller extinction angle and difference in cleavage. Basaltic hornblende also has the typical amphibole cleavage. Tourmaline has strong absorption when elongation of the crystals is normal to the vibration plane of the lower nicol.

Alteration.—Biotite is often more or less altered to chlorite.

Occurrence.—Biotite is a widely distributed and common mineral. It occurs in igneous rocks of nearly all types. It is also a prominent constituent of schists and gneisses and may be found in contact-metamorphic zones. Biotite is common in detrital sediments. It is often bleached or otherwise altered.

CHLORITE GROUP

Mg,Fe,Al silicate Monoclinic

$$n_\alpha = 1.562 \text{ to } 1.605$$
$$n_\beta = 1.575 \text{ to } 1.605$$
$$n_\gamma = 1.577 \text{ to } 1.610$$
$$2V = 0 \text{ to } 50°;\ \text{Opt. } (+) \text{ or } (-)$$
$$b = Y,\ a \wedge X = 0 \text{ to } -8°$$

Color.—Colorless, pale green to medium green, yellow-green, or blue-green, rarely violet. Most varieties are somewhat pleochroic.

Form.—Chlorite occurs in tabular to prismatic pseudohexagonal crystals and also in aggregates. It is often more or less spherulitic.

Cleavage perfect in one direction parallel to {001}.

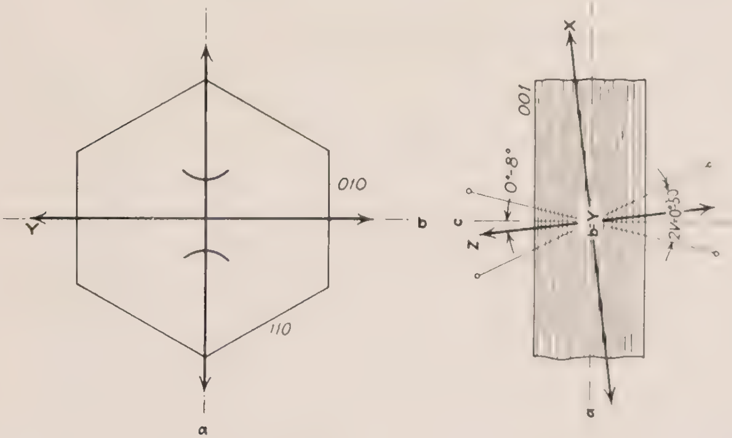
Relief fair, $n >$ balsam.

Birefringence usually weak, $n_\gamma - n_\alpha = 0.005$ to 0.015; the interference colors are sometimes normal first-order colors, but they are often anomalous: Berlin blue, greenish gray, brownish red, etc.

Extinction.—The extinction angle with reference to cleavage traces varies from 0 to about 8°.

Orientation.—The cleavage traces are almost parallel to the slower ray.

Twinning—Polysynthetic twinning according to the mica law is fairly common.



(*a*) (*b*)

FIGS. 242 *a*,*b*.—Orientation diagram of chlorite. Sections (*a*) parallel to (001) and (*b*) parallel to (010).

Interference Figure.—The figure is either uniaxial or biaxial (positive or negative) with a small to moderate axial angle. The axial plane is {010}. Dispersion, $r < v$.

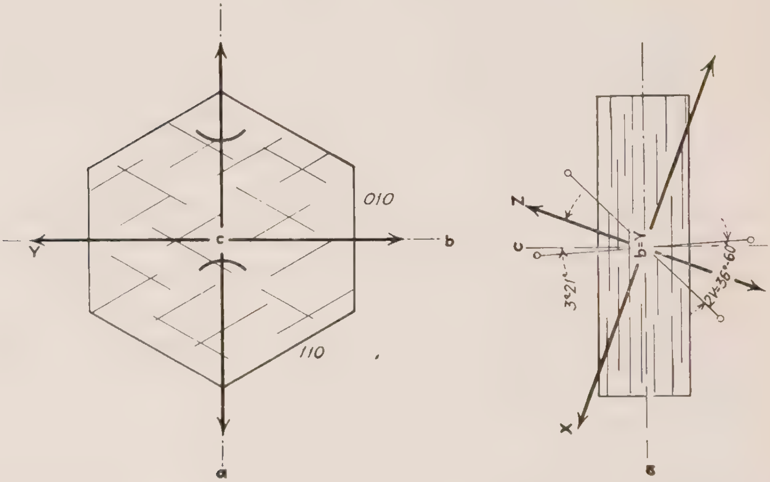
Distinguishing Features.—Chlorite is distinguished from the micas by weaker birefringence. Varieties with anomalous interference colors are rather easy to distinguish, for the other minerals with anomalous interference colors have higher relief.

Occurrence.—Chlorite is a very common and widely distributed secondary mineral in igneous rocks. It is often an alteration product of biotite, hornblende, and other silicates. It is also a prominent constituent of some metamorphic rocks. Common associates are talc, magnetite, and garnet. It is also a secondary mineral in chromite.

Chloritoid

$H_2(Fe,Mg,Mn)Al_2SiO_7$ (Ottrelite) Monoclinic

$n_\beta = 1.75$ to 1.77
$2V = 36$ to $60°$; Opt. (+)
$b = Y$, $c \wedge Z = +3$ to $+21°$



(a) (b)

FIGS. 243 *a,b*.—Orientation diagrams of chloritoid. Sections (*a*) normal to the *c*-axis and (*b*) parallel to (010).

Color.—Green, greenish gray to colorless. Usually more or less pleochroic.

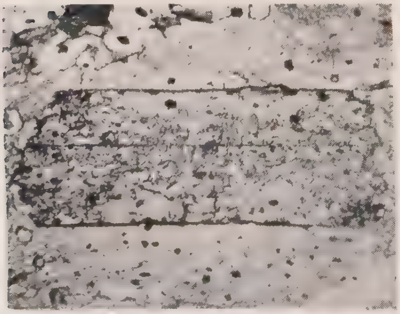


FIG. 244.—(×12) Chloritoid in schist.

Form.—Chloritoid, one of the group known as *brittle micas*, commonly occurs in pseudohexagonal tabular crystals. Inclusions are often present. It often shows a kind of "hourglass" structure.

Cleavage perfect in one direction {001} and imperfect parallel to {110}.

Relief high, $n >$ balsam.

Birefringence weak to moderate, $n_\gamma - n_\alpha = 0.007$ to 0.015. Basal plates are practically isotropic.

Extinction.—Almost parallel up to *ca.* 20°.

Orientation.—The crystals are length-fast.

Twinning.—Polysynthetic twins after the mica law are very common.

Interference Figure.—The figure is biaxial positive with a moderate to rather large axial angle. The axial plane is {010}. Dispersion, $r > v$ or $r < v$.

Distinguishing Features.—Chloritoid somewhat resembles some of the chlorites, but the relief is much higher and the cleavage less perfect.

Occurrence.—Chloritoid occurs in metamorphic rocks such as mica schists and phyllites as metacrysts.

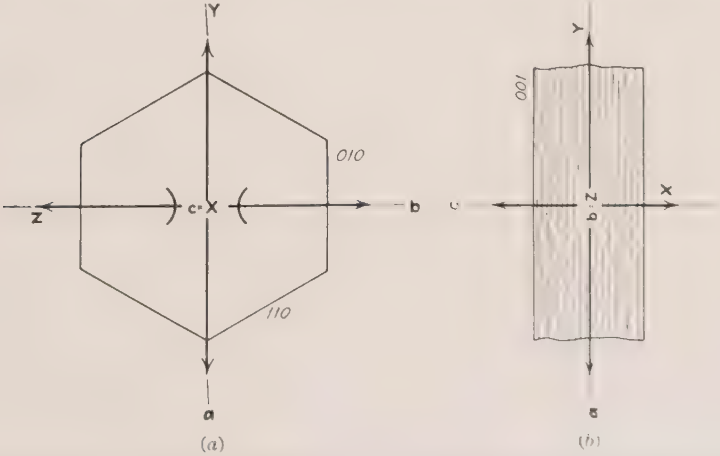
TALC

$Mg_3(OH)_2Si_4O_{10}$ Monoclinic(?)

$$n_\alpha = 1.539$$
$$n_\beta = 1.589$$
$$n_\gamma = 1.589$$
$$2V = 6 \text{ to } 30°;\ \text{Opt. } (-)$$
$$a = Y,\ b = Z,\ c = X$$

Color.—Colorless.

Form.—Talc occurs in coarse to fine platy or fibrous aggregates which often have a more or less parallel arrangement. Shreds and plates are often bent. Euhedral crystals of talc are unknown.



(a) (b)

FIGS. 245 *a*,*b*.—Orientation diagrams of talc. Sections parallel to (*a*) (001) and (*b*) (010).

Cleavage perfect in one direction {001}.

Relief fair, $n >$ balsam.

Birefringence very strong, $n_\gamma - n_\alpha = 0.050$; the maximum interference colors are upper third order. Sections parallel to the cleavage give very low first-order gray colors since $n_\gamma - n_\beta$ is almost nil ($0.000x$).

Extinction.—The extinction is parallel to the cleavage traces in most sections; in a few sections the extinction is 2 or 3°; hence talc is probably monoclinic.

Orientation.—Cleavage traces and shreds are length-slow as in muscovite.

Interference Figure.—Cleavage flakes give a biaxial negative figure with a small axial angle. Dispersion, $r > v$ distinct.

Distinguishing Features.—Talc greatly resembles muscovite and pyrophyllite, but may often be distinguished by the smaller axial angle provided an interference figure can be obtained.

It may be necessary to make a chemical or microchemical test in order to prove the identity of talc. The association with other magnesium minerals indicates the presence of talc rather than muscovite or sericite.

Occurrence.—Talc is the principal constituent of talc schists and soapstones. It is often a hydrothermal mineral formed at the expense of antigorite and tremolite in shear zones of serpentines. Dolomite and magnesite are frequent associates.

Pyrophyllite

$HAlSi_2O_6$ Monoclinic(?)

$$n_\alpha = 1.552$$
$$n_\beta = 1.588$$
$$n_\gamma = 1.600$$
$$2V = 53 \text{ to } 60°;\ \text{Opt. } (-)$$
$$a = Z,\ b = Y,\ c = X$$

Color.—Colorless.

Form.—Pyrophyllite occurs in subhedral crystals which are tabular parallel to {010} and much elongated. The crystals are usually curved and distorted. A radial structure is common. It also occurs in fine aggregates.

Cleavage perfect in one direction {001}.

Relief rather low to moderate, $n >$ balsam.

Birefringence very strong, $n_\gamma - n_\alpha = 0.048$; the maximum interference color is upper third order. Sections parallel to the cleavage give gray or first-order colors since $n_\gamma - n_\beta = 0.012$.

Extinction parallel or almost parallel to cleavage traces and parallel to the elongate sections.

Orientation.—Cleavage traces are parallel to the slower ray. Elongate sections not showing cleavage are length-slow.

Twinning.—Twinning like that found in the micas is present but is not well defined.

Interference Figure.—Sections parallel to {001} or cleavage flakes give a biaxial negative figure with a rather large axial angle. The axial angle is parallel to {010} or the length of the crystals.

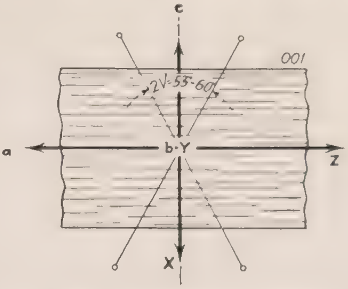


Fig. 246. Orientation diagram of pyrophyllite. Section parallel to (010).

Distinguishing Features.—Pyrophyllite usually has a peculiar elongate tabular habit. Muscovite and talc greatly resemble pyrophyllite. Talc has a much smaller axial angle. Microcrystalline pyrophyllite is very difficult to distinguish from sericite or talc by optical means; it may be necessary to make chemical or microchemical tests.

Occurrence.—Pyrophyllite occurs in metamorphic rocks and has often developed as a hydrothermal alteration product. Common associates are andalusite, sillimanite, kyanite, lazulite, and alunite.

THE CLAY MINERALS

The minerals that characterize clays are widely distributed in sedimentary rocks, and in addition the same minerals may be found in veins or as alteration products of igneous and metamorphic rocks. The most common clay minerals are kaolinite, dickite, halloysite, and montmorillonite. Kaolinite occurs in large quantities both as a residual and as a transported kaolin in the southeastern United States. It is usually formed by the decomposition *in situ* of rocks containing feldspars. Dickite resembles kaolinite in physical properties and is much like it under the microscope. It is commonly formed by hydrothermal solutions in veins or dikes and occasionally occurs associated with sulfids in ore deposits. Halloysite is found as a porcelain-like mass or fine white powder in shales and sandstones and as a replacement of limestone. Kaolinite and halloysite commonly occur together. Montmorillonite is one of the most widely distributed of the clay minerals. It occurs as an alteration product of volcanic ash and tuff. The rock bentonite, common in the western United States, is composed largely of the mineral montmorillonite. Montmorillonite is also found in minor amounts as an alteration product in pegmatite dikes.

Clay Minerals

	Mineral	Chemical composition	Crystal system	n_α	n_β	n_γ	$n_\gamma - n_\alpha$
1	KAOLINITE	$Al_2O_3.2\ SiO_2.2\ H_2O$	Monoclinic	1.561	1.565	1.566	0.005
	Dickite	$Al_2O_3.2\ SiO_2.2\ H_2O$	Monoclinic	1.560	1.562	1.566	0.006
	Nacrite	$Al_2O_3.2\ SiO_2.2\ H_2O$	Monoclinic	1.557	1.562	1.563	0.006
	Halloysite	$Al_2O_3.2 + SiO_2.nH_2O$	Aggregates	$n = 1.55$			0.001
	Allophane	$Al_2O_3.xSiO_2.nH_2O$	Amorphous	$n = 1.47–1.49$			0.000
2	MONTMORILLONITE	$MgO.Al_2O_3.\ 5\ SiO_2.nH_2O$	Monoclinic	1.492	1.513	1.513	0.021
	Beidellite	$Al_2O.3\ SiO_2.nH_2O$	Monoclinic	1.517	.....	1.549	0.032
	Nontrontite	$Fe_2O_3.3\ SiO_2.nH_2O$	Monoclinic	1.580	.....	1.615	0.035
3	Potash-bearing clay	?	?	1.543	.....	1.565	0.022

The clay minerals may be conveniently separated into three groups from the standpoint of microscopic classification: (1) The kaolin group is characterized by weak birefringence and indices of refraction approximating those of quartz. (2) The montmorillonite group has a comparatively high birefringence but indices of refraction for the most part lower than Canada balsam. (3) The potash-bearing clay is frequently found as an alteration product of old volcanic ash, particularly in the Ordovician of the eastern United States, or at times as a gouge clay in ore deposits. Clays of this group have indices of refraction higher than balsam and strong birefringence.

The most important clay minerals exhibit distinguishing features in thin sections. A number, however, present problems in identification best solved by coordinated optical and X-ray methods. A strong artificial illumination is advisable in determining the birefringence of the clay minerals. A summary of the optical properties of the more important clay minerals based upon determinations by C. S. Ross is given in the above tabulation.

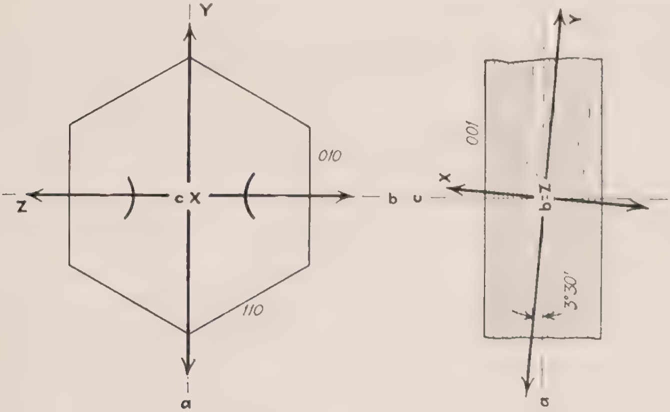
KAOLINITE

$Al_2O_3.2\ SiO_2.2H_2O$ Monoclinic

$$n_\alpha = 1.561$$
$$n_\beta = 1.565$$
$$n_\gamma = 1.566$$
$$2V \text{ variable; Opt. } (-)$$
$$b = Z,\ c \wedge X = 1 \text{ to } 3\tfrac{1}{2}°$$

Color.—Colorless to pale yellow.

Form.—Kaolinite occurs in fine mosaic-like masses of crystlas, in veinlets replacing feldspars and other minerals, and in scale-like individuals. Occasionally small plates show accordion-like outlines.



(a) (b)

FIGS. 247 *a,b*.—Orientation diagrams of kaolinite. Sections (*a*) normal to the *c*-axis and (*b*) parallel to (010).

Cleavage perfect in one direction parallel to {001}.

Relief low, $n >$ balsam.

Birefringence weak, $n_\gamma - n_\alpha = 0.005$. In normal sections kaolinite gives gray and white interference colors.

Extinction.—The angle of extinction on (010) against the base is 1–3½°.

Orientation.—The cleavage traces and crystals are length-slow.

Twinning.—Minute crystals of kaolinite do not appear to show twinning.

Interference Figure.—Kaolinite is ordinarily too fine-grained to give an interference figure. The axial plane is normal to {010} and nearly parallel to {100}.

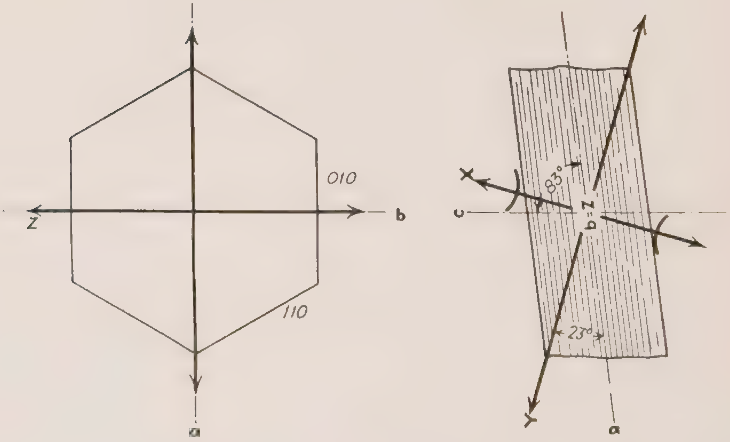
Distinguishing Features.—It is distinguished by low relief and weak birefringence. From dickite it is distinguished largely by its smaller extinction angle.

Occurrence.—Kaolinite is found as a weathering product of igneous and metamorphic rocks. It is produced particularly by the decomposition of feldspars. It occurs as a prominent clay mineral in sedimentary beds.

Dickite

$Al_2O_3.2\ SiO_2.2H_2O$ Monoclinic

$$n_\alpha = 1.560$$
$$n_\beta = 1.562$$
$$n_\gamma = 1.566$$
$$2V = 52 \text{ to } 80°;\ \text{Opt. } (+)$$
$$b = Z,\ c \wedge X = 15 \text{ to } 20°$$



(a) (b)

Figs. 248 *a,b*.—Orientation diagrams of dickite. Sections (*a*) normal to the *c*-axis and (*b*) parallel to (010).

Color.—Colorless to pale yellow.

Form.—Dickite occurs in small pseudo-hexagonal flake-like crystals.

Cleavage.—Perfect in one direction parallel to {001}.

Relief low, $n >$ balsam.

Birefringence weak, $n_\gamma - n_\alpha = 0.006$; the maximum interference colors are middle first order.

Extinction.—Angle of extinction on {010} against base varies from 15 to 20°.

Orientation.—The cleavage traces and crystals are length-slow.

Twinning.—No apparent twinning.

Interference Figure.—Ordinary thin sections yield poor interference figures or none at all. The axial plane is normal to {010}. Dispersion, $r < v$.

Distinguishing Features.—Dickite is distinguished from kaolinite by slightly higher birefringence, larger crystals, and a larger extinction angle.

Occurrence.—The mineral is commonly found associated with metallic minerals in ore deposits. It is usually produced by hydrothermal action and may occur as a replacement of quartz in quartzite.

Halloysite

$Al_2O_3.2 \pm SiO_2.nH_2O$ Aggregates
(Crystal system
unknown)

$$n = 1.551$$

Color.—Colorless.

Form.—Halloysite occurs in extremely fine-grained or colloform masses and commonly shows shatter cracks.

Relief low, n slightly > balsam.

Birefringence very weak, almost isotropic.

Distinguishing Features.—Halloysite is distinguished by extremely weak birefringence and an index of refraction almost equal to balsam and shatter cracks. It is commonly associated with other clay minerals.

Occurrence.—The mineral occurs in altered areas in limestone associated with diaspore, alunite, or gibbsite; in clay beds associated with kaolinite; and probably in extremely weathered portions of some shales.

MONTMORILLONITE

$MgO.Al_2O_3.5SiO_2.nH_2O$ Monoclinic

$$n_\alpha = 1.492$$
$$n_\beta = n_\gamma = 1.513$$
$$2V = 10 \text{ to } 25°; \text{Opt. } (-)$$

Color.—Pale pink, greenish, or colorless.

Form.—Massive, clay-like microcrystalline aggregates in the shape of shards. Nearly always in extremely fine scale-like crystals. Crystals of this type have been described by E. T. Wherry as a one-dimensional colloid since they are usually so thin.

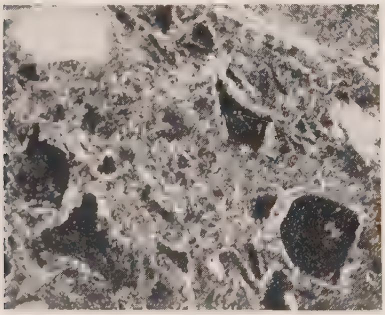


FIG. 249.—(∧20) Montmorillonite, more or less altered glass shards, and feldspar fragments in bentonite. (× nicols.)

Relief rather low, $n <$ balsam.

Birefringence rather strong, $n_\gamma - n_\alpha = 0.021$. Although the birefringence is strong, the crystals are usually so thin that interference colors in thin sections seldom go above the second order.

Interference Figure.—Individual crystals are usually so small and thin that figures cannot be obtained.

Distinguishing Features.—The most characteristic feature of montmorillonite is microcrystalline aggregates in the shape of shards.

Occurrence.—Montmorillonite is the chief constituent of bentonite, which is altered volcanic ash. It also occurs in fuller's earth as a primary constituent and has been found as an alteration material in pegmatite dikes.

ANTIGORITE

$H_4Mg_3Si_2O_9$ Orthorhombic

$$n_\alpha = 1.560$$
$$n_\beta = 1.570$$
$$n_\gamma = 1.571$$
$$2V = 20 \text{ to } 90°; \text{Opt. } (-)$$
$$a = Y, b = X, c = Z$$

Color.—Colorless to pale green.

Form.—Antigorite occurs in anhedral crystals or aggregates of fibrolamellar structure. It often occurs as pseudomorphs after pyroxene (bastite), olivine, etc.

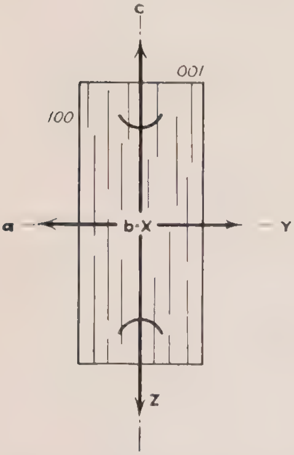


Fig. 250.—Orientation diagram of antigorite. Section parallel to (010).

Fig. 251.—(×20) Antigorite in serpentine. (× nicols.)

Relief rather low, $n >$ balsam.

Birefringence weak, $n_\gamma - n_\alpha = 0.011$; the maximum interference color is first-order yellow. This yellow is slightly anomalous, as it has a greenish tinge.

Extinction parallel.

Orientation.—The crystals are length-slow.

Interference Figure.—The figure is biaxial negative with variable axial angle. The axial plane is {100}. Dispersion, $r > v$ weak.

Distinguishing Features. Chrysotile is distinguished from its dimorph antigorite by the fine fibrous structure. Antigorite usually shows aggregate structure and is in practically all cases an alteration product of some other silicate mineral.

Occurrence.—Antigorite is the main constituent of serpentine, a metamorphic rock. It has been formed from olivine, enstatite, augite, etc., by hydrothermal alteration. Common associates are chrysotile, talc, magnetite, chromite, and picotite.

Chrysotile

$H_4Mg_3Si_2O_9$ Orthorhombic

$$n_\alpha = 1.542$$
$$n_\beta = ?$$
$$n_\gamma = 1.555$$
$$2V = 30 \text{ to } 35°;\ \text{Opt. } (+)$$

Fig. 100, Page 114

Color.—Colorless.

Form.—Chrysotile occurs in cross-fiber veinlets.

Relief low, n slightly greater than balsam.

Birefringence moderate, $n_\gamma - n_\alpha = 0.013$; the maximum interference color is bright yellow of the first order.

Extinction parallel.

Orientation.—The fibers are length-slow.

Distinguishing Features.—The other forms of asbestos (tremolite, anthophyllite, and crocidolite) all have higher indices of refraction than chrysotile. Tremolite has oblique extinction.

Occurrence.—Chrysotile usually occurs in veinlets in serpentine which consists largely of the mineral antigorite.

Iddingsite

$MgO.Fe_2O_3.3SiO_2.4H_2O$ Orthorhombic

$$n_\alpha = 1.674 \text{ to } 1.730$$
$$n_\beta = 1.715 \text{ to } 1.763$$
$$n_\gamma = 1.718 \text{ to } 1.768$$
$$2V = 25 \text{ to } 60°;\ \text{Opt. } (+) \text{ or } (-)$$
$$a = X,\ b = Y,\ c = Z$$

Color.—Brown. Pleochroism slight to distinct. Absorption, $Z > Y > X$.

Form.—Iddingsite, as far as known, always occurs as partial or complete pseudomorphs after olivine. It shows a lamellar structure.

Cleavage in three directions {100}, {001}, {010} at right angles.

Relief high, $n >$ balsam.

Birefringence very strong, $n_\gamma - n_\alpha = 0.038$ to 0.044; the maximum interference color should be in the third order, but the color of the mineral modifies or masks the interference color.

Extinction parallel to the cleavage traces.

Interference Figure.—The figure is biaxial, either positive or negative, with a moderate axial angle. The axial plane is $\{010\}$. Dispersion, $r > v$ or $r < v$ strong.

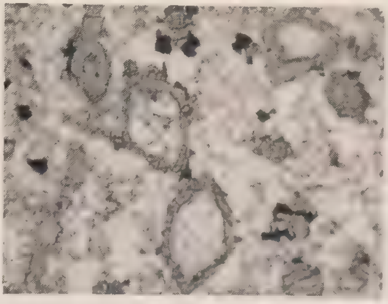


FIG. 252.—(×16) Iddingsite alteration border around olivine phenocrysts.

Distinguishing Features.—The reddish brown color and lamellar structure together with the mode of occurrence are distinctive for iddingsite.

Alteration.—Iddingsite is sometimes found more or less altered to limonite or indefinite hydrous iron oxids.

Occurrence.—Iddingsite is found in basalts and basalt porphyries as an alteration product of olivine. It is a deuteric or hydrothermal mineral and is not formed by weathering.

Glauconite

$KMg(Fe,Al)(SiO_3)_6.3H_2O$ Monoclinic(?)

$$n_\alpha = 1.590 \text{ to } 1.612$$
$$n_\beta = 1.609 \text{ to } 1.643$$
$$n_\gamma = 1.610 \text{ to } 1.644$$
$$2V = 16 \text{ to } 30^\circ;\ \text{Opt. } (-)$$
$$X\ ca.\ \perp \{001\}$$

Color.—Green, yellow-green, or olive green. Pleochroic from yellow to green.

Form.—Glauconite occurs in grains or pellets which are in part aggregates of minute crystals and in part single crystals. Euhedral crystals have not been observed.

Cleavage perfect in one direction $\{001\}$.

Relief moderate, $n >$ balsam.

Birefringence rather strong, $n_\gamma - n_\alpha = 0.020$ to 0.032; the highest interference colors are second-order colors, but they are masked by the color of the mineral. Many specimens show aggregate polarization.

Extinction.—The extinction with reference to cleavage traces is practically parallel but angles of 2 or 3° have been recorded.

Orientation.—The cleavage traces are length-slow as in the micas.

Interference Figure.—Cleavage flakes give a biaxial negative figure with a small axial angle, but the figure is difficult to obtain on account of the small size of the crystals. Dispersion, $r > v$.

Fig. 253.—(×50) Glauconite (dark) in arkose.

Distinguishing Features.—Glauconite much resembles some of the iron-rich chlorites such as chamosite, but the latter has a higher index of refraction and weaker birefringence. Chamosite has an oölitic structure and is often altered to hematite.

Alteration.—Glauconite is sometimes altered to limonite.

Occurrence.—Glauconite occurs in sands, sandstones, and limestones. It is especially abundant in the loosely consolidated sandstone known as *greensand*, which is prominent in the Cretaceous of New Jersey. A common associate is collophane.

THE ZEOLITE GROUP

The zeolites are hydrous sodium calcium aluminum silicates which commonly occur as secondary minerals in cavities of

Zeolite Group

Mineral	Chemical composition	Crystal system	n_α	n_β	n_γ
Analcite	Na	Isometric	$n = 1.487$		
Heulandite	Ca	Monoclinic	1.498	1.499	1.505
Stilbite	Ca,Na	Monoclinic	1.494	1.498	1.500
Chabazite	Ca,Na	Hexagonal	$n_\omega = 1.478–1.485$, $n_\epsilon = 1.480–1.490$		
Natrolite	Na	Orthorhombic	1.473 1.480	1.476 1.482	1.485 1.493
Mesolite	Na,Ca	Monoclinic	1.505	1.505	1.506
Thomsonite	Na,Ca	Orthorhombic	1.512 1.530	1.513 1.532	1.518 1.542
Scolecite	Ca	Monoclinic	1.512	1.519	1.519

subsilicic volcanic rocks, especially basalts. While variable in optical properties they all have low indices of refraction and rather weak birefringence. The last four in the list are fibrous or columnar, but there are also other fibrous silicates such as ptilolite, mordenite, and laumontite. A few rare zeolites such as harmotome and brewsterite contain barium.

Analcite

$NaAl(SiO_3)_2.H_2O$ Isometric

$$n = 1.487$$

Color.—Colorless.

Form.—Analcite occurs in equant crystals of trapezohedral habit which are octagonal to rounded in sections. It may also occur in the groundmass in irregular masses.

Cleavage imperfect cubic, which in sections appears as two sets of lines at right angles.

Relief moderate, $n <$ balsam.

Birefringence.—Analcite is either dark between crossed nicols or shows very weak double refraction (not over 0.002). Use the sensitive-violet plate to detect the double refraction.

Distinguishing Features.—Leucite very much resembles analcite but has a slightly greater refractive index (1.508 as against 1.487).

Occurrence.—Analcite is a secondary mineral in cavities and seams of igneous rocks, usually associated with other zeolites and calcite. In some igneous rocks, such as teschenites and analcite basalts, it occurs in the groundmass as a late magmatic mineral. In several western localities it occurs in lake beds.

Heulandite

$H_4CaAl_2(SiO_3)_6.3H_2O$ Monoclinic

$$n_\alpha = 1.498$$
$$n_\beta = 1.499$$
$$n_\gamma = 1.505$$
$$2V = 0 \text{ to } 48°; \text{Opt. } (+)$$
$$b = Z, c \wedge Y = -6°$$

Color.—Colorless.

Form.—Heulandite usually occurs in distinct crystals which are tabular parallel to {010}.

Cleavage perfect in one direction {010}.

Relief rather low, $n <$ balsam.

Birefringence weak, $n_\gamma - n_\alpha = 0.007$; the interference colors range up to white of the first order. Sections parallel to {010} which include cleavage flakes have very weak birefringence since $n_\beta - n_\alpha = 0.001$.

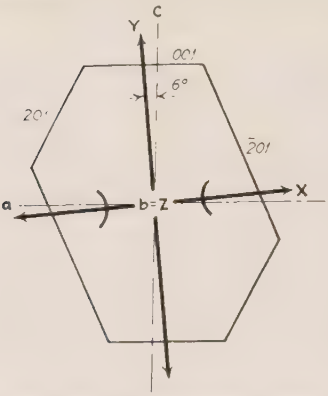


FIG. 254. Orientation diagram of heulandite. Section parallel to (010).

Extinction parallel to the cleavage traces.

Orientation.—Cleavage traces are parallel to the faster ray.

Interference Figure.—The figure is biaxial positive with a moderate axial angle. The axial plane is normal to {010}. Dispersion, $r < v$.

Distinguishing Features.—Heulandite resembles stilbite but has better cleavage and is optically positive, while stilbite is optically negative. The side pinacoid {010} sections of heulandite are unsymmetrical and the corresponding sections of stilbite symmetrical on account of twinning.

Occurrence.—Heulandite is a secondary mineral in the seams and cavities of igneous rocks, especially basalts. Stilbite is a common associate.

Stilbite

$H_4(Ca,Na_2)Al_2(SiO_3)_6.4H_2O$ Monoclinic

$$n_\alpha = 1.494$$
$$n_\beta = 1.498$$
$$n_\gamma = 1.500$$
$$2V = 33^\circ \pm;\ \text{Opt.}\ (-)$$
$$b = Y,\ c \wedge X = 5^\circ$$

Color.—Colorless.

Form.—Stilbite usually occurs in sheaf-like aggregates.

Cleavage good in one direction {010}.

Relief rather low, $n <$ balsam.

Birefringence weak, $n_\gamma - n_\alpha = 0.006$; interference colors are gray and white of the first order.

Extinction.—Extinction of sections showing the best cleavage is parallel. The extinction angle of sections with the highest interference colors is about 5°. The extinction is usually wavy and not uniform.

Orientation.—The cleavage traces are parallel either to the slow ray or to the fast ray.

Twinning.—Twins with {001} as twin-plane are common.

Interference Figure.—The figure is biaxial negative with a moderate axial angle. The axial plane is {010}. Dispersion, $r < v$.

Distinguishing Features.—Heulandite is similar to stilbite, but it has better cleavage and is optically positive instead of negative.

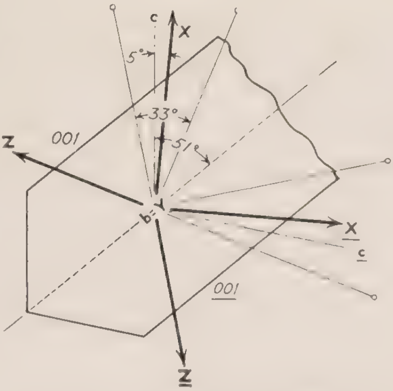


Fig. 255.—Orientation diagram of stilbite. Section parallel to (010); twin-plane = (001).

Occurrence.—Stilbite is a secondary mineral in cavities and seams of igneous rocks. Usual associates are calcite, heulandite, and other zeolites. It has been found as a hot-spring mineral in the interstices of sandstone.

Chabazite

$(Ca,Na_2)Al_2(SiO_3)_6.6H_2O$ Hexagonal

$$n_\omega = 1.478 \text{ to } 1.485$$
$$n_\epsilon = 1.480 \text{ to } 1.490$$
$$\text{Opt. } (+);\ c = Z$$

Color.—Colorless.

Form.—Chabazite is usually found in euhedral rhombohedral crystals which approach the cube ($10\bar{1}1:\bar{1}101 = 85°14'$).

Cleavage imperfect rhombohedral, hence almost rectangular.

Relief moderate, $n <$ balsam.

Birefringence very weak, $n_\epsilon - n_\omega = 0.002$ to 0.005; interference colors are first-order gray.

Extinction.—The extinction is symmetrical to crystal outlines and cleavage traces.

Interference Figure.—The figure is either uniaxial or biaxial with a very small axial angle. The optical character is positive.

Distinguishing Features.—Chabazite may be mistaken for other zeolites, especially analcite. The birefringence of chabazite is a little higher than that of analcite.

Occurrence.—Chabazite is a secondary mineral in cavities and seams of igneous rocks, especially basalts. It is often associated with calcite, prehnite, and other zeolites.

Natrolite

$Na_2Al_2Si_3O_{10}.2H_2O$ Orthorhombic

$$n_\alpha = 1.473 \text{ to } 1.480$$
$$n_\beta = 1.476 \text{ to } 1.482$$
$$n_\gamma = 1.485 \text{ to } 1.493$$
$$2V = 60 \text{ to } 63°\text{; Opt. } (+)$$
$$a = X,\ b = Y,\ c = Z$$

Color.—Colorless.

Form.—Natrolite usually occurs in long prismatic crystals or fibrous aggregates which are often more or less radiating. Cross sections of crystals are nearly square ($110 \wedge 1\bar{1}0 = ca.\ 89°$).

Cleavage parallel to the length of the crystals.

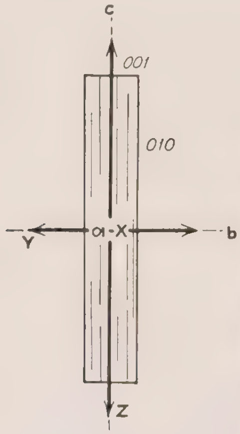


FIG. 256.

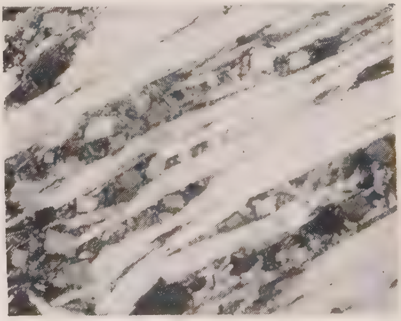


FIG. 257.

FIG. 256.—Orientation diagram of natrolite. Section parallel to (100).
FIG. 257.—(×12) Natrolite in rock section.

Relief moderate, $n <$ balsam.

Birefringence moderate, $n_\gamma - n_\alpha = 0.012$ to 0.013; the maximum interference color is yellow or orange of the first order.

Extinction parallel in longitudinal sections, symmetrical in cross sections.

Orientation.—The crystals are always length-slow.

Interference Figure. A good figure is difficult to obtain on account of the small size of most of the crystals.

Distinguishing Features.—Scolecite resembles natrolite but is length-fast instead of length-slow and has oblique extinction. Thomsonite has parallel extinction but is length-slow in some sections and length-fast in others.

Occurrence.—Natrolite is a secondary mineral found in cavities of igneous rocks, especially basalt. The associates are other zeolites and calcite.

Mesolite

$Na_2Ca_2Al_2(Si_3O_{10})_3.8H_2O$ Monoclinic

$$n_\alpha = 1.505$$
$$n_\beta = 1.505$$
$$n_\gamma = 1.506$$
$$2V = ca.\ 80°;\ \text{Opt. } (+)$$
$$c \wedge Y = 2 \text{ to } 5°$$

Color.—Colorless.

Form.—Mesolite usually occurs in fibrous aggregates.

Cleavage perfect in two directions $\{110\}$ and $\{1\bar{1}0\}$.

Relief moderate, $n <$ balsam.

Birefringence very weak, $n_\gamma - n_\alpha = 0.001$; the maximum interference color is first-order gray.

Extinction.—The maximum extinction angle in longitudinal sections is very small, from 2 to 5°.

Orientation.—The fibers are in part length-slow and in part length-fast.

Twinning.—Twins with $\{100\}$ as twin-plane are universal, but the twinning is not conspicuous.

Interference Figure.—The figure is biaxial positive with a very large axial angle. The figure lies across the fibers. Dispersion, $r > v$ strong.

Distinguishing Features.—Mesolite very much resembles the other fibrous zeolites. In common with thomsonite the fibers are in part length-slow and in part length-fast. From thomsonite it may be distinguished by the maximum extinction angle of 2 to 5° and by its large axial angle.

Occurrence.—The occurrence of mesolite is the same as other zeolites, in the cavities of basalts and related rocks.

Thomsonite

$NaCa_2Al_5(SiO_4)_5.6H_2O$ Orthorhombic

$$n_\alpha = 1.512 \text{ to } 1.530$$
$$n_\beta = 1.513 \text{ to } 1.532$$
$$n_\gamma = 1.518 \text{ to } 1.542$$
$$2V = 44 \text{ to } 55°; \text{ Opt. } (+)$$
$$a = X, b = Z, c = Y$$

Color.—Colorless.

Form.—Thomsonite usually occurs in fibrous or columnar aggregates. Euhedral crystals are very rare.

Cleavage in one direction {010}.

Relief rather low, $n <$ balsam.

Birefringence weak to moderate, $n_\gamma - n_\alpha = 0.006$ to 0.012; maximum interference colors range from first-order white up to low second-order blue in different specimens. Cross sections of fibers show the highest interference color for a given thickness.

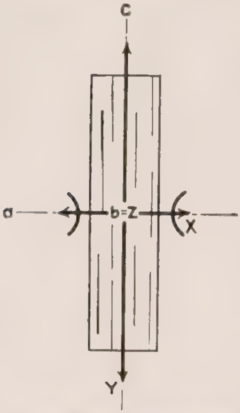


FIG. 258.—Orientation diagram of thomsonite. Section parallel to (010).

Extinction parallel.

Orientation.—Some of the fibers are length-slow and some length-fast since $c = Y$.

Interference Figure.—The figure is biaxial positive with rather large axial angle. The figure lies across the fibers since the axial plane is {001}. Dispersion, $r > v$ strong.

Distinguishing Features. Thomsonite is much like the other fibrous zeolites in general appearance and optical properties. Natrolite is length-slow and scolecite length-fast, while some of the fibers of thomsonite are length-slow and some length-fast. The same is true of mesolite, but in mesolite the maximum extinction angle $c \wedge Y$ is about 3°. The axial angle of mesolite is much larger than that of thomsonite.

Occurrence.—Thomsonite occurs as a cavity filling in subsilicic volcanic rocks such as amygdaloidal basalts.

Scolecite

$CaAl_2Si_3O_{10}.3H_2O$ Monoclinic

$$n_\alpha = 1.512$$
$$n_\beta = 1.519$$
$$n_\gamma = 1.519$$
$$2V = 36°;\ \text{Opt.}\ (-)$$
$$b = Z,\ c \wedge X = -15 \text{ to } -18°$$

Color.—Colorless.

Form.—Scolecite occurs in crystal aggregates with a columnar to fibrous structure.

Cleavage distinct in two directions {110} at angles of *ca.* 88°.

Relief low, $n <$ balsam.

Birefringence weak, $n_\gamma - n_\alpha = 0.007$; so the interference colors are gray and white of the first order.

Extinction.—The maximum extinction angle in longitudinal sections is −15 to −18°.

Orientation.—The crystals are always length-fast.

Twinning.—Twinning is common. The *c*-axis [001] is the twin-axis and {100} the composition face.

Interference Figure.—The figure is biaxial negative with a moderate axial angle. The axial plane is normal to {010}. Dispersion, $r < v$ strong.

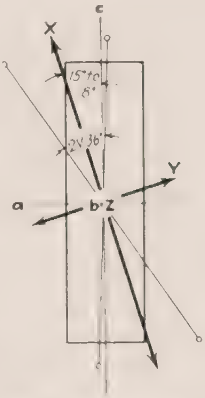


Fig. 259. Orientation diagram of scolecite. Section parallel to (010).

Distinguishing Features.—Scolecite is much like natrolite and other rare fibrous zeolites. The oblique extinction of about 17° and twinning are the most distinctive features of scolecite.

Occurrence.—Scolecite is a secondary mineral found in cavities of igneous rocks, especially basalts.

MINERALOIDS

The term mineraloid is given to the mineral-like constituents of rocks which are not definite enough in chemical composition or in physical properties to be included in the list of minerals. The most common and abundant mineraloid is naturally occurring glass or volcanic glass, which is widespread and often of geological importance. Obsidian, perlite, pitchstone, pumice, etc., are petrographic terms, but glass as a whole may be treated as a mineraloid.

Palagonite, an alteration product of fragmental basaltic glass formerly classed as a mineral, is undoubtedly a mineraloid.

Some authorities would doubtless place lechatelierite or silica glass in the list of mineraloids. Silica glass, however, is probably definite enough in composition and properties to be listed as a mineral. It is more closely related to the silica minerals than to volcanic glass.

Hydrocarbons also may be treated as mineraloids. Hydrocarbons are very difficult to obtain in thin sections on account of their solubility in balsam.

VOLCANIC GLASS

SiO_2,Al_2O_3,Fe_2O_3,FeO,MgO, Amorphous
CaO,Na_2O,K_2O,H_2O, etc.

$$n = 1.48 \text{ to } 1.61$$

Color.—Colorless to gray or reddish.

Form.—Usually massive, sometimes vesicular, perlitic, etc. Often contains spherulites of orthoclase, microlites, crystallites, and phenocrysts.

Cleavage absent but may have perlitic parting.

Relief low to moderate, n usually less than balsam but sometimes greater. The index of refraction increases as the silica decreases.

Birefringence usually nil, but some varieties show weak double refraction which is due to strain.

Distinguishing Features.—Opal may be mistaken for glass, but the refractive index of opal is distinctly lower.

Alteration.—Volcanic glass is often more or less devitrified (see Fig. 249, page 288). The alteration products are usually rather indefinite, but sometimes feldspars, tridymite, cristobalite, or montmorillonite are the result of devitrification. Palagonite is always the result of alteration of glass fragments.

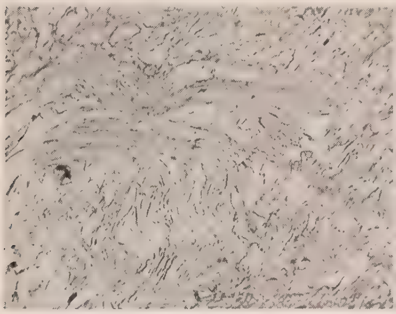


Fig. 260.—(×12) Volcanic glass (pumice) showing flow texture.

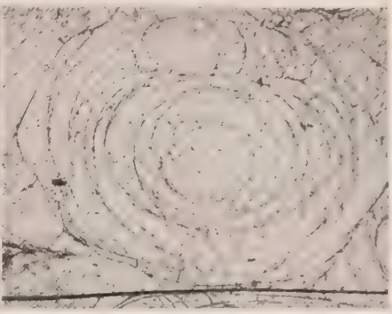


Fig. 261.—(×12) Volcanic glass (perlite) showing perlitic texture and crystallites.

Occurrence. Glass often occurs as an independent igneous rock such as obsidian, pumice, perlite, or pitchstone. Most volcanic glass corresponds to rhyolite in composition. Glass is also found as a narrow selvage to basalt dikes. This variety is known as tachylyte. Glass is a prominent constituent of vitrophyre and occurs in the groundmass of many volcanic rocks.

Silica glass has been described as a mineral under the name *lechatelierite* (see page 168).

Palagonite

SiO_2,Al_2O_3,Fe_2O_3,FeO,MgO, CaO,H_2O (Altered Glass) Amorphous

$$n = 1.47 \text{ to } 1.63$$

Color.—Usually yellow to yellowish brown but also brown and greenish.

Form.—Palagonite is found as a rim or zone around glass fragments or in massive form. It often shows an apparent oölitic structure which is due to the filling of spherical vesicles.

Relief low to medium, n either less or greater than balsam.

Birefringence nil to very weak. Palagonite is a hydrogel and the weak birefringence sometimes noted is probably due to strain.

Distinguishing Features.—Palagonite resembles opal, collophane, and volcanic glass. The index of refraction is too high for opal and nearly always too low for collophane. It is distinguished from glass by the high water content.

Alteration.—The palagonite formed from basaltic breccia fragments at Roseburg, Ore., has, according to A. C. Waters, been altered to chlorite.

Occurrence.—Palagonite is found in palagonite tuffs and palagonite rock. It is formed by the hydration of fragmental basaltic glass. The glass fragments are in whole or in part converted into the palagonite. Associates besides glass are calcite, zeolites, chlorite, pyroxene, olivine, and plagioclase (the last three are relict minerals from the original glass).

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