# PETROGRAPHIC METHODS

THE AUTHORIZED ENGLISH TRANSLATION OF

PART I

Anleitung zum Gebrauch des Polarisationsmikroskops
(Third revised edition)

AND

PART II

Die Gesteinsbildenden Mineralien
(Second revised edition)

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# PETROGRAPHIC METHODS

## PART I

## THE POLARIZING MICROSCOPE

## PART II

## ROCK MINERALS

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# PREFACE

Although there are several excellent treatises on rock minerals in thin section there is, nevertheless, a demand for a text which sets forth all the methods used in a detailed study of rocks, in a clear and concise manner. The fact that Part I of the original German text, published by the Herder Publishing Company, of Freiburg, in Breisgau, appeared in the third edition in 1910 and Part II in the second edition in 1907, seems recommendation enough for presenting it to the English reading student. As it was found inexpedient to adhere strictly to a mere translation of the German an attempt has been made rather to render it freely into English.

I am greatly indebted to Professor E. H. Kraus, of the University of Michigan, for encouragement in this effort, for very helpful suggestions in its execution, and for material aid in reading the manuscript and correcting the proof. I wish to express here my sincere appreciation for his interest in this work. Also to Mr. W. F. Hunt, of the University of Michigan, I express my hearty thanks for aid in reading the manuscript and correcting proof.

R. W. Clark.

Mineralogical Laboratory,
University of Michigan,
*January*, 1912.

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## CHAPTER I

**ERRATA.**

| | | | | |
|---|---|---|---|---|
| Page 18 | Caption to Fig. 32*a* should read Lomb. | | | |
| Page 22 | Line 14 | " | " | 1/2 mm. |
| Page 64 | ⊛ | " | " | ϵ |
| Page 132 | Caption to Fig. 161 | " | " | Heating Apparatus. |
| Page 184 | " " " 183 | " | " | Trachyte. |
| Page 188 | " " " 195 | " | " | Pyroxene. |

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# Introduction

The investigation of inorganic substances does not entail a study of an almost inexhaustible number of forms as is the case in the organic world where the structure is often so detailed that even the strongest objectives of a modern microscope cannot resolve them. Inorganic bodies occur in a comparatively large number of different forms and strong magnification is rarely needed in the investigation of them, because their structure is seldom very minute.

The methods of microscopic investigation employed in the study of organic nature are not applicable in inorganic research because of the infinite number of chemical compounds already known and the large additions that are being made daily. If the microscope were merely an instrument for magnification, as it is with zoologists, botanists, and medical investigators, neither the chemist nor the mineralogist would be warranted in undertaking microscopic studies.

Nevertheless, the modern microscope is very useful in the investigation of inorganic substances. It is a sort of optical universal apparatus which reveals not only the outer form, but also the inner structure of a substance. It leads to results rapidly and easily, which if obtained by other methods would involve much time and labor. The introduction of the microscope into chemical and mineralogical laboratories has been made possible by numerous improvements devised in the last thirty years and by its transformation into a polarizing instrument. It is not yet used as much as it might be or as extensively as its adaptability warrants. The splendid aid such a microscope affords, is too little appreciated, especially in synthetic and analytical chemistry. In many instances there is no other way of determining the characteristics of a substance so rapidly and positively, making lengthy tests often unnecessary.

Microscopic methods are especially serviceable in the investigation of rocks. Petrography, the science of rocks, owes the great progress it has made in the last third of the nineteenth century to microscopic investigations. These methods, so fruitful to the petrographer, have only recently been applied to chemical investigations, but their general introduction can be accomplished only with considerable effort. However, microchemical investigations based upon modern microscopic technic have yielded results that are extremely promising.

Anyone, who has had opportunity to study the methods of microscopic analysis thoroughly, must confess that, with a little practice, they are very useful in recognizing rapidly, easily, and positively the composition of a substance even in very small quantities. Nevertheless, the optical methods found at first only a very limited use in this promising field. Synthetic chemistry has made use of microscopic methods still less, although they would be very helpful to organic chemists in particular on account of the large number of compounds. The unnecessary loss of time which would be saved if organic chemists had a means of identifying their compounds both rapidly and accurately, no one can estimate. If it were only known how quickly all the optical properties of a crystalline precipitate can be determined after a little practice, it would be found justifiable to recommend most urgently that chemists become skilled in microscopic technic. The usual statements made in the literature concerning such precipitates generally take into consideration only the simplest morphological properties and these are frequently the least constant characteristics of a substance.

Chemists have adopted petrographic methods in spite of the fact that their materials are quite different. In a way, a petrographer is at a disadvantage because, in the investigation of slides, he has to deal with sections orientated at random while in the crystalline powders, which a chemist studies, the various crystals assume a common characteristic position on the object glass on account of their development. It is much easier to determine the crystal system in the latter case, which is not easily done in many instances in rock slides. On the other hand, variously orientated sections of one and the same mineral can be studied by a petrographer and he is able to determine the optical properties of a substance in all directions, while with isolated crystals this is often impossible. Some knowledge of physical crystallography is an absolute prerequisite for investigations in both these fields and its successful application to microscopic studies requires much practice.

The first demand made of a polarizing microscope is that its combinations of lenses shall be as perfect as possible. Magnification is of secondary importance, the other optical adjustments being the most important part of the instrument. A large, plane, achromatic field combined with objectives and oculars transmitting as much light as possible are the first things demanded of a microscope by a mineralogist as well as by a botanist, zoologist, or medical investigator. The lens systems are used for the various optical methods, which have been developed in microscopic technic, and the optical properties, as well as the observations of the image of the object investigated, are dependent upon the sensitiveness of the lenses.

The mineral constituents of rocks can be recognized by the naked eye only in a few cases. Macroscopic examination is never sufficient to reveal all the details of the composition of a rock. Texture also, which is of great importance in the classification of many rocks, can be observed by the unaided eye only when it is comparatively coarse. Before a thorough study of the composition and texture of rocks is undertaken, the student should become well acquainted with the means by which such knowledge may be obtained.

Microscopic examination of thin sections is very important. It is quite necessary for the student to become as well acquainted with microscopic optical methods as possible even though only a superficial knowledge of petrography is desired, because an approximate determination of rocks is frequently impossible without them. On the other hand, to think that the macroscopic characteristics of a rock should be ignored and the same determined only in thin section under the microscope, is an error that must be avoided, although it was prevalent during the earlier stages of the development of petrography. The macroscopic appearance of a rock with reference to texture and constituents furnishes a clue, which in many instances simplifies or supplements the microscopic investigation. For this reason the general exterior appearance of a rock must be carefully observed before the microscopic investigation is begun. Mineralogy is the science that teaches one to recognize the minerals by their macroscopic properties. Petrographic investigation should not be undertaken without a thorough knowledge of mineralogy, although the list of rock-forming minerals of frequent occurrence is very small. Mineralogy is the indispensable foundation upon which petrographical investigation is based.

Good results cannot be obtained in the microscopic study of rocks unless the student has a comprehensive knowledge of the optical properties of crystals and has had much practice in the application of microscopic methods. Familiarity with a polarizing microscope is a prerequisite for all petrographic work. Serious errors in the determination of rock constituents may be avoided by such knowledge. Special emphasis must be laid upon the fact that simply knowing the appearance of certain minerals in some rocks, or in a large number of rocks, is not sufficient to give that confidence which is necessary in petrographic investigation. As the appearance of one and the same mineral varies greatly in different rocks, a continual source of error is thus introduced and only general confusion results if the knowledge of minerals is purely superficial and not sufficiently based on microscopic optical methods.

The microscopic optical methods necessary for petrographical investigation are discussed thoroughly in the first part of this book. A knowledge of these fundamental principles must precede all petrographic work.

A positive statement concerning the detailed composition of a rock cannot always be made upon the results of microscopic investigations alone. A thin section confines the examination to an extremely limited portion of the rock. In general, therefore, one cannot expect to ascertain the complete composition of a rock even after a very exhaustive study of one or more thin sections. This is especially true of certain constituents that are only sporadically present, but still are of considerable importance for the rock as a whole. It often happens, after careful investigation by optical methods, of certain mineral sections in a slide, that the student does not feel sure that he has determined the mineral correctly. An attempt is made to supplement these methods as much as possible in various ways and this may be done either by a series of chemical tests on the slide itself or by isolating the different constituents by chemical or physical means so as to facilitate studies on them. We distinguish, therefore, between methods of separation and methods of investigation, and each of these is divided into a chemical and a physical group. A clear conception of the mineral composition of a rock, upon which a safe classification is possible, can be obtained only through a combination of all these methods.

Finally it may be added that the most accurate determination of the composition of a rock, obtainable by a combination of all these methods, is one of the goals of petrography, but that with it, the final object of petrographical research has by no means been reached. It strives to explain not only the present condition of the rocks, but also the origin and alteration of them. All descriptions of rocks should be full enough to permit of the determination of their geological relations. Petrographical investigation becomes important only in connection with geological studies and in this respect it is one of the most important chapters in the whole science of geology. Without its aid geology comes to some conclusions which have been proved in many instances to be erroneous. The purpose of this book is to make the determination of the rock-forming minerals possible and space cannot be devoted to the consideration of these other points. Description of the minerals and the methods of studying them is the sole object of this text.

# PART I

## THE POLARIZING MICROSCOPE

# CHAPTER I

## The Microscope

**The Simple Microscope or Lens.**—The simplest form of the microscope, the lens, serves to shorten the focal distance of the eye and to increase the focal angle so that objects which are too near to be seen distinctly by the naked eye can be seen by the use of the lens. The shortest distance that a normal naked eye can see distinctly is about 25 cm. If the distance from the eye be less, the image becomes indistinct and it requires a system of lenses to make it sharp. *Magnification is, therefore*, always reduced to the focal length of 25 cm. A convex lens casts a *real* image SR, Fig. 1, of the object *rs*, which is farther from the lens than its focal length. The image is inverted, on the opposite side of the lens from the object, and is beyond the focal length of the lens. It usually cannot be observed by the eye directly, but becomes visible when cast upon a screen and can be reproduced directly on a photographic plate. If the object is less than the focal distance from the lens, the rays do not unite in a point on the other side of the lens, Fig. 2, but the image RS appears in a normal position on the same side as the object *rs*, and is designated as a *virtual* image. It cannot be projected.

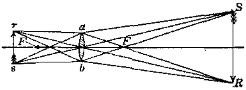


FIG. 1.—Real Image.

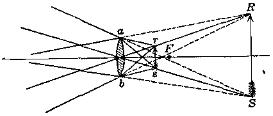


FIG. 2.—Virtual Image.

The faces of a convex lens are portions of spherical surfaces and, in consequence of this, the rays passing through various parts of the lens converge approximately at a common point only when the curvature of the lens is very small. If the faces have a greater curvature the rays through the edge unite at another point than that at which the rays through the center converge, and we see the phenomenon of *spherical aberration*, Fig. 3. This causes convexity of the image and indistinctness in various portions of the field of vision, which is very annoying and fatiguing to the eye. The image appears distorted because all parts of the field are not magnified equally. The border is magnified more than the center so that a cross-sectioned object like Fig. 4 appears as indicated in Fig. 5.

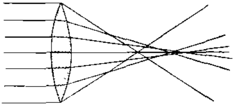


Fig. 3.—Spherical Aberration.

Another deficiency of a simple lens is its dispersion, i.e., the property of bodies to refract light of various wave lengths differently. In the normal case, colors having the shortest wave lengths are refracted most, i.e., violet rays are deviated more than red. The formula for such dispersion is $v > \rho$. It thus happens that the object appears to have a colored border because the various colors converge at different places, Fig. 6. This phenomenon is called *chromatic aberration.*

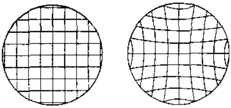


Fig. 4. Fig. 5.
Figs. 4 and 5.—Cross-sectioned Object Magnified
Uniformly. Ununiformly.

These two difficulties can be reduced if only those rays which pass through the center of the lens are used. This was accomplished in the older types of lenses in the manner indicated by Figs. 7 and 8, the former being the Brewster, the latter the Coddington model. The outer part of the lens is cut off in each case by grinding out a portion. The elongated cylindrical lens devised by Stanhope, Fig. 9, also reduces this deficiency. On it the face turned toward the object has less curvature than the other face. All of these models have the disadvantage that their focal lengths are very short. Fraunhofer improved upon them by combining two plano-convex lenses set

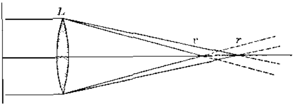


Fig. 6.—Chromatic Aberration.

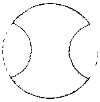


Fig. 7.
Brewster's Lens.

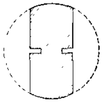


Fig. 8.
Coddington's Lens.

with their convex faces toward each other, Fig. 10. This model has been varied in many ways.

Fig. 9.—Stanhope Cylinder Lens.

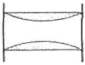


Fig. 10.—Fraunhofer Lens.

Lenses which are completely or almost entirely corrected for spherical and chromatic aberration are said to be *aplanatic* and *achromatic*. Such a condition is obtained, however, only by a combination of different kinds of glass. Thus, flint glass has nearly twice as great a dispersion as crown glass. A system of lenses can be arranged as in Fig. 11, consisting of a converging lens L of crown glass and a double concave lens of flint glass L′. The colors are dispersed by the convex lens, but are *reunited in the point p by the concave lens*, the so-called Bruecke lens. The best modern lens is one composed of a double convex lens of crown glass L, *Fig. 12, between two diverging* meniscuses of flint glass F. It is almost perfectly aplanatic and achromatic and combines with these advantages a large field, a *long focal length, and distinctness.* The entire field, which is very large, is only used when the lens is placed very close to the eye. It is used principally in the investigation of rocks when a magnification of six to twelve is desired.

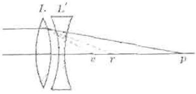


Fig. 11.—Correction of Chromatic Aberration.

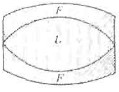


Fig. 12.—Steinheil Triplet.

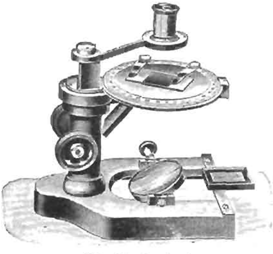


Fig. 13.—Lenstand.
(After Voigt & Hochgesang.)

The *Verant* lens, consisting of a combination of two lenses, is quite serviceable for a smaller magnification up to about four. It has a horn eyepiece which must be fitted to the eye and this places it in the proper position to obtain an image entirely free from distortion. A Zeiss anastigmatic lens can be used for stronger magnification up to about twenty-seven. It consists of a combination of four lenses and in spite of its comparatively large magnification has a wide field and the object can be placed quite a considerable distance from it. The lens ought to be held firmly in a stand for that purpose while the eye is moved slowly over it.

It is best to fasten the lens upon a stand, especially when stronger magnification is used, to insure the necessary stability and to leave the hands free for manipulation. Fig. 13, page 3, shows such a stand equipped to use polarized light. It may also be provided with a rotating stage.

**The Compound Microscope.**—The compound microscope, or simply the microscope, is distinguished from the simple microscope or lens by a combination of two independent systems of lenses. The simplest form of such a microscope consists of two double convex lenses as shown in Fig. 14, in which the path of the rays through the microscope is shown diagrammatically. One of the lenses, *ab* Fig. 14, has a shorter focal length than the other, and since it is always next to the object it is called the objective. It casts a real magnified image RS of the object *rs*. This image is a little further from it than the focal length of the lens and is inverted. It is projected within the focal length of the eyepiece or ocular and is, therefore, again magnified and appears as a virtual image at S'R'. This has the same relative position as the real image, i.e., it is inverted with respect to the object. It thus appears that the objective casts a real image of a close object and this image is in turn observed by means of the ocular, as a magnified virtual image. Since the real image is inverted with respect to the object and the virtual image not, objects observed through the compound microscope always appear reversed. For purposes of projection such as

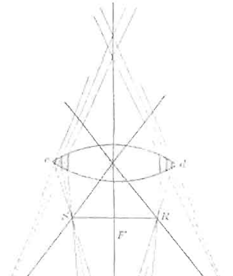
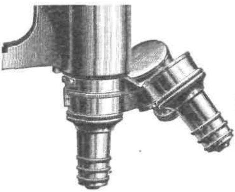


FIG. 14.—Passage of Rays through a Compound Microscope.

is common in photography, the ocular is generally removed and the real image of the object is projected upon a photographic plate or upon a screen.

The ocular and objective are placed in a metallic tube to exclude all disturbing outside light between them and, as shown in Fig. 14, they are placed much farther apart than the sum of their focal distances. They are corrected for a fixed distance, but nevertheless the ocular must be so arranged that this distance can be altered somewhat, as desired, because even in a correct *apochromatic* system, object glasses of various thickness may require lengthening or shortening of the tube.

The ocular is generally set in the upper part of the tube and (in the simpler instruments) the objective is screwed into the lower part of it. However, if the objective is changed frequently, considerable time is lost in manipulating, which is very annoying. To avoid this the whole series of objectives can be fastened on a *revolver* so that the change can be effected by simply rotating it, Fig. 15, or the tube can be fitted with an objective *clamp*, Fig. 16, into which the objective can be slipped by means of a ring on the upper part of it, so arranged that it is always approximately centered. Finally, a *guide bar* can be constructed on the objective, which fits accurately into a groove in the tube, Fig. 17.



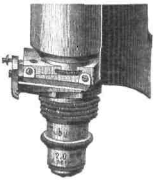


*FIG. 15.—Revolver. FIG. 16.—Tongs. Objective Holders. FIG. 17.—Groove.*

A more thorough discussion of the construction of modern objectives and oculars would lead us too far and they are generally very perfectly constructed by the more reliable firms. It is evident that a system of lenses must be even more achromatic and aplanatic than a simple lens. At best a system of lenses is only approximately perfect in both these respects and the image appears quite perceptibly distorted when a *periscopic ocular* is employed in order to use the whole field of the objective. This is especially true with low magnification. Generally, the correction for chromatic aberration is perfect only for a part of the spectrum, so that a faint coloring appears particularly with strong objectives. This is entirely avoided in *apochromatic* lenses, which are constructed of special glasses. In them there is an equal difference of magnification for the colors in all zones of the field of vision and this is completely counter-balanced by a compensating ocular, constructed in the reverse order.

To obtain a high magnification it is generally advisable to use a strong objective with a medium to weak ocular, because the amount of light in the image is entirely dependent upon the *numerical aperture* of the objective. Abbe defines the *numerical aperture*, or simply aperture, as the product of one-half of the angle of aperture of the lens and the index of refraction of the medium between the objective and the object. Figs. 18 and 19 show that the angle of aperture of the system of lenses, i.e., the angle of the cone of rays that is taken in by the objective is not the sole criterion for the amount of light from a given point. In each case the angle of the cone of light, and therefore the amount of light transmitted from the object, is the same. Fig. 18 represents a type of a *dry system* of lenses in which the outer rays of the cone of light, when extended, fall outside of the objective because, when they pass from the slide into the air, they are refracted away from the normal and in this case are diverging at a larger angle than the angle of aperture of the lens. Thus the object is illuminated by a smaller cone of light.

If a liquid is placed between the object and the objective the latter becomes an *immersion system*, Fig. 19. The liquid should have an index of refraction approximately the same as that of the cover-glass on the object and the lower lens of the objective, e.g., oil. The light upon passing into the object is refracted, as in the other case, but when it passes through the oil into the objective it suffers but little deviation. Every point of the object is illuminated by the full strength of the cone of light used.

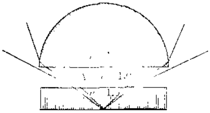


FIG. 18.—Passage of Rays in a Dry System.

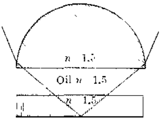


FIG. 19.—Passage of Rays in an Immersion System.

The aperture of a dry objective cannot be more than 1 theoretically, because $n=1$ and the maximum of $\sin u$ is 1. With a water immersion the theoretical value may be as high as 1.33, when half of the angle of aperture is 90°, but this is impossible in practice. With oil it may reach 1.5 and with bromnaphthalene it may be over 1.6. It must always be kept in mind that the lenses of the objective, the cover-glass, and the liquid between them must have the same indices of refraction. The increased illumination of an immersion objective is shown by the fact that even a water immersion takes in 1.77 times as much light as a dry system with the same angle of aperture.

The *resolving power* of objectives will now be briefly discussed. The shortest distance that can be distinguished by an objective is represented by the quotient of $\lambda$ divided by the aperture of the objective, where $\lambda$ is the wave length of the light employed. Structures of 0.00015 mm. can be distinguished by a monobromnaphthalene immersion making use of the violet rays and taking their impression on a photographic plate. This is more easily accomplished by oblique illumination with a ray of light or with a central cone of light. On account of the greater wave length of the light in the illuminous part of the spectrum, the distances must be about twice as great to make the object distinct. Finer detail can be obtained by *photographic methods than by direct observation, especially when only ultraviolet* rays are used. The objectives must, however, be especially corrected for these rays. Ultramicroscopy, devoted to the study of extremely small particles of approximately molecular dimensions, is only mentioned here for the sake of completeness.

It may be suggested that the best source of light for microscopic investigation is daylight and indeed a northern sky covered with thin white clouds. Direct sunlight as a source of illumination is extremely disadvantageous for the eye and must be changed into diffused light by the use of a screen. Only two of the artificial sources of light are of importance, namely, the electric arc and the Lassar lamp. The latter gives a blue light produced by passing it through a color filter.

To produce monochromatic light, either a flame colored by sodium, lithium and so forth or Geissler tubes or a light filter may be used. If very intense illumination is employed, the Abbe *spectro-polarizer* may be advantageously used. It is inserted in place of the regular polarizer and gives illumination from a small part of the spectrum.

The tube is fastened to the stand by means of a large screw for *coarse adjustment and a micrometer screw for fine adjustment.* It is movable vertically to and from the stage, which is firmly fixed on the stand. The illuminating apparatus is seen through a hole in the stage. It serves as a collecting system for the light reflected from a concave mirror below. It is necessary that the aperture of the illuminating system be at least as great as that of the objective if the entire aperture of the latter is to be used. The former, however, need not be so carefully corrected for spherical and chromatic aberration. The Abbe illuminating apparatus is of the most perfect construction for, when it is employed as an immersion system, its aperture is the same as the strongest objective and at the same time it affords a sufficiently large illuminated field, when used with the weakest objectives. *A condenser is used in the simpler microscopes, but it must be* removed when using low power objectives because of the small illuminated field.

**Polarizing Apparatus.**—The polarizing microscope differs from an ordinary microscope chiefly in having an attachment for producing *plane polarized* light. Ordinary light vibrates in all planes at right angles to the direction of propagation of the ray as shown in Fig. 20. Plane polarized light, on the other hand, vibrates only in one plane, Fig. 21. The plane of polarization

PP, Fig. 22, of a ray of light AB, i.e., the plane in which the poles lie, is always perpendicular to the plane of vibration SS.

In using transmitted polarized light, the direction of propagation AB, Fig. 22, is perpendicular to the plane of the object. The light vibrates in a plane at right angles to this direction, this plane being called the plane of vibration SS′, Fig. 22, while its *trace on the plane of the object SS′, Fig. 21, is the vibration* direction of the light. The velocity of the light is dependent upon the rate of vibration, or in other words, the elasticity of the medium under investigation in a direction at right angles to the direction of propagation. In examining a slide we observe the differences in the optical elasticity in different directions, which lie in the plane of the object itself, and are thus perpendicular to the direction of propagation of the light. The plane of polarization PP′, Fig. 22, is perpendicular to the plane of vibration SS′.

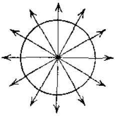


Fig. 20.—Ray of Ordinary Light.

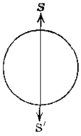


Fig. 21.—Plane of Vibration of a Ray of Polarized Light.

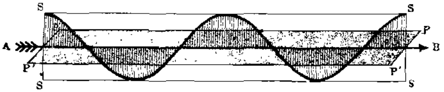


Fig. 22.—Ray of Polarized Light with Plane of Vibration, Plane of Polarization and Direction of Propagation.

Ordinary light can be changed into partially polarized light by reflection or refraction. Polarization by reflection is most complete when the light strikes the reflecting surface at a certain angle, which is dependent upon the reflecting substance. This angle of incidence $i$ is determined by the formula $\tan i = n$. This angle possesses another notable property, viz., that the reflected portion of the ray incident at that angle travels at right angles to the refracted portion. It is called the angle of polarization, and for ordinary glass is about 57°. Naturally it varies with different colors, although only to a small extent. By repeated reflection at this angle the amount of light may be increased and for this reason a series of thin glass plates is often employed, which produce almost perfectly polarized light.

A *ray of ordinary light* L, *Fig.* 23, *which falls upon a series of* glass plates at the polarizing angle is partially reflected as a ray of plane polarized light P. Its plane of vibration is perpendicular to the plane of the incident light LOB. The refracted portion of the ray P′, which passes through the plates is likewise polarized, but not so perfectly. Polarization becomes more complete the oftener the ray is refracted, i.e., the greater the number of plates. The plane of vibration of the refracted polarized ray is perpendicular to that of the *reflected ray and is therefore parallel to the* plane of incidence. Polarization of the refracted ray is the more complete the smaller the angle of incidence. Polarization by refraction often becomes quite annoying, especially in the case of very strong objectives, for example, those with a very large *angle of aperture*, because *in them peripheral rays of light often* pass through at oblique angles of considerable size.

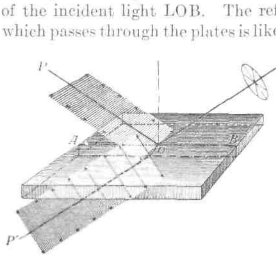


Fig. 23.—Polarization by Reflection and by Refraction.

The simplest and oldest polarizing instruments are based upon the use of a reflecting glass plate. Such is the Noerremberg *polariscope* or *orthoscope*, Fig. 24. Light from *a* strikes the *reflecting plate* AB, *the polarizer, at the polarizing angle and is* reflected as plane polarized light to the mirror *c*, and from it into the axis of the instrument. The polarized light passes through the plate AB and the rotating stage above it, and strikes the blackened mirror S, the analyzer, which can be rotated about *a vertical axis. When S is parallel or antiparallel to AB, it* reflects the light polarized by the latter, but when in a crossed position it extinguishes the light and appears dark.

A simple polarizing apparatus can be prepared from double refracting crystal plates in which the absorption of light in one direction is much greater than in the other, for example, in deeply colored tourmaline. Fig. 25 shows tourmaline tongs of this sort. Each arm of the tongs contains a plate of tourmaline cut parallel to the optic axis and so fastened that it can be rotated. The plates are so thick that no light passes through in the direction of greatest absorption. If like directions in the two plates are parallel light is transmitted, but in crossed positions the field of vision appears dark.

FIG. 24.—Orthoscope.

FIG. 25.—Tourmaline Tongs.

Polarization of light by reflection or refraction is by no means complete enough for finer investigations, while that produced by absorption gives polarized light which is deeply colored. For this reason such apparatus is used only in the simplest and cheapest instruments, while in a good polarizing microscope, nicol prisms or similar devices are employed. These completely polarize the light and produce colorless illumination with but little loss.

The construction of nicol prisms, or simply nicols, depends upon the ability of double refracting crystals to decompose a ray of ordinary light into two rays of polarized light vibrating at right angles to each other. These rays are refracted differently. The original form of a nicol, Fig. 26, was an elongated cleavage piece of calcite, the ends of which were cut so as to make an angle of 68° instead of 71° with the long edges. Then the calcite is cut through at right angles to the artificial faces and the two halves are cemented together in the same position with Canada balsam. The two polarized rays vibrating at right angles to each other pass through the lower half of the prism as far as the layer of Canada balsam, but the ordinary ray (*o*) is refracted more than the extraordinary ray (*e*). In the direction in which the ordinary ray vibrates, calcite is a much denser medium for light than Canada balsam, and since this ray impinges upon the layer of balsam with a sufficiently high angle of incidence it is totally reflected and eliminated. The other ray (*e*) is refracted about equally in calcite and Canada balsam and since it impinges upon the balsam with a smaller angle of incidence, it passes through the combination with only slight refraction. Thus a nicol prism produces light polarized in one plane, the plane of vibration being that of the extraordinary ray and a principal section of the calcite. The vibrations of the ray are parallel to the short diagonal of a cleavage piece of calcite.

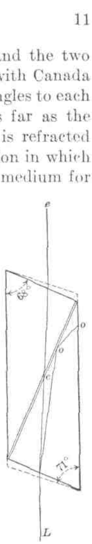


FIG. 26. Construction of a Nicol Prism.

This original form was afterward altered and modified in many ways. One modification which has been used quite extensively was suggested by Hartnack and Prazmowsky. Aside from having the end faces perpendicular to the others they used linseed oil instead of Canada balsam as the cement. This allows the calcite to be used more advantageously. Ahrens produced a double prism of similar construction but much shorter, and it is characterized by an especially large angle of aperture.

*Prisms of sodium saltpeter have recently been recommended extensively.* On account of its optical properties, it is more adaptable for such apparatus than calcite. However, its application has been limited on account of its hygroscopic nature. Combinations of glass with calcite or saltpeter have been used with great success. The upper portion of the prism may be constructed of glass having an index of refraction and dispersion as nearly as possible identical with that of the extraordinary ray in calcite, or only a thin cleavage piece of the double refracting material may be cemented between two glass wedges.

More completely polarized light can be obtained with such a combination than with a simple calcite prism in which the light reflected from the edges is always a disturbing element. Since the indices of refraction and particularly *the dispersion of the glass and the extraordinary ray in calcite are not* exactly the same, such combinations can only be used as polarizers and not as analyzers because they are not entirely achromatic. The name "nicol" has been retained for all these constructions.

**The Polarizing Microscope.**—Fig. 27 shows a cut of one of the simpler polarizing microscopes made by W. and H. Seibert. A cross section of this instrument is shown in Fig. 28. The illumination by a mirror, as well as the ocular, objective, and the movement of the tube by a coarse and a micrometer screw are the same as in an ordinary microscope. This instrument differs, however, from the ordinary model in many ways. Cross hairs, F, Fig. 28, consisting of two fine threads of spider's silk stretched exactly at right angles to each other, are placed in the inner focus

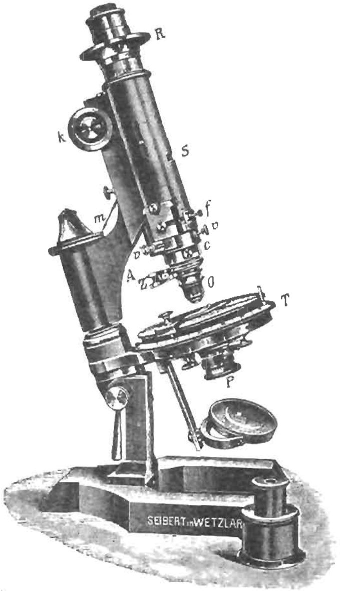


Fig. 27.—Polarizing Microscope by W. & H. Seibert in Wetzlar.

of the Huygen's ocular, which is arranged to fit into the upper end of the tube.

The part of the tube carrying the ocular can be drawn out and contains a slit in which a Bertrand-Amici lens can be placed, S, Fig. 28. The drum *m* on the micrometer screw for fine focusing of the tube is graduated, especially on the larger instruments, so that the vertical movement of the objective can be measured accurately.

The screw *k* for coarse adjustment of the tube should be placed quite high so that the objective can be moved vertically within wide limits, thereby allowing the use of high apparatus on the stage, for example, the universal rotating stage. The arm A, of the stand which holds the tube must be curved as much as possible so that it will not prevent the rotation of the stage with such accessory apparatus on it.

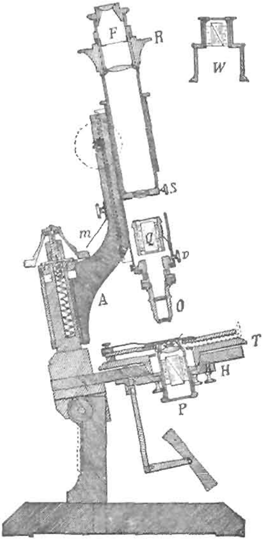


Fig. 28.—Cross Section through the Microscope in Fig. 27.

A nicol prism, the analyzer, is generally placed within the tube so that it can be withdrawn horizontally. Under certain conditions it is advantageous to rotate the nicol through 90° by means of *f*, a circular scale indicating the angle of rotation. In some cases the nicol is fixed and then another nicol W, placed over the ocular, is used when rotation is necessary. The ocular is then supplied with a graduated ring R so that the amount of rotation can be read. The latter form of analyzer is found only in the older models.

The clamp Z, Fig. 27, on the lower end of the tube holds the objectives firmly. A slit *c* into which the compensators, placed between two small glass plates, can be inserted, is made in the tube above the clamp. The objective holder is fitted with two micrometer screws, $v$ and $v'$, at right angles to each other with springs opposite each, so that the objective can be moved slightly in a horizontal direction. After each change of objectives the axis of the latter can be centered exactly with the axis of rotation of the stage by means of these screws. They are therefore called the *centering screws.*

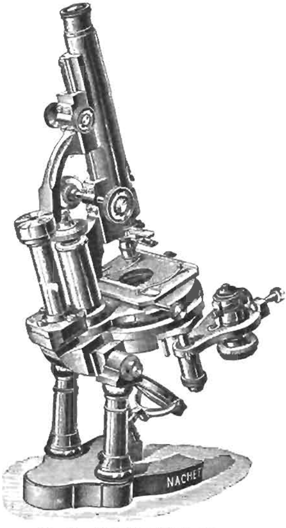


FIG. 29.—Polarizing Microscope by A. Nachet in Paris.

On other models the centering is effected on the stage, i.e., instead of adjusting the axis of the objective with the axis of rotation of the stage, the center of the stage itself is shifted by a similar pair of centering screws. Centering on the stage is not so advantageous, for it lessens the stability of the stage, which is of considerable importance, especially with high magnifications.

Frequent centering causes much time to be wasted, especially with the older instruments on which the objectives are always screwed in. This is very annoying, however, so some instruments have been constructed which make centering unnecessary. Thus in the French model, Fig. 29, devised by Nachet (Paris), the objective and the stage are connected by a strong arm and can be rotated simultaneously, thus avoiding all eccentric rotation. This can also be accomplished on the microscope shown in Fig. 30, which was first constructed in Geneva. The objective holder TM with the micrometer screw M is fastened onto the stage and rotates with it. Especially beginners are at a disadvantage in using these models for the *head of the micrometer screw changes its position with rotation* of the stage, and when it is necessary to use the screw there is a tendency to remove the eye from the ocular.

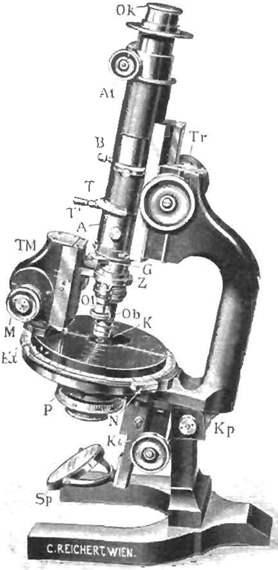


FIG. 30.—Polarizing Microscope by C. Reichert in Vienna.

This defect was avoided by a model first made in England, Fig. 31 being a similar instrument devised by Voigt and Hochgesang. Here the two nicols can be rotated simultaneously, the rotation of one being transmitted to the other by means of a vertical rack and pinion. The object and stage do not move.

Models of this sort are strongly recommended for work with the rotation apparatus, to be described later, and are made in various designs.

By improving this model, Voigt and Hochgesang have recently produced a new instrument called a *polarizing microscope-polymeter*, Fig. 32. S is the coarse focusing screw of the microscope which is constructed particularly wide, and T is a lateral micrometer screw. This is a new feature and is entirely independent of the rest of the instrument. The analyzer can be rotated with the circle R alone and likewise the tube with the ocular and cross hairs can be rotated on the circle $K^2$; while the objective remains stationary. The two nicols can be rotated simultaneously by

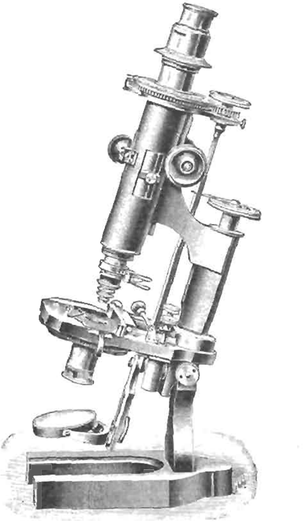


Fig. 31.—Polarizing Microscope with Rotating Nicols. (Voigt & Hochgesang in Gottingen.)

shifting F. Thus this new model is characterized by great stability and convenience, together with a wide range of usefulness.

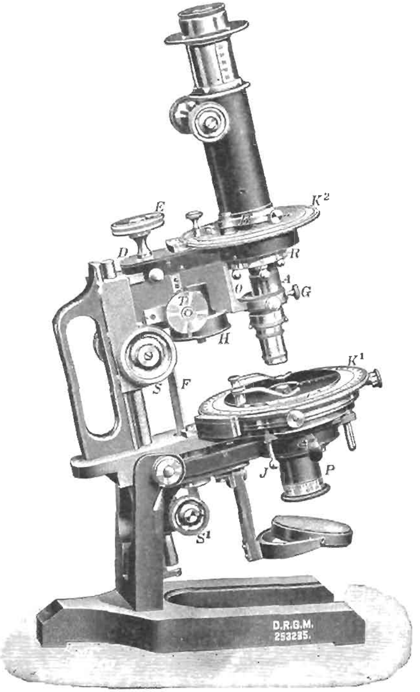


Fig. 32.—Polarizing Microscope Polymeter. (Voigt & Hochgesang in Gottingen.)

The stage T, Figs. 27 and 28, can be rotated about a vertical axis and is graduated so that the amount of rotation can be noted. A vernier is often placed on the scale, but it is generally of little value because the accuracy of microscopic measurements is much too small to permit closer reading than ¼°, an amount that is easily estimated. The stage is also equipped with a series of holes for attaching accessory apparatus. Of these the object clamp is very important and is used to hold the object in place particularly when the stage is inclined. The form shown in Fig. 33 is the most satisfactory because it allows a definite point on the object to be orientated rapidly in the center of the field of vision. It is also useful when the stage can be fixed in any position by means of a set screw.

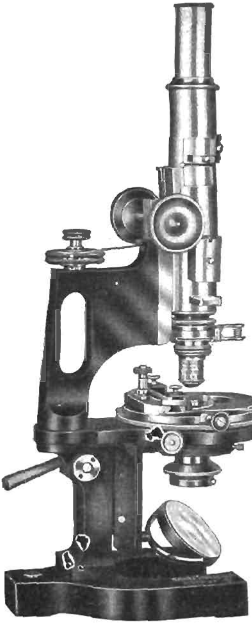


Fig. 32a.—Polarizing Microscope. Bausch & Lamb.

A mechanical stage is frequently used on the larger instruments for investigations particularly with strong objectives, Fig 34. By means of two screws at right angles to each other the object can be moved laterally. With such an apparatus the whole slide can be investigated much more evenly because one is independent of the more or less arbitrary movement of the hand. If the grooves in which the stage slides are equipped with scale divisions, the stage itself may be used to locate the portions of the slide investigated by simply noting the position of the scale with reference to a fixed position of the object on the stage.

It is better though to indicate the position of a mineral in the slide either by a free hand colored ring or by means of an object marker. The latter is adjusted in place of the objective after the mineral has been accurately centered. This little apparatus may have an eccentric diamond point that can be regulated and set in a holder with a spring so that it rests upon the cover-glass when the tube is lowered. Then the stage with the slide held firmly in place is rotated and a small circle is scratched on the cover-glass marking the proper spot. The marker may also have the form of an objective similar to the one above, but on the lower end there is a round opening which can be smeared with some oil color, ink, or a solution of shellac. This leaves a small circle on the cover-glass of the slide.

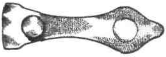


FIG. 33.—Object Clamp.

Beneath the stage on the models shown in Figs. 27 and 28 there is a plate with a hole in the center through which a tube can be moved in a vertical direction by means of a lever. The illuminating apparatus and the second nicol, the polarizer P, are placed in the tube. It is very desirable to be able to remove the nicol and the illuminator separately from the tube, i.e., each piece should be fastened in a separate holder. The illuminating apparatus consists of a lens of small aperture upon which rests the condenser with large aperture. In case of observations with very weak objectives the condenser can be swung out of the path of the rays by means of tongs placed within the rotating stage. When the condenser rests upon the polarizer and the tongs are freed from it, it moves in a vertical direction with the polarizer and other illuminating apparatus. An iris diaphragm which is never lacking on zoological and medical instruments, is placed only on the larger models of the polarizing microscope, because it requires

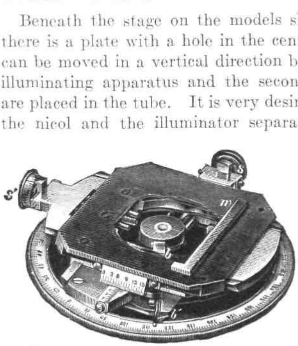


FIG. 34.—Mechanical Stage by R. Fuesz in Steglitz.

rather complicated apparatus and the same effect is obtained by the vertical movement of the illuminating apparatus.

The polarizer can be rotated and there is either a series of notches on the holder into which a catch on the polarizer slips, or there is a graduated scale so that it can be placed parallel to the cross hairs in the ocular at any time.

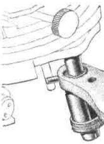


FIG. 35.—Device for removing the Condenser by A. Nachet.

Many other devices have been suggested to overcome the annoyance of removing the condenser by hand. The condensing lens may be placed in a simple slide in the stage of the microscope, but as vertical movement is then impossible, there can be no gradation of the illumination or adjustment for variation of thickness of the object glasses. It may also be fastened in a fixed clamp, but here again the limit of vertical movement is small, which makes an iris diaphragm necessary. The lens may also be fastened in a slide at a fixed distance above the illuminator in such a manner that it retains the vertical movement, but can be drawn out laterally. Finally Nachet perfected a very simple device which does not interfere with the movement of the illuminating system. It consists of a lateral screw below the stage by means of which the condenser can be rotated into position over the illuminating apparatus like a visor, Fig. 35.

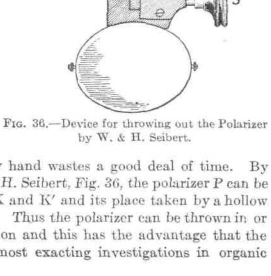


FIG. 36.—Device for throwing out the Polarizer by W. & H. Seibert.

In some cases, especially with very strong objectives or with objects that transmit but little light, it is advantageous to remove the polarizer entirely, because it absorbs more than half the light at one's disposal. For this reason it had better be set in a holder separate from that of the rest of the illuminating apparatus, for then it can be withdrawn from the tube at any time. Orientation of the nicol by hand wastes a good deal of time. By means of a device made by W. and H. Seibert, Fig. 36, the polarizer P can be moved in a groove by the knobs K and K' and its place taken by a hollow cylinder with an iris diaphragm J. Thus the polarizer can be thrown in or out without changing its orientation and this has the advantage that the instrument can be used for the most exacting investigations in organic microscopy at any time. The illuminating apparatus in this device can be moved together with the other in a vertical direction by the screw S′. The condenser C can be slipped out by the tongs Z. This complicated device can also be replaced by the simple visor arrangement and it is also apparent that an Abbe illuminating apparatus might be used.

Fig. 32A represents one of the latest models of a petrographic microscope made by the *Bausch* and *Lomb* Optical Company in *Rochester*, N. Y.

**Material for Observation.**—The largest number and the most important microscopic observations are made in transmitted light. It is therefore necessary to prepare the objects for investigation so that they will be sufficiently transparent to allow the inner structure to be studied and so that there will be no overlapping of different individuals, and at any one place on the object the material be homogeneous. In organic microscopic investigations this is accomplished to a large extent by means of an instrument called a *microtome*. In mineralogy and petrography such thin preparations can rarely be used on account of the difficulty of preparing them. However since the structure of the formations considered here are by no means so fine, a slice of a rock or mineral ground to a thickness of from

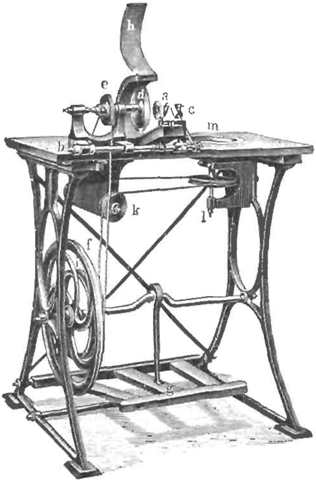


FIG. 37.—Cutting and Grinding Machine by Voigt & Hochgesang.

0.03 to 0.04 mm. is sufficient. Slices of 0.02 mm. thickness or less are necessary only in rare cases for detailed study of objects with fine structure.

A cutting or grinding apparatus is used for preparing thin sections, the larger ones being driven by motor or foot power as in Fig. 37. The smaller machines are supplied with a crank to be turned by hand, but this hinders the operation considerably. The specimen is fastened on to the holder *a* with shellac cement and, by means of the weight *c*, is pressed against the cutting plate *d*, which rotates above it. The best cutting plates are covered around the edge with diamond dust and must always be kept moist with oil. Emery or carborundum powder and water can also be used. When the specimen has been cut once the holder *a* is moved to the left a short distance, depending upon the desired thickness of the section and a second cut is made. The necessary thickness naturally varies with the coherence of the rock, but must be in the neighborhood of 1–2 mm. Next, one surface is finely ground with emery or carborundum dust on the slightly convex disk *m* which rotates horizontally and then it is cemented with warmed Canada balsam on to a thick glass. Care must be taken that the cement is neither too brittle nor too soft because in either case the preparation may be easily torn loose in the grinding. It is best to evaporate Canada balsam on a water bath to the proper consistency. Its viscosity is then reduced by heating on a hot plate. Then the section is carefully ground down to the desired thickness by using successively finer grained carborundum or emery.

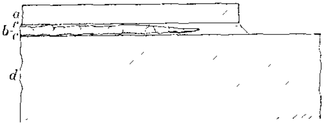


FIG. 38.—Cross Section through a Slide.

The slides are usually cemented on to an object glass by means of Canada balsam and are then covered with a cover-glass, using the same cement. The thickness of the cover-glass may be 0.10–0.15 mm., but not more on account of the short focal lengths of the stronger objectives. The thickness of the cover-glass is of little importance with weak objectives, but the stronger ones are corrected for a fixed thickness, and if other thicknesses are used the length of the tube must be changed. For certain special investigations, principally the determination of the index of refraction, the preparation is left uncovered. When the grinding has been carefully done the thickness of the slide may be quite uniform except that it may decrease toward the edges as shown in Fig. 38, which represents a cross section through the edge of a thin section magnified about 50 times. *a* is the cover-glass, *d* the object glass, and *b* the rock slide on which the rough surfaces can be distinctly seen. The slide itself is enveloped on both sides with Canada balsam.

The form and size of the object glass plays an important rôle, while the thickness may vary between limits, which depend upon the focal length of the illuminating apparatus. Square object glasses about 32x32 mm. are *most satisfactory for investigations with the polarizing microscope, and at* the present time these are almost always used in petrography. If a longer form is preferred, it must not be so long that, when placed on the stage of a polarizing microscope and rotated, it will strike some part of the instrument and be displaced.

The study of rock powders often leads to good results for rapid orientation. This was the earliest method of microscopic rock analysis. Thin cleavage *plates of minerals having a good cleavage, often give very characteristic* optical reactions and when artificial crystals are to be investigated the best results are obtained in many cases when the crystals are allowed to form on the object glass by the evaporation of a drop of the solution; or a fine crystalline powder may be imbedded in Canada balsam or some other liquid.

Reflected light is used comparatively rarely for observations with a *polarizing microscope except for opaque objects,* minute crystals, and etch figures. Preparations of this character are best left uncovered.

It may be mentioned finally that the methods of staining, which are so important in organic microscopy, are used only in exceptional cases in the investigation of inorganic bodies and, then particularly in the investigation of loose fibrous or scaly structures, but even then they are of less value than in organic preparations.

## CHAPTER II

# The Adjustment of a Polarizing Microscope

Before a microscope can be used it must be tested to see that the various parts of the instrument perform their functions properly. The tests consist of:

1. Testing the system of lenses;
2. Centering the stage;
3. Adjusting the cross hairs and the nicol prisms.

These operations are called "the adjustment of the instrument."

### 1. Testing the Lenses

**Aplanatic and Achromatic Properties.**—Although accurate correction for spherical and chromatic aberration in the illuminating lenses plays a comparatively small rôle and need only be considered for microphotography, yet the sharpness of the image and the clearness of the observations depend upon the most perfect aplanatic and achromatic properties of the lenses. Convexity of the image is the first thing that appears when using a defective objective. It may be recognized by inability to make the center and the edge of the image of equal sharpness. The haziness of the image in different parts of the field makes work with such objectives extremely fatiguing to the eye. It is encountered in fairly well constructed weak objectives only with a periscopic ocular, which uses the entire field of the objective, but in stronger lens systems it may affect and fatigue the eye with ordinary oculars. Along with the haziness, there is a distortion of the image due to the fact that different zones in the field are magnified differently. A cross-sectioned micrometer is used to recognize this imperfection, Figs. 4 and 5, page 2. Chromatic aberration is likewise troublesome. It occurs with stronger magnification and is not entirely corrected in the best achromatic lenses. Minute opaque bodies appear colored, especially if the reflecting mirror is placed obliquely or if the light from one side is shut off by a screen. If the illumination is principally from the left, an object will appear reddish on the left and violet on the right if the chromatic correction has been insufficient, and if too great, the colors are reversed. The only lenses that are perfectly corrected for chromatic aberration are the apochromatic lenses, but even with these a compensating ocular must be used.

The system of lenses may be tested for perfect achromatic correction by the Abbe test plate. This is a silvered glass plate on which series of parallel lines are etched at different microscopic distances from each other. An apochromatic system makes such a series appear perfectly clear and without colored borders.

**Light Intensity, Magnification, and Resolving Power.**—The amount of light which passes through an objective is dependent upon the aperture, if properly constructed. It is, however, influenced quite appreciably by small errors in the construction of the lens system so that there may be an appreciable variation in the amount of light in different systems with the same aperture. Since the amount of light is also dependent upon the magnification demanded, only the most carefully designed and constructed objectives may be used for the highest magnification, less perfect ones being practically useless. There is also serious objection to the unlimited increase in the magnification of lens combinations, which in many cases, seems to be the chief object of the manufacturers. On the one hand the amount of light is not sufficient for clear observations, while on the other hand the maximum sensitiveness of the objective is limited by the aperture. Abbe compiled a table showing the total magnification that may be expected from a microscope with objectives with the following apertures:

| Aperture | 0.1 | 0.2 | 0.3 | 0.6 | 0.95[1] | 1.20 | 1.30[2] |
|---|---|---|---|---|---|---|---|
| Magnification | 53.0 | 106.0 | 159.0 | 317.0 | 501.0 | 635.0 | 688.0 |

Some idea of the amount of light passing through an objective can be obtained by testing it with a weak ocular in diffused light produced by a white thinly clouded sky. One testing of this character is generally quite sufficient for ordinary practice.

The magnification, however, must be measured directly, because it is often necessary in work with the microscope to give numerical values of the sizes of the objects observed. A table showing the possible magnifications with the various objectives and oculars generally accompanies each instrument, but it is important to check it. The simplest method of accomplishing this is to focus on an object micrometer with the lens system to be tested. One millimeter is divided into a hundred parts and the image is projected upon a sheet of paper by means of an Abbe sketching device, to be described later. A few of the lines are then sketched on the paper and the distance between them is measured. It must be remembered that the amount of magnification varies with the length of the tube and the measurement should be made with the normal length to which the objectives are corrected.

Granting that its construction is perfect, the resolving power of an objective is a function of the aperture. This can be determined theoretically with an Abbe *apertometer.* For practical purposes a test object, which generally accompanies a microscope, is to be preferred, especially one made

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[1] Greatest aperture of a dry system.

[2] Greatest aperture of an ordinary oil immersion.

of *diatoms*, the fine surface structures of which may serve as a standard of the *resolving power* of the objective.

The *pleurosigma angulatum* with its characteristic fluting in three directions is the best object for testing the strongest dry systems. The fine details of sketch of the *surirella gemma,* especially the striations running *perpendicular to the fine cross fluting, serve to estimate the sensitiveness* of an oil immersion up to an aperture of 1.30. An Abbe test plate with its various systems of lines can be used for the same purpose. The observations are more perfect when the object is illuminated by oblique rays of light.

Finally false light, i.e., light produced by reflection of any sort, must be avoided in microscopic observations, although it is much less annoying here than in microphotography. For microphotographic purposes all metallic parts, especially within the tube of the microscope, should be blackened to prevent reflection.

Under certain conditions such reflection may be caused by the lenses of the ocular itself, so that it seems advisable to place a device on the ocular in some cases, which corresponds to a lengthening of the holder of the ocular lenses and cuts off the light falling obliquely on the upper lens of the ocular. In other instances, especially with weak objectives having a long focal length, the light under the objective, which falls on the slide and is reflected by it into the tube, causes a great deal of annoyance. Confusion can be avoided by shutting out the light with the hand or by placing a black screen around the instrument. Such devices must always be arranged so that they do not interfere with the movement of the instrument.

A thin cleavage plate of mica observed in convergent polarized light is the best device to determine whether the angle of aperture of the illuminating system is sufficient for the objectives with the largest numerical aperture that may be employed. If an immersion objective is used, the illuminating apparatus must also be used as an immersion. The interference figure *will be equally illuminated throughout the field, if the objective and the* illuminating system are properly adjusted. If the angle of aperture of the illuminating apparatus is not sufficient, the edge of the image will appear dark. If the adjustment is not proper the field of vision is unevenly illuminated or a sharply outlined portion of the field, corresponding to the cross section of the polarizer, appears light.

Microscopes made by the best firms rarely require the adjustments mentioned above. Centering of the axis of rotation of the stage and adjustment of the vibration directions of the nicols, on the other hand, are dependent upon numerous contingencies and are not infrequently altered during work, so that a frequent revision of them is strongly advised. The steps necessary will therefore be described more thoroughly.

## 2. Centering the Stage

The center of rotation of the stage must fall as nearly as possible in the axis of the objective, i.e., the microscope must be *centered*, or the displacement, which an object undergoes upon rotating the stage, prevents exact observation to a large extent.

Centering is naturally unnecessary in those microscopes in which the object rotates simultaneously with the objective, Figs. 29 and 30, page 14, or the nicol prisms rotate, Figs. 31 and 32, page 16. In centering other models a small speck on the object is brought exactly to the intersection of the cross hairs and the stage is rotated through 360°, while the displacement of the speck is constantly observed. The speck will generally describe a circle whose center *x*, Figs. 39 and 40, does not coincide with the intersection of the cross hairs *o*. The centering screw

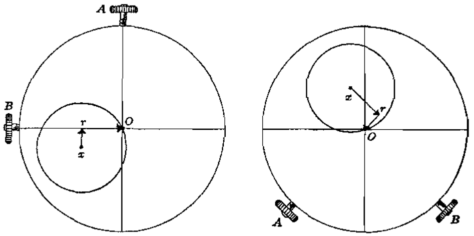

Fig. 39.

Fig. 40.

Centering the Stage.

A is turned until the point *x* has passed through the distance *xr*, i.e., until it falls upon the cross hair lying transverse to this screw. Then with the screw B it is moved through the distance *ro*, i.e., the center of the circle *x* appears to lie at the intersection of the cross hairs. The speck first selected is again brought to the center of the cross hairs and is tested to see whether it changes its position upon a complete rotation of the stage. Generally there is a slight movement and this is corrected in the same manner as before until centering is perfectly accomplished.

In general each change of objectives introduces a small eccentricity, although in perfectly constructed instruments having objective tongs, Fig. 16, page 5, this error is not large enough to cause a noticeable interference with the work. The centering screws operate at an angle of 45° to the cross hairs instead of parallel to them in certain instruments, especially where they are placed on the stage. The instructions given above must be changed then according to the diagram, Fig. 40.

The line of sight of the microscope must coincide exactly with the axis of rotation of the stage and this cannot be obtained by simply centering.

The adjustment of the instrument for this is checked by placing a signal such as a dark cross on the lower lens of the objective and illuminating it by a vertical illuminator from above. This is then reflected by a plane parallel mirror laid upon the stage. If the instrument is properly adjusted the image from the mirror must coincide with the cross and must not change its position upon rotating the stage.

### 3. Adjustment of the Cross Hairs and the Nicol Prisms

It is important to know whether the vibration direction of the polarizer is from front to rear or from right to left when it has been set in the proper position indicated on it. In the earlier nicols with rhombic cross section, as already explained, the vibration direction is parallel to the short diagonal, but in the various later makes it must be determined in each case. A thin deeply colored tourmaline crystal, which shows darker color and stronger absorption of the light when its principal crystallographic axis is at right angles to the vibration direction of the polarizer, is used. A pile of glass plates or, in the simplest case, a reflecting surface can also be employed. The light polarized by reflection vibrates perpendicular to the plane of incidence. If such a reflecting surface inclined at the polarizing angle is observed through a nicol prism, it will appear dark as soon as the vibration direction of the nicol is perpendicular to it, i.e., parallel to the plane of incidence.

The adjustment of both nicols must be tested. If the microscope is to be used for any kind of measurements in polarized light the vibration directions of one of the nicols must be as nearly as possible parallel to one of the cross hairs, which are exactly at right angles to each other. This is best accomplished by the aid of a colorless needle-like crystal imbedded in Canada balsam. The crystal must have parallel extinction and an index of refraction as near that of the Canada balsam as possible. The reaction is especially distinct when the crystal shows an intense interference color of a low order between crossed nicols.

Long needle-like crystals of quartz about 0.1 to 0.15 mm. thick are particularly useful for this purpose. Cleavage pieces of anhydrite and so forth are a little less adaptable, but can be more readily obtained. If a long edge of the crystal imbedded in Canada balsam is placed parallel to one of the cross hairs and the vibration direction of the polarizer is exactly the same, light will pass through the crystal unaltered. Quartz, which has an index of refraction nearly the same as Canada balsam, is entirely invisible between crossed nicols and remains invisible upon rotation of the analyzer through 90°. If, however, upon rotating the analyzer a slight illumination or coloration of the quartz takes place, it is an indication that the vibration direction of the polarizer does not correspond exactly with the direction of the cross hair. This is corrected by rotating the polarizer until the phenomenon can no longer be noticed. The analyzer is checked in the same manner, the polarizer being marked in its proper position and then used as the movable nicol. The quartz crystal is then placed parallel to the second hair and the test is again made to see that no coloration takes place. When such is the case, we have proof that the vibration direction of one of the nicols is parallel to one of the cross hairs and further that the two hairs are exactly at 90° to each other.

In many instances it is impossible to find a position of the nicol prism in which the crystal entirely disappears because very frequently an optical disturbance is produced by the lenses. Partial polarization by refraction, especially in the stronger systems, may also occur. Further, the lenses may acquire considerable double refraction, due to tension in the metallic holder caused by rapid changes of temperature. If the tension in the latter case is not too great, a normal condition of equilibrium will be attained after a short time. However, if the effect on polarized light is quite distinct, such a lens system will give rise to much inconvenience and inaccuracy. It may be noted that if the optical disturbance becomes apparent upon inserting the polarizer, the defect belongs to it, but in other cases to the objective. Since nicol prisms are generally set in cork, the volume of which changes as it gradually dries out or is affected by changes in temperature and in the humidity of the air, tbe tests for the orientation of the nicol prisms must be frequently repeated. This is especially advisable before accurate measurement of the vibration directions of a crystal is attempted.

## CHAPTER III

# Observations in Ordinary Light

Ordinary light is unpolarized. The observations to be considered next can be carried out without the use of the nicol prisms. The following properties can be studied in ordinary light: (1) index of refraction, (2) form and cleavage, (3) size and thickness of the object, (4) inclusions, (5) color, and (6) appearances in reflected light.

**Methods of Determining the Index of Refraction.**—The first and most important observation that we are able to make with a simple microscope is that of refraction. A ray of light which passes obliquely from one medium to another is deflected from its original direction, i.e., it is refracted because the rate of transmission of light in various mediums is generally different. Refraction may be expressed by the law: $\frac{\sin i}{\sin r} = \frac{v}{v'}$, Fig. 41, in which $i$ is the angle between the incident ray and the normal, $r$, that of the refracted ray, and $v$ and $v'$ are the respective velocities of light in the two mediums. It follows from the above formula that when a ray of light passes from a medium with greater velocity $v$ to one with smaller velocity $v'$, it is refracted toward the normal, because then $r<i$. If in the above equation the first medium is air in which the velocity of light may be assumed to be equal to one, $v=1$, the index of refraction of the second medium with respect to air may then be expressed by the formula, $\frac{1}{v'} = \frac{\sin i}{\sin r}$, or the velocity is the reciprocal of the index.

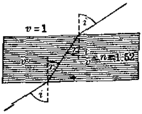

Fig. 41.
Refraction of Light.

If light passes from a medium with smaller velocity $v'$ into one with greater velocity $v$, the conditions are reversed, and the angle between the normal and the refracted ray is larger than for the incident ray. The ray is refracted away from the normal. For a certain angle of incidence $i$, the value of $r$ will equal 90°, i.e., light incident at this or a greater angle does not pass into the second medium, but is totally reflected. The angle of incidence for which $r = 90°$ is called the critical angle. The greater the difference of velocity in the two mediums, the smaller the critical angle, e.g., for air and glass ($n = 1.5$) it is 40° 45′, for the diamond ($n = 2.4$) it is 23° 45′.

If the ray falls perpendicularly upon the contact of the two different mediums $\sin i = 0$, and hence, $\sin r = 0$ as well, i.e., normal incident light suffers a change in velocity, but it is not deflected.

If isolated crystals are observed under the microscope only those parts will appear clear and transparent which are bounded by smooth parallel surfaces that lie at least approximately perpendicular to the axis of the microscope. It is only in such cases that the transmitted rays suffer very little or no deviation. If the inclination of the surfaces is considerable, total reflection takes place at the contact between the crystal and air. Such portions then appear dark. If the faces of a crystal are uneven or if unpolished plates, such as thin sections, are being studied, they appear more or less clouded because the unevenness of the surface allows only a portion of the light to pass through unrefracted, while the flank surfaces of the depressions and elevations cause total reflection of the light due to their inclined positions, Fig. 38, page 22.

If a slide with rough surfaces is immersed in water ($n = 1.33$) and covered with a cover-glass, the rough appearance will entirely disappear, but the slide becomes far more transparent because now the difference in refraction between the crystal and the medium surrounding it is less and the critical angle becomes greater. If a liquid with higher index is used the rough appearance will disappear more the more nearly the index of the liquid approximates that of the substance in question. When the indices of the two mediums are exactly alike the section will appear as though polished and the uneven surfaces perfectly even, but if a liquid of higher index is employed, the unevenness of the surface will reappear. The outline of the crystal, which when uncovered shows very distinctly, will gradually disappear as the index of refraction of the surrounding liquid approaches that of the crystal and is entirely invisible when the two indices are alike, provided the crystal is colorless. With more strongly refracting liquids it reappears.

In many instances the best method for observing this difference of index of refraction is in as nearly parallel light as possible. If the rays which pass through a preparation are quite divergent, then at each point on the uneven surface light impinges from many different directions. Therefore a portion of the light will pass through all parts of the preparation, and the unequal illumination and, consequently, the rough appearance of the surface, show much less. Since the index of refraction is one of the most important properties in microscopic determinations, it is customary not to polish the slide, and observations are begun in approximately parallel light so that this difference will appear more distinctly.

The illuminating apparatus of the microscope produces rays of light which are more or less convergent so that, for the investigation of the index of refraction, rays as nearly parallel as possible must be isolated from the cone of light. Narrowing of the cone of light is generally accomplished by means of an iris diaphragm J, Fig. 42, placed a short distance below the illuminating apparatus. This cuts out those rays which pass through the outer edge of the lens. The light passing through the middle part of the lens is only slightly convergent, as shown in Fig. 42. The effects of this device, which is generally considered to be indispensable, can be produced even better by sinking the whole illuminating apparatus as shown in Fig. 43. When it is lowered in its holder the outer part of the cone of light is eliminated and that which passes through the slide consists of rays which diverge but slightly. In each method it seems to be expedient to use as strong an illuminating system as possible. In using a microscope

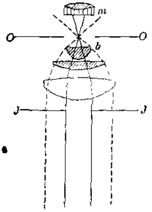

Fig. 42.
Cone of Light narrowed by Iris Diaphragm.

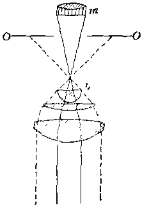

Fig. 43.
Sinking Condenser.

without an Abbe illuminating apparatus it is always advisable to leave the condenser in place as long as it does not diminish the field of vision, although this is contrary to the usual instructions. With the weakest objectives, however, it must, in all cases, be removed. It is therefore expedient to carry out all investigations on the microscope with the condenser *in place and it is only* removed on passing over to the lowest magnifications.

**Differences in the Indices of Refraction Under the Microscope.**— Since complete disappearance of a crystal in a liquid is only to be observed when the indices of refraction of the two are about equal, and since a crystal stands out in relief from the surrounding medium in the same manner whether the index is higher or lower, one is in doubt whether to ascribe the relief to one or the other cause. The determination as to whether the index of the crystal is higher or lower than that of the liquid, however, is very simple. The cone of light is cut down until the contact between the crystal and the liquid, or between two crystals, appears as a sharp line, and then the objective is raised. A distinct band of light can be recognized parallel to the contact between the two mediums and *this moves toward the substance with the higher index upon raising the tube,* while the more weakly refracting object appears to have a dark border. Upon lowering the tube, the opposite phenomenon is observed.[1]

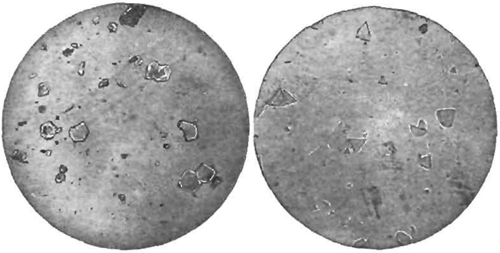
FIG. 44.—Higher FIG. 45.—Lower
Index of Crystal in Canada Balsam with Raised Tube.

Fig. 44 shows crystals of barium nitrate ($n = 1.57$) in Canada balsam with the tube raised. The band of light can be distinctly recognized within the edges of the crystal. The opposite is the case in Fig. 45, which shows tetra-

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[1] This is the Becke method.

hedrons of sodium uranyl acetate having a lower index of refraction than the surrounding Canada balsam, and therefore when the tube is raised, a sharp bright band can be seen outside, and a dark one inside the crystal.

This phenomenon can be explained in the following manner. All the rays from the illuminating apparatus striking obliquely on the contact of two differently refracting substances, Fig. 46, pass from the medium with lower index on the left into the one with higher index on the right. On the other hand, only a portion of the light will pass from the higher refracting medium into the lower, because within a certain angle $\beta$ total reflection of the light takes place. This angle is dependent upon the ratio of the indices of refraction in the two bodies and is larger the greater the difference between the indices.

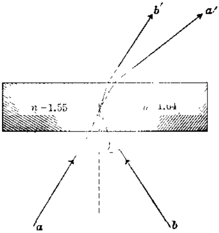

FIG. 46.—Behavior of Rays on the Contact between two Different Media.

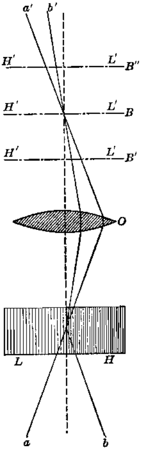

FIG. 47. — Observation through the Microscope.

If the cone of light is narrowed down so that only those rays are present which fall within the angle $\beta$ it is evident that a strongly illuminated zone will appear on the side of the contact line on which the light passing through the border is added to that which is totally reflected, i.e., on the side of the more strongly refracting substance, and on the other side where no light passes through, there will be an equally pronounced dark band. Fig. 47 shows diagrammatically this phenomenon as observed in the microscope. If the ocular is placed in the plane of the image B, the contact between the two substances appears as a sharp line. When the tube is raised to the position B″ the band of light will be observed on the side of the substance with the higher index of refraction, due to the inversion of the image, and when the tube is lowered so that the ocular comes to the position B′, the light band appears on the side of the lower refracting medium. The following general rule may be applied: *Upon raising the tube the light zone moves toward the substance with the higher index of refraction.*

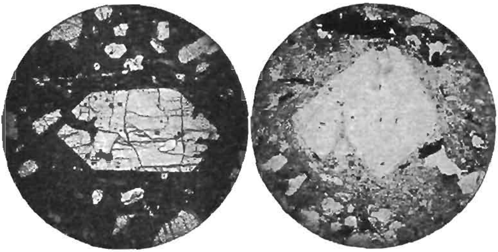

Fig. 48.—High Fig. 49.—Medium
Index of Mineral in Canada Balsam.

Fig. 50.—Mineral with Low Index in Canada Balsam.

Figs. 48–50 show this phenomenon as ordinarily observed on a thin section embedded in Canada balsam. If a mineral like quartz ($n=1.54$, Fig. 49) has approximately the same index as Canada balsam, the unevenness of the surface, represented by Fig. 38, p. 22, can scarcely be observed at all, if very nearly parallel light passes through the slide. Thin sections of such colorless minerals are scarcely visible when the illuminating apparatus is completely lowered. It is different in Figs. 48 and 50 representing slides of olivine, $n = 1.68$, and haüyne, $n = 1.48$, respectively. The index of refraction of the former is considerably higher, that of the latter lower than Canada balsam, $n = 1.54$. The irregularities of the surface are filled up with a medium that is optically different and therefore, when the illuminating apparatus is lowered, they appear very distinctly because various points on the surface are inclined at different angles to the rays of light which are deflected differently and some are totally reflected. The result is the rough chagrined appearance of the thin section under investigation. Since the roughness appears more readily the greater the difference of index of refraction between the mineral and Canada balsam, the amount of lowering of the illuminating apparatus or of closing of the iris diaphragm necessary to show this difference is an excellent means for the approximate determination of the index of refraction of minerals in thin sections. Care must be taken that the slides are uniformly ground, otherwise there will be great differences in the properties of the surfaces.

If isolated crystals are studied instead of thin sections, the roughness of the surface is rarely of importance. Observation of the crystal form in ordinary light can only be accomplished when there is a great difference between the indices of refraction of the crystal and that of the surrounding medium, and this can be recognized by narrowing up the cone of light from below.

If a grain is embedded in a liquid with approximately the same index of refraction, its form will not be observed at all, or at best will be very indistinct, even when the cone of light is narrowed down as much as possible. This is well illustrated by quartz embedded in Canada balsam ($n = 1.54$). If, however, the quartz crystal is embedded in linseed oil ($n = 1.48$) or monobrom-naphthalene ($n = 1.66$) its form will be distinct even when the illuminating cone is much wider.

**Determination of the Index of Refraction.—Immersion Method.**—By this method the difference in the indices of refraction of two mineral grains in contact with one another in a thin section can be determined accurately as well as the individual indices of refraction of isolated crystals or fragments embedded in a liquid of known index. A series of liquids called indicators is arranged so that the index of each exceeds that of the preceding one by 0.01–0.02. A series of potassium mercuric iodide solutions with different concentrations furnishes a scale, which is quite easily controlled, and the index of refraction is readily obtained from the accompanying table by determining the specific gravity.

POTASSIUM MERCURIC IODIDE SOLUTIONS.

| S[1] | nD |
|---|---|
| 3.2 | 1.733 |
| 3.1 | 1.715 |
| 3.0 | 1.696 |
| 2.9 | 1.677 |
| 2.8 | 1.658 |
| 2.7 | 1.640 |
| 2.6 | 1.621 |
| 2.5 | 1.602 |
| 2.4 | 1.583 |
| 2.3 | 1.565 |
| 2.2 | 1.546 |
| 2.1 | 1.527 |
| 2.0 | 1.509 |
| 1.9 | 1.491 |
| 1.8 | 1.473 |
| 1.7 | 1.455 |
| 1.6 | 1.437 |
| 1.5 | 1.419 |

These indicators have the disadvantage that the index of refraction changes somewhat during the operation, due to the evaporation of water. Hence, homogeneous liquids of definite chemical composition are better. The following table is given by Schroeder van der Kolk:

| | |
|---|---|
| Water | 1.33 |
| Ethyl alcohol | 1.36 |
| Amyl alcohol | 1.40 |
| Chloroform | 1.45 |
| Castor oil | 1.48 |
| Benzol | 1.50 |
| Monochlorbenzol | 1.52 |
| Clove oil | 1.54 |
| Monobrombenzol | 1.56 |
| Aniline | 1.58 |
| Bromoform | 1.59 |
| Cinnamon oil | 1.60 |
| Carbon disulphide | 1.63 |
| α-Monochlor naphthalene | 1.64 |
| α-Monobrom naphthalene | 1.66 |
| Klein's solution | 1.70 |
| Thoulet solution | 1.73 |
| Methylene iodide | 1.75 |

Solutions with intermediate values can be prepared by mixing these indicators and this process is continued until a mixture has been found in which the crystal disappears as completely as possible. Complete disappearance can usually not be obtained in white light, on account of the difference of dispersion between the crystal and liquid. For this reason it is better to use monochromatic light. When the proper mixture has been

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[1] S = specific gravity, nD index of refraction for the *Na* line.

found, its index of refraction should be determined by means of a Bertrand total reflectometer, which allows a very accurate determination of the index to be made rapidly, using only a single drop of the liquid for this purpose. This immersion method gives sufficiently good results for all practical purposes, provided the comparison of indices of the liquid and mineral is carried out according to the methods described, pages 33-36.

The method of oblique illumination proposed by Schroeder van der Kolk gives more accurate results. Oblique illumination is produced either by placing the mirror on the microscope obliquely or by inserting a piece of cardboard laterally between the mirror and the illuminating apparatus. In the larger microscopes the iris diaphragm can be moved horizontally or there is a device which when pushed in stops the light eccentrically. Usually, however, a piece of cardboard is quite efficient. Oblique illumination can also be obtained by screening one side above the ocular. An *Exner refractometer* can be used for this purpose. It consists of a hood to be placed over the ocular with a diaphragm at the focal distance from the ocular. This diaphragm can be closed laterally by means of a slide. If a grain is immersed in a liquid it affects transmitted parallel light in much the same manner as a converging lens, i.e., it converges the rays if its index is higher than that of the liquid and in the opposite case it causes them to be divergent. If a bundle of parallel oblique rays passes through the preparation, only that light is taken up by the objective, in the first case, which is on the same side as the screen, Fig. 51, while in the second case, only that on the opposite side is received by the objective, Fig. 52.

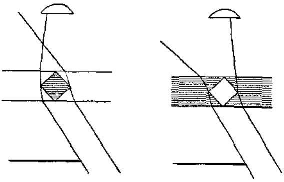

FIG. 51. FIG. 52.
Oblique Illumination.
Crystal higher Crystal lower
Index than the Liquid.

However, since the objective produces inversion, the reverse phenomenon is seen in the microscope. *If the grain has a higher index of refraction than the liquid, the dark band is seen on the side next to the screen, but if the grain has a lower index it appears on the opposite side.*

This method is extremely delicate when liquid and crystal have very nearly the same indices, and especially when their dispersions are at the same time quite different. It may happen that the mineral, which generally has the weaker dispersion, will possess a lower index for blue and a higher index for red than the liquid. A brilliant colored border, blue on the side of the screen and red on the opposite side, is an indication that liquid and mineral have very nearly the same indices of refraction. In rare cases, when the mineral has a stronger dispersion than the liquid, the position of the colors is reversed. To determine the indices of refraction of double refracting crystals by this method, it must be possible to make a determination of each index successively. The ordinary ray of uniaxial crystals can be recognized in polarized light, after its vibration direction has been placed parallel to that of the polarizer, in that the optical reaction is very sharp even though the grains be very irregular, because the refraction of the ordinary ray is the same in all directions. The extraordinary ray, however, cannot be determined as accurately especially in substances which have no good cleavage because it appears at every point on the surface with different values due to the different inclinations of the surface toward the optic axis. To determine the principal indices of refraction of double refracting substances accurately, a section must be taken whose orientation has been previously determined in convergent polarized light.

A center screen is very serviceable for observing the differences between the indices. It causes the object to be illuminated by the strongly diverging outer rays from the illuminating apparatus and can be placed in a slide in the polarizer, but must be adapted for the angle of aperture of the ocular. This method is especially useful in the investigation of minute objects, and in the study of inclusions and so forth.

An *accurate method for determining the index of refraction of microscopic objects*, consisting of a combination of an Abbe total reflectometer with a microscope, was suggested by C. Klein. By this method all indices of refraction in any microscopic cross section of a mineral can be determined, but the part of the slide surrounding this section must be covered with black varnish, and good results can be obtained even with comparatively small individuals. The method of observation is the same as with an Abbe total reflectometer itself and need not be discussed further here. It need only be stated that the stand upon which the hemisphere of the Abbe apparatus rests is hollow, the hemisphere itself is placed over the opening on a ground plane surface, so that the object to be investigated can be observed on the microscope in transmitted ordinary or polarized light. However, this apparatus, which is quite complicated and comparatively expensive, has not been used as extensively as it deserves to be.

The total reflectometer constructed by Wallerant is somewhat simpler and can be attached to any microscope. It consists of a plate to be set on the stage and carries a prism of strongly refracting glass, which can be rotated about a horizontal axis parallel to its refracting edge, either alone or in combination with an *alidade* reading to 2′. The edge itself is ground off parallel to the base of the prism, so that when the apparatus is used on the microscope, light is transmitted through it. An uncovered thin section, polished as perfectly as possible, is firmly pressed on the base of the prism by two clamps, the contact being made with methylene iodide. The extinction directions of the section are then determined in transmitted light. The prism is now rotated until convergent rays from a powerful source of light are incident upon one of the lateral faces. The light is reflected by the section and emerges from the other surface of the prism in the axis of the microscope. The object is centered as accurately as possible and the vibration directions as previously determined by the extinction are brought into position, and the prism rotated until the distribution of light and shadow indicate the critical angle for total reflection. The iris diaphragm in the tube is now closed until only the section to be studied is visible. Now the ocular is replaced by a telescope containing a spectroscope, which isolates the yellow rays from the white light. The edge of the section is then placed parallel to a cross hair in the telescope and a reading taken. Then the cross hairs are illuminated by light sent in from the side by means of a total reflecting prism. The prism bearing the section is rotated with the alidade until the image of the cross hairs reflected from its base coincides with the object A second reading is then made and the angle of total reflection determined.

The liquids employed so frequently in organic microscopy to increase the illumination of an object depend upon the principle of compensation of the refraction of light. Preparations of crystals and rocks are generally embedded in Canada balsam, the index of which may vary between 1.53 and 1.545, depending upon the amount of evaporation. Canada balsam is especially adapted for this purpose because it is quite liquid when fresh and upon heating slightly is transformed into a clear transparent almost colorless cement that sticks firmly and becomes very slightly double refracting if at all, upon cooling as other resins generally do. Solutions of hardened Canada balsam in benzol, xylol, etc., are sometimes used especially with substances that cannot be warmed. The index of refraction is then somewhat less on account of the dilution. For chemists Canada balsam has a disadvantage in that it is a very good solvent not only for organic substances, but also for numerous inorganic salts, and its solvent action is sometimes increased by the addition of benzol. A more feebly refracting cement is needed in rare instances and then linseed oil is employed, $n = 1.48$. When placed in the direct rays of the sun for a few weeks it bleaches and polymerizes

**Determination of Form and Cleavage.**—A *stereoscopic microscope, with which an object can be observed as a body,* is well adapted for determining the form of crystals and especially for the investigation of etch figures that are not very deep. The distinctness of form that can be obtained, especially with a Zeiss binocular microscope simplifies greatly the deciphering of microscopic crystals. The model shown in Fig. 53, constructed by the above firm according to the principle of Grenough, has the advantage that the image of the crystal appears in its true position due to prisms in the tubes. Since there are two objectives, each in the axis of an observation tube, strong magnification cannot be used. Other devices for *stereoscopic investigation* with a microscope, such as a double ocular or stereoscopic ocular which can be placed on a simple microscope, give good results only with low magnification, but they do not at the same time produce the distinctness of form obtained by a binocular microscope. The

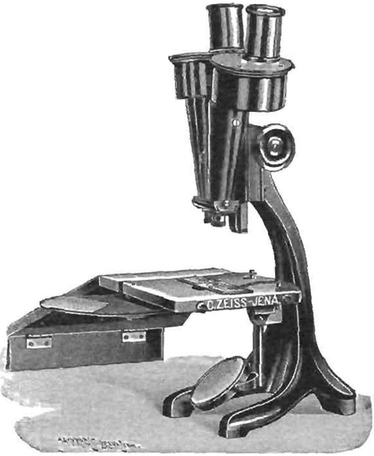

FIG. 53.—Grenough Binocular Microscope by C. Zeiss in Jena.

importance of stereoscopic observation is confined to a small number of cases and the binocular microscope cannot replace a polarizing microscope. The next step in the microscopic determination of crystals is to observe and sketch the form as accurately as possible. (See methods for sketching crystals at the end of Part I.) This must not be confined to the determination of the outline alone, but care must be taken to decipher as well as possible the properties of the crystal as a whole. Without this, entirely erroneous conclusions may be reached because the angles between the edges often appear greatly distorted in consequence of the irregular position of a crystal in the slide.

The *measurement of characteristic angles* goes hand in hand with the determination of crystal form, but only such angles are to be considered as are bounded by edges lying exactly in the plane of the stage, or by planes perpendicular to this direction.

One leg of the angle to be measured is placed parallel to one of the cross hairs and a reading of the position of the stage taken. Then the stage is rotated until the other leg is parallel to the same cross hair and another reading taken, the difference between the two being the angle sought. The edge can be placed in parallel position much more perfectly, the longer and straighter it is and the more aplanatic the ocular lenses are. It seems better too in making such measurements, not to make the edge coincide exactly with the cross hair, but to leave a small space between the two so that the parallel position can be found much more accurately. In favorable cases, if the position is not perfect, the reading to whole degrees and the estimating to quarter degrees are quite sufficient.

FIG. 54a.

FIG. 54b.

FIG. 54c.

Measurement of Angles with a Lesson's Prism.

A Leeson's prism can be advantageously used for the accurate measurement of plane angles, especially on very small crystals. It consists of an achromatic quartz prism that is placed over the ocular so that it can be rotated in a graduated holder. With it, two images of the object partially overlying each other are seen, Fig. 54*a*. The prism is rotated until one edge of the angle to be measured coincides in both images, Fig. 54*b*. A reading of the scale is then made and the other edge treated in the same manner, Fig. 54*c*. More accurate results can also be obtained when a glass plate with a system of fine parallel lines etched upon it is set at the focus of the ocular in place of the cross hairs. A long line crosses the middle of the system perpendicularly. This and the middle line of the system are somewhat heavier so that the object can be easily centered. The edges of the angle to be measured are then brought into parallel position with the fine lines, one after the other.

An *ocular goniometer* also deserves some mention at this time. This is an ocular in which one of the cross hairs can be rotated with respect to the other, and the amount of rotation read on a circular scale. The movable hair is placed parallel successively to the legs of the angle to be measured. This method has the advantage that the slide need not be moved. Microscopes in which the nicols may be rotated simultaneously possess the advantages of an ocular goniometer inasmuch as the cross hairs also rotate with respect to the object.

Actual reflection goniometric measurements can be made with a microscope if a small reflection goniometer or the rotating apparatus, to be described in the appendix, is combined with a microscope. However, such microscopic-goniometric measurements will only give good results after considerable practice and after all, are of very little use. If in such investigations the microscope itself is to be used to observe the reflection of the surfaces, a Gauss mirror appliance is valuable. It consists of a mirror placed obliquely on the ocular and a black cross hair under the objective. After the surface has been placed approximately perpendicular to the axis of the microscope, the tube is lowered half the focal distance of the objective and the mirror image of the cross hairs is seen in the ocular. When the surface is accurately adjusted the image coincides with the cross hairs. This device can only be used with the lowest power objectives.

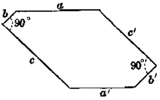

FIG. 55.—Distorted Crystal.

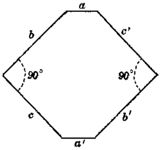

FIG. 56.—Normal Development.

The form of crystals observed in the microscope is frequently distorted in many ways, especially in cases of rapid crystallization, so that the image of a crystal can be deciphered only with difficulty on account of the irregular development of similar faces.

In such cases, however, the angles between the edges are always constant and a measurement of them affords a means of finding the faces belonging to a form and of recognizing the symmetry of the crystal. Fig. 55 represents a cross section of a distorted crystal, which at first glance appears entirely unsymmetrical. Measurement of the plane angles shows that the angles *bc* and *b′c′* are both approximately 90°, while the other angles have equivalents among themselves. It is presumably an orthorhombic crystal in which the prism faces *bc* and *b′c′* have been developed unequally, Fig. 56.

Rapid crystallization produces in many cases imperfect growth and depressions bounded by more or less regular forms appear on the surface of crystals. The cause is more rapid growth on the edges than in the middle of the faces. These irregularities pass over into skeletal crystals, Fig. 57, which may be developed in a large variety of delicate forms. Star-shaped skeletal crystals of snow, ice flowers, etc., are the best known forms of this type. These skeletal forms in turn pass over into minute growths resembling arrow heads, rods, etc., which cannot be definitely determined as crystals and are called *crystallites*, Fig. 58.

FIG. 57.—Skeletal Crystals of Olivine.

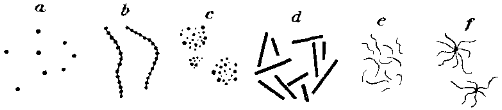

FIG. 58.—Crystallites.
*a*, Globulete; *b*, Margarite; *c*, Cumulite; *d*, Baculite; *e*, and *f*, Trichite.

Minerals observed in thin sections very frequently show more or less regular cracks which indicate cleavage. In many cases a few straight sharp cracks cut across the whole section, for example, mica, Fig. 59. The cleavage is *perfect* even though the number of cracks is small. The cracks may be discontinuous, as in hornblende, Fig. 60. Here the cleavage is *distinct*, or good. If the cracks are more or less curved, but following on the whole certain directions, the cleavage is said to be *imperfect*, garnet, Fig. 61. Different systems of cleavage, of equal or unequal value, may be present enclosing a characteristic angle, which can

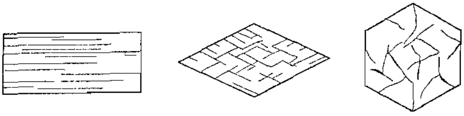

FIG. 59–61.—Perfect. Distinct. Imperfect.

Cleavage.

be determined by measurement. Much more importance is generally ascribed to the measurement of cleavage angles in thin sections than it really deserves, because the size of the angles is largely dependent upon the orientation of the various cross sections of a crystal and this of course is variable. In any case, it must be shown by raising and lowering the tube that the cleavage cracks traverse the section as nearly vertically as possible.

Investigation of cleavage fragments of crystals or of rock-forming minerals often gives very characteristic results, and it is often serviceable for rapid orientation or for supplementing the observations on thin sections.

In isolated crystals, cleavage cracks are not often observed and then only if the cleavage is very perfect. Sometimes crystals can be crushed and cleavage fragments formed, the form of which is a more characteristic feature of the substance than can be found in a thin section. Cracks parallel to gliding planes may appear similar to cleavage cracks in microscopic objects and there is no way of distinguishing them. Occasionally more or less regular parting, which may be due to various causes, appears quite similar to cleavage cracks.

**Measurement of Size and Thickness.**—While it is frequently interesting to know the size of an object, its *thickness* is more often determined. A micrometer, which is sometimes placed on the stage and sometimes in the ocular, is used for the determination of size. When placed on the stage, it gives the size directly, but when in the ocular the results must be recalculated for the objective used and for the length of the tube. On the other hand, errors made in the object micrometer divisions are increased by the total magnification of the instrument, while those of the ocular micrometer are only increased by the magnification of the ocular itself.

In certain cases a scale on the mechanical stage, Fig. 34, page 19, in which divisions on the drum of the screw permit 1/1000 mm. to be estimated, serves as an object micrometer. The small errors, which are apt to occur in cutting the thread of the screw, make such operations unreliable.

Divisions of only 1/10 mm. are demanded of a micrometer placed in the ocular so that the requirements of the execution are much less and errors likewise smaller. Such an ocular micrometer can simply be placed in the ocular at the focal distance, or a micrometer ocular can be constructed in such a manner that a cross hair at the focus of the ocular can be moved by means of a screw with a measuring drum working at right angles to the axis of the instrument, while an immovable cross hair indicates the center of the field. In other cases the scale itself is fixed and a Ramsden ocular with a central division is moved over the scale by means of a measuring drum. The division to which this mark must be brought as nearly as possible, is made upon the upper plane surface of a lens, which is in turn adjusted for the objective so that the eccentricity produced by lateral displacement of the ocular is compensated.

A micrometer possessing divisions as represented in Fig. 4, page 2, and placed in the ocular, may serve to determine the relative amounts of minerals in thin sections. Such an adjustment is called a *planimeter ocular*.

The measurement of the thickness of microscopic objects is generally possible only when the optical properties are quite accurately known. Good results can seldom be obtained with isolated crystals, but frequently in thin sections quite accurate determinations of the thickness are possible because certain known minerals are nearly always present and their thickness can be estimated by means of the interference colors. The measurement of the thickness is not very reliable with other methods even in the most favorable cases.

A method, which was frequently used formerly, is that of Duke de Chaulnes for the determination of the index of refraction. It can be also used in reversed manner for measuring the thickness. A point *o*, Fig. 62, is sharply focused and a plane parallel plate of a transparent substance is inserted between it and the objective. In consequence of the refraction of the rays *or* and *os* one receives the impression that the light emanates from *o'*. The objective must then be raised by means of the micrometer screw until it is focused on *o'*. With a known thickness of the plate, the distance *oo'* is dependent upon its index of refraction. If the latter is known, we have a basis for estimating the thickness of the plate. The change of focus of the objective can be read directly from the divisions on the drum of the micrometer screw.

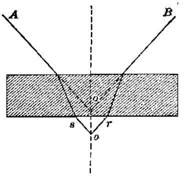

FIG. 62.—Duke de Chaulnes Method.

This method is often used but care must be exercised not to overestimate the accuracy of it because a great deal of practice is necessary to obtain reliable results. A small foreign body, e.g., a dust particle, which occurs between the object and the cover-glass is focused and then the apparatus lowered until the same signal is seen reflected from the under side of the slide. The amount of lowering of the objective constitutes the value $b$ and the thickness of the slide is given by the equation $d = bn$, where $n$ is the index of refraction of the section measured.

The measurements are most accurate when stronger magnifications are used because the amount of displacement of the real image from the objective increases with an increase of magnification. The image of the point chosen must be brought exactly into the plane of the cross hairs and the proper adjustment can be recognized when, upon moving the eye above the ocular, the image and cross hairs do not show relative displacement. Since, in general, the index of refraction $n$ is not positively known and constitutes the greatest error in this method, an immersion system can be employed with good results for this determination. Then it is not necessary to fix the value of the index of refraction itself, but only to determine the difference between the index of the mineral and the immersion oil.

Methods that depend upon observations of the interference colors are much more exact. There may be well orientated sections of minerals present in the slide with known indices of refraction from which their thickness, which indicates the thickness of the slide, can be estimated. Such cross sections can be introduced into the slide artifically by cementing cleavage plates of barite on different sides of the rock section and grinding them down with the section. Measurements thus made are at any rate a close approximation.

**Inclusions.**—The presence of inclusions is of importance in certain cases because a large number of crystallized bodies, especialy minerals, possess the ability to enclose large amounts of foreign substances upon crystallization. This is often so extensive that the greater part of the crystal consists of such foreign bodies. These inclusions can be recognized in ordinary light by the differences in the indices of refraction and color.

Some of the inclusions occurring in this way are crystallized substances and must be determined according to the ordinary methods. Inclusions of gas, liquid, and glass, which frequently furnish important clues to the genetic relations, are also found. Gas inclusions in crystallized bodies always stand out in strong relief, because the index of refraction of the gas is far below that of the crystallized substance. In parallel light it is surrounded by a single broad, dark band produced by refraction and total reflection, Fig. 63. Separation into different zones is never observed in gas bubbles because all gases are miscible. In observing gas inclusions care must be exercised to note that the gas bubble is really in the object and not in the Canada balsam. Air bubbles in the balsam naturally appear very similar to gas inclusions, but by sharp focusing with the micrometer screw they can be seen to lie either above or under the object itself.

Liquid and glass inclusions on the other hand appear to be separated into different zones. The liquids include salt solutions, water, and, in some minerals, liquid carbon dioxide. In all cases a small bubble of gas or air is present in the liquid, which under certain conditions, especially in very small inclusions and under variations of temperature, moves about quite perceptibly. The index of refraction of all liquids existing in nature lies between that of the mineral and the gas bubble, so that the edges of both liquid and bubble appear as heavy lines in parallel light, Fig. 64. Sometimes liquid inclusions seem to consist of several immiscible liquids with different indices of refraction beside each other, or they may contain small crystals. If the liquid in such an inclusion is carbon dioxide it can be recognized by heating the preparation for some time a trifle above the critical temperature of carbon dioxide. The bubble will disappear and the border of the inclusion will become darker.

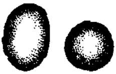

Fig. 63.
Gas Inclusions.

Fig. 64.
Liquid Inclusions.

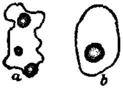

Fig. 65.
Glass Inclusions.

Glass inclusions likewise contain one or more bubbles, but they are always immovable and do not show such heavy contours compared with the including crystal if the latter has a low index of refraction. They appear more distinct the higher the index of refraction of the crystal. The bubble itself is always surrounded by a broad dark band, Fig. 65. A regular arrangement of inclusions is very characteristic in many cases, for example, Fig. 66, leucite.

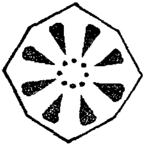

Fig. 66.—Leucite with Slag Inclusions.

**Color.**—Another observation that can be made in ordinary light is that of the color. Particulars concerning the naming of the colors are scarcely necessary. It may be pointed out that many bodies, which are very dark or entirely opaque in large crystals are colorless or nearly so in thin section, for example, augite, while others which are very light colored in macroscopic crystals show their color quite distinctly in the thinnest sections, thus, andalusite and cyanite. It need not be further emphasized that a layer of any substance appears lighter colored the thinner it is. The thinnest sections are generally not chosen for determining the color.

When light passes through a body it suffers diminution of intensity and is either partially or entirely absorbed. If the absorption is only slight and is about the same for the different colors of the spectrum, the body appears colorless and transparent, but *if the absorption is complete* even in the thinnest sections, the body is said to be opaque. If certain colors of the spectrum are absorbed more than others the substance appears colored. Distinction is made between characteristic colors, or those belonging to the substance itself, and dilute colors produced by intermixture of foreign material present in such a fine state of division that it cannot be detected with the strongest magnification. Coloring produced by inclusions, on the other hand, can always be detected in this manner.

Since the naming of the colors is in general very subjective, attempts have been made to express them accurately by means of comparison with an objective color scale. A Radde color scale is especially serviceable for this purpose. It shows the various colors in a horizontal series while the various shades of each are arranged in the vertical columns. Spectroscopic dispersion of the colors obtained with a spectroscope-ocular is of very little value. See page 49 concerning false colors, *pseudochroism*, which is often observed on small opaque bodies with strong objectives. The color of thin plates, which are in themselves colorless, belongs in the same category. It is most beautifully observed in preparations of diatoms.

**Observations in Reflected Light.**—These observations are confined, in general, to surface properties, which cannot be determined in transmitted light, such as the luster of opaque substances, metallic luster, etch figures, etc. Light coming in from below is cut out for this purpose and only light falling on the object from above is used, but it can be increased by reflectors or converging lenses.

If light incident on the preparation from above is used, it is desirable to use an objective with long focal length because otherwise the objective holder cuts out a large portion of the light. Low power objectives are therefore more serviceable for such observations and if stronger magnification is needed, in spite of the loss of light, stronger oculars, which are supplied almost entirely for this purpose with the larger instruments, are used.

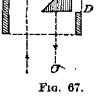

Fig. 67.
*Vertical Illuminator.*

If objectives of shorter focal length are employed, a vertical illuminator inserted above the objective is used. Fig. 67 gives a cross section of such an illuminator. *It consists of a total reflecting prism* K *which* sends the light L, coming in through the opening D, down through the objective O upon the preparation. The prism covers one half of the objective and leaves the other half free for observation and through it the light, reflected from the object, reaches the eye. It must be noted that, in using this method, the object must not be covered with a cover-glass because it would reflect the greatest part of the light. Uncovered preparations are best for investigations in reflected light. A vertical illuminator cannot be used with the stronger objectives on account of the great loss of light produced by the double transit of the light through the objective.

## CHAPTER IV

# Observations in Parallel Polarized Light

Observations in polarized light are of especial importance in the investigation of crystallized bodies because by this means the inner structure of a crystal can be determined. For this purpose a nicol prism, the *polarizer,* is placed between the source of light and the object to be studied. By rotating the stage through 360° the phenomena can be observed which a crystal shows in various planes in which the plane polarized light from the polarizer is vibrating. A second nicol prism, the *analyzer,* with its vibration direction exactly at right angles to that of the polarizer may be placed above the objective and the phenomena of interference of light between crossed nicols may then be observed. Before the phenomena thus observed can be discussed in detail, the optical properties of crystals must be reviewed briefly.

## 1. Optical Properties of Crystals

**Single and Double Refraction.**—If a small illuminated opening in a dark screen is viewed perpendicularly through a cleavage piece or a plane parallel plate cut in any direction from a crystal of fluorite or halite, it appears in the same place and in the same manner as it would if the plate were not there. If instead of the plane parallel plate a prism of the same substance is used and the opening is viewed through two surfaces oblique to each other, the image will appear removed from its original position and will be surrounded by a colored border, but only one image of the opening will be seen. All amorphous bodies and crystals of the cubic system behave in the same manner. They are called singly refracting or **isotropic** substances.

If the index of refraction is determined by the deviation of light in a series of such prisms of a singly refracting substance, it will be found to be the same regardless of the orientation of the prism in the crystal. Singly refracting bodies deviate light in all directions in the same manner. They are therefore called *isotropic*. Since the refraction of light in a prism is dependent upon the index of refraction of the substance in question and, since the index is inversely proportional to the velocity of the light, it follows that in an isotropic body light is propagated in all directions with the same velocity.

Crystals of the other systems do not behave in this manner. If a spot of light is observed in the same manner as before, through a transparent cleavage piece of calcite it appears double. One of the images is seen in the true position and the other is removed from it. Depending upon the position of the calcite the second image is above or below, to the right or to the left. If the calcite be rotated, it will be observed that the latter image moves in a circle around the former. It may also be noted *that the line joining the two images is always the bisector* of the obtuse angle of the cleavage fragment. All crystals that are not cubic, act in a similar manner and are therefore called doubly refracting or **anisotropic**.

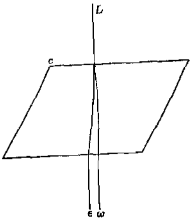

Fig. 68.—Double Refraction in Calcite.

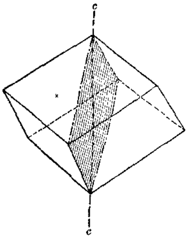

Fig. 60.—A Principal Section in Calcite.

**Double Refraction of Light in Calcite.**—Of the two rays produced by the double refraction of calcite, or any other hexagonal or tetragonal crystal, the one, ω, Fig. 68, gives an image of the object in its true position, *i.e.* with perpendicular incidence of the light it suffers no deviation. It follows the ordinary laws of refraction and is therefore designated as the *ordinary* ray. The other ray, ε, is deviated from its path. Different laws of refraction govern it and it is, therefore, called the *extraordinary* ray.

Any plane of a crystal having a principal crystallographic axis, i.e., those belonging to the hexagonal or tetragonal crystal systems, is called a *principal section*, provided it contains the optic axis. Thus, the dotted plane, Fig. 69, is one of an infinite number of principal sections containing the *c* axis of calcite and it is, indeed, the one passing through two edges of the rhombohedron. A line joining the two images produced by double refraction in every section of calcite corresponds to the projection of a principal section on the face in question. From this, it follows that the deviation of the extraordinary ray in calcite, or in any hexagonal or tetragonal crystal, is in a principal section. In a cleavage piece of calcite the line joining the two images produced by double refraction is the bisector of the obtuse angle of the calcite rhombohedron, Fig. 70.

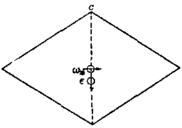

Fig. 70.
Double Refraction in a
Rhomb of Calcite.

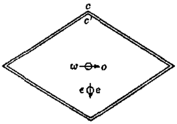

Fig. 71.
Double Refraction in two parallel
Rhombs of Calcite.

If the images seen through a piece of calcite are observed through a second cleavage piece of the same thickness, it will be found that they do not behave as two illuminated openings. When the two cleavage pieces are exactly parallel, Fig. 71, it will be noted that the distance between the two images is doubled, i.e., the double refraction of one piece is simply added to that of the other. If one calcite is rotated, four images are generally seen, which are equally bright when the principal sections of the calcite form an angle of exactly 45°, Fig. 72.

The significance of the phenomenon that both images from the first calcite did not, upon rotation of the second, behave as two openings illuminated by ordinary light, was formerly very difficult to understand. An explanation was only possible after the difference between ordinary and polarized light was discovered. The former consists of light vibrating in all azimuths at right angles to the direction of propagation, while in the latter the vibrations are always executed in but one plane, which is likewise perpendicular to the direction of propagation, Fig. 22, page 8. It is a noteworthy fact that our eye is not adjusted to discern this difference between ordinary and polarized light and, that appliances which themselves produce polarization, are necessary to recognize it.

The phenomena represented in Figs. 71–74 can only be *explained on the supposition that the vibrations of light in the two images produced by the first calcite are polarized in two directions at right angles to each other*; and further, that the vibration directions of the two rays are perpendicular to each other in calcite, the one taking place in the principal section and the other at right angles to it. According to Fresnel's hypothesis, which is here taken as a basis, *the vibration direction of the extraordinary ray is always in the principal section* while that of the ordinary ray is perpendicular to it.

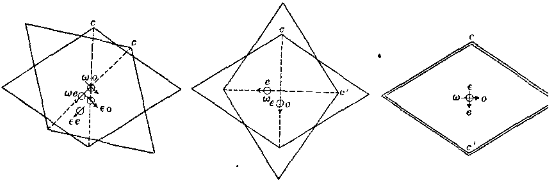

Fig. 72. Fig. 73. Fig. 74.
Double Refraction in two Rhombs of Calcite Rotated.
45° 90° 180°

The phenomena of Figs. 71—74 can be explained in a very simple manner. In Fig. 71 the light which emerges from the first calcite as the extraordinary ray $\varepsilon$ passes through the second parallel to it, likewise as the extraordinary ray $e$ and suffers the same amount of deviation in the second as in the first and in fact in the same direction. The other ray passes through both calcites as the ordinary rays $\omega$ and $o$ and is not deviated. If the second calcite is rotated through an angle of 45°, Fig. 72, the ordinary ray $\omega$ of the first is resolved by the second into two components, which *correspond* to the two vibration directions of the ordinary ray $o$ and the extraordinary ray $e$ in the second calcite. Thus, two images are formed, of which one $\omega o$ produced by a light passing through both calcites as an ordinary ray, suffers no refraction.

The other $\omega e$ owes its origin to the component corresponding to the extraordinary ray of the second calcite and is therefore refracted in its principal section. In the same manner the extraordinary ray of the first calcite $\epsilon$ gives rise to two images $\epsilon o$ and $\epsilon e$, which are shown in corresponding positions in Fig. 72. In a position in which the two principal sections enclose an angle less than 45°, the two images $\omega o$ and $\epsilon e$ are brighter than the other two. Upon rotating more than 45° the two latter become brighter at the expense of the former until, after a rotation of 90°, the images appear as shown in Fig. 73, only $\omega e$ and $\epsilon o$ being visible. When at last the calcite has been rotated through 180° the conditions are as in Fig. 74. The ordinary ray of the first passes as an ordinary ray through the second, and the extraordinary ray as an extraordinary. The former is not deviated at all, while the latter is refracted just as far in one direction in the first calcite as it is in the opposite direction in the second calcite so that all four images coincide.

If several differently orientated plates are cut from a crystal of calcite, two images of an illuminated pinhole can generally be seen through them, but the distances between the images will vary according to the orientation of the plates. If the indices of refraction are determined in these plates it will be observed that the index of the more strongly refracted ray is the same in all the plates, while that of the other varies. The minimum value of the latter is obtained in a plate cut parallel to the principal crystallographic axis, i.e., in a plate in which the light passing through the calcite vibrates parallel and perpendicular to that axis. The difference between the velocities of the two rays is *greatest when the light is propagated perpendicular to the principal crystallographic axis.* Plates parallel to the base give but one value for the index of refraction. In this case the light is propagated parallel to the principal crystallographic axis. Hence it follows that for light traveling in that direction calcite behaves as a singly refracting substance and further that the elasticity is the same in all vibration directions perpendicular to the principal axis.

**Uniaxial Crystals.**—That direction of propagation in a doubly refracting crystal in which light suffers no double refraction, i.e., perpendicular to which all vibration directions are equal, is called the *optic axis.* Calcite and all other hexagonal and tetragonal crystals, i.e., all crystals with a principal crystallographic axis, possess but one such direction and are therefore called *uniaxial*. The ray which is propagated in all directions with equal velocity is the *ordinary ray*. The other ray, the index of refraction and the velocity of propagation of which are dependent upon the direction in which the vibrations take place, is the *extraordinary ray*. It follows from the above that the index of refraction or its reciprocal, the velocity of the extraordinary ray, more nearly approaches that of the ordinary ray the smaller the angle between the optic axis and the direction of propagation of the ray through the crystal. In the direction of the optic axis the double refraction or the difference between the indices disappears because all vibrations perpendicular to the optic axis have equal values.

The difference between the indices of the two rays passing through a uniaxial crystal, i.e., its *double refraction*, is greatest when the light travels through the crystal perpendicular to its principal crystallographic axis, which is also the optic axis. It becomes zero when the direction of propagation coincides with the optic axis and polarization of the light no longer takes place. In the directions lying between these two, the double refraction is less the smaller the inclination of the ray of light to the optic axis.

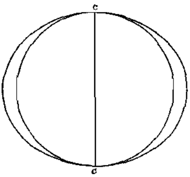

Fig. 75.

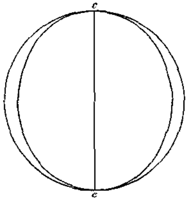

Fig. 76.

Principal Section of a Wave Surface of a Uniaxial Crystal.
Positive. Negative

This phenomenon can be best understood by considering a wave surface, which includes all points to which light would travel from the center of a crystal in a given unit of time. Since the portion of the light passing through as an ordinary ray vibrates in all directions with equal velocity it reaches the surface of a *sphere* in the time interval. On the other hand the extraordinary ray possesses different velocities in different directions and its velocity is equal to that of the ordinary ray only in a direction parallel to the optic axis. Its ray surface must be in contact with that of the ordinary ray at the ends of the axis. These are the only points which the two wave surfaces have in common. The change of velocity of the extraordinary ray is the *same on all sides for equal inclinations of the direction* of propagation to the optic axis and increases regularly up to the maximum perpendicular to the optic axis. Therefore the wave surface of the extraordinary ray must be a rotational form different from a sphere. It is an *ellipsoid of rotation,* Figs. 75 and 76.

The index of refraction of the ordinary ray is indicated by $\omega$, and that of the ray differing from it the most, the extraordinary ray, by $\varepsilon$. The double refraction is expressed by the difference $\varepsilon$-$\omega$. There are two possible cases; one, as in calcite, where $\omega > \varepsilon$ that is, the ordinary ray is more strongly refracted than the extraordinary. Then $\varepsilon$-$\omega$ is negative and such crystals are said to be *negative* or because the extraordinary ray is farther from the normal than the ordinary ray, they are also called *repellant* crystals, Fig. 77. In the other case $\varepsilon > \omega$, the crystal is said to be *positive* or *attractive,* Fig. 78. Since the velocity is the reciprocal of the index of refraction, the extraordinary ray of a negative crystal and the ordinary ray of a positive crystal have the greatest velocities. The direction of greatest elasticity and least index of refraction is called $\mathfrak{a}$[1] and the corresponding index $\alpha$; the direction of least elasticity $\mathfrak{c}$ and its index $\gamma$, while $c$ is the principal crystallographic axis. $c = \mathfrak{a}$ is the symbol of a negative

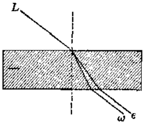

FIG. 77.—Negative

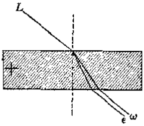

FIG. 78.—Positive

Double Refraction.

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[1] Usage differs somewhat. In America X, Y, Z is proposed by Iddings for $\mathfrak{a}$, $\mathfrak{b}$, $\mathfrak{c}$ respectively, while in France $n_p$ (p = petit, small) $n_g$ (g = grand, large) and $n_m$ (m = moyen, medium) are used for $\alpha\gamma\beta$ respectively. $\mathfrak{b}$ and $\beta$ refer of course to biaxial crystals.

crystal, $c = \mathfrak{c}$ that of a positive, while $\gamma$-$\alpha$ shows the amount of double refraction in all cases.

**Biaxial Crystals.**—The conditions are more complex in crystals of the orthorhombic, monoclinic, and triclinic systems. If an illuminated opening is observed through several plates of aragonite variously orientated, it will be noted that, in general, two images are seen, but both appear to be displaced from their original positions. In this case the light is resolved into two extraordinary rays which are always polarized at right angles to each other. If the indices of refraction are determined with a series of prisms of aragonite it will be noted that none of them is constant. The maximum and minimum, i.e., the greatest double refraction, is observed in a prism in which the direction of propagation of the ray is parallel to the crystallographic $a$ axis. The two rays vibrate at right angles to each other and parallel to the other two crystallographic axes, which are at the same time the directions of greatest and least velocity of light or the directions of smallest and greatest index of refraction in the crystal. In all other directions the indices of refraction are intermediate between these two extremes, including also light vibrating in the direction of the $a$ axis. Three optical directions perpendicular to each other must be distinguished in aragonite and these coincide with the $a$, $b$, and $c$ axes. On the other hand, there is no relationship existing between the value of a vibration direction whether $\mathfrak{a}$, $\mathfrak{b}$, or $\mathfrak{c}$ and the crystallographic axis because in the orthorhombic system the crystallographic axes can be placed in any position desired. The three principal vibration directions of light, the axes of optical elasticity in a biaxial crystal, can be designated in various ways depending upon whether the index of refraction or its reciprocal value, the velocity of light, is to be emphasized.

| | | | |
|---|---|---|---|
| Index of refraction | smallest $\alpha$ | $\mathfrak{a} = 1 : \alpha$ largest. | Velocity of |
| | medium $\beta$ | $\mathfrak{b} = 1 : \beta$ medium | light. |
| | largest $\gamma$ | $\mathfrak{c} = 1 : \gamma$ smallest | Elasticity. |

Let us now consider more in detail the bundle of planes, the axis of which is the direction of medium index, $\beta$. Light passing through the mineral perpendicular to one of these planes is resolved into two rays, one of which always vibrates in the direction of medium velocity and the other is perpendicular to it. Its vibration direction coincides either with that of the largest ($\gamma$) or of the smallest ($\alpha$) index or it corresponds to a medium value between these two. Among these values there is one $\beta'$, Fig. 79, equal to $\beta$. For the direction of propagation AA, which lies in the plane $\alpha\ \gamma$ and perpendicular to the plane $\beta\ \beta'$, there are two perpendicular vibration directions of equal value. AA is an optic axis. Since the plane $\alpha\ \beta$ in aragonite is a plane of symmetry, another direction equal to AA and symmetrical to it, must lie on the other side of $\alpha$ in the plane $\alpha\ \gamma$, and $\alpha$ and $\gamma$ will bisect the angle between these two optic axes. Another such direction is crystallographically impossible and therefore aragonite, and with it all crystals of the orthorhombic, monoclinic, and triclinic systems, are *biaxial*.

The plane in which the two optic axes lie is called the *plane of the optic axes*. The directions of largest ($\gamma$) and smallest ($\alpha$) index bisect the angles of the optic axes and are called middle lines or *bisectrices*. The direction of medium index ($\beta$), perpendicular to the plane of the optic axis, is called the *optic normal*. The optic axes form an acute angle on one side and an obtuse on the other. The bisector of the acute angle is called the first middle line or the *acute bisectrix* $Bx_a$ and the bisector of the obtuse angle, the second middle line or *obtuse bisectrix* $Bx_o$. If the acute bisectrix is the direction of the smallest index ($\alpha$) the crystal is said to be *negative* and in the other case *positive*. The value of the intermediate index can be the arithmetic mean of the largest and smallest indices for a certain color only when the optic angle for that color is 90°, otherwise it is the nearer

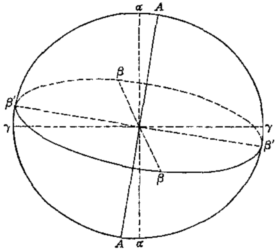


*Fig. 79.—Construction of an Optic Axis in Aragonite.*

that of the obtuse bisectrix the smaller the acute optic angle, and when it becomes 0° *the two directions are equivalent* and the crystal is optically uniaxial.

Since the index of refraction is different for different colors in one and the same crystal, the size of the optic angle must vary with the color. Sometimes the acute angle for red ($\rho$) is larger than that for violet ($\upsilon$), which is indicated by the symbol of dispersion $\rho > \upsilon$. The opposite $\upsilon > \rho$ is also encountered.

As seen in the case of aragonite, the plane of the optic axes in orthorhombic crystals is always parallel to one of the three pinacoids because the directions of greatest and least elasticity coincide with two of the crystallographic axes. In the monoclinic system *only one of the three principal vibration directions* coincides with the *b* axis and this is the case for all colors. The plane of the optic axes lies parallel or perpendicular to the clinopinacoid and the other two vibration directions fall in the plane of symmetry, wherever they may, but are always perpendicular to each other. They may have quite different *positions in that plane for different colors, thus causing dispersion* of the bisectrices or the planes of the optic axes. In the triclinic system the optical elements are orientated entirely independently of the crystallographic axes and likewise the relationships for the different colors are independent of each other. Even here, however, the three principal vibration directions for any one color are perpendicular to each other.

The velocity of light in any direction in a biaxial crystal can be easily shown by the Fresnel principle. An ellipsoid is described about the three axes of elasticity of a biaxial crystal and a plane is placed in the center perpendicular to the direction of propagation of the ray. The form of such a section is always an ellipse, except in the two positions perpendicular to the optic axes, where it is a circle. The lengths of the large and small axes of the elliptical section correspond to the velocities of the two rays propagated perpendicular to the section.

## 2. Investigations with One Nicol—the Polarizer

**Surface Color and Pleochroism.**—When light enters an anisotropic crystal it is generally resolved into two rays propagated with different velocities. These rays are absorbed differently and, when this difference is great enough, variation in color may be noted. If a doubly refracting crystal is illuminated with ordinary light, the mean of the two vibrations is observed at any moment because, as a result of the rapid change of the planes of vibration in a ray of ordinary light, equal amounts of light pass through the crystal at a given instant parallel to each of the vibration directions. Upon looking through a surface of a crystal in ordinary light a mixed color is observed, which is called the *surface color*. If, on the other hand, plane polarized light enters a doubly refracting crystal, the two components corresponding to the vibration directions in the crystal will be alike only when they form an angle of 45° with the vibration directions of the nicol. One direction will become zero, i.e., only those vibrations parallel to the other direction will be observed, when the vibration direction of the nicol coincides with it.

The properties of each ray passing through a crystal can be studied in succession by placing the vibration directions parallel to that of the polarizer between crossed nicols and then removing the analyzer to observe the color. Thus the color for certain directions and the differences for different directions of vibration can be observed. These colors are called the *colors of the axes*. Variation in color for different directions in a crystal is called *pleochroism*.

For these investigations the polarizer beneath the preparation is used, while the analyzer is pushed out of the tube. If the analyzer were used the interference phenomena, caused by the partially polarized light reflected from the mirror, although not very distinct, would greatly interfere with the results. If the colors parallel to the axes are to be observed side by side, instead of one after the other, a Haidinger lens, Fig. 80, is used. This consists of a tube with a rectangular opening in one end and contains an elongated piece of calcite K, which is of the proper length to give two images of the opening side by side. The vibration directions of the polarized light are perpendicular to each other in these two images produced by double refraction. If the crystal in front of the opening is rotated until the two images show the greatest possible difference in color, the two principal colors of the face are observed. A similar device is the *dichroscopic ocular*, which may be used for observing the two principal colors under the microscope. Here, however, the results are disturbed by the partial polarization of light reflected from the mirror, as indicated above.

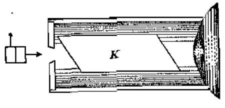


FIG. 80.—Haidinger Lens.

Cross sections of cubic crystals or of amorphous substances always show the same color upon a complete rotation of the stage above the polarizer because in them the absorption of light is the same in all directions. In uniaxial minerals all directions perpendicular to the optic axis are of equal value in an optical sense. Only the color of the ordinary ray is observed on the base of a uniaxial crystal in ordinary light and this is the same as the surface color. Such a section does not change its color upon rotation of the stage. The absorption of light is the same for the ordinary ray in any section and its color can be observed in any direction, while the absorption of the extraordinary ray is variable and differs the more from that of the ordinary ray the nearer its vibration direction approaches the direction of the optic axis. The color of the ordinary ray can be observed in any section, while that of the extraordinary ray appears only in a section parallel to the optic axis of the crystal. If the difference in absorption for the two principal directions of an uniaxial crystal is sufficiently large to be observed it will be seen most perfectly in a section parallel to the optic axis. Since in the case of uniaxial crystals there are only two principal colors, it is common to speak of *dichroism*.

In biaxial crystals there are three different vibration directions for color as well as for indices of refraction. These crystals possess three principal colors and are termed *trichroic*. The pure color belonging to one of these vibration directions can be observed only in a section parallel to it. In all others mixed colors are seen. In the orthorhombic system the vibration directions of the greatest, least and intermediate indices of refraction are at the same time the color axis. In the monoclinic system only the *b* axis is simultaneously a color axes. The other two lie anywhere in the plane of symmetry, but are not very far removed from the vibration directions of light. In the triclinic system all these directions are independent of each other but even in this case, if a vibration direction is placed parallel to the polarizer instead of a color axis, the error is scarcely noticeable.

**The Phenomenon of Pleochroism.**—The difference of absorption of light in various directions, which is known as *pleochroism*, is so slight in numerous cases, especially in colorless crystals, that it cannot be observed even with thick plates of the mineral. Since the color of a section, and likewise the difference of color in different directions, is less distinct the thinner the layer, it follows that in thin section, pleochroism can only be observed in substances having a great difference of absorption in different directions. Although in the observation of weak pleochroism the subjective ideas of the observer and a certain amount of practice are important, still the investigation of pleochroism is a valuable aid in microscopic research.

It is very useful in the study of pleochroism to keep three possible cases in mind. This can be done best by the aid of a color scale such as a *Radde color scale*, which shows the different colors in a horizontal row and the different intensities of each from the darkest to the lightest tints in vertical columns. The following cases are possible:

1. Different parts of the spectrum are absorbed in different parts of the crystal in such a manner that the intensity of the light which travels in these directions remains approximately the same. Various colors appear in different directions, but one is about as bright as the other. Compare horizontal series of the color scale.

2. In each direction approximately the same portions of the spectrum are absorbed but with unequal intensity. The same color is observed in all directions, but with different intensities. Compare vertical series of the color scale.

3. In different directions different colors of the spectrum are absorbed with different intensities. The different colors are seen in different shades. Compare the diagonal of the color scale.

These three cases often give rise to very characteristic phenomena, e. g., pleochroic pyroxene almost always shows the same depth of color, in one direction light green, in the other light yellow. Common hornblende of the same color shows stronger absorption of the green ray and its pleochroism is from dark green to light yellow, while in biotite only simple differences of absorption of the same color are effective and it changes from light brown to dark brown.

The strength of pleochroism in one and the same crystal is dependent upon its thickness and very frequently the phenomenon can be observed in thicker layers when it is not noticed at all in thin sections. The absorption is rarely so great that no light is observed passing through the crystal in that direction. The color of the more strongly absorbed ray can almost always be recognized, even in the most strongly absorbing minerals if the section is thin enough.

The orientation of the differently absorbed rays in a crystal is of importance because it tends to be strikingly constant in one and the same substance, as also in the larger isomorphic series. Two points of view are to be considered in practice: 1. The relationship of the more strongly absorbed ray to the crystallographic development of the substance in question, i. e., to the long direction of its cross section, the *principal zone*. Almost all important rock-forming minerals with great differences of absorption show stronger absorption of the ray vibrating parallel or nearly parallel to the principal zone. They have a deeper color when the longer edge of the cross section is parallel to the vibration direction of the polarizer, Fig. 81. Tourmaline behaves in the opposite manner and shows a lighter color, Fig. 82. Stronger absorption of light in the direction perpendicular to the principal zone is one of the most important means for determining this mineral, which often occurs in minute individuals that are difficult to determine by other optical properties. 2. The relation between the refraction and absorption of the two rays vibrating in a section. There is no regular connection between these two properties and although in most cases in rock-forming minerals the most strongly refracted ray is the most strongly absorbed, this is by no means always the case. In the above mentioned example, tourmaline, the extraordinary ray is the least refracted and the least absorbed. Its absorption symbol is $\mathfrak{C} > \mathfrak{a}$ or since tourmaline is optically negative $\omega > \varepsilon$. In apatite, which is likewise negative, the more strongly refracted ray is orientated in reverse manner. Here the symbol is $\mathfrak{a} > \mathfrak{C}$ or $\varepsilon > \omega$. Similar results are encountered in optically biaxial minerals. Common hornblende, for example, universally shows $\mathfrak{c} > \mathfrak{b} > \mathfrak{a}$, *while with riebeckite and arfvedsonite, on the other hand,* $\mathfrak{a} > \mathfrak{b} > \mathfrak{C}$.

Pleochroism can be produced in an artificial manner under certain conditions and may become a very good characterisitic of a substance. When members of the olivine or amphibole groups containing iron are roasted, they assume strong colors and decided differences of absorption. This serves to distinguish them from the pyroxenes which generally do not show any pleochroism as the result of such operations. Fibrous and scaly mineral aggregates can be colored directly with aniline dyes, whereupon many of them such as talc and serpentine become distinctly pleochroic. Many artificial crystals, colorless in themselves, acquire not only color but *often distinct pleochroism upon crystallization from a dye solution. This phenomenon has been known a long time in the case of strontium nitrate.*

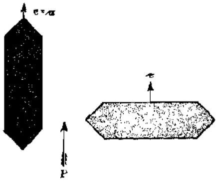


FIG. 81.—Stronger absorption Parallel to Principal Zone.

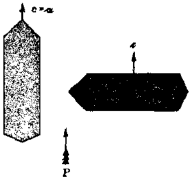
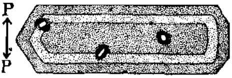


FIG. 82.—Stronger Absorption Perpendicular to Principal Zone.

For the sake of completeness pleochroic halos, Figs. 83 and 84, will be considered briefly. In numerous minerals, particularly in cordierite, andalusite, mica, hornblende, tourmaline, etc., it will be noticed that certain rounded spots show stronger pleochroism than the rest of the mineral generally does. *If these portions are studied more carefully small inclusions of foreign minerals will be discovered in the center of such pleochroic halos* and the outline is surrounded on all sides by a more pleochroic zone. Since it is possible to produce phenomena analogous to the pleochroism in these minerals by illuminating with radium preparations and, further since most of the inclusions forming the centers of such halos—zircon, rutile, orthite, etc.—are radio-active, there can be no doubt that the pleochroism of the halo depends, for the most part at least, upon the action of active rays. It is noteworthy that refraction, double refraction, and frequently also dispersion are greatly changed in the pleochroic halos. They are sometimes decidedly lower, sometimes much higher. Besides the radioactive inclusions surrounded by pleochroic halos there are frequently other crystalline inclusions in the same crystal, which are not classed with radioactive minerals (and do not show this phenomenon), for example, the long apatite needles in Fig. 84.

Two other phenomena which are observed now and then must also be mentioned. One of these is *pseudodichroism,* a phenomenon which occurs in perfectly colorless crystals. If there are a large number of parallel orientated inclusions in a crystal and the refraction of these differs considerably from that of the surrounding crystal, light passing through is disturbed by the inclusions if they are steeply inclined to the direction of propagation of the light. The less refracted red rays are bent toward the middle and the more strongly refracted violet rays toward the edge of the field of vision. Only those rays vibrating parallel to the direction of the inclusions suffer this sort of refraction, while those vibrating at right angles to it are not changed. If the crystal is so orientated in the center of the field that the direction of the inclusions is parallel to the principal direction of the polarizer, it appears a brilliant brown. If it is on the edge, it is colored gray, but in each case it becomes colorless upon rotating through 90°.



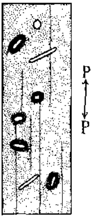


Fig. 83. Fig. 84.
Pleochroic Halos around Inclusions of Zircon in
Tourmaline. Biotite.

The occurrence of interference colors without the use of the analyzer is the other of the phenomena referred to above. If a layer of a doubly refracting mineral, orientated at random occurs in a slide under a thin crystal of a very strongly absorbing mineral—biotite or tourmaline—the absorbing crystal, which scarcely allows one of the rays to pass through, acts as an analyzer itself and the mineral beneath it shows interference colors. Complementary colors appear upon a rotation through 90°, because the absorbing direction of the preparation is first perpendicular and then parallel to the principal direction of the polarizer. The occurrence of interference colors in minerals with a high double refraction—calcite and rutile—which are crossed by twininng lamellæ greatly inclined to the face of the slide, is a similar phenomenon.

## 3. Investigations with Crossed Nicols

Observations between two nicols are carried out almost entirely with the planes of vibration of the two crossed, and for this reason they are called *observations with crossed nicols.*

The following determinations are to be made in parallel polarized light with the microscope, as commonly constructed, which affords an enlarged image of the object investigated:

(a) Recognition of double refraction.

(b) Determination of the position of the vibration directions.

(c) Measurement of the strength of double refraction.

(d) Determination of the relative velocities of the two rays vibrating in a cross section.

**Recognition of Double Refraction.**—If a singly refracting substance, or a section through such a substance, is placed between crossed nicols, the plane polarized light from the polarizer passes through the crystal unaltered to the analyzer, and since its vibration direction is at 90° to that of the approaching ray no light will pass through. No change occurs upon rotating the stage through 360°. A singly refracting substance appears dark in all positions between crossed nicols.

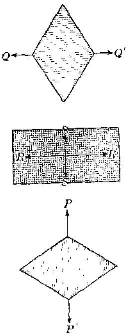


FIG. 85.—Vibration Directions in Crystal Parallel to Those of the Nicols.

*If a doubly refracting crystal is observed between crossed nicols, the light coming from the polarizer suffers no change in the crystal only when the vibration directions* RR' *and* SS' *in the crystal are exactly parallel to the vibration directions* PP' *and* QQ' *in the two nicols*, Fig. 85. If the vibration directions RR' and SS' are oblique to PP' and QQ', as in Figs. 86 to 88, the plane polarized light from the polarizer is resolved into two components O*r* and O*s'* corresponding to the vibration directions of the crystal. After another resolution in the analyzer the components passing through it, O$\rho$ and O$\delta$ are combined. The plate appears illuminated in all other positions because a portion of the light always passes through the analyzer. The magnitude of the components O$\rho$ and O$\delta$ indicates the brightness and it follows from a comparison of Figs. 86 to 88 that the maximum is reached when the vibration directions of the crystal are at 45° to those of the nicols, Fig. 87.

Since the vibration directions RR' and SS' are parallel to PP' and QQ' four times in a horizontal rotation of the stage through

360°, doubly refracting crystals are alternately light and dark four times in a rotation of 360° between crossed nicols. Maximum brightness is obtained when the vibration directions of the crystal are at 45° to those of the nicols. It diminishes upon further rotation and passes gradually over into complete darkness when these directions are respectively parallel. This latter position is also called the *position of extinction,* and the vibration directions in the crystal, the *extinction directions.* The determination of the latter is an important aid in many cases for ascertaining the crystal system.

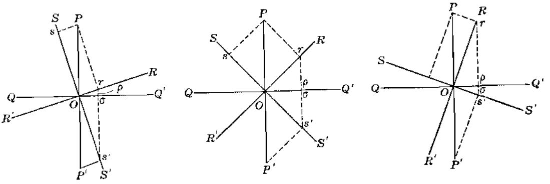


FIG. 86. FIG. 87. FIG. 88.
Vibration Directions in Crystal Oblique to Those of the Nicols.

Gray interference colors of the lowest order (see Fig. 96, page 75), corresponding to the lowest degrees of double refraction, are extremely difficult to distinguish from total darkness. Therefore, when thin sections of very weak double refracting crystals are examined, it is sometimes difficult to distinguish whether or not, there is any effect on polarized light at all. To recognize very weak double refraction, use is made of certain accessory devices—sensitive tint plate, Bravais double plate, etc.—which will be described more in detail under the head of stauroscopes. The change of interference color in such devices, caused by even extremely low double refracting plates, is much more easily determined than the difference between absolute darkness and very weak illumination, so that the presence of double refraction can be definitely determined, even in the most doubtful cases.

## Determination of the Position of the Vibration Directions.

The position of the vibration directions can be determined from the above by placing the crystal between crossed nicols in the position of perfect darkness. Then the vibration directions of the crystal lie parallel to those of the two nicols, and the latter are exactly parallel to the cross hairs in an adjusted microscope.

A characteristic crystal edge or cleavage direction is brought parallel to one of these hairs by rotating the stage, and a reading is made on the scale on the stage. Then the analyzer is inserted and the stage rotated until the crystal appears perfectly dark, and another reading of the scale is made, the difference being the angle which the vibration direction makes with the edge or cleavage in question.

*The position of absolute darkness may not be found accurately on account of the gradual transition from light to dark. The beginner will experience considerable difficulty in finding the true position of darkness. The method of procedure is as represented in Fig. 89. PP′ and QQ′ represent the vibration*

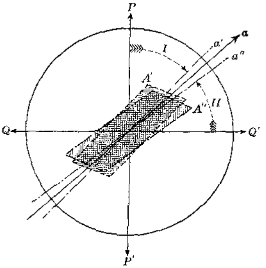


Fig. 89.—Determination of Extinction Direction.

directions of the two nicols. The stage is rotated in the direction of the arrow I until the crystal appears entirely dark and its long edge, which may formerly have been parallel to PP′, has reached the position A′. Then it is rotated further toward QQ′, and the crystal becomes light again. It is then rotated back in the direction of the arrow II until darkness is obtained, say in the position A″. The direction *a*, which bisects the angle between the two directions *a′* and *a″*, i.e., the mean of the two positions, is the true vibration direction. If this operation is repeated several times, the mean of a large number of readings will come very near to the true position of darkness. Even though the greatest care is exercised, an error of ± ½°, as is generally the case with microscopic measurements, can scarcely be avoided.

In general parallel or symmetrical extinction, Figs. 90 and 91, is observed in hexagonal, tetragonal and orthorhombic crystals, because the vibration directions coincide with the crystal axes. The determinations are made in white light because the vibration directions are the same for all colors. Monoclinic crystals show parallel or symmetrical extinction only upon faces in the zone of the *b* axis, and for all colors, while on all other faces the extinction is oblique, Fig. 92, i.e., the extinction directions are unsymmetrical with respect to the crystal edges. Since this variation is different for different colors, the position of absolute darkness cannot be obtained with white light. The extinction is best determined in monochromatic light if an accurate measurement, and not merely an approximate orientation is to be made.

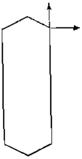


FIG. 90.—Parallel

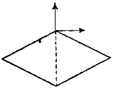


FIG. 91.—Symmetrical.

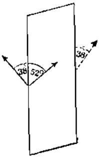


FIG. 92.—Oblique

Extinction.

When the extinction angle is determined it must be noted whether the measurement from the crystal edge is to the front or to the rear. The difference caused by confusion of these two directions is shown in Fig. 92. The dotted arrow shows the false vibration direction, the proper direction of which is given by the solid arrow. A beginner will do well to sketch the crystal and place the sketch parallel to the extinguished crystal, and then draw lines parallel to the vibration directions, i.e., parallel to the cross hairs. This shows the vibration directions sought in their true positions.

As mentioned above, hexagonal, tetragonal and orthorhombic crystals generally show parallel extinction because their development is usually parallel or symmetrical to the principal vibration directions. Monoclinic crystals are not uncommonly developed so as to be long prismatic parallel to the *b* axis, e.g., epidote and wollastonite, and then the principal zone is the position of parallel extinction. It is obvious that crystals thus developed may be confounded in thin section with those showing parallel extinction in all sections, because cross sections transverse to the direction of elongation are not very numerous. The true character of monoclinic crystals can, however, be easily determined if they are developed tabular parallel to the base or prismatic parallel to one of the directions lying in the plane of symmetry. Triclinic crystals may be developed in various ways and can *rarely be orientated properly.*

The value of the extinction angle of monocline crystals is determined on the clinopinacoid and where there is no statement to the contrary, this face is always understood. Other faces can be used for the determination of a crystal only when their extinction directions are accurately known. The directions cannot generally be determined from the inclination of the face to the *b* axis, because the extinction angle does not diminish in a regular manner in passing from the clinopinacoid to the orthopinacoid, and may even have a higher value on an intermediate face than on the clinopinacoid itself. Since the extinction angle on crystal faces that are easily determined has a characteristic value for any given substance, it should be given for the prism faces as well as for the clinopinacoid, especially in the case of monoclinic substances having a good cleavage parallel to the prism, for if the prism angle is known, the true optic angle can be calculated from these values.

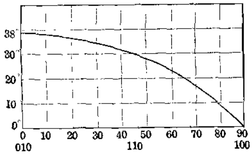


*Fig. 93.—Extinction Curve for Diopside.*

Diopside with an extinction angle of 38° on the clinopinacoid is the best example for illustrating this relationship. The crystal is mounted on a otation apparatus, as described in the appendix, and the extinction measured on the faces inclined at least 10° to each other in the zone of the *c* axis. These values are plotted as ordinates, while the abscissas represent the inclination of the various faces to the clinopinacoid, Fig. 93. The extinction for any face lying in that zone can be read from the curve plotted from this data. Thus, for example, a prism is inclined about 45° to the clinopinacoid, the prism angle being not far from 90° in pyroxene, and the extinction on that face is about 30°. Great importance must be attached to the character of such curves in the investigation of thin sections. The extinction on the orthopinacoid is symmetrical, but the angle increases very rapidly on faces to either side so that parallel extinction is obtained only on faces very accurately orientated, as is rarely the case in thin sections. It is therefore easy to reach the false conclusion that the mineral is triclinic because it shows oblique extinction in all sections.

In triclinic minerals the determination of the extinction angles is of value only when the orientation of the face upon which they are observed is accurately known. The orientation of the clinopinacoid of monoclinic crystals can be easily determined by convergent light, as will be described later, because this face is either parallel or perpendicular to the plane of the optic axes, but such determinations are generally impossible in triclinic minerals. However, now and then the direction of cleavage cracks, twinning, etc., offer a clue, and the measurement of the extinction angle in triclinic minerals is important only in such sections. Extinction is of especial importance in the investigation of cleavage pieces.

**Stauroscopes.**—The simple method of ascertaining the position of absolute darkness, described above, is not sufficient for refined measurements and a number of methods have been devised which yield more accurate results, especially with colorless minerals. After the position of extinction has been found as accurately as possible with crossed nicols, one observes upon rotating the analyzer, whether in all positions of the nicols it shows the same tint as the surrounding field. The position is correct only when that is the case.

There are a number of accessory devices, which can be used for special purposes. These are all grouped together under the name of stauroscopes. The most important are:

1. The Kobell stauroscope.
2. The Brezina double plate.
3. The Caldron double plate.
4. The Bertrand plate.
5. The sensitive tint plate, gypsum test plate.
6. The Bravais double plate.
7. The Biot quartz plate.
8. The half shadow polarizer.
9. The twin polarizer.

1. The Kobell stauroscope consists of a plate of calcite cut perpendicular to the optic axis, and can be inserted between the upper lens of the ocular, and the ocular analyzer placed over it. An interference figure of an optically uniaxial crystal is seen, but it is destroyed as soon as even the slightest double refracting substance is placed between the two nicols. The vibration directions of the crystal studied are properly placed only when the interference figure is perfectly restored.

2. The Brezina double plate consists of two plates of calcite placed side by side. They are cut equally oblique to the base, but in opposite directions and are symmetrical with respect to the plane of contact between them. The interference figure in this case shows a single band surrounded by colored curves in the middle of the field of vision. If the vibration directions of the crystal are not exactly the same as those of the nicols that part of the band over the crystal appears to be broken off from the rest of the dark bar.

3. The Caldron double plate is placed within an ocular of its own, because the inserted plate demands a greater distance between the ocular lenses than

is usual. It consists of two wedge-shaped pieces of calcite so placed that the plane of contact between them, when viewed from above, appears as a sharp line and the vibration directions in the two halves are symmetrical to it. If this border line is exactly parallel to the vibration directions of the two nicols, each half shows the same degree of extinction. If a double refracting plate is placed in the path of the rays, and its vibration directions do not coincide with those of the nicols, the luminosity of the two halves of the double plate does not change uniformly because their vibration directions *are oblique to each other. Equal luminosity can only be regained* by orientating the extinction directions of the crystal plate accurately.

4. The Bertrand plate, like the Caldron, is usually placed in an ocular *of its own. It consists of four sectors of alternating right and left rotating* quartz cut perpendicular to the optic axis with a thickness of about 2.5 mm. The interference colors of the four sections are bluish-white, but they are changed uniformly when a double refracting crystal is placed on the stage with its vibration directions not exactly parallel to those of the nicols, Fig. 94. If they are parallel, the four sectors must all have and retain the same color when the nicols are rotated horizontally.

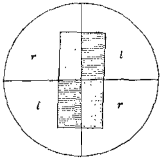


Fig. 94.—Bertrand Plate.

5. The sensitive tint, violet I, Fig. 96, page 75, at the beginning of the second order of colors is produced by a thin plate *of a colorless* feebly refracting mineral, quartz or gypsum, of the proper thickness to give this particular *interference color between crossed nicols.* It is fastened between two small strips of glass and inserted into a slot above the objective in such a manner that its vibration directions are at 45° to those of *the nicols.* As shown in Fig. 96 a retardation of 0.00001 mm. is sufficient to change this color to purple on the one side or to indigo on the other. The same figure also shows that violet I is more susceptible to a distinct change of color than all the interference colors occurring between crossed nicols. Deep violet of the first order, which is produced with parallel nicols by a plate of half the thickness of the one above can also be used as a sensitive tint. Violet II, at the beginning of the third order of colors, although it is often used as a stauroscope, is however, less valuable for this purpose because with it marked changes of color take place only with great differences of thickness. The sensitive tint is not only used to determine the vibration directions accurately, but frequently also as a compensator or as a means of recognizing very low double refraction, because the insertion of a crystal with a very feeble double refraction is sufficient to influence the color decidedly.

6. *A Bravais double plate extends the applicability of the sensitive tint.* It is set in the inner focal plane of the ocular and on account of its thinness, the ocular scarcely requires correction. One of the small plates described *under 5 is cut diagonal to its vibration directions and the two halves are* rotated through 180° to each other. Thus the vibration directions of the halves are at 90° to each other, Fig. 95. The plate is so placed in an ocular *that the junction of the two parts* coincides with one of the cross hairs.

The change which one half suffers when a double refracting crystal is introduced is reversed in the other half and these two lying side by side allow the slightest change of color imaginable to be recognized. This method is so accurate that the double refraction of a glass cube can be observed when pressed between the fingers. This is the most accurate method of all for *recognizing the double refraction as well as for determining the extinction* direction. The determination of the latter is, however, less accurate because it depends upon the change of the interference colors and cannot be made in monochromatic light, i. e., this method cannot be used for determining accur*ately the extinction directions of monoclinic* and triclinic crystals.

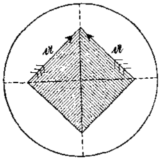


FIG. 95.—Bravais Double Plate.

7. The Biot quartz plate, cut perpendicular to the $c$ axis, is 3.75 mm. thick and upon rotating the analyzer gives various character*istic interference colors between two nicols.* In a definite position of the analyzer the delicate violet of the sensitive tint is obtained. This serves ostensibly for the determination of the extinction directions of colorless crystals, *while other tints give better results with colored* substances. When the proper position of extinction has been found, it can be checked by rotating the analyzer and noting the interference colors. The Biot quartz plate is generally so mounted that it can be inserted in the slot above the objective.

8. The half shadow polarizer is a nicol which has been cut through the middle in a direction slightly oblique to its principal section and the pieces recemented together in reversed positions. The vibration directions form a small angle with each other. It is used in place of the polarizer and the two halves appear in equal half shadows when the vibration direction of the analyzer is parallel to the line of division.

9. The twin polarizer differs from the above in that the vibration directions in the two halves are at 90° to each other. The application of both devices is very limited because the line of junction and the crystal must be seen sharply at the same time which means that only objectives with large focal lengths can be used.

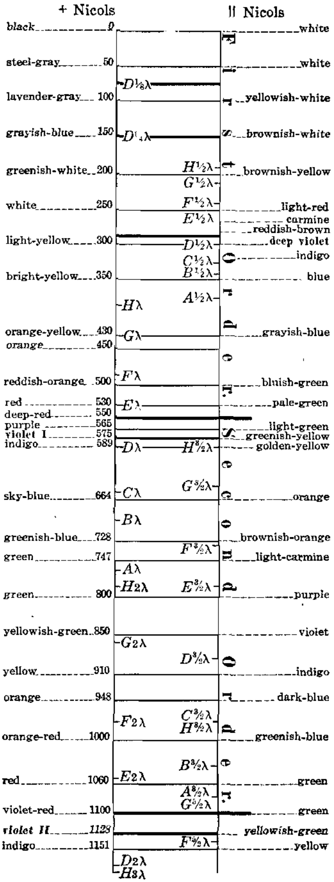
Those stauroscopes which depend upon a change of interference colors can only be employed for determinations in white light. They cannot be used when accurate determinations of the extinction directions of strongly dispersing monoclinic and triclinic crystals are to be made. This determination must be carried out in monochromatic light. A Brezina double plate or Kobell stauroscope is to be preferred in such cases.

**Strength of the Double Refraction, Interference Colors.**—The two rays into which light is resolved by a double refracting crystal are propagated differently in the crystal. Upon emerging from the crystal one ray is retarded a certain amount behind the other and this retardation depends upon the difference of elasticity of the two vibration directions perpendicular to the direction of propagation, and upon the thickness of the crystal. When the two rays are brought back to one plane of vibration by the analyzer they show a difference of phase. The rule is that two plane polarized rays produced by the double refraction of a single plane polarized ray of light, interfere with each other when they are reverted again to the same plane of polarization.

Since ordinary light is composed of various colors with different wave lengths, $\lambda$, the phasal difference will be different for the various *colors for a definite thickness of the crystal, which corresponds* to a fixed retardation of one ray over the other. For a definite color the two rays are compounded by the interference and that color appears with especial brilliancy, while for other colors the two vibrations destroy each other and no light of that color passes through the analyzer. Thus, instead of white light, colors appear and they are called *interference colors.*

There are two cases to be distinguished in the interference of light depending upon whether the plane of vibration of the analyzer is parallel or perpendicular to that of the polarizer. In the first case the rays emerging from the crystal interfere with the same phase, and in the latter case with reversed phase. With parallel nicols those colors appear with greatest intensity which are extinguished with crossed nicols, and vice versa, so that the interference colors observed with parallel nicols are complementary to those seen between crossed nicols.

Let us consider more in detail the latter case, which is practically the only one used in microscopic technic, and assume *for the sake of simplicity, that with a double refracting crystal* of definite thickness the same absolute retardation of the two rays is produced for all colors. The wave length $\lambda$ of extreme violet amounts to about 380 $\mu\mu$, that of extreme red about 775 $\mu\mu$, millionths millimeters or microns. With crossed nicols those colors are emphasized which interfere with a phasal difference of $1/2\ \lambda$ or an odd multiple of $1/2\ \lambda$, while those colors are extinguished which interfere with a retardation of one or several whole wave lengths. The interference color of a crystal can be determined when the thickness and double refraction are known, because the retardation is dependent upon both of these factors. If the thickness of the preparation is known, the double refraction can be determined from the interference color, or inversely if the double refraction is known, the thickness can be estimated.


+ Nicols
‖ Nicols
black 0
white
steel-gray 50
white
D⅛λ
lavender-gray 100
yellowish-white
grayish-blue 150
D¼λ
brownish-white
greenish-white 200
H½λ
brownish-yellow
G½λ
white 250
F½λ
light-red
E½λ
carmine
reddish-brown
light-yellow 300
D½λ
deep violet
C½λ
indigo
bright-yellow 350
B½λ
blue
Hλ
A½λ
orange-yellow 430
Gλ
grayish-blue
orange 450
Fλ
reddish-orange 500
bluish-green
red 530
Eλ
pale-green
deep-red 550
purple 565
light-green
violet I 575
greenish-yellow
indigo 589
Dλ
H³⁄₂λ
golden-yellow
G³⁄₂λ
sky-blue 664
Cλ
orange
Bλ
greenish-blue 728
brownish-orange
F³⁄₂λ
green 747
light-carmine
Aλ
H2λ
E³⁄₂λ
green 800
purple
yellowish-green 850
violet
G2λ
D³⁄₂λ
yellow 910
indigo
orange 948
dark-blue
F2λ
C³⁄₂λ
H⁵⁄₂λ
orange-red 1000
greenish-blue
B³⁄₂λ
red 1060
E2λ
green
A³⁄₂λ
G⁵⁄₂λ
violet-red 1100
green
violet II 1128
yellowish-green
indigo 1151
F⁵⁄₂λ
yellow
D2λ
H3λ

If it is assumed that the retardation of the two rays in a crystal illuminated by polarized light amounts to only 50 $\mu\mu$, Fig. 96, a small phasal difference will be experienced by all colors upon emerging from the crystal, and small but equal amounts of light for each color will pass through the analyzer, and the impression of a gray color is made between crossed nicols, +*nicols*. If the retardation is a little greater, violet will be more prominent, giving a lavender gray tint. The other colors follow in order, grayish-blue, grayish-white, white and yellow, until when the retardation is about 300 $\mu\mu$, or about half the wave length of very intense yellow, that color is especially bright, while at the same time extreme violet, $\lambda = 380$, is almost entirely extinguished. The general impression is that of a brilliant yellow color. If these interference colors are observed with a spectroscope, the yellow part of the spectrum will appear brilliantly illuminated, but diminishes toward both sides until where violet is reached no light is visible.

If the retardation is about twice as great, or about 575 $\mu\mu$, it equals the wave length of yellow, lying near the Na line. This color will be destroyed, while a brilliant violet interferes with nearly $1\frac{1}{2}$ $\lambda$ phasal difference, and appears with double intensity, while at the other side of the spectrum some is visible. The resulting interference color is a reddish-violet, violet I, Fig. 96. When studied spectroscopically the violet part of the spectrum is seen to be strongly illuminated and a dark line appears in the yellow. Violet is the least luminous color in the spectrum and is therefore greatly influenced by extremely small changes in the retardation as shown in Fig. 96. It is called the *sensitive red* or violet.

In the same manner the changes which white light undergoes with different retardations can be calculated, and it is found that blue follows violet, green follows blue, etc., until finally violet is reached again, and the same order of colors repeated. A series of colors from one violet to another is called an *order* and distinction is made between first, second, third orders, etc.

Let us consider more carefully a color of the third order, one which results by a retardation of 1500 $\mu\mu$. This is twice the wave length of brilliant red, three times that of a blue-green, and four times that of extreme violet. These colors will all be extinguished, while yellow and blue will be intensified. The total result is a yellowish tint, because of the greater intensity of the yellow part of the spectrum. This color, however, appears somewhat mixed when compared with the one above, and does not give the impression of a pure yellow. If the retardation amounts to about 5000 $\mu\mu$, it corresponds to 7 $\lambda$ for intense red, 8 $\lambda$ for orange, 9 $\lambda$ for yellowish-green, 10 $\lambda$ for green, 11 $\lambda$ for blue, 12 $\lambda$ for bluish-violet, and 13 $\lambda$ for violet. These colors will all be extinguished, while the intermediate red, yellow, green, blue, and violet colors are intensified; when these colors are united they form white. This interference color is called white of the higher order in contradistinction to the white of the first order produced by very slight retardations. It may be very difficult for beginners to distinguish between these two white interference colors. The white of the higher order produced by manifold interference frequently has a delicate appearance similar to mother of pearl, while white of the first order is generally mixed with gray, green, or yellow.

The differentiation of the various orders of interference colors is quite difficult for a beginner. In a normal case the colors of the first order with their deep hard tones can be separated from those of the second order, which are unusually brilliant, luminous colors. In the third order the colors become duller and more mixed, and farther up the brilliancy is rapidly lost, until in the fifth and sixth orders white of the higher order is reached. It may be held as a rule for the estimation of interference colors under all conditions that the colors appear harder and purer the lower they are. This difference will appear quite distinctly even to an inexperienced eye by comparing the red of the first and second orders.

The two nicols are generally crossed for observing the interference colors and only in comparatively rare cases is observation between parallel nicols advisable. Such a case would be that of a very low double refracting crystal, which is not very bright between crossed nicols, and the presence of double refraction cannot be positively determined. Fairly distinct colors may be observed then between parallel nicols, see Fig. 96.

**Modification of the Interference Colors.**—In deriving the interference colors above, it was assumed that the retardation of one ray over another was the same for all colors, but this is by no means the case. Just as the index of refraction is different for different colors, so the difference between the indices, which produces the interference color in polarized light, varies.

This can be deduced from the table of the indices of calcite for various lines of the spectrum.

| | $\omega=\gamma$ | $\varepsilon=\alpha$ | $\gamma-\alpha$ |
|---|---|---|---|
| A | 1.650 | 1.483 | 0.167 |
| B | 1.653 | 1.484 | 0.169 |
| D | 1.658 | 1.486 | 0.172 |
| F | 1.668 | 1.491 | 0.177 |
| H | 1.683 | 1.498 | 0.185 |

The interference colors for various substances are not entirely the same, although the mean retardation may be identical, because of the differences in indices of refraction for the various colors. These differences are generally not very large but in spite of that, the difficulty of observing the interference colors is considerably increased by the dispersion of the double refraction even in ordinary cases. If that is the case, as in the example already cited, calcite, and likewise in quartz and most of the other rock-forming minerals, the double refraction for red is less than that for violet and there appears according to Becke a brilliant *supernormal* interference color of the first order. With greater dispersion it may attain the luminous properties of the second order. If $\gamma-\alpha$ is greater for red than for violet, which is more rarely the case, the interference colors are duller, *subnormal*. Naturally this behavior often causes great inconvenience in the methods of compensation to be described later. The various colors cannot be entirely compensated because they have varying double refraction in various parts of the spectrum.

It is possible that in the dispersion, the double refraction for some color may be zero, so that, for one end of the spectrum the double refraction will be positive and for the other end negative, while for some intermediate color it will be zero. The latter color will be extinguished and instead of a normal gray or grayish-blue color of the lowest order, a deep color appears that is complementary to the extinguished color. Such interference colors are called *abnormal* in the narrower sense.

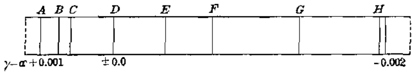


FIG. 97.—Double Refraction of Fuggerite for Different Parts of the Spectrum.

This is the case in the mineral fuggerite with low double refraction, Fig. 97. It is weakly positive for one end of the spectrum and weakly negative for the other, but between the two, near the Na line, the double refraction is 0. That color is always extinguished in polarized light by a plate of any thickness, while the light emerging from the preparation combines to form not a gray of the first order characteristic of low double refraction, but a color complementary to the yellow, that is, a deep blue which becomes more luminous the thicker the slide.

The blue color can be seen only after prolonged observation in very thin slides, but in thicker slides it may appear as a very brilliant Prussian blue. An experienced eye can recognize at once the difference in shade between it and a normal interference color. A beginner can easily recognize the abnormal property of the color by making use of the $\frac{1}{4}\lambda$ mica plate as a compensator. Anomalous interference colors are never entirely compensated by the plate, but are changed to a dirty brownish-gray when the vibration directions of the mineral are crossed with respect to those of the compensator. Under similar conditions indigo or blue of the second order, which may appear similar to the abnormal color, are reduced to a brilliant orange by a reduction of 150 $\mu\mu$, Fig. 91, so that the anomalous property of the other color can be seen most distinctly. The same is true if the equivalent directions are parallel in the two objects. The anomalous blue changes to a dirty white, while the normal passes over into a brilliant greenish-blue. Various complementary colors may occur as abnormal interference colors according to the location in the spectrum of the zero point of double refraction.

Another series of abnormal interference colors depends upon the dispersion of the vibration directions in monoclinic and triclinic crystals. In cross sections of these minerals the vibration directions for different colors differ from each other. In consequence of this all colors are not extinguished at the same time upon rotating between crossed nicols. Instead of complete extinction there is a change of colors from yellow to violet. The properties of the interference colors are materially influenced by this dispersion when the vibration directions are at 45° to those of the nicols. In sections nearly perpendicular to an optic axis extremely abnormal colors may occur. Such interference colors are called *dispersion colors*. It must also be remembered that the interference colors are greatly modified by the color of the mineral itself and by considerable differences of absorption in different directions.

The larger the angle of aperture of the illuminating and observing systems of the microscope the less pure will the interference colors appear. This is partly because light passing through the lenses in a very oblique direction is partially repolarized, and partly because light travels through the crystal in very diverging directions and therefore suffers different retardations. The polarization colors are mixed with each other and this naturally makes exact determinations very difficult. When wide-angled systems are used, the illuminating cone of light should be narrowed down for observations in parallel polarized light as far as the source of light will permit.

**Measurement of Double Refraction by Means of Interference Colors.**—An interference color depends upon the difference of retardation of one ray over another. In one and the same substance it bears direct relation to the thickness of the plate. Therefore, the color can be used to determine the double refraction or the thickness of a slide. The appended table shows the thickness in millimeters which plates of various crystals, cut parallel to the optic axis or to the axial plane, must have in order to give a brilliant reddish-violet of the first order, the retardation being 0.000575 mm.

| | $\gamma-\alpha$ | Thickness in mm |
|---|---|---|
| Mercurous chloride | 0.640 | 0.00086 |
| Triphenyl benzol | 0.348 | 0.0016 |
| Rutile and sulphur | 0.287 | 0.0019 |
| Calcite | 0.172 | 0.0032 |
| Olivine | 0.036 | 0.015 |
| Quartz | 0.009 | 0.06 |
| Apatite | 0.004 | 0.14 |
| Apophyllite | 0.001 | 0.55 |

A few of the more important rock-forming minerals show the following maximum interference colors in a normal section about 0.03 mm. thick:

*a.* Gray to grayish-white; pennine, vesuvianite, apatite, zoisite, nepheline.

*b.* White to yellowish-white; feldspar, quartz, serpentine, topaz, cordierite, enstatite, andalusite, clinochlore, gypsum.

*c.* Yellow to orange; hypersthene, wollastonite, cyanite.

*d.* Red I to indigo; tourmaline, sillimanite, glaucophane.

*e.* Blue to green; augite, hornblende.

*f.* Yellow to orange; chondrodite, olivine.

*g.* Red II to blue; mica, ægirine, etc.

If the section is 0.04 mm. thick most of the minerals under *b* above will be yellow to orange and the interference colors of the others will be raised accordingly, mica, for example, assuming a dull color of the fourth order. If on the other hand the thickness of the slide is only 0.02 mm. all the minerals under *b* will have a dull gray interference color of the lowest order, and the color for mica will scarcely be as high as the middle of the second order. In either case the interference color is of no use in determining the mineral.

Various methods can be used to determine the double refraction of a crystal by means of the interference colors observed between crossed nicols. These methods may depend in part upon a comparison of the interference color of an unknown, with that of a known crystal, and in part upon the compensation of the double refraction by the use of the compensators to be described later. Each of the latter shows a series of interference colors so placed that they can be compared directly. It is necessary to know accurately the thickness of the slide and the orientation of the cross section for all methods of measuring the double refraction by means of the interference colors.

Approximate determinations are the simplest and give results most rapidly. For this purpose the interference color of the object is compared with a table of interference colors such as the one devised by Michel-Lévy and Lacroix. After a little practice very good results may be obtained with it.

Somewhat more accurate determinations can be made with the quartz wedge comparator, likewise constructed by Michel-Lévy. A cross section of it is shown in Fig. 98. It is attached to the side of an ocular O. The light L is reflected into it by the mirror S, and after total reflection by the prism C, passes through the quartz wedge G between two nicols A and P. The quartz wedge can be moved by means of a screw. The light finally passes into a prism R, the reflecting face of which is silvered, and is totally reflected into the field of vision of the ocular. There is a small, round, unsilvered spot in the center of the latter prism and upon this, the small prism R′ is cemented. Through this opening the interference color of the crystal M lying under the objective is observed while the rest of the field, which receives its light from the totally reflecting prisms, shows the interference color of that portion of the quartz wedge which is in the path of the rays. A circular area is observed in the field of the ocular, which shows the interference color of the mineral lying upon the stage and this is surrounded by a ring of the interference color from the quartz wedge. The latter can be made to agree with the color of the inner area by moving the wedge. *The thickness of the quartz wedge at this particular point can be* observed on a scale and the order of the interference color determined directly.

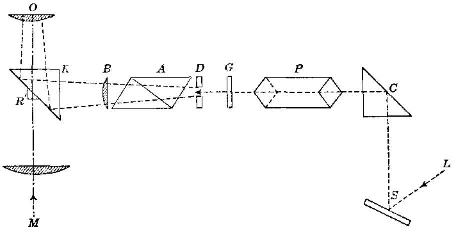


FIG. 98.—Quartz Wedge Comparator devised by Michel-Levy.

This apparatus is very interesting, but is only applicable in exceptional cases. The modifications which the interference colors undergo, (1) by the varying double refraction for different colors, (2) by the different indices of refraction of the crystal, and (3) by its transparency are sufficient to make an absolute comparison of the interference colors very difficult. In addition there are a number of obstacles in the determination of the interference colors of which the difference in the illumination of the objects to be compared may be mentioned, so that this method can be used advantageously with colorless minerals only. The thickness of the slide can be measured as it is being ground, by placing small basal cleavage pieces of barite on each of the four corners of the slide and grinding them down with it. The interference color of the barite can be used to indicate the thickness, provided the surface is not clouded as is very often the case.

This determination of thickness is very accurate when the interference colors are gray or grayish-blue of the lowest order. It has been proposed in such cases to place a horizontal mirror directly under the preparation. The light would then be returned through the analyzer by means of a mirror in the tube above it and through the slide to the mirror below, from which it would be reflected a second time through the slide and analyzer, before it reaches the eye, and the impression would be that a plate of double the thickness was being observed between parallel nicols. Even in such cases more reliable results are obtained by means of compensators. It is to be noted that most of the minerals show low gray colors in sections with an approximate thickness of 0.02 mm. and even more so with a thickness of 0.01 mm. It is advisable for ordinary investigations not to have the slide ground too thin.

The determination of the double refraction in thin sections by interference colors is not very accurate, because of the fact that the section is accurately orientated only in exceptional cases. To determine the difference in velocity of the two rays in an optically uniaxial mineral, it is necessary to use a section cut absolutely parallel to the optic axis because the true value for the extraordinary ray can be obtained only in such sections, and in like manner the true value of $\gamma - \alpha$ in biaxial substances is seen only in a section parallel to the plane of the optic axes. In every case in which an accurate determination is to be made, the orientation of the cross section must be accurately established.

**Interference Colors in Variously Orientated Cross Sections.**—Sections parallel to the optic axis show the highest interference colors produced by a uniaxial mineral. The colors become lower the greater the inclination of the section to the optic axis, until with an inclination of 90° there is no effect on parallel polarized light whatever. Sections of optically uniaxial minerals cut perpendicular to the optic axis behave in perfectly, parallel polarized light as isotropic substances. However, more or less convergent rays pass through microscopic preparations, and if the double refraction is high, or the thickness of the slide considerable, these rays passing obliquely through the sections produce considerable illumination of the image, because they do not traverse the crystal in the direction of its isotropic axis. Hence, sections of uniaxial minerals perpendicular to the optic axis are weakly illuminated and remain so upon the rotation through 360°. This corresponds entirely to the phenomenon, which biaxial crystals cut perpendicular to an optic axis show, except, as will be pointed out directly, the cause of the illumination in the latter case is for the most part different.

Sections of biaxial crystals parallel to the plane of the optic axes show the highest interference colors of all, because here the maximum and minimum velocities enter into consideration. In a section perpendicular to the acute bisectrix, the interference colors are lower the smaller the angle between the optic axes. In any case the interference color of such a section is lower than that of a section perpendicular to the obtuse bisectrix, the interference colors of which more nearly approach those of a section parallel to the axial plane the larger the obtuse optic angle. In a section perpendicular to an optic axis, a ray of light is resolved into an infinite number of rays lying upon the surface of a cone each polarized in a different direction. This phenomenon is called *interior conical refraction* and the result is no interference color, but equal illumination. Such sections of biaxial crystals appear light between crossed nicols and remain uniformly light upon a complete rotation of the slide through 360°. This phenomenon is less distinct the thinner the slide and the lower the double refraction of the crystal. It can scarcely be recognized at all in thin sections of very feebly double refracting crystals, which appear uniformly dark in parallel polarized light.

**Chromoscope for Interference Colors.**—The accurate determination of the interference colors is one of the most important processes in the technic of a polarizing microscope. Even the beginner must be able to do it in as positive a manner as possible. The differentiation of the various orders of color is quite difficult, particularly in the first three orders, which occur most frequently and this difficulty can be overcome only by careful practice and the repeated observation of interference colors, which can be easily determined. Various methods have been used to present the subject of interference colors in as objective a manner as possible. At first a color table was prepared, which corresponded more or less with the natural colors and showed an arrangement of the important series of colors from the first to the fourth orders. Even in the most favorable cases a poor idea of the actual conditions could be obtained from it, because subjective and technical factors played a great rôle in the preparation of the colors, which made an approximation to the true properties of the original very difficult. The ink used generally constitutes another bad factor, for aniline dyes are always used for this purpose, but they fade in a comparatively short time, and thus make the general impression even more inaccurate. The excellent reproductions of interference colors in the table of birefringences by Michel-Lévy and Lacroix lose their true value for instructional purposes in a comparatively short time.

The interference colors are a simple function of the thickness of a crystal, the double refraction being constant. Therefore, a thin wedge of a homogeneous crystalline substance, observed in white parallel polarized light, shows the colors in parallel bands beside each other analogous to a table of colors. Such a wedge usually made of quartz generally accompanies a polarizing microscope as a compensator. With a length of 4–5 cm., it shows the first four orders of colors which are the principal ones to be distinguished. Above these the interference colors so nearly approach white of the higher order that they can scarcely be distinguished even by a skilled observer. If such a wedge is pushed slowly across the field in such a position that its vibration directions are at 45° to those of the nicols, the various orders of color can be observed in succession. Only a small portion of the series can be seen at one time because of the narrowness of the field of vision of the microscope, and hence, analogous colors of the various orders cannot be observed simultaneously so as to be compared with each other, the differentiation of which is of great importance. Smaller wedges of this character could be made, which, when observed with a low power objective would show the first four orders of color in the field at once. Instead of such a wedge, a wedge-shaped crystal of ammonium metavanadinate, which is quit easily prepared, could be used to bring the interference colors beside each other in distinct bands in the field of vision. Careful study of a single color is interfered with by the narrowness of the bands in the field, and also by the fact that analogous colors of the various orders are separated by bands of different colors.

An apparatus devised by Weinschenk, called a *chromoscope for interference colors,* has been found to be very useful in these fundamental studies. It consists of a glass plate *a*, Fig. 99, as a polarizer and an arm *b* attached at the angle of polarization of the glass and carrying a nicol prism *d* that can be rotated and used as an analyzer. The arm also bears a lens *e* with a two fold magnification and so arranged that it can be thrown out of the line of vision. The holder *c* is so placed that its front surface corresponds to the normal to the direction of polarization. A quartz wedge 8 cm. long and 3 cm. wide is placed in the holder with its vibration directions at 45° to the edges of the holder. Then a mica plate of the same size is placed under it with its equivalent directions crossed so that with it, demonstrations can be made with the lowest interference colors. With this arrangement, the first four orders of colors from low gray to red of the fourth order are obtained in regular, broad, parallel bands. By inserting the lens the magnification is doubled, but two orders of colors can still be seen simultaneously. Two plane parallel gypsum plates, each 8 cm. long but only 1 cm. wide, with vibration directions at 45° to the edges, accompany the apparatus. These plates alone yield red of the first and second orders. The two gypsum plates are then placed beside each other on the quartz wedge so that their equivalent directions are parallel, the lower plate show-

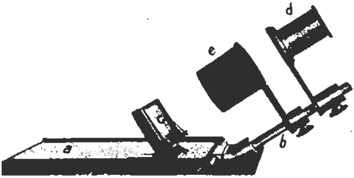


FIG. 99—Chromoscope for Interference Colors.

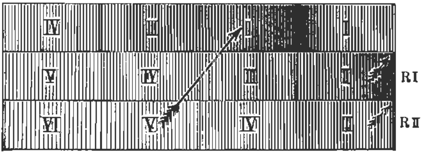


FIG. 100.—Quartz Wedge in Chromoscope with Parallel Orientated Gypsum Plates Red I and Red II.

ing red of the second order, the upper red of the first order, as shown in Fig. 100. From the top downward, bands of red of the first, second and third orders, each 1 cm. wide, are in contact with each other and can be compared directly. Thus the phenomenon of the addition of double refraction can be studied. Fig. 101 shows the gypsum plates rotated through 180° from which the compensation of the double refraction can be derived. The numerals in Figs. 100 and 101 indicate the order of the colors in their respective positions. The longest arrow shows the direction of the fastest ray in the quartz wedge, the smaller ones being used for the gypsum plates.

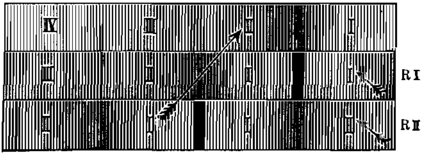


FIG. 101.—Quartz Wedge in Chromoscope with Oppositely Orientated Gypsum Plates Red I and Red II.

Interference colors that occur in wedge-shaped layers within a slide not infrequently serve to determine the order of the color in microscopic study of thin sections and isolated crystals. They often aid materially in defining the crystal form. Wedge-shaped individuals may be formed in thin section (1) by the flaking off of a mineral with good cleavage, (2) by the edge of the individual being quite oblique to the surface of the slide, and (3) by the edge of the slide itself being somewhat thinner, which is generally the case. The interference color in the principal part of the section can be determined by beginning in the thinnest place where the color is lowest and counting the bands in order, i.e., noting how often red is repeated. In the case of oblique twinning lamellæ of very strong double refracting minerals, such color bands produced by wedge-shaped sections often lead to the erroneous conclusion that there is a whole series of such lamellæ, when in fact there is but a single one cut across very obliquely. An example of this phenomenon is shown in Fig. 102, which represents an augite crystal cut very obliquely through a simple twin.

Interference colors on the wedge-shaped outer portions of isolated crystals are frequently of importance in determining the crystal form, as for example, the bands around the edge of an artificial crystal of anglesite, Fig. 103, from which the form can be easily observed. They also aid in the approximate determination of the double refraction. If these bands are very close to the edges of a crystal that are quite flat, it is evident that the substance has high double refraction, etc.

Crystals are found now and then which do not extinguish at all when rotated between crossed nicols, but show a change in interference colors. In a very few cases this may depend upon a strong dispersion of the vibration directions or upon the fact that the crystal is twinned and the twinning plane is approximately parallel to the plane of the stage of the microscope in which case the vibration directions of the two individuals will be oblique to each other. When the vibration directions of one individual are parallel to those of the nicols, the interference color of the other is seen and vice versa, while in intermediate positions transition colors are present. These two cases may be distinguished by observation in monochromatic light when there will be complete extinction if the cause of the change of color is based upon dispersion of the vibration directions, but there will be no extinction in the case of overlapping twins.

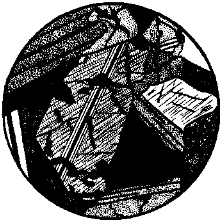


FIG. 102.—Simple Twinning Lamellæ in Augite.

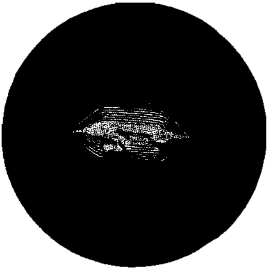
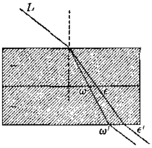


FIG. 103.—Artificial Crystal of Lead Sulphate between Crossed Nicols.

**Character of the Double Refraction.**—The interference color is dependent upon the retardation of one ray over the other in its passage through a double refracting crystal. In a plate cut parallel to the optic axis of a negative uniaxial mineral the extraordinary ray, vibrating parallel to the optic axis, exceeds by a definite amount the ordinary, vibrating perpendicular to it and is refracted less. If a second crystal plate is laid upon the first in parallel position, that ray, which in the first traveled with the greater velocity and less refraction, will likewise be the faster and less refracted ray in the second, while the other is propagated in each case with a smaller velocity and greater refraction, Fig. 104. The phasal difference between the rays upon emerging from the second crystal will be equal to the sum of the retardations in each. The double refraction and with it the interference color of two crystals are added together when equivalent vibration directions lie parallel. If one of the crystals is rotated 90° or if, as represented in Fig. 105, an equivalent plate of a positive crystal is used instead of a second negative one, that ray which travels in the first with the greater velocity and smaller refraction will be propagated in the second with a smaller velocity and greater refraction, while the reverse holds for the other ray. The phasal difference, which the two rays show upon emergence from this combination, will be equal to the difference of the retardations in each. The double refraction and with it the interference color of two crystals is compensated when equivalent vibration directions are crossed.



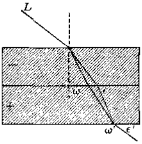


FIG. 104.—Addition FIG. 105.—Compensation of the Double Refraction.

If the retardation in one plate is equal to the retardation in the other a combination of them in crossed position will act as an isotropic body in parallel polarized light, i.e., the double refraction of one entirely nullifies the double refraction of the other, as respresented in Fig. 105.

**Compensators.**—The use of compensators depends upon the phenomena described above. They serve to determine the character of the double refraction by raising or lowering the interference color and sometimes an accurate determination of the interference color can be made by perfect compensation. The most important compensators are:

1. Quarter undulation mica plate.
2. Plates with reddish-violet I, II, etc.
3. Fedorow mica wedge.
4. Quartz wedge.
5. Birefractometer.
6. Babinet compensator.

7. Twin compensator.
8. Biot rotating quartz.
9. Wright wedge.

Of these accessories 1 and 2 accompany the simplest polarizing microscopes, while the others are used more for special investigations. Numbers 5–7 are generally placed in a special ocular from which they can be removed by a screw. When they are used, the nicol in the tube must be thrown out, which is then replaced by an analyzer placed over the ocular. The others are inserted in a slot in the tube just above the objective or in a slot above the ocular in the older models where the analyzer was placed on top. The slots are sometimes arranged so that the long edge of the plate lies at 45° to the vibration directions of the nicols and sometimes so that they are parallel. In all cases, however, the vibration directions of the compensators must form an angle of 45° with those of the nicols, hence they are constructed differently according to the different modifications of the instruments. In the first case the vibration directions are parallel to the edges of the rectangle and the direction of greatest or of least elasticity may be parallel to the long edge. Formerly the quarter undulation plates were nearly always made with the direction of the smallest velocity corresponding to the long edge, and the other plates with reversed orientation, Fig. 106. At the present time the quarter undulation plate is also orientated in this way, in order to obviate the great confusion which arises from the use of the other plates. It is still better to construct them all as shown in Fig. 107, where the vibration directions form an angle of 45° with the edges of the plate. The direction of greatest velocity a is marked on it with a diamond point. It has the added advantage in that it is only necessary to invert the plate to bring about an exchange of the principle vibration directions while the crystal remains stationary.

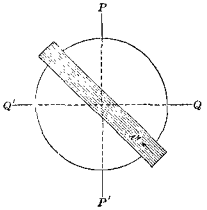


FIG. 106.—Parallel.

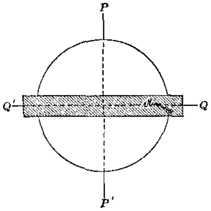


FIG. 107.—Diagonal.

Compensator with Vibration Direction.

Very frequently complete compensation cannot be obtained on account of the dispersion of the double refraction in different substances, which may be very troublesome for accurate determinations of the double refraction. In crystals with distinct super- or sub-normal interference colors, measurements cannot be made very exactly. Although compensators can be made from any colorless, double refracting material, gypsum, mica and quartz are used in general for this purpose.

1. A quarter undulation mica plate is a thin cleavage piece of colorless mica which causes a retardation of both rays of about 1/4 wave length for sodium light, i.e., about 150 $\mu\mu$. Observed between crossed nicols it appears grayish-blue of the first order, and between parallel nicols brownish-white. In many instances plates which cause a retardation of only 1/8 $\lambda$ are of good service. The quarter undulation mica plate is used to orientate the other compensators. It shows a biaxial interference figure in convergent light. Since it is optically negative the direction of the axial plane corresponds to the direction of least elasticity.

2. The compensators with reddish-violet I, II, etc., have already been described under the head of stauroscopes. Their additional use as compensators justifies repetition at this time.

FIG. 108.—Mica Wedge.

Violet I is generally used to determine the character of the double refraction, while violet II and plates with higher interference colors are used with very strong double refracting substances. They are generally prepared from gypsum or quartz.

3. The Fedorow mica wedge, Fig. 108, consists of a pile of 16 plates of mica of equal thickness. Each plate produces a retardation of 1/4 $\lambda$ and is shorter by a definite amount than the one next under it. With this apparatus the first four orders of color appear in 16 divisions and each division can be made so wide that the field of vision of the microscope shows a single homogeneous interference color at any given time.

4. The quartz wedge is a small plate of quartz cut in the shape of a wedge and the retardation at various places is shown by a scale. It is inserted in the slot above the objective until complete darkness or, still better, the sensitive violet I is obtained by means of compensation. The thickness of the quartz is read

off at this point, from which the double refraction of the crystal can be calculated.

5. The birefractometer consists of an ocular within which a quartz wedge can be moved by means of a rack and pinion. A micrometer scale is etched upon the glass strip that covers the wedge. From it the thickness of that portion of the wedge in use can be read directly. It is still better to have the quartz wedge so made that only one half of the field of vision is colored, while the scale is placed upon the other half. With this arrangement the apparatus can be used not only as a compensator but also as a comparator in which case the crystal is placed in the vacant half of the field and its interference color is compared with the color of the movable quartz wedge.

6. The Babinet compensator consists of two thin quartz wedges with equal refracting angles, lying one on the other, Fig. 109. In one wedge the optic axis is parallel, in the other perpendicular, to the sharp edge. The upper wedge is not movable but the lower one can be moved by a rack and pinion, and the amount of the movement can be read on a drum. In the zero position there is a dark band in the center of the field marked by an oblique cross hair, *Andreas cross hair*, because both wedges are of equal thickness at that place and since their equivalent directions are crossed their double refraction is entirely compensated. On either side there is a symmetrical series of bands with an increasing order of interference colors. When a double refracting plate is inserted the dark band is removed from the middle of the field. The movable wedge is then moved in by means of the screw until the band lies again exactly in the middle and the amount of displacement is read on the drum. If the crystal is rotated 90° the black band is removed toward the opposite side. It is again placed on the cross hair and the mean of the two readings is indicative of the double refraction of the crystal. An approximate adjustment of the central band should be made in white light, because in monochromatic light dark bands occur in place of the colored ones, but the fine adjustment should be consummated in sodium light. The double refraction of the plate in question can be calculated form the formula $\gamma - \alpha = \frac{2\,r\,tg\,\psi m}{d}$

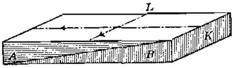


Fig. 109.—Babinet Compensator.

in which $r$ is the amount of displacement for one rotation of the screw, $\psi$ is the angle of the wedge of the comparator, $m$ is the number of rotations of the screw, and $d$ is the thickness of the plate under investigation.

7. The twinning compensator can be described most easily by calling it a Babinet compensator which is cut through the center parallel to the direction of the long arrow in Fig. 109. One half is rotated on the fresh cut through 180° with respect to the other, and each portion is left movable in opposite directions. In the normal position there is a dark band across the entire field of vision corresponding to the complete compensation of the double refraction in the two oppositely orientated portions of the wedge. If a double refracting crystal is placed in the path of the rays the band recedes just as far toward the right in one half of the field as it does toward the left in the other half, and the amount of displacement necessary to unite both parts of the band again indicates very accurately the double refraction. Bravais constructed another type of twinning compensator, Fig. 110. The two parts, rotated through 180° to each other, were not placed side by side but one over the other. Then the whole field of vision is dark in the normal position because the double refraction of the oppositely orientated portions of the wedge is compensated completely. When a double refracting substance is placed in the path of the light, darkness is restored by moving one of the wedges. The displacement of the wedge is indicative of the double refraction but it is by no means as accurate as in the previous case.

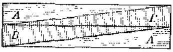


FIG. 110.—Bravais Twin Compensator.

8. The Biot rotating quartz is also a very useful device for determining the character of the double refraction. A plate of quartz perpendicular to the axis is ground so thin that circular polarization is no longer apparent. This is set in a holder so that it can be inserted in a slot above the objective and rotated on a horizontal axis. In the normal position it produces no change but as soon as it is rotated, the vibration direction of the ordinary ray being the axis of rotation, it becomes double refracting. Any amount of compensation can be obtained by more or less rotation.

9. The simple wedges cannot always be used advantageously because the lowest interference colors cannot be perceived on

account of the thinness of the wedge. Wright therefore fastens a gypsum or quartz wedge on an oppositely orientated plane parallel plate of gypsum which gives violet I. By the subtraction of one order of colors the lowest colors of the first order, beginning at the zero point, are obtained instead of those bordering violet I.

**Use of Compensators.**—To use any of these compensators the crystal under investigation is centered and its vibration directions placed at 45° to those of the nicols. Except when using a Babinet or a twinning compensator, the uses of which were described above, the interference color of the object is first observed and then the compensator inserted and the direction of change in the interference color noted, i.e., whether the interference color of the combination corresponds to the sum or the difference of the retardations in the crystal and in the compensator. If, for example, an optically uniaxial negative crystal with a prismatic development is orientated on the stage of the microscope so that its long direction coincides with the direction of greatest velocity in the compensator, the interference color increases. It appears as if the crystal had become thicker. If the conditions are reversed, the interference color is lowered as if the layer were now thinner. Those crystals, which show very low interference colors, are apparently an exception to this rule. For example, a crystal that shows gray-blue of the first order, when compensated by violet I in crossed position, shows a brilliant orange-yellow interference color, which nevertheless indicates subtraction because that is lower than violet I. This can be best shown by rotating the crystal 90°. Then a higher blue of the second order appears. In general it is not known from simple observations in parallel polarized light that the crystal observed is uniaxial and prismatically developed. That the direction of greatest velocity is parallel to its long edge, its principal zone, is all that can be determined. The determination of the relative velocities of the two rays vibrating in a cross section is designated as *determination of the optical character of the principal zone.* That direction in which a crystal or crystal section is elongated is taken as the principal zone. The principal zone is negative when the direction of greatest elasticity, and positive when the direction of least elasticity is parallel to the long edge.

The determination of the optical character of the principal zone is very useful in the determination of crystals. Its value can be best appreciated for the study of thin sections by comparing the optical character of the principal zone with the true optical character of the crystal. This indicates the crystallographic habit, the position of the optic plane, and so forth.

The example cited above shows that, in an optically uniaxial crystal in which the principal axis corresponds to the principal zone, the optical character of the latter is the same as the optical character of the crystal. If a uniaxial negative crystal is tabular parallel to the base, a transverse section will show a decided elongation but the principal axis is perpendicular to it, i.e., the direction of smallest velocity is parallel to the principal zone and its character is positive. The following table shows the various possibilities.

| Character of crystal | Uniaxial | Character of principal zone |
|---|---|---|
| + or − | Prismatic habit | + or −. |
| + or − | Tabular habit | − or +. |
| | Biaxial | |
| + or − | Prismatic; $Bx_a \parallel$ principal zone<br>Tabular; $Bx_o \perp$ tabular face | + or −. |
| + or − | Prismatic; $Bx_o \parallel$ principal zone<br>Tabular; $Bx_a \perp$ tabular face | − or +. |
| + or − | Prismatic; optic normal $\perp$ principal zone<br>Tabular; optic normal $\parallel$ tabular face | ±. |

The character of the double refraction of the principal zone varies in different sections of a biaxial substance when the vibration direction in that section of the zone is the optic normal.

The determination of the character of the principal zone is frequently impossible, either because an actual characteristic zone cannot be recognized or because the interference color is white of the higher order. In the former case it is impossible to speak of a principal zone, while in the latter, other methods must be used. Either the wedge-shaped borders of the crystal or slide are used and the ordinary methods of compensation applied to the brilliant bands of color, or compensators corresponding to a higher order of color can be employed, and by subtraction brilliant interference colors of lower orders produced.

## CHAPTER V

# Observations in Convergent Polarized Light

**Direction of the Rays in Convergent Light.**—It is important in many cases to study the optical properties of a crystal or crystal section not only in one direction but in as many different directions as possible. Either convergent polarized light is used for this purpose, by means of which the optical properties of a crystal can be observed in various directions at one time, or a rotating apparatus, described in the appendix, is used and the different directions studied in sequence.

Fig. 111 shows diagrammatically the passage of the rays in convergent light. The lenses L and L′ are so arranged that the upper focus of L coincides with the lower focus of L′ at the point *f*. The crystal K to be investigated is placed between the two lenses. Each of the illuminating cones of light with its apex in the lower focal plane F of the lens L is converted by that lens into a bundle of parallel rays, and these bundles emerge from the lens with all possible inclinations to the axis of the lens within its angle of aperture. These parallel rays pass through the object between the lenses and are reunited in points in the upper focal plane F′ of the lens L′.

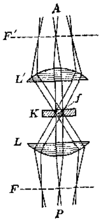


Fig. 111.
Convergent Light.

Every point in the image, thus produced, corresponds to a direction in the crystal. In convergent light the optical phenomena, which an object shows in all the directions in which light is propagated through it, are observed side by side. The different retardations which the light has experienced in the various directions in a crystal cannot be observed without the aid of other devices, because the eye is not properly adjusted and, hence, nothing at all is seen in convergent light until such apparatus is used.

If instead of ordinary light polarized light produced by the polarizer P and the analyzer A is used, interference phenomena become visible at each point of the image when double refracting crystals are studied. This corresponds to a retardation of one ray over the other upon passing through the crystal in that particular direction. The interference figure thus obtained is one of the most important means of determining the optical properties of a crystal.

It must always be kept clearly in mind that in observations in convergent light any given portion of the interference figure does not correspond to a definite *point on the crystal but rather to* some direction in it. The image is not changed, if a homogeneous crystal is moved parallel to itself on the stage. It is, in general, altered immediately if the direction of observation is changed by *rotating the crystal on an axis.*

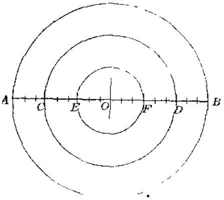


FIG. 112.—Field of Vision in Convergent Light.

The simple lenses L and L′ are now replaced by combinations of plano-convex lenses. The special case here considered is one in which a converging lens is placed over the polarizer and L′ is replaced by any objective.

The circle AB, Fig. 112, represents the field of vision in convergent polarized light. For the sake of simplicity, the angle of aperture may be taken equal to 90°. Rays, which have left the crystal plate with an inclination of 45° to the vertical, emerge around the outer edge of the field. Assuming the index of refraction $\beta$ for the crystal to be 1.60, it follows from the law of sines, $\sin V = \frac{\sin E}{\beta},$ that the rays at the edge of the image have passed through the crystal at an angle of 26 1/2° to the vertical, or the entire field includes a cone of light in the crystal with an angle of 53°. If a smaller circle is taken in the field of vision, for example, one with 2/3 the diameter, CD, it embraces all rays which emerge from the crystal under an inclination of about 28 1/2° to the vertical or pass through the crystal at 17 2/3°, Fig. 113. Then, if a circle with only 1/3 the diameter of the field is taken, EF, it includes those rays which leave the crystal at an angle of 13°, and are propagated through it under an angle of about 9°. Finally, in the center of the image O, Fig. 112, the optical phenomena correspond to those rays which pass through the crystal plate exactly vertically. From the above, it appears that with an objective with a definite angle of aperture the cone of rays passing through a crystal will be greater the smaller the value of $\beta$, the denominator of the equation for the law of sines. Feebly refracting minerals give a much more extensive perspective of their optical properties than those with higher indices of refraction. The value of $\beta$ can be greatly reduced by increasing the aperture by means of an immersion system.

**Methods of Observation in Convergent Polarized Light.**—The simplest method to pass from the observation of the object to that of the interference figure consists in removing the ocular and observing the interference phenomena, RS, Fig. 113, produced by the objective alone. It consists of a small image visible in the upper focal plane of the objective. This is the Lasaulx method. Inversion of the image does not occur in this method of observation. The observed interference figure has the same position as the object, but is inverted with respect to the microscopic image. The rays which have passed through the crystal from left below to right above appear in the image on the right. Images thus produced are generally very small but sharply defined. They can be magnified but a part of the distinctness is lost by the process. A low power microscope can

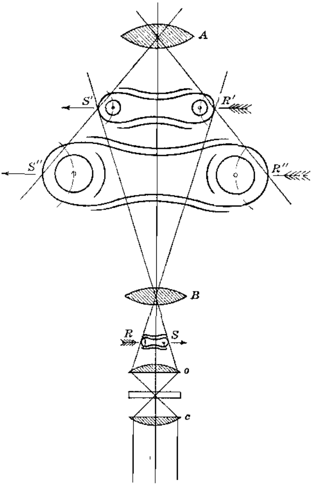


Fig. 113.—A Biaxial Interference Figure.

be obtained by using the ocular A, Fig. 113, and the Bertrand lens B, inserted in the tube as an objective. This can be focused on the small interference figure by elongating the tube and it gives a magnified image R″S″, which is observed in the ocular. *The image thus observed is inverted with respect to the object* and has the same position as the microscopic image of the object.

The proper centering of the Bertrand lens must always be checked first by placing a uniaxial crystal, tabular parallel to the base, in the microscope. If the position of the lens is correct, the dark cross, described below, must coincide with the cross hairs of the ocular. The interference figure can also be magnified by placing a Klein lens above the ocular. This lens can be moved in a vertical direction in its holder. The magnified image in this case is likewise inverted with respect to the object, but its position coincides with the microscopic image of the object. A real image R′S′, *adapted for projection and photography, is obtained by using the Bertrand* lens without the ocular, or by using a projection ocular. This image is likewise inverted with respect to the object.

The interference figure observed appears smaller the higher the power of the objective used. More convergent bundles of rays are obtained from stronger objectives, because in general the aperture of the system increases with the magnification. The interference figure obtained with a high power objective, allows directions at greater inclinations to each other to be studied, provided the aperture of the illuminating apparatus is great enough for that of the objective. For observations in convergent light, the condenser must always be in position and high power objectives[1] used.

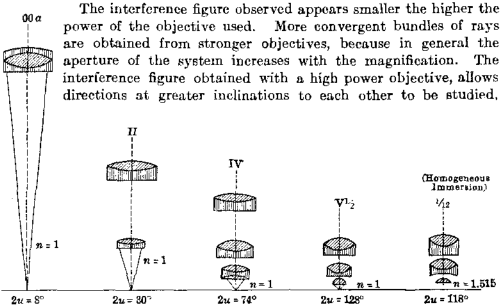


FIG. 114.—Angle of Aperture of the most Important Objectives of W. and H. Seibert.

Cross sections of the various objectives made by W. and H. Seibert are shown in Fig. 114 in which $2u$ is the angle of aperture. Fig. 115 shows the corresponding interference figure of each in an optically biaxial mineral with an apparent optic angle of about 85°.

If the aperture of the illuminating apparatus is not sufficiently large for

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[1] When such objectives are not available convergent light can be produced by a small air bubble in the Canada balsam or by a soap bubble, which takes the place of the lens O The interference figure so produced appears magnified in the microscope.

the objective, only the inner part of the image will be illuminated and the border will appear dark. If one of a large number of minute individuals is to be studied in convergent polarized light, or if a crystal consists of many small twinned individuals, the optical nature of which is to be determined, *an ocular diaphragm should be used. With it only the light passing through* that portion of the object in the center of the field of vision reaches the eye. The simplest method for such observations is to center the desired portion of the object carefully and upon removing the ocular, place a diaphragm with a small perforation in its center over the end of the tube. The object can be centered by using a Ramsden ocular with an iris diaphragm in the lower focal plane. The diaphragm is narrowed until only the portion of the object to be studied is visible in parallel light. Then the ocular is removed while the iris diaphragm remains in the tube. In investigations by the Bertrand method the iris diaphragm is placed in the upper focal plane of the lens which is inserted into the tube.

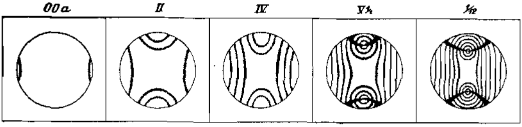


FIG. 115.—Interference Figures Corresponding to the Objectives in Fig. 114.

**Optically Uniaxial Crystals.**—Let us consider more closely the behavior in convergent polarized light of a plate of a uniaxial crystal cut perpendicular to the optic axis. One of the several bundles of parallel rays AA′, Fig. 116, passes through the plate perpendicularly and is parallel to the optic axis. It is at the same time the axis of the cone of light. There is no double refraction in the direction of the optic axis so the center of the interference figure will appear dark. If a second bundle of rays $A'm$, which passes through the crystal slightly inclined to its axis, is considered, the light will be resolved into two rays, one vibrating in the principal section of the crystal and the other perpendicular to it. These rays will emerge from the crystal with a small phasal difference corresponding to the small inclina-

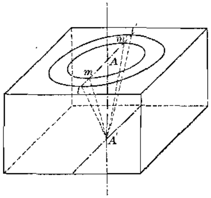


FIG. 116.—Construction of an Uniaxial Interference Figure.

tion to the axis, and weak illumination will appear at that point. Other bundles of rays $A'l$ pass through the crystal more inclined to the axis and have a decidedly greater retardation corresponding to this greater inclination. Thus, there is a continual increase of interference color from the center toward the edge of the image. All rays with equal inclination to the axis have the same retardation so the interference colors appear in concentric rings around the dark middle point in the order shown in Fig. 96. They are most brilliantly illuminated in those sections forming an angle of 45° with the vibration directions of the two nicols. As light is not resolved in those sections coinciding with the vibration directions of the nicols, they remain dark under all conditions. Therefore, the interference figure consists of a dark cross, the arms of which are parallel to the vibration directions of the nicols and cut across the colored concentric rings, Fig. 117.

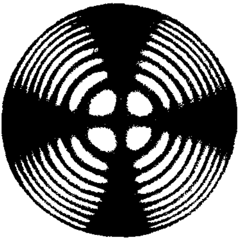


FIG. 117.- Interference Figure of a high Double Refracting Uniaxial Crystal.

All directions perpendicular to the optic axis are equal in uniaxial crystals so there is no change in the image when the stage is rotated through 360°, and all these directions coincide in turn with the vibration directions of the nicols. Interference figures of optically uniaxial crystals cut perpendicular to the optic axis are not changed by a complete horizontal rotation of the section.

The behavior of uniaxial crystals in sections perpendicular to the optic axis between parallel nicols can be understood from the above discussion. Light is not resolved in that principal section of the crystal which corresponds to the vibration direction of one of the nicols and in the direction perpendicular to it. A light cross appears instead of the dark one, described above, cutting across the concentric colored rings, whose colors are complementary to those obtained between crossed nicols.

If the face through which the observation of the interference figure is made is not exactly perpendicular to the optic axis, the rays observed in the center of the field are not those which pass through the crystal parallel to the optic axis. The intersection of the arms of the dark cross is displaced from the center of the field and the colored rings, the center of which is this intersection point, are eccentric with respect to the field of vision. When the slide is rotated, the intersection of the cross arms describes a circle about the center of the field. See the upper series in Fig. 118. The directions of the arms of the cross are dependent only upon the vibrations of the nicols and, since these are not changed, the arms retain their directions but are displaced across the field parallel to the original positions.

If the section is cut so obliquely that $w \sin \mu > u$, in which $w$ is the index of refraction of the ordinary ray in the crystal, $\mu$ is the angle of inclination of the section to the optic axis, and $u$ is the aperture of the ocular, and the apparent direction of the optic axis falls outside of the angle of aperture of the ocular, a comparatively reliable clue can still be obtained that the crystal is uniaxial. As shown in the lower series of Fig. 118, the extreme portions of the black cross pass through the field of vision in a regular manner when the crystal plate is rotated. The difference between interference figures in oblique sections of uniaxial crystals and those of biaxial crystals is emphasized in Fig. 118, in that the black bars which pass across the field are represented exactly parallel to the vibration directions of the two nicols. This is not the case when the axis emerges very obliquely and the aperture of the objective is quite large. Then, as they are shifted, their directions are changed very decidedly just as in a biaxial interference figure. But sections of biaxial crystals with small optic angles, cut not too obliquely, show perfectly parallel shifting of the bars, particularly when objectives with small apertures are used. It may also be noted that the emergence of the optic axis from a cleavage fragment of calcite, where $w \sin \mu = 1.165$, can only be seen by means of an immersion system.

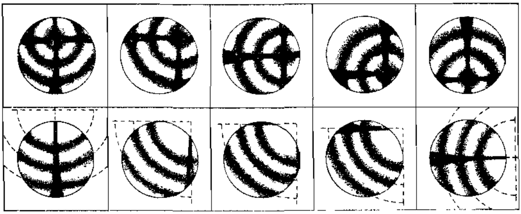


FIG. 118.—Interference Figures of Uniaxial Crystals Cut Oblique to the Axis.

The behavior of a plate of a uniaxial crystal cut parallel to the optic axis in a rock section cannot be distinguished in ordinary light from that of a biaxial crystal cut perpendicular to its obtuse bisectrix. This will be treated more fully farther on. It is impossible to distinguish, by simple means, a section of a uniaxial crystal parallel to the optic axis from a biaxial. The greater the inclination of the plate to the optic axis the more positive the determination. However, the direction of the optic axis or that of the acute bisectrix can be determined in the interference figure in a biaxial crystal with not too large an optic angle. Let us assume that the cross section given in Fig. 119 is parallel to the optic axis *cc* of a crystal, which is observed in convergent light at 45° to the vibration directions of the nicols and the characteristic distribution of the interference colors is seen. The observed phenomena can be best shown in a plate cut from the section parallel to its long direction, Fig. 120, and one perpendicular to it, Fig. 121. The simplest explanation can be given with the assumption that the angle of aperture of the objective is 180°, which cannot actually be obtained in practice but can be approached approximately. If the behavior of the rays in the section *cc* perpendicular to Fig. 119, as shown in Fig. 120, is studied, it will be seen that the rays whose image appears in the center of the field of vision have passed through the crystal perpendicular to its optic axis. They interfere with the full value of the double refraction of the crystal $\gamma$-$\alpha$. The rays, however, which appear on the extreme edge of the field, have passed through the crystal in the direction *cc*, i.e., the direction of the optic axis, and have suffered no double refraction whatever. In those quadrants through which the optic axis passes the interference color is lowered toward the edge of the field but it is not reduced to zero as it would be in the theoretical case under consideration. Red I, in the middle of the field, changes into a distinct yellow as shown in Fig. 122. In the section given in Fig. 121 the rays in the middle of the image are likewise propagated perpendicular to the optic axis and interfere with the greatest double refraction. The rays in the outer portion of the image have the same direction of propagation and hence the same double refraction. The distance traversed by the rays increases with their obliquity, causing an increase in the retardation and consequently a raising of the interference colors, red

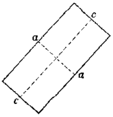


FIG. 119.—Section of an Uniaxial Crystal Parallel to the Optic Axis.

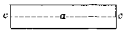


FIG. 120.

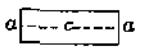


FIG. 121.

Section through Fig. 119.

Parallel to *cc*. Parallel to *aa*.

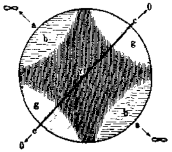


FIG. 122.—Uniaxial Crystal Parallel to the Optic Axis in Convergent Polarized Light.

I passing over into blue. The section of quartz cut parallel to the optic axis may serve to illustrate this as shown in the following table:

| | | I. | | II. | |
|---|---|---|---|---|---|
| $u$ | $p$ | $d$ | $w$ | $d$ | $w$ |
| 0° | 1.0000 | 0.0091 | 0.0091 | 0.0091 | 0.0091 |
| 20° | 1.0652 | 0.0069 | 0.0073 | 0.0091 | 0.0095 |
| 40° | 1.3054 | 0.0038 | 0.0050 | 0.0091 | 0.0119 |
| 60° | 2.0000 | 0.0010 | 0.0020 | 0.0091 | 0.0182 |

$u$ is the angle of inclination of the rays toward the normal to the section, $p$ is the distance traversed in the direction indicated, $d$ the amount of double refraction in this direction, and $w$ the retardation of the two rays resulting from the last two factors. The columns under I give the value for those directions which lie in the section corresponding to Fig. 120, while those for the section corresponding to Fig. 121 are to be found in the columns under II.

The interference figures of uniaxial minerals are often affected by inclusions, twinning lamellæ, etc. When disturbing inclusions are present the interference figure is undistorted only when the vibration directions of the inclusions correspond to those of the nicols. In other cases the dark cross in the interference figure does not remain unaltered upon rotating the object, but it opens giving rise to two rather irregular hyperbolas that reunite on further rotation. Such minerals behave like biaxial crystals with a very small optic angle. The latter phenomenon is very common so that positive determinations cannot always be made. It may occur that the black cross appears open normally, and does not close upon rotating the object. This is caused by double refraction in the lenses and a normal image can frequently be produced by rotating the objective.

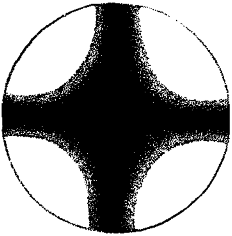


FIG. 123.—Interference Figure of a low Double Refracting Uniaxial Crystal.

In very thin plates of low double refracting substances the bundles of rays inclined most to the optic axis do not suffer sufficient double refraction to produce brilliant interference colors. Illumination occurs only at the extreme border of the field in the four sectors lying between the principal sections of the nicols. The greater part of the image is a broad, poorly defined cross, Fig. 123. For recognizing very weak double refraction in convergent light, a sensitive tint plate may be used. When it is inserted the interference figure, which was formerly scarcely visible, becomes distinct by a blue color in two opposite quadrants and orange in the other two. If on the other hand, the plate is thick or the substance has a very high double refraction, the rings are very close and the color is of a lower order in the center, but gives way rapidly to white of a higher order toward the edge. A distinct interference figure can be obtained even with a low power objective.

**Crystals with Circular Polarization.**—It is not necessary to go very deeply into the phenomenon of circular polarization in convergent light because it can only be observed distinctly in much thicker slides than are used in ordinary microscopic studies. Circular polarization is the property possessed by certain bodies, whereby light is resolved into its components in that direction in which double refraction does not usually take place. Since all directions perpendicular to this one are equivalent, resolution of the light can only give rise to circular vibrations which move in opposite directions and possess slightly different velocities. Circular polarization can take place in isotropic crystals in all directions but in double refracting crystals only in the direction of an optic axis. Upon emerging from the crystal the two circular vibrations unite in a plane polarized vibration, the plane of which is rotated somewhat corresponding to the retardation of one ray over the other. Circular polarizing crystals rotate the plane of polarization of light

When a circular polarizing crystal section is observed in parallel, monochromatic light, it appears light between crossed nicols, if it is sufficiently thick, and there is no change in its luminosity when the plate is rotated horizontally. When one of the nicols is rotated through a definite distance, the section becomes dark. Depending upon whether this rotation is to the right or to the left, crystals are classified into right- or left-handed crystals, and the amount of rotation of the nicol necessary to produce complete darkness indicates the strength of the circular polarization, provided the thickness of the plate is known. The rotation of the plane of polarization is generally quite different for different colors, e.g., in quartz extreme violet is rotated 2 1/2 times as much as extreme red. If a plate cut perpendicular to the optic axis is thick enough, it will show interference colors in parallel polarized light, and these colors remain unchanged during a complete rotation of the plate. When one nicol is rotated, the colors change in such a manner that the various colors of the spectrum are extinguished in order, the others uniting to form a mixed color. Upon rotating the nicol in the direction of the hands of the clock, these complementary colors follow in the order of the spectrum for a right-handed crystal, and in the reversed order for one which is left-handed.

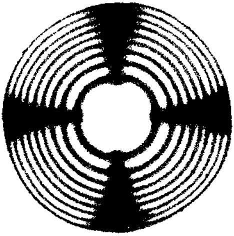


FIG. 124—Interference Figure of a Uniaxial Crystal with Circular Polarization.

The phenomena of a uniaxial, circular polarizing crystal can be very easily deduced form the above. An interference color produced by circular polarization appears in the center of the image and the dark cross disappears,

Fig. 124. The color is constant throughout the whole of the center of the field and behaves exactly as the interference color of the plate did in parallel polarized light. This phenomenon is generally not seen in microscopic preparations because circular polarization is nearly always too weak to produce an illumination which is observable in a thin layer.

**Character of the Double Refraction of Uniaxial Crystals.**—In observing the interference figure of a uniaxial crystal it was seen that the phenomenon was produced by double refraction of the rays passing obliquely through the plate. The light is resloved into two vibrations corresponding to the extraordinary and ordinary rays. The extraordinary ray vibrates in a principal section and, since all planes through the optic axis are principal sections, all radii of the interference figure are vibration directions of the extraordinary ray. The tangents which are perpendicular to the radii are the vibration directions of the ordinary ray, Fig. 125.

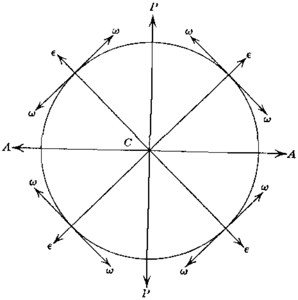


FIG. 125.—Vibration Directions in an Uniaxial Interference Figure.

If one of the compensators already described, e.g., violet I, is inserted in the microscope so that its vibration directions are at 45° to those of the nicols, the directions of greatest and least elasticity in the plate will be parallel to a principal section of the crystal. A reddish-violet color appears instead of the dark cross, as indicated in Fig. 126, while the corners of the four sectors are colored yellow and blue. A negative crystal is represented in Fig. 126. Its extraordinary ray is the faster, or the velocity of the ray vibrating in the principal section or in the radius of the image is the greater, and is equal to 𝔞. Addition of the double refraction takes place in those sectors through which the vibration direction of the faster ray in the compensator passes radially, and a higher interference color appears. It is the brilliant blue following violet I. In the other sectors the vibration direction of the slower ray in the compensator is parallel to the radius of the interference figure and compensation takes place. The interference color is lowered in these two sectors, i.e., it changes to yellow.

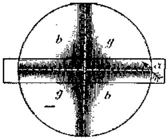


Fig. 126.—Interference Figure of a Negative Uniaxial Crystal with Gypsum Test Plate.

The simple mnemonical rule for this phenomenon is: *The line joining the blue sectors and the direction of greatest velocity in the test plate form a minus sign for optically negative crystals. In positive crystals the other sectors show the blue interference color. The line joining the blue sectors and the direction of greatest velocity in the test plate form a plus sign for optically positive crystals.*

A quarter undulation plate gives characteristic reactions in a similar manner. The dark cross breaks up into two black spots and the line joining them corresponds to a vibration direction in the test plate. It is parallel to the direction of greatest velocity in the test plate for positive crystals, Fig. 127, and perpendicular to it for negative crystals, Fig. 128. The colored rings may be observed to move out in those two quadrants and move in in the other two.

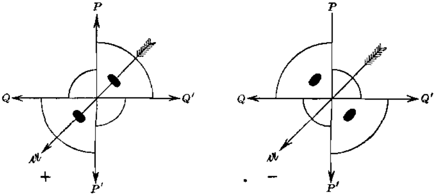


Fig. 127.—Positive Fig. 128.—Negative
Uniaxial Interference Figure with a Mica Test Plate.

Figs. 127 and 128 show diagrammatically the conditions described above. The phenomenon is based on the direction of greatest velocity of light in the mica plate, but if, as is frequently the case, the direction of least elasticity is parallel to the long direction of the test plate, the two images must be interchanged.

The eighth undulation plate likewise gives a characteristic reaction in which the dark cross breaks up into two curves similar to the middle portion of a figure 8. The figure is closed on both ends by close colored rings and lies parallel to the direction of greatest velocity in the mica when the crystal is negative, and in the reverse position when it is positive.

The investigation of the character of the double refraction of a thin, feebly double refracting mineral with a quarter undulation mica test plate between crossed nicols does not give very positive results, because the dark spots as well as the rings fall outside of the field of vision. The violet I plate is better in such cases. Its brilliant color reaction is distinct even with the feeblest double refracting substances. Great precautions are necessary in the investigation of the weakest double refracting crystals with violet I because the object glass itself often gives a very weak interference figure which becomes quite distinct with the sensitive tint. A quarter undulation plate is sufficient in almost all cases if the observations are made between parallel instead of crossed nicols. The four angles of the brownish cross, which now appears, are alternately white and deep brown passing over into blue. The two latter quadrants, which in negative crystals are parallel, are in positive crystals crossed to the direction of greatest velocity in the mica plate, and can be easily recognized by their color. A mica test plate gives the best results with very strongly double refracting substances in which the innermost colored ring is very small, and also with highly colored substances.

FIG. 129.—Interference Figure of a Biaxial Crystal Perpendicular to an Optic Axis.

**Biaxial Crystals.**—If a plate of a biaxial crystal with not too small an optic angle is cut perpendicular to an optic axis and observed in convergent polarized light, an image similar to that of a uniaxial crystal will be seen. There is only one bar in place of the dark cross and nearly circular ovals replace the truly circular rings of the uniaxial figure, Fig. 129. The black bar is parallel to the vibration direction of one of the nicols, when the plane of the optic axes lies parallel to it, i.e., when the only principal section that can be placed through the plate is parallel to the vibration direction of a nicol. When the plate is rotated the bar with the rings rotates also, but in the opposite direction, about a point corresponding to the place of emergence of the optic axis. After a rotation of 90° the bar is parallel to the vibration direction of the other nicol. The vibration directions of the two nicols always form the bisectors of the angles between the dark bar and the direction of the plane of the optic axes. The bundle of rays passing through the crystal parallel to the optic axis suffers no double refraction in this case and the corresponding portion of the image is therefore dark. The point at which the axis emerges is the pivot for the black bar and is the only portion of the interference figure that always remains dark.

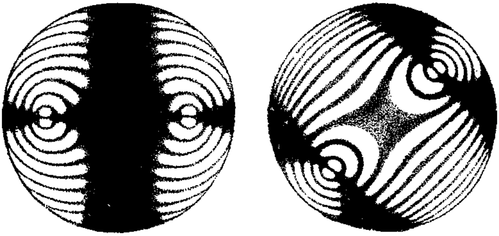


FIG. 30. FIG. 131.

Interference Figures of Biaxial Crystals Perpendicular to Acute Bisectrix.

A plate of an orthorhombic crystal cut perpendicular to the acute bisectrix shows the image represented in Fig. 130, when the plane of the optic axes is parallel to the prinicpal section of one of the nicols. The figure shows a black cross, corresponding to the two principal sections that can be placed through the plate. That bar of the cross, which is parallel to the axial plane, is sharply defined. The other bar, at right angles to it, is broad and indistinct. This cross cuts the system of lemniscates symmetrically. The inner curves are closed ovals while the outer ones unite to form a figure 8. The axes themselves emerge in the vertices of these curves. When the plate is rotated the cross opens, the arms uniting to form a curve which is very nearly an hyperbola when the plate has been rotated through 45°, Fig. 131. The colored rings rotate also with the plate but their form is not changed. The only points which always remain dark when the plate is rotated are the points where the axes emerge, and they form the vertices of the hyperbola. The distance between the vertices when the axial plane is at 45° to the nicols indicates the size of the optic angle.

The interference figure of biaxial crystals with very small optic angles approximates that of uniaxial crystals. The black cross appears to be surrounded by a single system of colored circular curves, Fig. 132, and it opens only slightly upon rotating the slide. As already remarked, this is sometimes seen in uniaxial crystals so that a definite distinction between uniaxial and biaxial substances may become quite difficult.

If the optic angle is very large, Fig. 133, it may happen that the axes do not emerge within the field of vision even when the strongest objectives are used. That is the case when $\beta$ sin V > A, aperture of the objective used. If $\beta$ sin V > 1, the optic axes do not emerge from the crystal into the air at all, because then total reflection of the light takes place, and the apparent optic angle is greater than 180°. If an immersion system is used with such crystals, the optic axes can be observed in all cases in a section perpendicular to the acute bisectrix, because then the difference between the indices of the crystal and the medium surrounding it is decreased, whereby the refraction of the rays emerging from the crystal into the immersion liquid is reduced, and the angle of total reflection increased.

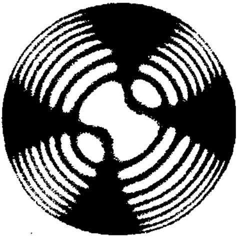


Fig. 132.

Fig. 133.

Interference Figure of a Biaxial Crystal with a very
Small Optic Angle. Large Optic Angle.

With an immersion system the two axes can often be seen in the field of vision in a section cut perpendicular to the obtuse bisectrix if the index of refraction of the crystal is not too great, and the optic angle is very large.

**Dispersion of the Optic Axes.**—The optic angle is different for different colors and is sometimes larger for red than for blue, Fig. 134. It is indicated by the dispersion formula $\rho > v$, or the reverse may be the case, $v > \rho$. Dispersion can scarcely be recognized in the microscope if it is very slight, especially when the

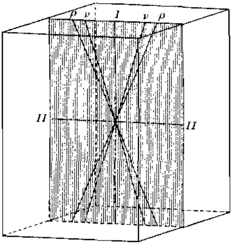


Fig. 134.—Axial Plane in an Orthorhombic Crystal.

substance has very low double refraction. If the dispersion is greater, there will be brilliantly colored bands around the vertices of the hyperbola in the interference figure and this band is broader and more brilliant the stronger the dispersion. Very strong dispersion of the optic axes can be noted even in parallel polarized light in the so-called *dispersion colors,* see page 79. If the hyperbolas are yellow on the convex side, and blue on the concave, the optic angle for blue is smaller than that for red, $\rho > \nu$, Fig. 135. Those rays which pass through a crystal parallel to an optic axis for a definite color suffer no double refraction for that color, and the complementary color appears in its place in the interference figure, i.e., in the vertex of the hyperbola.

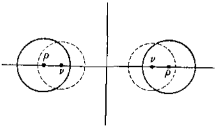


Fig. 135.—Orthorhombic Dispersion.

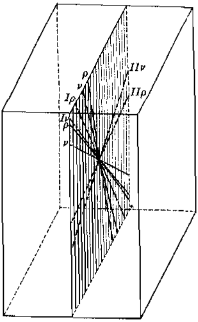


Fig. 136.—Axial Plane in a Monoclinic Crystal with Inclined Dispersion.

In the orthorhombic system the bisectrices and the optic normal for all colors coincide with the crystallographic axes, Fig. 134. One of the axes can be the optic normal for one color and another axis for another color, i.e., the planes of the optic axes for different colors can be crossed, as for example, in brookite. In any case the interference figure is symmetrical to the plane of the optic axes and the plane perpendicular to it. In the monoclinic system in which only the *b* axis coincides with a principal vibration direction, symmetry with respect to one or both of these planes may be lacking.

There are three different kinds of dispersion in the monoclinic system.

1. Inclined dispersion, the *b* axis is the optic normal, Fig. 136. The optic axes lie anywhere in a plane parallel to the clinopinacoid and the two axes suffer different amounts of dispersion.

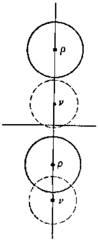


Fig. 137.
Inclined Dispersion.

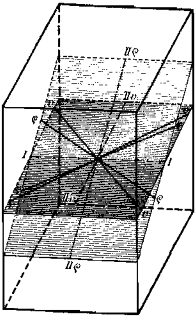


Fig. 138.—Optic Plane in a Monoclinic Crystal with Crossed (Horizontal) Dispersion.

The interference figure is symmetrical with respect to the plane of the optic axes but not to the plane perpendicular to it, because the bands of color are different on each arm of the hyperbola, Fig. 137.

2. Horizontal dispersion, the *b* axis is the obtuse bisectrix, Fig. 138. (The bisectrices I and II must be interchanged.) The planes of the optic axes for different colors are any planes perpendicular to the clinopinacoid. The interference figure is not symmetrical with respect to the plane of the optic axes but to the plane perpendicular to it, Fig. 139.

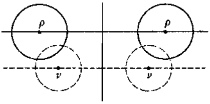


Fig. 139.—Horizontal Dispersion.

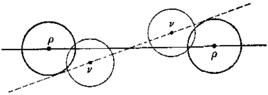


Fig. 140.—Crossed Dispersion.

3. Crossed dispersion, the *b* axis is the acute bisectrix, Fig. 138. The position of the plane of the optic axes is the same as in the previous case. In the interference figure the distribution of color to the right above is the same as to the left below, Fig. 140, that is, the colors are symmetrical to a point.

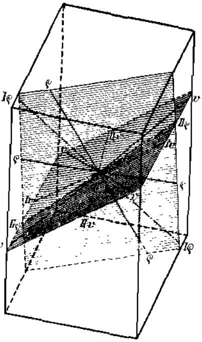


Fig. 141.—Optic Plane in a Triclinic Crystal.

As there is no relation, in the *triclinic* system, between the optic directions for the different colors and the crystallographic axes, the distribution of the axes as well as of the planes of the optic axes is entirely unsymmetrical, Fig. 141.

In general these differences of dispersion are quite small and are observed only in very favorable cases. The presence of distinct inclined or crossed dispersion must be considered as characteristic of a monoclinic crystal, but the absence *of this phenomenon is not sufficient* to determine the crystal as orthorhombic.

The presence of strong dispersion of the optic axes is a good earmark for a substance. In monoclinic crystals the character and strength of the dispersion are not definitely related to each other. Titanite, for example, shows very strong dispersion of the optic axes but the inclined character is scarcely noticeable. On the other hand in a certain group of pyroxenes, showing inclined dispersion, one axis is very weakly dispersed, the other very strongly.

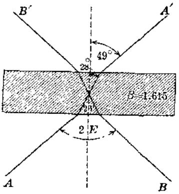


Fig. 142. *Apparent Optic Angle.*

**Measurement of the Optic Angle.**—The determination of the size of the optic angle is of some importance and can be carried out by various methods. The distance between the hyperbolas gives only the size of the apparent optic angle, which differs most from the true angle, the larger the latter, and the higher the intermediate index of refraction of the crystal. Those rays which pass through the plate parallel to the optic axes impinge upon the upper surface of the crystal obliquely and, emerging from a stronger to a lower refracting medium, are refracted away from the normal, Fig. 142. Thus, the apparent optic angle in air is always larger than the true optic angle. If 2E is the apparent, and 2V the real optic angle, $\sin \mathrm{V} = \frac{\sin \mathrm{E}}{\beta}$. Thus the real optic angle of a crystal can be calculated when $\beta$ is known. Diopside and orthoclase, for example, have very nearly the same apparent, optic angle in air, about 118°. However, in diopside, the value $\beta$, which is 1.678, is decidedly higher than in orthoclase, where $\beta = 1.524$. Thus, in the former the apparent optic angle corresponds to a much smaller real angle, 61 1/2°, while the real angle of orthoclase is 71°.

Only the apparent optic angle can be measured in a microscope. The distance between the vertices of the hyperbolas is used for this determination, which is made, if possible, in monochromatic light. With a micrometer scale in the ocular the law of Mallard can be used; $\sin \mathrm{E} = \mathrm{DK}$, where D is the number of divisions on the scale and K is the constant determined, once for all time, for one of the objectives. It can be determined best with a plate cut perpendicular to the acute bisectrix with a known apparent optic angle.

In using the simplest methods of observation in convergent light there is generally no need of a micrometer scale in the ocular. Such a scale can, however, be placed in the objective, so that it can be seen sharply at the same time as the interference figure, or it can be etched on the front lens of the objective. This has a disadvantage, however, that such an objective cannot be used so much for ordinary observations and, further, that the image produced by this method is extremely small, and the error in the measurement is therefore very large.

The measurement of the apparent optic angle can be best made with the microscope by using a Bertrand or Klein lens, each of which produces an enlarged interference figure. With a Bertrand lens, which transforms the ocular into a microscope, measurement can be made by means of an ocular micrometer, i.e., by means of a scale placed in the focus of the ocular itself. With a Klein lens, on the other hand, the scale can be shifted in the holder of the lens which is placed over the ocular. When the proper adjustment of the image and scale has been attained, there should be no relative displacement when the eye is moved back and forth over the lens. Otherwise there is considerable error resulting from the parallax.

If, instead of a fixed micrometer, the cross hairs in the ocular are so arranged as to be moved by means of a micrometer screw, their intersection

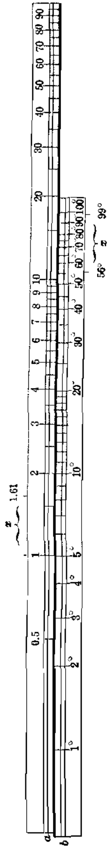


FIG. 143.—Schwarzmann's Optic Angle Scale.

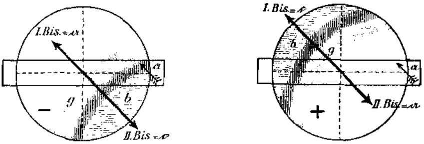
can be made to coincide in turn with the vertices of the hyperbolas. The amount of the displacement can be read off on the drum of the screw. This method gives results that are a little more accurate than with a fixed micrometer. Finally the interference figure can be transferred to coördinate paper by means of a sketching device. Now and then this method has many advantages.

The sine of the optic angle is obtained from the distance between the hyperbolas, and the simplest way to make this determination is to use a sine rule, for example, Schwarzmann's *optic angle scale*, Fig. 143. The two parts *a* and *b* slide on each other. The upper part *a* gives the number of divisions in the ocular micrometer and the lower part *b* the size of the corresponding optic angle when it has been adjusted for the ocular used. In Fig. 143 it is adjusted by measuring the optic angle of aragonite on a fixed micrometer in sodium light. There were 5.9 divisions on the scale corresponding to an apparent optic angle of 30° 15′. 30° 15′ on the lower scale is placed exactly under 5.9 of the upper, which constitutes adjustment of the scale for that objective. If a section of topaz is studied, 17.6 scale divisions will be noted. The division on the lower scale corresponding to that is 99°, which is the apparent optic angle for topaz.

The scale has another value, viz., that the real optic angle can be deduced from the apparent without any calculation if the value of $\beta$ is known. The value of $\beta$ is marked in the upper scale, for example 1.61 for topaz, and $x$ the distance from division 1 to the new division is measured with a pair of dividers. This distance, when measured backward from the apparent optic angle, gives the value of the real angle, which in this case is about 56°.

The optic angle can also be measured in those sections which are not exactly orientated. This is very important for petrographic investigation because perfectly orientated cross sections are rare in slides. The trace of the optic axes is best transferred to a projection from which the calculation of the optic angle can be made, if the intermediate index of refraction is known. These measurements are not of very great importance in the microscopic study of rocks, because in most of the isomorphous groups, which are the most widespread constituents of rocks, the optic angle varies within wide limits and no relationship appears to exist between the optic angle and the chemical composition.

**Character of the Double Refraction of Biaxial Minerals.**—The determination of the character of double refraction of biaxial minerals is important only when it it positively known whether the determination was made on the acute or obtuse bisectrix. It frequently happens in rock-forming minerals that the optic angle is not far from 90°, as in plagioclase, olivine, epidote, and *then the distinction is very difficult.* The *optic axes do not then* emerge from a section perpendicular to the acute bisectrix any more than they do in a section perpendicular to the obtuse bisectrix; thus this characteristic of the mineral must be abandoned because a positive acute bisectrix corresponds to a negative obtuse bisectrix, and vice versa.



Figs. 144–145.—Determination of the Character of the Double Refraction in a Section Oblique to an Optic Axis.

Sections that show the emergence of an optic axis in the field of vision of the microscope are very important. If the optic *angle is not too near 90° the dark bar produced by a slightly* oblique axis is distinctly curved with the convex side toward the acute and the concave side toward the obtuse bisectrix. When the plane of the optic axes is placed at 45° to the nicols and violet I is inserted, the bars appear violet but the convex and concave sides of the curves are colored differently as indicated in Figs. 144 and 145. The axial plane in each case is parallel to the direction of the greatest elasticity in the test plate, i.e., the bars are perpendicular to it. Hence in a negative crystal the convex side is yellow and the concave blue, Fig. 144, and this is reversed in Fig. 145. In that portion of the image toward the bisectrix 𝔞, the ray vibrating in the axial plane is propagated with the velocity 𝔠. In this case the axial plane lies parallel to 𝔞 in the compensator and hence subtraction of the double refraction takes place on this side of the axis. The interference color sinks from violet in the bar to yellow.

With a section about perpendicular to a bisectrix, the change produced by a quarter undulation plate inserted at 45° to the nicols is observed, when the axial plane is parallel to the vibration direction of one of the nicols. The black cross disappears and the curves in each pair of opposite quadrants are either moved closer together or farther apart. Thinning of the rings takes place in those quadrants cut by the direction of greatest elasticity in the test plate when the crystal is positive, and vice versa if it is negative. This test can only be made with safety in well orientated sections and is much less used than the method which depends upon compensation of the double refraction.

When the interference figure is placed in the 45° position with respect to the nicols, the middle of the field shows an interference color which corresponds to the retardation of the rays propagated in the direction of the bisectrix in question. One of these rays vibrates parallel to the axial plane and is propagated with the velocity belonging to the ray whose vibration direction is the other bisectrix. The second ray vibrates parallel to the optic normal *b* and has the corresponding intermediate velocity. If, for example, the section is perpendicular to the acute bisectrix of a negative crystal, that ray which vibrates in the axial plane is parallel to the obtuse bisectrix, which in this case is the direction of least elasticity for the crystal and is therefore smaller than the value of the optic normal perpendicular to it. A compensator is then inserted so that its direction of greatest elasticity is parallel to the axial plane in the crystal. Thus, equivalent directions are crossed and the impression is obtained that the thickness of the crystal has been diminished. The interference colors are lowered and the rings spread out. A biaxial crystal is negative if the double refraction is lowered, when the direction of greatest elasticity in the compensator is parallel to the axial plane in a section perpendicular to the acute bisectrix, and positive when it is increased. The reverse of this is true for a section perpendicular to the obtuse bisectrix.

Beginners often experience difficulty in making this determination with feebly double refracting substances, which show no color in the field, or only gray of the first order. This is especially true for those groups of rock-forming minerals on which observations in convergent polarized light are most frequently made, as the plagioclases. With sections perpendicular to the negative bisectrix of such crystals, the original gray changes to yellow when violet I, which is most frequently used for these determinations, is inserted. Apparently the interference color is raised instead of lowered but the gray in the slide has actually been subtracted from the red of the compensator, and yellow remains. This fact can be proved by rotating the compensator, for the field becomes blue, i.e., it acquires the next higher color after violet I, while the yellow is the next one lower and signifies subtraction of the interference colors.

It is often interesting to determine the position of the axial plane with respect to the edges of a crystal, this being sometimes a valuable characteristic of the mineral. The interference figure is placed in the 45° position. The line joining the vertices of the hyperbolas in the interference figure, or the line perpendicular to one arm of the curve is the direction of the plane of the optic axes. It is unimportant which method of observation in convergent light is used, because the rotation of the image is of no consequence in determining the direction of the plane.

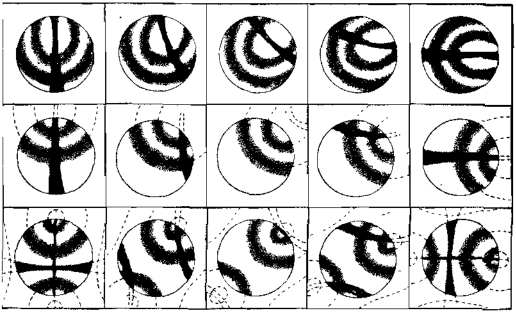


FIG. 146.—Biaxial Interference Figures in Sections Oblique to the Acute Bisectrix.

This rotation of the image is considered when the bisectrix is inclined toward the vertical, and it must be determined in which direction the deviation takes place. It must always be remembered that in observing without the ocular, the interference figure is reversed with respect to the image of the object, while in observing with the ocular the two images are placed parallel.

The phenomena produced by a biaxial crystal cut obliquely to the principal vibration directions are shown in Fig. 146. It represents the behavior of three differently orientated sections of topaz upon a rotation through 90°. Unlike the behavior of uniaxial crystals, Fig. 118, p. 101, it can be distinctly seen that the dark bar rotates about the point of emergence of the axis as a center, because in this case its direction is not dependent upon the position of the principal sections of the nicols alone, but upon the relation of them to the principal vibration directions of the plate.

Besides sections perpendicular to the acute bisectrix and those perpendicular to the optic axes, which have been amply described above, sections perpendicular to the obtuse bisectrix and those parallel to the plane of the optic axes are of special interest. If the real optic angle of a certain substance is nearly 90°, it is difficult to distinguish between acute and obtuse bisectrices especially in minerals with low indices of refraction. If one does not wish to make accurate measurements, or if they cannot be made, because there is no objective with a sufficient aperture, very useful results can be obtained in parallel polarized light. With two well orientated sections of equal thickness, perpendicular respectively to each of the bisectrices, the one perpendicular to the obtuse bisectrix gives the higher interference color. As the size of the acute optic angle decreases, and the obtuse becomes larger, the difference of the interference colors of the two sections naturally increases. In convergent light the lemniscates in the interference figure, perpendicular to the obtuse bisectrix, are wider, and the dark broadened bar cuts them only at the extreme edge of the field. The change is the same as if the observation were made with objectives with constantly decreasing magnification. The reverse order of the images in Fig. 114, p. 98, gives the best idea of this gradual change. When the apparent obtuse optic angle becomes very large, there is only an indication of the symmetrical distribution of color in the different quadrants, when observed in white light. The dark bars corresponding to the hyperbolas first appear in the field, when the plane of the optic axes is almost perfectly parallel to the vibration directions of the nicols. They are then very broad and not sharply defined so that it gives the impression that the plate is alternately light and dark throughout its whole extent.

The phenomena described above can be observed in plates parallel to the plane of the optic axes. They cannot be distinguished in white light from a plate perpendicular to the bisector of a large obtuse optic angle or those parallel to the optic axis of a uniaxial mineral. They can be distinguished sometimes in monochromatic light because in a section perpendicular to the obtuse bisectrix black curves occur corresponding to the colored ones in white light. These curves are portions of lemniscates which curve toward the point of emergence of the optic axes near the edge of the field, Fig. 132, p. 109. Analogous curves in a section parallel to the axial plane of a biaxial crystal or to the optic axis of a uniaxial crystal are hyperbolas, which do not show such bending. If this reaction does not possess the necessary sharpness for positive differentiation, it is still helpful, under certain conditions, to observe the interference figure in monochromatic light because with it the orientation of the section can be determined much better. The determination of the direction of extinction in a section of a monoclinic crystal should never be undertaken before it is proved in convergent polarized light that the section is really parallel to the clinopinacoid of the crystal, which is always perpendicular to one of the three principal vibration directions. It always gives an interference figure in monochromatic light, which is symmetrical with respect to two directions perpendicular to each other.

The direction of the acute bisectrix can be recognized distinctly by the distribution of colors in the interference figure in the 45° position of a section parallel to the axial plane in the same manner as was described on page 102 for sections parallel to the optic axis of a uniaxial mineral. It is necessary, however, that the real optic angle does not approximate 90° too closely. In the quadrants through which the acute bisectrix passes there is a lowering of the color or when the optic angle is quite large a slight raising of the color. In the other two quadrants the color is raised and in case the optic angle is large, the increase is much greater than in the other two quadrants. The following figures give the values for gypsum, which is optically positive and has an optic angle of 59° corresponding to the table on page 103. The values under I are for the planes inclined to the acute bisectrix and those under II for those inclined to the obtuse bisectrix.

| | | I | | II | |
|---|---|---|---|---|---|
| $u$ | $p$ | $d$ | $w$ | $d$ | $w$ |
| 0° | 1.0000 | 0.0098 | 0.0098 | 0.0098 | 0.0098 |
| 20° | 1.0652 | 0.0089 | 0.0095 | 0.0096 | 0.0100 |
| 40° | 1.3054 | 0.0066 | 0.0086 | 0.0089 | 0.0116 |
| 60° | 2.0000 | 0.0040 | 0 0080 | 0.0082 | 0.0164 |

The rays in plane I, inclined about 60° to the normal to the plate, show not quite half the retardation of the corresponding directions in plane II.

## CHAPTER VI

# Twins and Optical Anomalies

**Twins.**—Many crystals do not consist of a single homogeneous individual but of two or more individuals intergrown in a regular manner. They are called *twins, fourlings*, etc. The crystallographic laws according to which such intergrowth takes place can be determined in simple cases by careful microscopic observation, but with more complex intergrowths the results of such observations must be used with great care, if they have not been verified by accurate goniometric measurements.

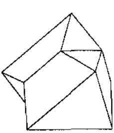


Fig. 147.—Cubic Twin with Reëntrant Angle. Magnetite.

Twinned intergrowths of cubic crystals can only be determined under the microscope by their outline. Reëntrant angles are a clue to the presence of twins, Fig. 147. Optical recognition of twins is not possible in uniaxial minerals, if the various sections are parallel to the principal axis. The vibration directions and the velocities of the extraordinary rays are the same for both individuals in every section through such a crystal. In convergent polarized light the behavior of the various individuals is the same in this case. Quartz is a characteristic example. It forms intergrowths and twins having parallel optic axes, which cannot be determined microscopically.

When the principal axes of the twinned individuals are inclined to each other it will be observed in every section oblique or perpendicular to the twinning plane, that the parts do not extinguish simultaneously. Thus in Fig. 148, when one part of the twin is dark, the other part, sharply separated from it by the twinning plane, is light, and vice versa. The angle, which the extinction directions in the two individuals form with each other must not always be taken as a basis for the calculation of the twinning law, because the true inclination of the two principal axes can only be determined when the slide is perpendicular to the twinning plane.

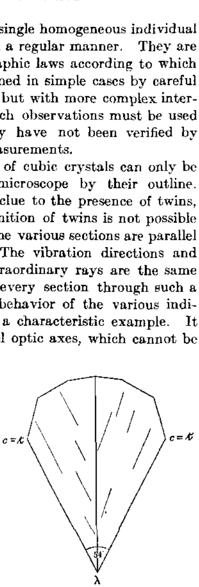


Fig. 148.—Uniaxial Twin with Inclined Axes. Rutile.

Twins in the orthorhombic system are generally more easily determined. A difference in color in various parts of strongly pleochroic substances is indicative of the presence of twins, even though the principal axes are parallel. Such twins are difficult to recognize, however, in case the pleochroism is not distinct. This is also the case when the axial plane is perpendicular to the twinning plane and the optic angle is very large, or the bisectrix of a very small optic angle lies in the twinning plane. In both these cases the extinction directions coincide and the interference colors are quite similar in the sections in which the twinning can usually be recognized most easily. In such cases the orientation of the different parts can be established with convergent polarized light. If, on the other hand, the crystallographic axes of the twinned individuals are oblique to each other, the intergrowth can be recognized by different extinction directions. The two individuals appear equally light when the inclination of each to the nicols is the same, Fig. 149.

Most of the twins in the monoclinic system are those in which the *b* axes of the two individuals are parallel. If the crystals are developed prismatic to this axis, the zone of the *b* axis will be the one most frequently studied. What was said for orthorhombic crystals with parallel principal axes applies also for sections of monoclinic inclined at a large angle to the *b* axis. Such twins cannot be positively determined in all cases by optical means. This is seen in the extremely common twins of epidote, which are but rarely recognizable. But the different positions of the vibration directions in the twins can be easily determined in sections perpendicular or oblique to the *b* axis, as shown in the example of diopside, Fig. 150.

Twins of triclinic crystals can be recognized in all sections because the vibration directions do not generally lie parallel.

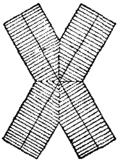


FIG. 149.—Penetration Twin with Inclined Axes. Staurolite.

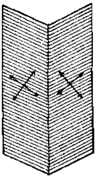


FIG. 150.—Monoclinic Twin. Diopside.

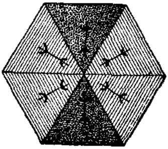


FIG. 151.—Penetration Trilling. Cordierite.

It is sometimes noted that not only two, but three or even more individuals are intergrown in a regular manner. Intergrowths of three individuals are called *trillings*. Characteristic penetration trillings of certain orthorhombic and monoclinic crystals are noteworthy. They possess a prism angle of approximately 120°, and unite to form an apparently hexagonal crystal, as shown in Fig. 151.

Fourlings generally assume the form of lamellar intergrowths. Twinning lamination is particularly common in monoclinic and triclinic substances but is not lacking in orthorhombic (olivine), hexagonal (calcite), tetragonal (rutile), and in cubic crystals (fluorite). In the latter it cannot be observed optically. Crystals, twinned in this manner, apparently consist of two or more individuals which penetrate each other in a lamellar manner, e.g., plagioclase, Fig. 152. so that one system of lamellæ belongs to one individual and the other to a second, etc. It sometimes happens that one system of twinning lamellæ, produced by twinning according to a certain law, is crossed by another system belonging to a second law. The phenomenon may assume very fine development and is called *lattice lamination* or cross hatching. Fig. 153 shows cross hatching in albite produced by twinning according to the albite and pericline laws.

This complicated structure of crystals consisting of numerous alternating twinning lamellæ is very widespread especially in the larger polymorphous groups, e.g., the epidote and feldspar groups. Modifications of lower symmetry approach those of higher symmetry with respect to external form by such repeated twinning. The approximation is the greater the finer the individuals, until, finally, a minuteness of the single components may be attained, such that they cannot be differentiated under the microscope. Then the optical properties agree with those of the modifications with higher symmetry. This gradual transition from lower to higher symmetry gave rise to the theory of Mallard, that numerous crystals belonging to groups with higher symmetry are the result of such twinning of individuals with lower symmetry.

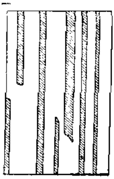


Fig. 152.—Twinning Lamination.

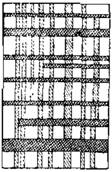


Fig. 153.—Lattice Lamination.

It has often been observed that substances which crystallize in one crystal system at a certain temperature, are resolved into a pile of complicated twins of individuals with lower symmetry when the temperature is changed. This was shown long ago for leucite and boracite, which, at the moment of their formation at higher temperatures, crystallize cubic, but upon cooling this modification is not stable and passes over into an apparently confused complex of double refracting lamellæ, Fig. 154. The cubic condition of equilibrium can be restored by heating the crystal up to a certain temperature, while cooling is followed again by the breaking up into the double refracting modification.

Many methods have been used to determine the monoclinic and triclinic crystals composed of twinning lamellæ, which occur so frequently in rocks. The sections of such crystals are orientated in various ways and the methods employed for their determination are based in part upon the mutual relations of the twinned individuals. The simplest method is the determination of the extinction angle in a series of sections in which the two individuals extinguish symmetrically with respect to the twinning plane, i.e., they are perpendicular to the twinning plane. Another method is the determination of the position of equal luminosity, which very thin plates of feebly, double refracting crystals show. Thicker plates, or those with higher double refraction, can only be used in monochromatic light. A twin, in which the vibration directions are oblique to each other in the two parts, *cannot be recognized as such in all positions between crossed nicols.* On rotating the crystal horizontally through 360°, there are eight positions in which the two halves appear equally light and the twinning plane entirely disappears. Four of these are crossed with respect to the other four. These two groups of positions of four each can be distinguished from each other in that when the lamellæ partially overlap like wedges, these overlapping parts in one group are just as light as the rest of the crystal, but in the other group they are darker. This method of determining the position of equal luminosity was formerly successfully employed in the determination of the plagioclases, but it did not find any general application and has been replaced by modern methods of determination.

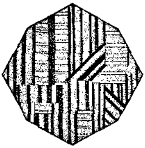


FIG. 154.—Twinning Lamination in Leucite.

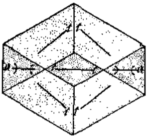


FIG. 155.—Segments in Garnet.

**Optical Anomalies.**—Optical anomalies are quite often observed in microscopic studies. Variations in the optic angle of biaxial crystals, the slight opening of the dark cross in uniaxial crystals upon rotating in convergent polarized light, and the uneven illumination of cubic crystals between crossed nicols are very common occurrences. A very faintly illuminated halo cut by a dark cross, *Brewster's cross*, often appears around inclusions in glass and cubic crystals in parallel polarized light.

Crystals with an external cubic form may be sometimes observed, which do not show normal optical behavior either in their entirety or in regularly *bounded portions. They appear double refracting.* The *phenomenon in* leucite and its decomposition into a complex of twins has been mentioned above. Strictly speaking, this phenomenon cannot be classed with anomalies as generally considered, but it is a genuine and characteristic *paramorph.* A characteristic type of optical anomalies for cubic crystals may be observed when a second substance is present in such minute quantities that it cannot be detected chemically. The two substances may or may not be *isomorphous. Thus a crystal of potassium alum* may contain slight amounts of ammonium alum and retain its outward cubical symmetry but internally it is composed of a number of double refracting pyramids.

It can generally be observed that the structure of such a crystal is most intimately related to its external form. It is composed of as many pyramids as there are faces, and each face of the crystal is the base of a pyramid, the apexes of which unite in the center of the crystal, Fig. 155. If the substance is without definite crystal form, its internal structure cannot, naturally, be influenced by it. The optical properties, which are based upon the internal structure of the crystal, are disturbed before the development of the form is completed. Such a division of the field into segments is observed quite frequently in cubic crystals and not infrequently also in uniaxial crystals. They are, however, rarer the lower the symmetry of the crystal, because anomalous crystals always correspond in their optical behavior to groups with lower symmetry. It is noteworthy that certain compounds are very susceptible to such optical influences so that they are rarely found in a normal condition, while in others optical anomalies are not known at all.

The phenomena grouped together as optical anomalies of isotropic bodies are of three kinds. 1. An uneven illumination between crossed nicols with a Brewster's cross in the neighborhood of inclusions. This is undoubtedly produced by tension and is found in amorphous as well as in cubic substances. 2. A division of the field corresponding to the external form. This is generally produced by foreign substances between the molecules and is likewise a tension phenomenon. 3. The occurrence of twin laminations or cross hatching. These can generally be referred to dimorphism of the substance in question, and paramorphism resulting from it.

# Appendix

## Accessory Apparatus

A number of more or less complicated devices are quite desirable in some cases as accessories to the microscope. They are of great importance in certain special investigations, and are mentioned here for the sake of completeness. It is not intended to give a long list of them or a detailed description of each but to give some idea only of their general applicability. There are three principal groups of such accessory apparatuses which are of great importance.

1. Rotation apparatus.
2. Heating apparatus.
3. Projection and reproduction apparatus.

The more important types of these will be briefly described.

### 1. Rotation Apparatus

Under this head are included all those simple or complex attributes to the microscope by which the object under investigation can be rotated about one or more axes other than the axis of the stage. The oldest of these were used exclusively for goniometric investigation. They were called *microscope goniometers* but they are scarcely of any importance at the present time. There is a whole series of adjustments from the simplest types to the universal stage, which are used principally for investigating the optical properties of an object in various directions.

These devices depend chiefly upon two different principles. One tends to eliminate refraction and total reflection of the rays coming from the oblique surfaces of the preparation. This is accomplished by placing the crystal or the microscopic preparation between two plano-convex lenses so that at all points both surfaces of the apparatus are perpendicular to the rays of light, which are sent through the preparation, and no deviation of the central rays, at least, can take place. The other makes it possible to observe an object immersed in a liquid of very similar index of refraction. The liquid is in the form of a horizontal or a vertical layer bounded by plane surfaces, and the crystal can be rotated in it in any manner. The first method is not very valuable in the study of thin sections. The other is used more frequently with isolated crystals but can also be employed very profitably with thin sections.

**Rotation Apparatus for Observations between Two Plano-convex Lenses.**—The simplest of these accessories was suggested by Schroeder van der Kolk and consits only of a single pair of lenses. One lens with a diameter of 25 mm. is placed in the opening of the stage and can be rotated in all directions. The other lens with a diameter of about 8 mm. is placed on the center of the slide. Both lenses must be so made that the preparation lies as nearly as possible in the focus of the system, i.e., the lower lens must differ from the form of a hemisphere by the thickness of the object glass and the upper one by the thickness of the cover-glass. The object glass of the preparation, which should be circular and have a smaller diameter than the lens itself, is laid upon the larger hemisphere, contact being made by a drop of glycerine. The particle to be investigated is then centered accurately when the preparation is as nearly horizontal as possible. The second lens is fastened on the cover-glass of the preparation by a small drop of glycerine also. This lens is moved about until the object to be observed, which appears twice as large as before, is exactly in the middle of the field of vision. The two principal vibration directions of the object are determined and then the lower lens is rotated about one of the directions as an axis, permitting observations to be made in parallel polarized light continuously. An object holder, Fig. 33, page 19, can be used to eliminate many of the accidents which may result by the rotation by hand. It rests on the preparation like a spring and can be rotated about a horizontal axis. The amount of rotation can be read off a small circular scale.

The principal vibration direction of the object under investigation is placed parallel to the axis of rotation of the apparatus and then the rotation can be carried out accurately and measured. With a prismatic crystal, which shows parallel extinction and gives no characteristic interference figure in convergent light, the rotation is made with the long axis of the crystal as the axis of rotation until it lies parallel to one of the vibration directions of the nicols. Two cases are possible. Either the crystal remains constantly extinguished during the rotation, or more and more illumination *appears and, after a definite rotation of the accessory apparatus, the* crystal must be rotated on a vertical axis through a definite arc to produce darkness again. In the latter case the crystal is monoclinic. If it remains constantly dark it is rotated on a second axis perpendicular to the first horizontal axis and the observations repeated in the same order. Now, if it remains dark during the whole rotation the crystal is tetragonal, hexagonal or orthorhombic, but if it gets gradually lighter during the second rotation it is monoclinic with a prismatic development parallel to the $b$ axis.

If there is parallel extinction in all cases the long direction of the crystal is used as the axis of rotation and it is placed at 45° to the nicols so that the crystal shows its most brilliant interference color. If, when the crystal is rotated, there is no change in the interference color, it is uniaxial. If there is a change, it is orthorhombic. It is thus obvious that this apparatus is an extremely important aid in the investigation of crystals. All the changes which take place in convergent polarized light can be followed by lengthening the tube slightly without otherwise changing the adjustments.

The apparatus would be much more useful if it were constructed of a series of large lenses with a hemispherical cup cut in the center of the plane surface. Large crystals, or precious stones, could be immersed in this cup in a liquid with the same index of refraction and the various directions studied in parallel and convergent light. This gives excellent results in the study of precious stones.

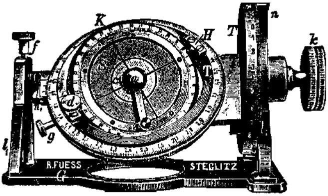


FIG. 156.—Fedorow Universal Stage.

There are a large number of other apparatuses of this kind based upon the same principle but only the large model of the *Fedorow universal stage* will be described in detail. Fig. 156 shows this stage with three axes of rotation. It consists of a stand $l_1l_1$ which can be placed on the stage of a microscope. The stage in the stand can be rotated about a horizontal axis by means of the screw $k$. The circle T with its vernier $n$ shows the amount of rotation. The axis can be fixed by means of the screw $f$. The vernier $n_1$ is firmly fixed on this axis and the stage K is rotated on an axis perpendicular to the first. The stage K bears a third axis $Hd$ which can be rotated about some axis lying in the plane of this stage. Finally the glass stage S carrying the preparation can be rotated in its own plane.

The preparation is placed on the stage, contact being made by glycerine. Then a plano-convex lens $a$ is placed under the stage S and another over the preparation concentrically. Here also glycerine serves to insure a good contact. The efficiency of the apparatus can be increased for the investigation of crystals with higher indices of refraction, by using a more strongly refracting glass for the stage, lenses and holders of the object. The liquid used for the contact must also have a higher index of refraction than in the former case. Although this apparatus has proved its usefulness for certain investigations, for example, in the study of the feldspars, the results obtained are not commensurate with its complicated construction. The necessity of having to use special kinds of glass with this apparatus naturally prevents its being used extensively.

**Rotation Apparatus for Investigation in Liquids.**—This method was first proposed by C. Klein and used for studying isolated crystals or fragments, but was later also employed in the investigation of thin sections. The simplest apparatus consists of a low glass dish the bottom of which is a plane parallel glass plate. On one side there is a tapering neck in which a glass stopper can be rotated. The inner end of this stopper is provided with a crystal holder and the outer end with a scale, Fig. 157. The dish is filled with a liquid having as nearly as possible the same index of refraction as the crystal to be studied. The crystal is placed in the holder exactly parallel to the zone under consideration. The extinction direction on the various faces in the zone can be determined with this apparatus. The real optic angle can also be measured directly if the index of refraction of the liquid corresponds exactly with that of the crystal.

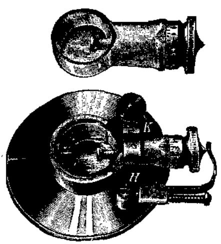


FIG. 157.—Simple Rotation Apparatus by R. Fuesz.

Special objectives with a wide focal angle and not too small a field as well as the appropriate condensers generally accompany this rotation apparatus, so that observations in convergent polarized light can be made although object and objective are separated considerably.

Klein's larger universal rotation apparatus for crystals can be used more extensively. The crystal can be quite accurately adjusted and centered on its holder and the measurements made with considerable precision. For using this apparatus the microscope is placed in a horizontal position and a small rectangular glass dish placed in the path of the rays of light. This dish contains the liquid in which the crystal is immersed, and can be rotated without striking the sides. The plane parallel walls are placed as nearly perpendicular as possible to the axis of the microscope.

A small goniometer can also be combined with the stage of a microscope in a similar manner. It however has the disadvantage that either the focal length of the objective must be much larger on account of the elevation of the adjusting and centering apparatus on the goniometer, or the goniometer must be placed entirely outside of the axis of the microscope and the crystal mounted on an especially long holder. In the latter case, the lever arm is so long that a very slight movement of the adjusting screws produces so large a displacement of the crystal that such a device has not proved practical.

The apparatus shown in Fig. 158 is constructed for investigation of thin sections according to this method. The dish B, which holds the liquid, is closed at *a* by a plane parallel glass plate. S is the stage, the middle part of which consists of glass. The object is fixed on it by means of the clamps *e* and $e_1$. The screw *k* is used to rotate the stage S in its own plane, the motion being transmitted by a cog wheel. With T it can be moved on a second axis perpendicular to the first. The instrument is made for various sizes of object glasses. Ordinary slides can be studied with it but the cover-glass and any adhering Canada balsam must first be removed.

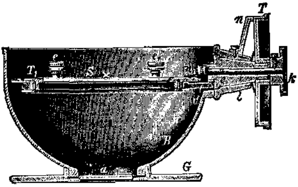


FIG. 158.—Universal Rotation Apparatus for Slides by C. Klein.

## 2. Heating Apparatus

Since the optical properties of crystals are dependent upon the temperature and in some substances change considerably with comparatively slight variations in temperature, a number of devices have been constructed for making microscopic observations at high and constant temperatures. Such an apparatus is also used to observe crystallization in its incipient stages at higher temperatures. For this reason a microscope equipped with such an apparatus, Fig. 159, is also called a *crystallizing microscope*, and can be used especially for physical-chemical investigations. Very high temperatures can be obtained with it without injuring the lenses because the lenses of the objective are continually water-cooled.

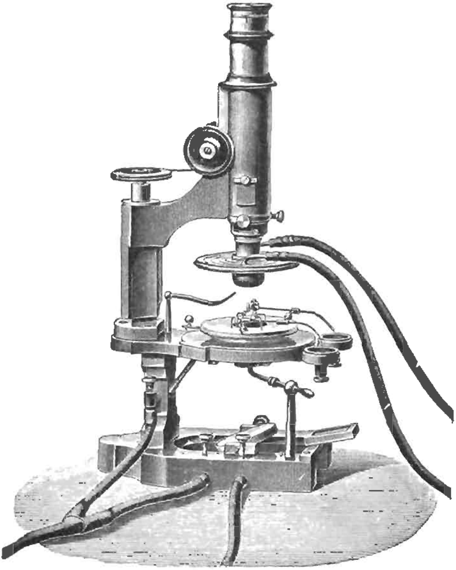


FIG. 159.—Chemical Microscope by Voigt & Hochgesang.

In a special, heating microscope recently constructed by Doelter an electric current is used to produce the heat. With regulating devices, high and very constant temperatures can be obtained. With the microscope shown in Fig. 160, which is also arranged for photography at high temperatures, temperatures of over 1000° with a magnification of 132 can be obtained by using a small furnace. These temperatures can be controlled accurately in intervals of 5° and can be held constant for a long time. With larger furnaces higher temperatures up to 1600° can be obtained but with a smaller magnification, up to 88. Observations in polarized light are possible up to about 1200°, when the object itself is too strongly luminous. The furnaces used are well insulated and are closed top and bottom with a quartz-glass plate. The lenses of the objective are not cemented and are water-cooled. In Fig. 160 this heating microscope is combined with a photographic camera.

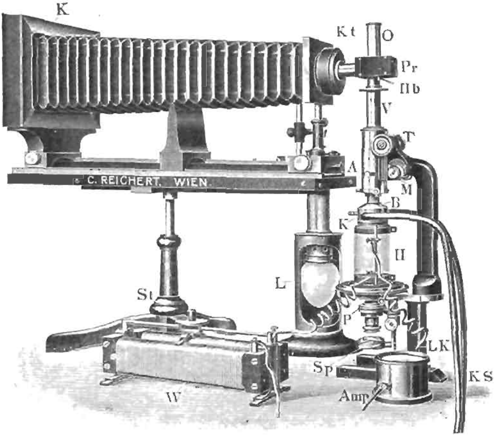


Fig. 160.—Electric Heating Microscope with Photographic Camera by Doelter. (C. Reichert in Vienna).

A very useful heating apparatus for smaller tests is shown in Fig. 161 at about 1/3 natural size. It is covered with asbestos and placed upon four glass legs to insulate it from the stage and the optical apparatus in the stage. The heating box A′ is closed at b and the opposite under-side by a plane parallel glass plate, while the heated air passes through the flue A. The preparation is placed on an object holder located in the hole *b* and heated by means of the gas burner *gg′*. To cool it off rapidly, cold air can be introduced through the tube *r*. The thermometer on the flue A can be read to 450°. It rests on the object like a fork and thus the temperature can be determined with great accuracy.

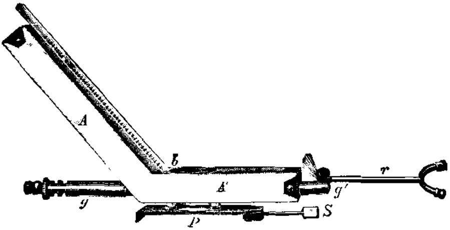


FIG. 161.—Projection Apparatus by W. & H. Seibert.

## 3. Projection and Reproduction Apparatus

There are a large number of devices made to obtain and reproduce microscopic images without any subjective influence. In so far as such a reproduction can be made by microphotography, the method deserves preference on account of its absolute objectivity. There are, however, a whole series of phenomena which a photographic plate does not reproduce with sufficient distinctness, especially when the image possesses some comparatively unimportant feature the importance of which should, however, be emphasized for certain purposes.

**Microphotographic and Projection Apparatus.**—Any microscope can be adapted for projection and demonstration purposes with microscopic preparations, by using a source of light with a system of lenses, as shown in Fig. 162. An electric arc is the best source of light but if electricity is not available, a lime or zircon light or a Welsbach burner can be used. The intensity of light diminishes in the order named. The real image produced by the objective is best for projection, at least with the comparatively low magnifications generally used in a polarizing microscope. An image, a yard in diameter, can be projected by using an arc light and a medium magnification. It may be thrown either on an opaque white screen or on a white transparent screen and viewed from the other side, but it must be exactly focused by means of the micrometer screw of the microscope. The large amount of heating produced by the system of lenses $L_1L_2$ must be avoided by inserting a cooling bath with circulating water K in the path of the rays. Even then great care is necessary on account of the sensitiveness of the Canada balsam in the nicols. As the nicols must be left so long in the path of the rays, even though cooled, it is advisable to *use a microscope equipped with an adjustment for throwing out the polarizer.*

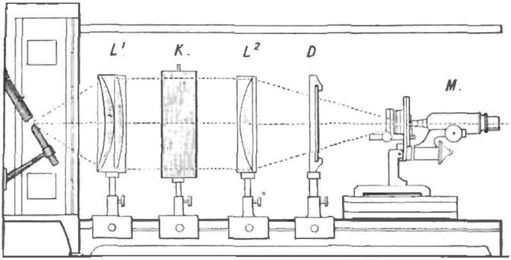


Fig. 162.—Projection Apparatus by W. & H. Seibert.

Fig. 163.—Photographic Camera by R. Fuesz. (1/5 Natural Size).

The larger and more complicated microphotographic apparatuses can be left entirely out of consideration for reproduction of the phenomena seen in a polarizing microscope, because their magnification is comparatively unimportant to the petrographer. Perfectly good results can be obtained with any camera after a little practice, provided it is properly set up with the microscope, and there is a strong, well-centered source of light. The real image of the object produced by a microphotographic objective, corrected for the chemically active light rays, is reproduced on the plate. A projection ocular is used only for stronger magnifications. The simple apparatus represented in Fig.

163, which can be set on the microscope, is very good for low magnifications.

Photomicrographs taken in diffused daylight often lack in sharpness, which is the result of long exposure and not very careful manipulation. Various sources of artificial light are much to be preferred on account of the greater constancy of the luminosity of these sources. An arc or lime light is the best. Recourse to color filters, which play so great a rôle in organic microphotography, is had here, only in special cases particularly for photography at very high temperatures.

Photographing with convergent polarized light is comparatively simple. The real image from a Bertrand lens without the ocular is focused directly on a photographic plate. The Bertrand lenses for ordinary investigations generally have too small an aperture to project the image beyond the tube of the microscope, and hence special lenses with larger focal lengths are needed for photography and projection purposes. It may also be remarked that colored photographs of interference figures have been successfully made by the use of Lumiere plates.

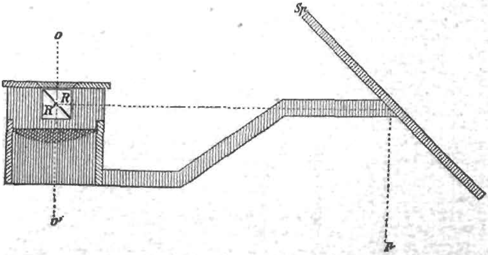


FIG. 164.—Drawing Apparatus by Abbe.

**Drawing Apparatus.**—There is a large number of drawing devices depending upon the principle of the camera lucida. The image observed in the microscope is thrown upon a sheet of drawing paper, where it appears uniformly distinct over the whole field and can be traced with a sharp pointed pencil. Two of these constructions have been found to be especially useful. The first of these is the *Abbe drawing apparatus*, the second the

*Nachet.* The former is to be preferred because there is no loss of light even when the strongest objectives are used.

The Abbe apparatus, Fig. 164, consists of two prisms RR′ cemented together, forming a cube. They are silvered on the plane of contact with the exception of a small spot in the center. The eye receives the image *o* from the ocular through this opening, while a mirror placed at a distance of 70 mm. reflects an image of the drawing paper on the silvered surface from which it is reflected to the eye. The difference in intensity of luminosity of the object and the drawing surface can be regulated by inserting plates of smoked glass with different depths of color in the path of the rays from the latter.

The Nachet drawing apparatus, Fig. 165, consists of a prism with a rhombic cross section *abcd* on the front of which a small prism *efg* is cemented over the ocular. The rays *o*′ coming from the object strike the face *ef* perpendicularly and pass to the eye unrefracted. The rays from the drawing pencil *p* suffer reflection at *cb* and *ad,* and then pass out of the apparatus the same as the others.

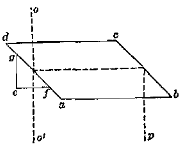


FIG. 165.—Nachet Drawing Apparatus.

It is obvious that an interference figure can also be drawn with this apparatus. It is very useful for measurements under certain conditions, especially when the interference figure has been traced on cross-section paper.

## Summary of Methods

When all the methods that may be employed for determining crystals with a polarizing microscope are assembled, the following are noted:

1. Observation of the index of refraction.
2. Determination of crystal form and cleavage.
3. Observation of inclusions.
4. Determination of color and pleochroism, including observations in reflected light.
5. Recognition of double refraction.
6. Determination of the position of vibration directions.
7. Measurement of the double refraction.
8. Determination of the optical character of the principal zone.
9. Distinction between uniaxial and biaxial crystals.
10. Determination of the optical character.
11. Determination of the position of the optic plane.

12. Measurement of the optic angle and determination of the dispersion.

Except for the sake of practice for beginners it is not necessary to adhere strictly to the order given.

In work with the polarizing microscope with a definite object in view, the crystal system is first determined and then the various properties necessary for the determination of the substance are observed.

The determination can only be made between crossed nicols and in many instances, especially with biaxial crystals, observations in parallel light must be combined with those in convergent light.

The following scheme is given for this determination:

1. All individuals of a substance remain dark between crossed nicols through a rotation of 360°: Cubic crystals.
2. Most individuals become alternately light and dark in a rotation through 360° between crossed nicols: Not cubic crystals.
   - 2*a*. The vibration directions always lie parallel or symmetrical to the outlines of the crystal: Hexagonal, tetragonal, or orthorhombic crystals.
   - 2*b*. The vibration directions lie partly parallel or symmetrical and partly oblique to the outlines: Monoclinic crystals.
   - 2*c*. The vibration directions always lie oblique to the outlines: Triclinic crystals.
   - $2a_1$. A uniaxial interference figure is obtained in convergent polarized light: Hexagonal and tetragonal crystals.
   - $2a_2$. A biaxial interference figure is obtained in convergent polarized light: Orthorhombic crystals.

Crystals of the hexagonal and tetragonal systems can be distinguished from each other only by crystal form and cleavage.

**This schematic arrangement can be modified in its detail, and there is a considerable difference between the investigation of isolated crystalline powders or cleavage fragments and determinations in thin sections. In the former case the individuals are frequently all, or nearly all, orientated in the same manner on account of crystallographic development or perfectness of cleavage and lie on one certain crystal face. In thin sections, on the other hand, accurate crystallographic orientation occurs only in exceptional cases. The cross sections are orientated in various ways rendering the determina-**

tion of the crystal system easier. These two cases will be considered separately.

When the observations are made on a powder and none of the individuals affect polarized light, the conclusion cannot be drawn that the substance is cubic. Whether or not it is uniaxial and all the individuals accidentally lie on the basal pinacoid can be determined by observations in convergent light. In a thin section determinations in convergent light are rarely necessary.

If there are individuals of a substance in the powder or in a thin section, which give different interference colors when the thickness is the same, recourse is taken at once to observations in convergent light. Whether the substance is uniaxial or biaxial can be best determined on those individuals which show the lowest interference color, because these are most inclined to an optic axis which will appear within the field of vision. It will be very difficult for a beginner to find all those individuals of one substance, especially when the crystals are colorless. The interference colors may be different and this may be accompanied by a difference in the whole habit in various directions. The appearance of colorless mica in thin section may be taken as an example. All sections transverse to the basal pinacoid show lath-shaped crystals, sharp cleavage cracks, and high interference colors. Sections of the same mineral parallel to the base have very weak or no double refraction on account of the small optic angle. There is also no trace of cleavage or elongation. The mineral appears this way also when powdered. The brilliant colors observed in the interference figure are proof, however, that the mineral has strong double refraction.

If it has been found that the substance in a powder is biaxial, an attempt should be made to obtain an interference figure as nearly symmetrical as possible. If the interference figure, obtained from an individual with symmetrical extinction, is symmetrical to two planes, the crystal is orthorhombic. If it is symmetrical to one plane only it may be monoclinic. The latter is certainly true if the fragment shows oblique extinction in parallel polarized light. If the crystals have a prismatic development or a prismatic cleavage they can be determined as orthorhombic by the parallel extinction of the individuals oblique to the plane of the optic axes. Distinction between monoclinic and triclinic individuals is very difficult because individuals with oblique extinction are also oblique to the axes, as is generally the case in triclinic crystals.

The distinction of uniaxial from biaxial crystals in powders is often very difficult when the crystals are elongated parallel to the principal axis or to the acute bisectrix or when they have good cleavages parallel to these faces. All individuals then lie approximately parallel to the corresponding principal optical directions. An interference figure parallel to the optic axis of a uniaxial crystal and that in a section parallel to the plane of the optic axes or perpendicular to the obtuse bisectrix are of such a character that even an experienced observer may often draw erroneous conclusions from them. When many crystals of approximately the same size are observed, it is noted that all needles of uniaxial crystals show the same interference colors for the same thickness and, when embedded in a mobile liquid and rolled by the movement of it, the interference color does not change. In biaxial crystals, however, there will be a difference when the thickness is the same, depending upon whether the observation is made parallel to the optic normal *or the obtuse bisectrix, and this change can be verified when the* crystal is rolled by the movement of the liquid.

The beginner usually experiences difficulty in determining the crystal system, partly on account of the optical anomalies and partly on account of the great similarity which the systems of lower symmetry show to those of higher symmetry in their optical behavior. Optical anomalies in cubic crystals are often of such magnitude that they show quite brilliant interference colors and in basal sections of uniaxial minerals the double refraction may be so low that no definite reaction can be obtained either in convergent or parallel polarized light and the mineral may be considered cubic. Such is the case in a cross section of apatite.

Uniaxial minerals frequently show a transition to biaxial by the opening of the dark cross of the interference figure when rotated, for example, quartz, and vesuvianite, while biaxial crystals approach uniaxial by a small optic angle, thus, phlogopite. Monoclinic and triclinic crystals assume the properties of orthorhombic when their oblique extinction cannot be measured, for example, muscovite and epidote, and oblique sections of orthorhombic minerals with a decided deviation from symmetrical extinction can sometimes be observed. The determination of the crystal system in such *cases can be made accurately only by a skilled observer.*

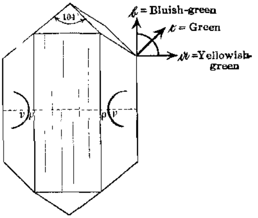


Fig. 166.

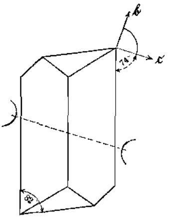


Fig. 167.

Optical Sketch of a Crystal.

Further investigation of minerals, after the crystal system has been determined, is best carried out systemmatically according to the scheme given on page 135, using the material in the corresponding chapters as a basis. All the optical properties of the crystal investigated can be shown in a sketch as represented in Figs. 166 and 167.

These methods of crystal drawing have proved very practical and give a clear idea of the results of the microscopic study. After the form, cleavage, inclusions, etc., have been drawn as true to nature as possible with the aid of a drawing apparatus, the vibration directions are determined and indicated on the drawing by arrows. The determination of the relative values of two rays vibrating in a cross section, combined with the investigations in convergent light, gives the directions of the axes of greatest, medium, and least elasticity which are indicated in the figure by $\mathfrak{a}$, $\mathfrak{b}$ and $\mathfrak{c}$. The index of refraction in any direction is indicated in the following way: if it corresponds with that of Canada balsam the corresponding arrow is drawn very lightly; if it is still lower the arrow is dotted; if it is higher the arrow is drawn heavier and is the heavier the greater the difference between the index of refraction for the corresponding vibration direction and that of Canada balsam. If pleochroism is present, it is determined and the arrow for the *corresponding direction is labeled accordingly. The amount of the double* refraction estimated from the interference color is indicated by arcs connecting the arrows for the vibration directions. Here, again, very low double refraction is indicated by dotted lines, while the heavier lines indicate stronger double refraction. When the double refraction is very strong, the lines are doubled. Investigation in convergent light reveals whether the substance is uniaxial or biaxial. If the former is the case and the axis emerges perpendicularly, a small circle with a black cross is drawn in the center of the sketch. If the plane of the drawing is parallel to the axis the same signal is made outside of the sketch. If the section is oblique the interference figure is sketched on the edge of the crystal about as it appears in the microscope. If the crystal is biaxial, the true position of the optic plane is indicated and the symmetry of the emergence of the axes as well as the approximate size of the optic angle is shown in the sketch. There are, naturally, cases in which a sketch of this character does not give the entire perspective of the optical properties, but in a large number of cases detailed descriptions are unnecessary, and a conception of all the optical properties of a crystal can be had at a glance, as far as they can be determined by the qualitative methods of microscopic technic. Fig. 166 is based upon crystals of hydrated basic copper sulphate, and Fig. 167 upon an artificially prepared manganese salt corresponding to vivianite.

## CHAPTER VII

# Preparation of Material

**Investigation of Rock Powder.**—Rock powders were used for the earliest studies of rocks under the microscope. The powder on the slide was covered with water ($n = 1.333$) to reduce the total reflection as much as possible. Later, cedar oil ($n = 1.52$) or Canada balsam ($n = 1.545$) was used. This very simple method can still be used to get very good results in determining rapidly the approximate properties of a rock or a mineral. There may be too little of some of the constituents to determine them in the usual way and then recourse is taken to this method, in which case the residues of chemical or mechanical separations are used. There is a large number of minerals that are difficult to determine in a slide, but which show characteristic features in powdered form. This is particularly true for minerals that cleave easily. Cleavage plates may be studied in convergent light, and minerals with similar characters can be easily distinguished. Scapolite, the different members of the mica group and similar minerals, topaz, cyanite, and prehnite are some which in many instances can be positively determined in cleavage plates only.

Table 19, I will aid in these determinations. The best method of preparing the material is to crush a small grain of the mineral between two object glasses by pressing between the fingers. The larger pieces resulting from this treatment are placed on another object glass and covered with *eugenol*, which has an index of refraction the same as Canada balsam ($n = 1.545$). Finally a cover-glass is placed on the preparation.

This method is especially applicable in the study of porous materials such as sand, and in the investigation of soil of any sort. The index of refraction of the grains may be determined accurately according to the Schroeder van der Kolk method (see Part I, page 38). This is of great importance in the determination of the feldspars which are otherwise difficult to recognize in a powder. (See feldspar group, method No. 7.)

Various grains of a mineral in a powder may have different thickness. This may make them appear to have different optical properties, which gives rise to much confusion in all investigations on powders, especially for a beginner. Slides, however, can be prepared from such material in the following manner: the powder is mixed with a thick paste of zinc oxide and potassium water glass and the mass is left to harden in a short glass tube of large diameter. A slide is made of the mixture, thus prepared, by the method of making rock sections, to be described below.

It will thus be seen that the microscopic investigation of rock powders is often quite important and, since these methods frequently lead to conclusions quite different from those obtained in studying a thin section, they should be strongly emphasized in petrographical studies.

In some cases, which are, however, quite infrequent, certain clues are obtained by observing the crystallographic form of the rock constituents. Great care must be taken in the preparation of such material that the grains are not broken. The isolated material is examined either without any liquid or immersed in one such as water, which has an index of refraction widely different from that of most of the rock-forming minerals.

The rock is coarsely crushed in a mortar for mechanical and chemical separations. Then by pounding and hammering, but not by rubbing, a powder is prepared in which the grains are as nearly of equal size as possible. Most of these grains consist of but a single mineral. Grains of various sizes are isolated by means of a series of sieves of from 25 to 250 meshes per square inch. The fine dust, which is formed in large amounts in all these operations, is thus removed. This is quite necessary, at least for the mechanical methods of separation, because the dust would remain suspended for a long time in the rather viscous liquids used in these operations. The dust is only used where there are microlitic constituents in the rock to be studied. On the other hand, a fine dust-like condition is especially favorable for chemical methods of separation and, in this case, it is the coarser grains that must be removed.

It is evident that the material to be studied and prepared by these various methods should be as fresh as possible and must not be taken from a weathered surface or otherwise altered portion of the rock. The material should be carefully studied first under the microscope before any further investigations or attempts at separation are made.

**Preparation of Thin Sections.**—Thin sections are the most important preparations for the study of rocks, not only because a large number of variously orientated mineral sections are shown side by side, but also because the texture of a rock, which is so important in petrography, can be studied.

The preparation of thin sections, especially of the harder rocks, was formerly an operation requiring unlimited time. They were ground by hand on an iron plate covered with wet emery powder. This method is still used for polishing small rock chips. The operation has been greatly simplified by modern cutting and polishing machines but, in spite of this, it is nevertheless a tedious task requiring much practice and skill. It is advisable to have such work done by a specialist, as for instance Voigt und Hochgesang in Goettingen, Germany, or W. H. Tomlinson, in Swarthmore, Pa. Nevertheless, every petrographer should be able to prepare usable sections. This may be necessary in some cases where a knowledge of a rock is desired at once. For this reason, the principal hand machines will be briefly described here.

A small cutting and polishing machine driven by hand or, if the necessary power plant is at hand, one equipped to run by power is an indispensable part of the equipment of a modern petrographical laboratory. Fig. 168 illustrates such a machine designed by Voigt and Hochgesang. Thin plates of quite hard rocks can be cut in a comparatively short time by means of a rapidly rotating metallic disk set with bort, emery, or carborundum powder. The plates can then be ground down on the polishing disk.

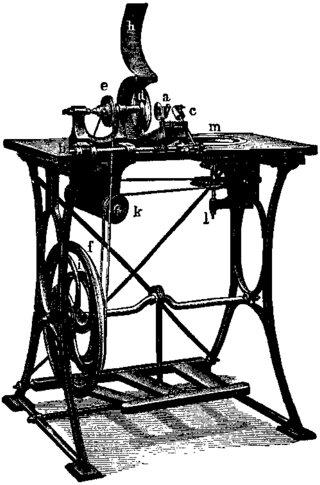


Fig. 168.—Cutting and Polishing Machine.

The polishing plate consists of a slightly convex iron disk, a lead plate being used for the coarser manipulations. It can be made to rotate rapidly. At first coarse powder, emery or carborundum, is placed on it with water, while fine powder is used for the finer polishing operations. The plate to be polished is pressed by hand, or by a mechanical device, as evenly as possible on the rotating disk until a plane surface is obtained. Then it is rubbed with fine wet powder and, finally, with dust entirely free from grains until the surface is polished. Thin sections are not given a high polish except in special cases, e.g., when they are to be used with a Wallerant total reflectometer (see Part I, p. 40).

When one surface has been ground as carefully as possible, it is firmly cemented to a small glass plate. Canada balsam, which is used as a cement, is placed on the glass and evaporated on a water bath until it is hard but not brittle. Then it is heated carefully until it becomes fluid and the ground fragment is warmed and carefully pressed into it. The fragment should be moved back and forth slightly to remove the air bubbles from the balsam. When no more bubbles can be seen through the glass the fragment is held firmly for a moment until the balsam has completely cooled. Then the same grinding process is carried out on the other side of the fragment, but naturally great care must be taken that the abrasive agent does not tear a portion of the fragment away. The final polishing is accomplished under special precautions using only a very small quantity of the finest grinding material. *It is tested from time to time under the microscope* to see whether the proper thickness has been obtained and also to see that the entire section has a uniform thickness. A perfect thin section should be a plane parallel plate 0.03 to 0.04 mm. thick and the surface should cover three or four square centimeters.

When the section is finished, it is carefully cleaned and removed from its bed by heating. A sufficient quantity of Canada balsam is warmed on an object glass and the section is pushed on to this and worked around until the balsam is free from air bubbles. Then a cover-glass about 0.10 to 0.15 mm. thick is cemented over it with Canada balsam. Great care must be used *to remove all the air bubbles from the balsam and also not to break* the section in transferring it or in pressing the cover-glass on it. The whole process of making sections requires much care and attention, and is extremely tedious, especially for one who has had very little practice. Even with as much care as is possible, it is difficult to prepare a section of the proper thickness large enough to be of much use, until the operator has had considerable experience. Since this involves the loss of a great amount of time, the average petrographer rarely acquires sufficient skill to make a good section.

The preparation of slides from schistose or clastic rocks, or from any loose fragmental rock is especially difficult. It often is a very tedious operation, and the results may be ruined by an intimate mixing of the abrasive agent with the rock. It is absolutely impossible to clean such a section. To be sure, it is possible to fill the capillary spaces, which exist in such rocks, by treating the fragment from which the section is to be cut, with a dilute solution of mastic or saponlac for a long time under pressure. However, the organic substance, thus introduced, may be dissolved out again by the Canada balsam *so that extreme precaution is necessary in the subsequent operations.*

Thin sections are used not only for microscopical investigations, but very frequently also chemical tests may be made upon them. If the section is covered, a portion of the cover-glass is cut with a diamond glass cutter, which is a stylus with a small cleavage piece of diamond fastened in the end, and removed by warming it slightly. The balsam still adhering to the uncovered portion must be carefully washed away with benzol or alcohol so that the chemical reagents may have easy access to the rock. For other investigations the rock section may be cut with a diamond stylus and a portion removed from the object glass by warming slightly so that it is isolated from everything else. After it has been thoroughly cleaned in benzol or alcohol, it may be digested in acid or ignited on a platinum foil, as the case requires. Sections of individual minerals may be removed from such a rock section and they can be investigated micro-chemically.

## CHAPTER VIII

# Methods of Separation

All methods employed to resolve a rock into its components or *to isolate a single rock constituent are designated as methods of separation.* Such processes are for various purposes. In some cases a rock constituent, whose accurate determination is not possible under the microscope, is isolated from the rock, and can then be investigated further, and a chemical analysis made. In other cases it is interesting, as well as profitable, to determine the proportional amounts of the several constituents of a rock. Finally, those minerals, which are only sporadically present, may be concentrated and important clues to the genetic relationships of the rocks concerned may be obtained by studying them.

The methods of separation generally give good qualitative results, but it often requires a combination of several of these methods to isolate a constituent for quantitative analysis, because the material must then possess a high degree of purity.

As mentioned above these methods are divided into:

1. Chemical methods of separation.
2. Physical methods of separation.

### 1. Chemical Methods of Separation

Chemical methods of separation are for the most part quite simple. They are based upon the different solubilities of various minerals in chemical reagents, but such differences are not so great that one rock constituent may be completely dissolved before the others show signs of solution. These methods, therefore, require great care and skill in order to obtain satisfactory results. Besides these difficulties, a part of the rock mass is always rendered unavailable for further investigation and a large amount of by-products, which must be removed, is precipitated in the course of chemical separations. Such methods become so involved in their application that they should be employed only under especially favorable conditions, where the physical methods, to be described later, are not effective.

In some cases acids, in others alkalies, are used for these separations, which may be carried out at ordinary or at elevated temperatures according to the conditions. High pressure may be necessary in some instances, and occasionally a molten solvent may be found quite valuable. The most important reagents are:

1. *Hydrofluoric Acid.*—In general, hydrofluoric acid attacks quartz and silicates high in silicic acid much more readily than it does those low in silicic acid. Among the more important rock-forming minerals, anatase, andalusite, cyanite, hematite, corundum, magnetite, perovskite, rutile, sillimanite, spinel, brittle micas, staurolite, topaz, tourmaline, cassiterite, and zircon are not attacked by hydrofluoric acid or a mixture of it with hydrochloric acid. Minerals of the garnet group, micas, hornblende, pyroxenes, titanite, etc., are attacked with difficulty, while the feldspars (plagioclase more readily than orthoclase), leucite, quartz and minerals of the sodalite group are easily attacked. Rock glass is the most susceptible of all.

Isolation of completely insoluble rock constituents is best carried out in an evaporating dish of hammered lead in which powdered fluorite may be treated with sulphuric acid. Thin layers of the rock powder to be treated are spread over one another separated by layers of fluorite and the whole mass is moistened with dilute sulphuric acid or hydrochloric acid. A tight cover is placed on the dish and all joints are sealed with wax or some other cement. The preparation is left standing until the hydrofluoric acid evolved has acted upon the rock powder. A crust of salts forms very rapidly on the mineral mass during the process and it must be destroyed from time to time. The reaction usually proceeds quite slowly, but it can be accelerated considerably by warming the lead dish a little. The advantage of this process is that large quantities of material can be used, which is of special importance in the isolation of constituents occurring in very small quantities.

In other cases the rock powder may be poured slowly, under constant stirring, into a concentrated solution of hydrofluoric acid, but naturally great precaution must be taken for protection from the vapors evolved. It is advisable to place the platinum dish, in which such a process is carried on, in a cold water bath or a freezing mixture until the first violent reaction has moderated, because the action of hydrofluoric acid on such powders frequently causes a decided increase in temperature. The reaction is interrupted at the proper moment by the addition of a large excess of water. The residue must be washed thoroughly and the gelatinous silica, formed during the process, separated from the unaltered mineral grains by pressing first with a platinum spatula and finally with the fingers. It is poured off with the wash water.

A quantitative separation of the gelatinous silica cannot be made in this manner and the residue must either be heated to change the balance of the silica into a powder that can be washed away, or, after thorough washing, it may be treated with an alkali, which dissolves the separated silica. Hydroxide of iron is generally precipitated in this process and must be extracted with hydrochloric acid. If a small quantity of silica still remains, the treatment is repeated until the material appears sufficiently pure when examined under the microscope.

2. *Hydrofluosilicic Acid.*—Pure hydrofluosilicic acid does not attack quartz. It can, therefore, be used as a means for the quantitative separation of quartz from a rock. However, secondary reactions take place producing a solvent for quartz so that a considerable portion of it is dissolved.

3. *Hydrochloric, Chlorous and Organic Acids.*—Dilute hydrochloric acid is used to isolate silicates from carbonate rocks. However, if the silicates occurring in a granular limestone are easily attacked by hydrochloric acid, as e.g., forsterite and gehlenite, strong organic acids such as acetic and citric are recommended. Even these do not always produce favorable results because they also attack silicates considerably. An aqueous solution of chlorous acid is the best reagent to use in such cases. It is best to prepare this solution fresh by treating a solution of barium chlorate with the calculated amount of dilute sulphuric acid, care being taken to avoid an increase in temperature. After removing the precipitate of barium sulphate, the clear filtrate is used. It attacks calcite quite energetically and has no effect upon most of the silicates. Being an oxidizing agent it may also be used for removing organic substances from rocks.

Pure, warm hydrochloric acid can be employed and by a skillful modification of the process, it is frequently possible to remove the calcite before any effect on the silicates is noticeable. Usually, better results are obtained than with organic acids. The carbonates are soluble in hydrochloric acid with evolution of carbon dioxide; the sulphides with the development of hydrogen sulphide, and usually with the separation of sulphur. Leucite dissolves with the formation of powdery silica, while scapolite and basic plagioclase are more difficultly soluble under the same conditions. Minerals of the sodalite group, nepheline, melilite, olivine, wollastonite, and most of the zeolites dissolve with the formation of gelatinous silica, while serpentine and chlorite are very difficultly soluble. Apatite, powdered hematite and magnetite dissolve without any formation of by-products. Magnetite dissolves most readily after addition of potassium iodide.

Concentrated hydrochloric acid· is used to separate various difficultly soluble silicates from each other. However, a perfect quantitative separation cannot often be affected by such means, because the mass must be digested at higher temperatures for some time until one of the constituents is entirely decomposed. During this process the other minerals have either been partially dissolved or considerably altered. For this reason the earlier custom of dividing a rock into a portion soluble in hydrochloric acid and one insoluble, for analytical purposes, has been entirely abandoned.

4. *Sulphuric Acid.*—Sulphuric acid alone is rarely used to separate rock constituents. Quartz can be separated quantitatively from the main mass of the silicates by digesting the rock powder with dilute sulphuric acid in a sealed tube at a temperature of 150° to 200°. The other constituents are destroyed by this reagent. Application of sulphuric acid in other cases is scarcely to be recommended.

5. *Alum.*—The methods for separating silicates from carbonate rocks, mentioned above, usually do not produce accurate results, which, however, can be obtained by the use of an alum solution. This dissolves the calcite rapidly and leaves most of the other constituents, even dolomite itself, unattacked. It may be used in cases where a quantitative determination of the proportions of calcite and dolomite in a carbonate rock is desired.

6. *Sodium Hydroxide.*—Opal can be dissolved out of a rock with sodium hydroxide. This process proceeds quite rapidly even at ordinary temperatures. If a rock powder is digested for a long time with sodium hydroxide on a water bath a large number of the silicates are materially altered; for example, the feldspars are changed into compounds easily soluble in hydrochloric acid. Other minerals, as pyroxene, quartz, etc., are not altered.

Finally some methods, that are used only in special cases, should be mentioned. Thus spinel and corundum remain unchanged when a rock powder is decomposed with sodium potassium carbonate. Carbonaceous substances can be removed from a rock by heating in an oxidizing flame. A solution of cuprammonium chloride will dissolve metallic iron. Finally bituminous substances can be extracted with ether, benzol, etc.

## 2. Physical Methods of Separation

Physical or mechanical methods of separation depend upon differences in physical properties of the minerals. Specific gravity is by far the most important of these so that the methods dependent upon it must be described in detail. Methods based upon magnetic differences and other properties of the minerals are of much less importance.

**Analyses by Washing.**—The methods so universally employed in commercial processes for separating substances according to their specific gravities can only be used where great differences in specific gravity are involved, as in the separation of ores from rock material. Specific gravity is not the only important factor in this process of separation either in quiet or circulating water. The size and development of the individual mineral particles are of special significance for, on the one hand, fine dust will remain suspended for a much longer time than coarse sand, and on the other hand, *thin plates will settle to the bottom more slowly than rounded grains.* Therefore, the washing process for separating rock constituents cannot be used except where the minerals have very different habits, as mica and quartz, or where the difference in specific gravity is quite considerable. Even then complete separation cannot be effected by washing in most cases.

The apparatus used in soil analysis for separating the various constituents according to their abilities to remain suspended in a liquid is not generally applicable in rock investigation, but another device may be employed for the washing tests. It consists of a series of funnel-shaped glass vessels one above another, each terminating at top and bottom in a glass tube. The powder to be separated is placed in the smallest funnel at the bottom. The lower tube of this funnel is connected with a water tap. A hose from the upper tube leads to the lower tube of the funnel next in size above it. All the connections are made in this manner and the upper glass tube of the largest funnel at the top of the series is made to discharge into a sink. A slow stream of water is passed through the apparatus and it carries the lighter particles along with it and deposits them in the funnel above, where the eddies are weaker on account of the larger size of the vessel. An Eichstaedt apparatus, based on the reduction of eddies with an increase of cross section, gives similar results.

The methods used in washing precious stones from a matrix give better results, especially after some practice. A shallow porcelain dish may be used for this purpose, or better still a flat shield-shaped safety trough in which the powder is spread out with a little water. The trough is held in one hand and is jarred by sharp quick taps with the other. The individual minerals become separated from each other in sharply defined zones. A percussion table, such as is used in ore dressing, can also be constructed, and operated most easily by hydraulic pressure. Serviceable results may be obtained occasionally by blowing or sucking with a regulated stream of air. Mica and graphite are but slightly affected by crushing, while other constituents are reduced to a fine dust that can be blown away by this method.

**Separation According to Specific Gravity.**—The so-called heavy liquids are used to isolate the rock constituents according to their specific gravities. This process is frequently employed, as the liquids have specific gravities higher than those of the individual rock constituents (Table 21, No. 11). After the rock powder to be separated is immersed in one of them it is well shaken and allowed to stand for some time. The heavier minerals sink to the bottom while the lighter ones float.

If the pure powder of two different minerals is well mixed, a quantitative separation of each can be made by using a liquid whose *specific gravity is about the mean between those of the* powders. The specific gravities of the two powders may, however, be so nearly equal as to differ by one unit in the second decimal place.

The relations are not so simple in the rocks. Here we rarely have to deal with particles that consist of but one mineral, as was the case in the example given, but the particles generally consist of several minerals intergrown in different proportions. It is, therefore, impossible to separate the individual minerals of a rock by this method. The separation must be carried out in single stages so as to separate the combinations resulting from such intergrowth from the pure minerals. All this reduces the efficacy of the method so that great differences in specific gravity are necessary to make a complete separation. Powders that have passed through a 25 to 50 mesh sieve are best for all these separations. If the grains are much finer, separation takes place very slowly until finally, if the division is as fine as dust, separation does not occur at all, because the fine particles remain suspended in the quite immobile liquid. The finest dust must be sifted out or washed away in all cases before the powder is placed in a heavy liquid.

The mobility of the liquid employed has a great deal to do with the rapidity and accuracy of the separation. Heavy organic liquids, which may be used, are generally quite mobile.

On the other hand, the heavy solutions of inorganic salts in water are but slightly mobile when concentrated, and some are so viscid that small particles may rise or sink in them very slowly.

Organic liquids have an unpleasant odor and evaporate quite rapidly, but do not act upon the minerals to be investigated. Inorganic solutions are odorless, attack certain minerals quite strongly, also the skin, and are, for the most part, quite poisonous. Thus each has its advantages and disadvantages.

To be of value for separations according to specific gravity, liquids must be capable of being easily evaporated and concentrated so that every gradation of density can be readily produced. In general the process is as follows: grains of the heavier and those of the lighter rock minerals are picked out of the powder. They are placed in the concentrated heavy liquid. The concentration is reduced, by dilution with water in the case of inorganic solutions and with ether or benzol in the case of organic liquids, until some of the grains sink while the others float. The whole mass *of rock powder is now put into the liquid thus prepared.* Another method of obtaining the proper density of the heavy liquid consists in the use of a scale of indicators of known density. The density of the minerals to be separated must also be known. Two of the minerals from the scale, corresponding in specific gravity to the minerals to be investigated, are put in the liquid, and then it is diluted until one sinks while the other floats. The following list of test minerals has been found to be quite practical:

| | Sp. gr. | | Sp. gr. |
|---|---|---|---|
| 1. Sulphur, Girgenti | 2.070 | 11. Quartz, St. Gotthard | 2.650 |
| 2. Hyalite, Waltsch | 2.160 | 12. Labradorite, Labrador | 2.689 |
| 3. Opal, Scheiba | 2.212 | 13. Calcite, Rabenstein | 2.715 |
| 4. *Natrolite, Brevik* | 2.246 | 14. *Dolomite, Muhrwinkel* | 2.733 |
| 5. Pitchstone, Meissen | 2.284 | 15. Dolomite, Rauris | 2.868 |
| 6. Obsidian, Lipari | 2.362 | 16. Prehnite, Kilpatrick | 2.916 |
| 7. Pearlite, Hungary | 2.397 | 17. Aragonite, Bilin | 2.933 |
| 8. Leucite, Vesuvius | 2.465 | 18. Tremolite, Zillertal | 3.020 |
| 9. Adularia, St. Gotthard | 2.570 | 19. Andalusite, Bodemais | 3.125 |
| 10. Nepheline, Brevik | 2.617 | 20. Apatite, Ehrenfriedersdorf | 3.180 |

Better results will be obtained in all separations with heavy liquids if the dimensions of the grains are about equal. This method fails completely with thin, scaly minerals like mica, for a portion of the mica will be found with each of the separated parts. Mica scales can be removed by allowing the powder to glide over an inclined plane of rough paper, or better by breathing into quite a large funnel and causing the rock powder to move over the moistened walls; then mica scales will stick to the walls and can be removed later by inverting the funnel and tapping it. This manipulation must be repeated several times.

Separations with heavy liquids can be carried out in any kind of a vessel, but a beaker is the best and simplest. Comparatively large quantities of the liquid must be used and this is always very expensive. It is also difficult to remove entirely the light mineral grains floating on the surface of the liquid, before the heavy residue is poured out. Under certain conditions, especially when large quantities of heavy constituents are to be treated, the separation can be made more rapidly in a beaker than in a separating funnel, because the large mass of powder sinking to the bottom of the funnel easily clogs up the delivery tube. The beaker is filled over two-thirds full of the liquid, whose specific gravity has been accurately fixed for the minerals in question, and then the powder is poured into it under constant stirring. The powder separates into two distinct parts. The beaker is then set in a large porcelain evaporating dish and left to stand until a layer of clear liquid appears between the floating material and that on the bottom. A hollow conical vessel, *a*, Fig. 169, is set into the liquid and held in a vertical position by a clamp around the neck *b*. A small funnel, *c*, rests in the upper end of the neck. A large dropping funnel, *d*, is so arranged above this that the mercury, which it contains, can drop into the small funnel. As the mercury flows slowly into the conical vessel, the latter gradually sinks until the beaker overflows. Then the influx of mercury is increased so that the vessel sinks very rapidly. This causes the floating material to be washed over quantitatively into the porcelain dish below.

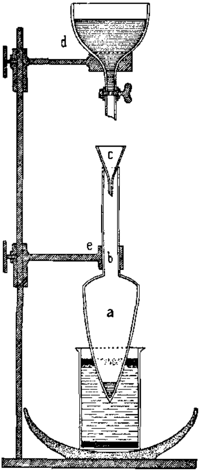


FIG. 169.—Apparatus for Separating Large Amounts of Rock Powder.

It is generally better to carry out the separations in a separating funnel which can be arranged in various ways. The funnel sketched in Fig. 170 has a very simple but practical form. It can be used in nearly all cases so that it will not be necessary to describe more complicated devices constructed for this purpose.

The stopcock B is closed and the funnel filled up to E with the liquid. Then the stopcock A is closed and the powder poured into the upper funnel. After shaking vigorously the stopcock A is opened again, whereupon the heavier constituents collect in D. Then A is closed again and the process repeated until the separation is complete.

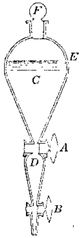


Fig. 170. Separating Funnel.

Organic liquids, aqueous solutions of inorganic salts, and molten inorganic salts may be used for separations depending upon specific gravity.

**Heavy Organic Liquids.**—Many organic liquids are characterized by a high density. Only those liquids are applicable for these processes that do not have an injurious effect upon the operator, do not evaporate too easily, and are quite permanent and not too expensive.

*Tetrabromacetylene* and *methylene iodide* have been found to be extremely useful. When pure, they are light yellowish, exceptionally mobile liquids, that can be diluted easily to any proportions by the addition of ether or benzol. Since the diluent is very volatile it can be readily removed from the liquid, thus concentrating it. Still there is always a considerable loss, because some of the heavy liquid is evaporated along with the diluent. This makes such work quite expensive, especially when methylene iodide is used. The loss is of less importance with tetrabromacetylene because the operator can prepare it himself.

Tetrabromacetylene is an almost colorless liquid that can be very easily prepared at any time. Pure acetylene is passed into bromine until the whole solution becomes light yellow. It is very stable and has no destructive effect upon the rock constituents. When concentrated its specific gravity is only 3.0, so that its application is quite limited.

Methylene iodide is distinguished from tetrabromacetylene by a much higher specific gravity, viz., 3.32 at 16° C. It is considerably above that of most of the rock-forming minerals. The density increases quite rapidly with a decrease in temperature until at its freezing-point, 5° C., the specific gravity is 3.35. Methylene iodide is decomposed quite readily even by the action of light, and this is a great disadvantage. Iodine separates out and colors the liquid brown. It can be removed by shaking the solution alternately with potassium hydroxide and water after which it can be dried with calcium chloride and filtered. Another method of purifying it is to reduce the temperature a little lower than 5° C. and allow the liquid to freeze. Light colored crystals of methylene iodide are formed and these are separated from the dark brown liquid by squeezing. Still this process is very expensive because methylene iodide is so high priced and some is always lost in the process. A powder that has been treated with methylene iodide should be washed with ether and the washing must be continued a long time before every trace of iodine disappears.

The specific gravity can be materially increased by dissolving iodine in the methylene iodide. It retains its mobility, but loses its transparency by this process. If iodoform instead of iodine is dissolved in the liquid, a strong smelling, transparent, yellow liquid is obtained with a specific gravity 3.45. However, it can only be diluted with pure methylene iodide. Finally iodine may be added to this solution and a liquid is obtained which is quite mobile, but nontransparent and has a specific gravity as high as 3.6.

The high index of refraction of methylene iodide ($n = 1.75$) makes it very valuable for optical determinations. This value is increased by the fact that, upon addition of iodoform or sulphur, the index can be increased to 1.78. It cannot be used with a Bertrand or an Abbe total reflectometer because, like all liquids containing iodine, it attacks the strongly refracting glass used on these instruments.

**Heavy Solutions.**—One of the first liquids used to separate rock minerals was a solution of acid mercuric nitrate in water with a specific gravity of 3.3 to 3.4. It was recommended by Count Schaffgotsch. It has a destructive effect on a number of the minerals because of its acid properties and has therefore a limited application. The loss of expensive material may be reduced to a minimum by exercising some care in working with heavy solutions. Since distilled water is used for dilution and washing, little or no expense is involved. Work with heavy solutions is less expensive under all conditions than work with organic liquids. On the other hand, the greater viscosity of the concentrated heavy solutions must be considered. The solutions generally used are:

1. *Potassium Mercuric Iodide, Thoulet Solution.*—A solution of potassium mercuric iodide, $HgI_2.2KI$, is the most convenient of

the various heavy solutions because it can be easily prepared and can be diluted or concentrated to any desired density. It is made by dissolving potassium iodide and red mercuric iodide in the ratio of 4:5 in water, and after the addition of a little metallic mercury it is evaporated on a water bath (not over a direct flame!) until a fragment of fluorite (sp. gr. =3.15) floats on it. Several needle-like crystals form upon cooling and the clear yellow transparent liquid has a specific gravity of nearly 3.2—in summer only 3.17. It is not very mobile when concentrated, but it can be diluted with water to any extent and concentrated again on a water bath. A small excess of potassium iodide does no harm because, upon evaporation, it separates out as a crystalline crust over the liquid, but an excess of mercuric iodide is injurious because it is precipitated upon the addition of water.

*If a solution of a definite specific gravity is to be prepared* by dilution, it cannot be done accurately by adding a measured amount of water to the concentrated solution, because there is a *strong contraction of the solution when it is diluted.* The density of the prepared liquid must be checked by a Westphal balance or by an indicator. The final steps in fixing the specific gravity of a solution should not be attempted by adding water, but by adding a less concentrated solution of the same kind.

Thoulet solution has some disadvantages among which are its poisonous character and its cauterizing effect on the skin. It attacks metals vigorously with the separation of mercury. It is also very difficult to remove from the mineral powder. Sometimes this can only be accomplished by repeated digestion with potassium iodide solution and water. Attention was called to its high index of refraction in Part I, page 37.

2. A solution of *cadmium borotungstate, Klein's solution,* $9WO_3.B_2O_3.2(CdOH)+16H_2O$ is much more difficult to prepare and is usually not made by the operator himself. When a dilute solution of it is evaporated on a water bath until a film of crystals forms over it, a yellow liquid with a specific gravity of 3.36 is obtained upon cooling. It is quite viscid, but it can be mixed with water in any proportions without decomposition, and its mobility is increased very rapidly upon dilution. The liquid is harmless, but is decomposed by carbonates as well as metals, and these must be removed before using it. The crystals of the tungstate, which form upon concentration, can be purified by

draining off the mother liquor. They melt at 75° C. to a liquid whose specific gravity is 3.6, but it is so viscid that it cannot be used to separate fine powders.

3. *Barium mercuric iodide, Rohrbach solution,* is quite mobile with a specific gravity of 3.59. It decomposes very easily so that even its preparation (100 parts $BaI_2 + 130$ parts $HgI_2$) must be carried out with great care. The concentrated solution cannot be diluted with water. A less concentrated solution must be added very slowly by pouring it over the concentrated solution in a thin layer and allowing the two to diffuse. The difficulties encountered in diluting this solution are so great that its application is limited and of late it is rarely employed.

**Heavy Molten Liquids.**—It is necessary to work at high temperatures with molten inorganic salts. Cadmium borotungstate has already been referred to. Other salts recommended for this purpose are:

*Lead chloride,* sp. gr. = 5.0, and *zinc chloride,* sp. gr. = 2.4. When melted they can be mixed with each other in all proportions. The melting-point is about 400° C. The operations may be carried on best in a small test-tube on a sand bath, and the powder to be separated should be poured into the melted mass in small portions. The liquid is very viscid and splutters a great deal so that it is quite dangerous to use it. When the separation is completed, the mass is cooled and the cake, thus forced, is cut through the middle horizontally. The mineral particles are freed from the mass and purified by digestion with water to which a little nitric acid has been added. *Mercurous nitrate* melts at 70° C. to a very mobile liquid with a specific gravity of 4.3. It can be liquefied very easily on a water bath and diluted in any proportions with warm water. It possesses, however, the very disagreeable property of decomposing with a rapid separation of a basic salt which has a high melting-point. For this reason the molten salt often begins to solidify before the separation of the rock powder is complete. If the melt is diluted with water it is somewhat less decomposable. Molten *silver nitrate* is also very useful. By heating to 200° C. a mobile liquid is obtained with a specific gravity of 4.1. This can be diluted in all proportions with potassium nitrate and a rock powder can be completely separated in this liquid. However, the high temperature at which one must work makes the use of this salt quite unpleasant. *Thallium silver nitrate* is prepared by dissolving equivalent amounts of thallium and silver in nitric acid. At 75° C. the double salt forms a liquid, as mobile as water, and has a specific gravity of nearly 5.0. It can be diluted in all proportions with water and concentrated again by evaporation on a water bath. It is necessary to work very carefully with this melt because the specific gravity increases upon cooling as well as upon the evaporation of the water. The separation should be carried out as rapidly as possible on a water bath at constant temperature. Then the mass should be solidified rapidly by directing a stream of cold water upon the outside of the containing vessel. Its properties are very similar to those of *thallium mercurous nitrate* with a specific gravity of 5.3, except that it is decomposed by sulphides. Both of these salts are, however, quite expensive on account of the high price of thallium.

**Magnetic Separation.**—The methods of magnetic separation give good results in many cases. Sometimes a simple magnet and, sometimes, an electro-magnet is used for this purpose. A simple magnet is very useful to draw out steel fragments which have been introduced into the powder during pulverization and would decompose Thoulet's solution. Besides metallic iron, only magnetite and pyrrhotite are attracted by a simple magnet. They are best removed by spreading the dry rock powder out on a paper stretched on a frame supported by four legs. Then a magnetized steel comb is drawn along underneath the paper. The magnetic particles are thus drawn to the edge of the paper.

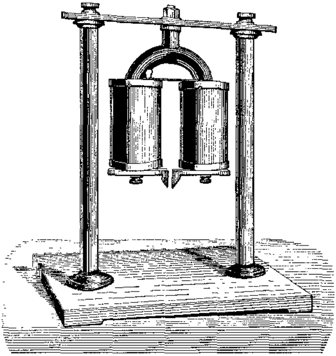


FIG. 171*a*.—Electro-magnet.

An electro-magnet has a much more extensive application. The best form of this is a horseshoe. A rectangular piece of soft iron is screwed on each pole and so arranged that by turning the pieces the distance between the poles can be regulated, Fig. 171 *a*. Thus, the strength of the electro-magnet can be controlled. Most of the minerals containing iron are attracted by it, while those free from iron—quartz, feldspar, etc.—remain behind unless they contain magnetic inclusions. The degree of magnetic attraction is independent of the amount of iron present. As yet, minerals have not been systematically arranged according to the degree of attraction, but a short classification of the most important minerals can be found in Table 19, No. VI.

To separate a rock powder electro-magnetically, it is spread out on a stiff piece of paper and passed back and forth under the poles of an electro-magnet, the strength of the magnet being regulated as described above. This paper is removed from time to time and a clean sheet is placed under the magnet. Then by breaking the circuit the attracted particles fall off.

The separation can be made in water or alcohol when very fine powder is to be treated. The rock powder is washed in the liquid and then the latter is caused to pass over the magnet. The process can be accomplished in much the same manner as it is on a large scale in the commercial separation of ores. Numerous minerals that are only slightly magnetic become strongly magnetic when heated to redness in an oxidizing flame. This phenomenon finds extensive application in science as well as in commercial processes.

**Other Methods of Separation.**—Difference in fusibility has been suggested as a means of separating minerals, but this method will not give good results except when the difference is very pronounced and the mineral particles are of even size. The powder is spread out on a platinum foil and heated to glowing in a blast flame until the more easily fusible part is melted together, then the unmelted portion is simply shaken off.

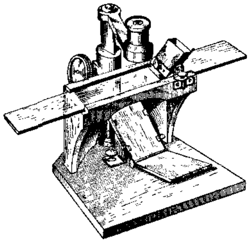


FIG. 171.—Lens Stand. (W. and H. Seibert.)

Finally, there are cases in which certain rock constituents must be sorted by hand. A lens is used in this work, but it must not have too strong a magnification because, on the one hand, the short focal length of a high power objective lowers it so as to be in the way of the operator and, on the other hand, the unsteadiness of the hand is more evident. The instrument shown in Fig. 171 is quite useful for such operations. A strip of glass whose width equals the diameter of the lens, can be pushed back and forth under the lens. The powder is spread out evenly on this glass by means of a distributer and is observed through the lens. The individual grains are then removed with a pair of small forceps or a sharp moistened splinter of soft wood. The powder can also be immersed in a liquid on the glass strip to make the grains more transparent. It is often advantageous to use a pointed glass tube attached to a suction pump to remove the desired grains. These are drawn through the tube over into a glass flask arranged for this purpose. With a little practice very fine rock particles can be sorted out with this apparatus. It can also be used to examine the particles in polarized light by placing a glass plate at the proper angle below the stage and a nicol prism above the lens. In this way the apparatus has an extensive applicability. A binocular microscope, Part I, page 41, also gives good results in such cases.

## CHAPTER IX

# Methods of Investigation

Investigation with a polarizing microscope is the most important and most frequently used of all the methods of petrographical research. Next in importance to the microscope are the quantitative and qualitative chemical analyses which enable one to make as complete a determination of a rock as does an optical examination of a thin section. A determination of the specific gravity and other physical properties is also made to complete the information concerning a mineral.

The methods of investigation, like those of separation, fall naturally into two groups. These are the chemical and physical methods. The treatment here includes only certain subordinate sections of each because the general chemical methods are not within the province of this book, while the optical methods have been thoroughly discussed in Part I.

Under the heading of chemical methods, only such chemical reactions are discussed as are adapted to a rapid recognition of minerals in the simplest way possible, especially with very small amounts of the material. Special reactions, which are very characteristic for certain minerals, will also be given. The physical part includes all physical methods except the optical investigations.

## 1. Chemical Methods of Investigation

### (*a*) General Reactions

The methods of micro-chemistry may be mentioned first, as of importance in the general reactions of a number of the elements. These can only be applied successfully when there is nothing to interfere with them. In many cases the tests are so simple and easy that good results may be obtained with them, but in just as many other cases they are very complicated and the obtaining of unquestionable results is not dependent upon a large amount of practice alone but also upon numerous other contingencies, the efficaciousness of which cannot be positively determined in every case. Only such of the numerous micro-chemical methods will be discussed as are comparatively simple and give definite results.

**Reactions with Fluosilicic Acid.**—The reactions with fluosilicic acid, which is replaced by hydrofluoric acid in the investigation of silicates, are especially important for petrographical studies because the fluosilicates formed are very soluble and crystallize easily. They do not possess the importance generally ascribed to them because, in addition to the characteristic salt of any base, frequently double salts also separate out, and the composition of these as well as the conditions under which they form have not as yet been thoroughly studied. They do not seem to give good results in the investigation of minerals like the feldspars containing aluminium and alkalies because a double salt is always formed in varying amounts and its exact composition is unknown. These investigations are carried out on an object glass covered with a uniform thin layer of Canada balsam free from bubbles and not completely hardened. It can be prepared by placing some balsam on a glass and warming it slightly. A celluloid plate can also be used, but celluloid always shows some double refraction phenomena, and this interferes with the optical investigation. A drop of pure fluosilicic acid (with silicates pure hydrofluoric acid suffices) is placed on the mineral splinter and the solution is left in a closed box of dry wood to evaporate completely. The crystals are formed first toward the end of the process. Every trace of acid must be positively absent before investigating under a microscope, or there is danger of etching the objective. The fluosilicates of sodium, potassium, and calcium have higher indices of refraction than Canada balsam, while the indices of magnesium, iron, and manganese fluosilicates are lower.

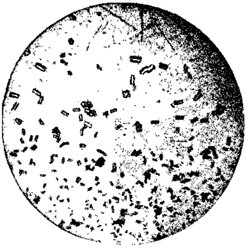


Fig. 172.—Sodium Fluosilicate.

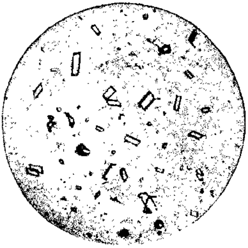


Fig. 173.—Calcium Fluosilicate.

*Sodium fluosilicate,* hexagonal; low double refraction, negative; mostly in short, thick prisms and twins as shown in Fig. 172, or in long needle-like or pyramidal crystals rarely tabular, parallel to the base. *Potassium fluosilicate,* cubes and octahedrons, usually quite large; often distorted, tabular octahedrons, quite similar to the plates of sodium fluosilicate mentioned above. *Lithium fluosilicate*, not very characteristic; acicular and monoclinic, apparently hexagonal. *Magnesium fluosilicate*, as well as the similar compounds of iron, manganese, nickel and cobalt: rhombohedral, colorless or very light colored; short to long prismatic, often with many faces; high double refraction, positive; characterized by brilliant interference colors. *Calcium fluosilicate*, short, monoclinic prisms with inclined terminations, Fig. 173, low double refraction, negative; $b = \mathfrak{a}$, $c : \mathfrak{b} = 40° f$. Irregular growths with rounded outline are generally observed; crystals, rare. The crystals of *strontium* and *barium fluosilicates* are quite similar to these. The latter are usually very small, since they are quite insoluble. *Aluminium fluosilicate* is a gelatioous substance. It forms rhombohedral double salts with the alkalies and these salts have strong double refraction.

**Reactions with Certain Elements.**—For these reactions the minerals to be tested are dissolved in sulphuric or hydrochloric acid, or they can be fused in a platinum crucible with sodium potassium carbonate and a small amount of saltpeter or potassium acid sulphate. Sometimes potassium fluoride or fluorite is added. The salts obtained from these operations may then be further studied. Flame or blowpipe reactions give more definite results in many cases than micro-chemical tests, the latter being used in special cases. The most important and reliable reactions that will be considered are the following:

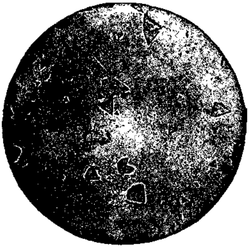


FIG. 174.—Sodium Uranyl Acetate.

*Sodium.*—The yellow color of the sodium flame serves as an indication of this element. The slightest trace of sodium impurities will produce the yellow flame, hence it is better to make a micro-chemical test for the sake of accuracy. A drop of an acetic acid solution (N. B. free from sodium!) of uranyl acetate is added to the solution to be investigated. Sharply defined, light yellow tetrahedrons of sodium uranyl acetate are formed with an index of refraction less than that of Canada balsam. Fig. 174 shows these crystals under the microscope with the tube slightly raised. If magnesium, or a similar element, is present in the solution, a triple acetate containing all these elements is formed. It is easily obtained in large rhombohedral crystals of very light yellow color, low index of refraction, and very high negative double refraction. It generally forms combinations similar to a cubic icositetrahedron. If there is but a small amount of sodium present, some magnesium salt can be added, if not already present, and a very sensitive reaction for sodium can be obtained with the triple acetate, since it contains only 1.5 per cent. sodium.

*Potassium.*—The violet colored flame of potassium is obscured by sodium if it is present at the same time. The potassium color can be recognized when the colored flame is observed through a blue cobalt glass, but numerous potassium silicates do not give the characteristic coloration. These must be heated with gypsum, free from alkali, or with a mixture of gypsum and fluorite. Potassium is best precipitated as potassium platinochloride which begins to crystallize only after a long time has elapsed. Crystallization can be accelerated by adding a drop of alcohol. Sharp, yellow octahedrons and combinations of it with the cube are formed, which have a very high index of refraction. Ammonium, rubidium and cæsium give rise to the same type of crystals.

*Lithium.*—The carmine red colored flame of lithium is obscured by sodium. Nevertheless a very small quantity of lithium can be recognized in the presence of a predominating amount of sodium in an ordinary flame. The powdered mineral is stirred by a heated platinum wire, which with the adhering particles is dipped into tallow. The lithium color appears when this preparation is burned in an ordinary candle flame. The determination by means of a spectroscope is absolutely positive, while micro-chemical reactions, e.g., precipitation as a carbonate, are less reliable. If a little potassium carbonate is added and the solution evaporated, lithium carbonate crystallizes in slender needles having a strong double refraction, parallel extinction, and a negative character of the principal zone. These needles almost invariably unite to form sheaf-like or plume-shaped aggregates, and are characterized by a lower index of refraction than Canada balsam.

*Calcium.*—The yellowish-red flame of calcium salts is not characteristic enough. A micro-chemical test for calcium is better. A drop of very dilute sulphuric acid is added to the solution of a calcium salt and upon evaporation slender needles of gypsum crystallize out, which tend to unite into star- or sea urchin-shaped aggregates, especially in acid solutions. When the calcium content is small, it is better to evaporate the sulphuric acid off of the object glass and to take up the residue with a drop of water. Then, the individuals appear as needles with oblique terminations making an angle of 65 1/2°, Fig. 175. They unite very readily to form the characteristic swallow-tail twins with a reëntrant angle of 131°. See the description of the mineral gypsum on a subsequent page for its optical properties. Calcium oxalate forms small crystals very difficult of determination.

*Strontium and Barium.*—The purplish-red flame of strontium and the yellowish-green of barium are not very reliable tests without the aid of a spectroscope, but good tests may be obtained micro-chemically. Some potassium oxalate is added to a neutral solution of the salts, which is left to stand for some time on an object glass, covered so as to retard evaporation. Barium oxalate crystallizes out in fan-shaped crystal skeletons and needles with oblique end faces, 115°. They have an extinction $c : \mathfrak{b} = 24°$. The lowest index of refraction exceeds that of Canada balsam only slightly. The double refraction is very high. Strontium oxalate usually shows two types of crystallization, but four-pointed stars are especially characteristic. When they lie horizontally, they do not affect parallel polarized light and in convergent light they give an expanded cross that shows positive double refraction. It is quite significant that when they are embedded in liquid Canada balsam they disappear entirely and cannot be found again in polarized light. The other type of crystallization shows small rectangles with horn-like projections on the corners. The crystals have strong double refraction and an index of refraction somewhat higher than the other type of crystals. Barium oxalate crystallizes from hot solutions in elongated six-sided, tabular crystals that can be recognized as penetration twins of two or more individuals. They are perhaps triclinic with cross sections like crystals of stilbite. The double refraction is rather low. Strontium salts, under these conditions, give small lancet-shaped bars with a positive principal zone, parallel extinction, and medium double refraction. The index of refraction is less than that of Canada balsam. They form star-shaped twins at an angle of about 90° and give no interference figure in convergent light. These tests, as well as numerous other micro-chemical tests, are of little value to prove the presence of these two alkali earths.

FIG. 175.—Gypsum.

*Beryllium.*—There is no practical method to prove absolutely the presence of beryllium in small amounts.

*Magnesium.*—The micro-chemical test for magnesium is carried out after the iron and manganese salts have been precipitated by a slight excess of ammonia in the presence of sal ammoniac. The solution is greatly diluted and sodium phosphate added. It is then allowed to evaporate, and as the solution is concentrated, hemimorphic orthorhombic crystals of magnesium ammonium phosphate, Fig. 176, form. They are much more perfect than when they are precipitated rapidly by an excess of ammonia. They have a rather low double refraction, and lower indices of refraction than Canada balsam. The positive bisectrix has a somewhat oblique position in the trapezoidal crystals. The axial angle is very small and the optic plane coincides in direction with the *parallel edges* of the crystals.

FIG. 176.—Magnesium Ammonium Phosphate.

*Iron.*—The formation of Prussian blue upon the addition of potassium ferrocyanide to an oxidized solution of iron salts is a far better test for the presence of iron than any micro-chemical reaction. Even if there is an exceptionally small content of iron, the solution is colored a distinct green. If there are but traces of iron in the solution, the best test is to note the red color upon the addition of potassium sulphocyanide.

*Nickel and Cobalt.*—These two elements are rare constituents of rock-forming minerals. Small amounts of nickel can be detected by adding yellow ammonium sulphide to an ammoniacal solution of nickel. The liquid becomes brownish if only a trace is present. Still smaller traces can be detected by the rose-red to brown color resulting upon the addition of sodium trithiocarbonate to a nickel solution. Sodium trithiocarbonate is prepared by shaking a sodium sulphide solution with carbon disulphide. Cobalt must be removed as potassium cobalt nitrate before this test can be carried out, because cobalt blackens the solution. The best test for nickel is the following: a strong ammoniacal solution is either violently shaken in air or is boiled with powdered $\alpha$-dimethyl glyoxime when a scarlet precipitate is formed.

The simplest test for cobalt is the blue bead of microcosmic salt. If potassium nitrite is added to a dilute ammoniacal solution of cobalt, which is then acidified with acetic acid, small cubes of deep yellow potassium cobalt nitrite are precipitated. They often appear entirely opaque under the microscope. The following reaction is more sensitive: potassium sulphocyanide is added to a solution containing cobalt and ethyl alcohol carefully poured over it. The alcohol assumes an intense blue color.

*Manganese.*—The smallest traces of manganese can be detected by fusing the mineral with sodium carbonate and saltpeter on a platinum foil. If there is considerable manganese, the melted mass appears green, but if the content of manganese is quite small and silica is present, it is sky blue. This color may be clearly observed with extremely small traces of manganese

*Chromium.*—The presence of chromium can be proved by fusion in a bead of microcosmic salt in an oxidizing flame. The bead is red when hot, and emerald green when cold. The mineral may also be fused with sodium carbonate and saltpeter on a platinum foil and the melt dissolved in hot water. When the solution is acidified with nitric acid and a drop of silver nitrate added, it becomes brilliant red and deep red rhombohedrons of silver chromate, with an angle of about 70° and a high index of refraction, are formed. With only traces of chromium the solution has a fluorescent yellow color like that characteristic of a dilute solution of eosine.

*Tungsten.*—Minerals containing small traces of tungsten form a blue glass when fused with phosphorous pentoxide in a platinum crucible.

*Molybdenum.*—A solution of 1 gr. phenyl hydrazine in 70 gr. of 50 per cent. acetic acid gives a good reaction for molybdenum. The mineral is dissolved and digested two minutes in the reagent, and if molybdenum is present, the solution becomes red and can be decolorized again by shaking with chloroform.

*Cerium, Lanthanum, Didymimium, Yttrium, Erbium, Thorium,* etc.—No reactions are known for positively detecting the so-called rare earths in the small quantities in which they occur in rocks. The micro-chemical methods that might be used do not give rise to well developed crystals and, furthermore, the difference between the various earths has not been thoroughly studied. Spectrum analysis appears to be the only method that affords any degree of certainty in the determination of the rare earths. Even by this method, only the recognition of *neodymium* and *praseodymium* is positively certain. The mineral grain to be studied is focused under the microscope with such a magnification that the grain nearly covers the whole field of vision. Then a good spectroscope is placed over the ocular when the presence of neodymium will be noticed by a broad absorption band in the yellow and a somewhat narrower one in the green. If praseodymium is present, the strongest absorption occurs between blue and violet and a weaker one in the blue. This test is used on rock-forming minerals only when monazite is a constituent of the rock. Monazite generally contains both elements.

*Aluminium.*—A fragment of a mineral is moistened with cobalt nitrate solution and heated to redness in a blowpipe flame in order to test for aluminium. It becomes blue, if aluminium is present, but this color is easily obscured by oxide of iron. The presence of aluminium can be proved micro-chemically by adding slightly diluted sulphuric acid and a small grain of some cæsium salt to a solution of the mineral, when well developed octahedrons of cæsium alum will be formed. These are characterized by an especially high index of refraction. If dendrites form instead of the crystals they can be recrystallized in water and octahedrons obtained. Ferric salts give the same reaction, but the two can be differentiated by treatment with ammonium sulphide vapor. If larger amounts of ferric oxide are present, the reaction is indistinct. Iron must be reduced first with sulphurous acid before the test for aluminium is made.

*Boron.*—The green flame is a sufficient test for the presence of boric acid in minerals. It is obtained when the powdered mineral is mixed with fluorite and potassium bisulphate in a platinum crucible and placed in a flame—*Turner's test.* The reaction proceeds better if the mineral is decomposed by fusion and the melt dissolved in hydrochloric acid. Methyl alcohol is added to this solution and when ignited it burns with a green flame. For a micro-chemical test, the mineral, for example tourmaline, is fused in a platinum crucible with sodium carbonate, if it is too difficultly soluble in hydrofluoric and sulphuric acids. The fused mass is then dissolved in concentrated sulphuric and hydrofluoric acids. A platinum cover with a drop of water adhering to the under side of it is placed on the crucible and the latter is warmed until the acid begins to vaporize. The drop of water takes up the silicon tetrafluoride as well as the boron fluoride which develops. This solution is placed on an object glass covered with Canada balsam and potassium chloride is added. Upon evaporation rhomboidal or elongated six-sided tabular crystals of potassium fluoborate separate out. When these are recrystallized from hot water they develop prisms with domes and pyramids. The indices of refraction are lower than that of Canada balsam and the double refraction is so low that it can only be recognized in thick crystals with a gypsum test plate. The principal zone is negative.

*Carbon.*—If carbon is present in a rock as such or as a constituent of an organic compound, it is converted into a carbonate by fusing the substance with potassium antimonate. The carbonate can then be tested by its effervescence with acid. If only a very small quantity of carbonate is present, the rock powder is spread out with water on an object glass and a cover-glass is placed over it. Then a drop of dilute hydrochloric acid is placed in contact with the edge of the cover-glass and a piece of filter paper is inserted under the other side of the glass. The acid is slowly drawn under the cover and the formation of small gas bubbles in the solution can be observed under the microscope.

*Silicon.*—The formation of skeletons of silica in a bead of microcosmic salt cannot always be definitely observed. The best method for the detection of silica is a micro-chemical test carried out in the same manner as was described for boron, except that sodium chloride is used instead of potassium chloride. The powder may also be decomposed by fusion with sodium carbonate and the melted mass treated with pure hydrofluoric acid. In both cases the crystallization of sodium fluosilicate is to be observed.

*Titanium.*—Minerals in which titanium is suspected are fused with potassium bisulphate, dissolved in water and treated with hydrogen peroxide. With small traces of titanium the solution is colored light yellow, and with larger quantities deep brown. The color is most easily recognized if the operation is carried out on a porcelain plate.

*Zirconium.*—It is difficult to prove the presence of zirconium oxide in rocks with absolute certainty, because it is usually present only in very small quantities. The substance is fused with about double its amount of sodium carbonate for a long time and the fusion product dissolved in hot acidified water. Zirconium is found in the insoluble residue as small six-sided crystals similar to tridymite. The index of refraction is lower than that of Canada balsam. They often gather into packets similar to a pile of coins. Another method of testing for zirconium consists in fusing the powder with potassium bisulphate and precipitating the zirconium oxide with ammonia. After filtering, the precipitate is dissolved in hydrochloric acid and a little tin foil is dropped into the solution. If zirconium oxide is present the solution colors turmeric paper brown, while solutions containing titanium do not color it after reduction.

*Tin.*—If a mineral is thought to contain tin, it is fused on a charcoal tablet with sodium carbonate and potassium cyanide. The tin is reduced to a metallic bead that can be seen with a lens. If the bead is not observed, the melt is placed on a platinum foil and dilute hydrochloric acid with a very little platinum chloride added. An intense red-brown color results if tin is present. A borax bead, containing a little copper oxide and tin, heated alternately in an oxidizing and reducing flame, becomes ruby colored. This is a very sensitive reaction.

*Vanadium.*—Vanadium is often present in rocks in very small quantities. The rock powder is fused with sodium carbonate and saltpeter and the melt dissolved in slightly acidified water. The solution becomes red in color when hydrogen peroxide is added, provided vanadium is present. When a grain of sal ammoniac is added to a solution of the melt, microscopic crystals of ammonium metavanadinate are formed. They have a very characteristic shape like that of a whetstone or a hatchet.

*Niobium and Tantalum.*—A mineral is fused with a large amount of caustic potash to test for niobates and tantalates. The melt is dissolved in water and hydrochloric acid added. Both salts are thrown down as a white precipitate, and after filtering, the precipitate is dissolved in sulphuric acid. A piece of zinc is dropped into the solution which is then heated to boiling. Niobates color the solution smalt blue, the color being retained for a long time upon dilution until gradually the white powder forms again. Tantalates produce a grayish-blue color which rapidly fades when the solution is diluted.

*Phosphorous.*—Phosphoric acid is present in rocks only in small amounts. When a rock powder is heated to redness with magnesium powder in a glass tube, the phosphoric acid is reduced, causing a brilliant pyrotechnic display. When the product formed is thrown into water the odor of phosphine can be readily recognized even though only a small trace of phosphorous is present. By another method the rock powder is digested with nitric acid and the solution treated with ammonium molybdate. After a long time a sulphur yellow precipitate of ammonium phosphomolybdate is formed. Under the microscope it seems to consist of small, yellow, rounded dodecahedrons or of delicate skeletal crystals. However, if soluble silicates are present at the same time, there is danger of confusing the ammonium phosphomolybdate with ammonium silicon molybdate which may be formed. It is well to render the silica insoluble by evaporating and heating on the object glass, and then to redissolve the powder before the addition of ammonium molybdate. The formation of magnesium ammonium phosphate, mentioned above under magnesium, is also a useful reaction for the detection of phosphorous.

*Sulphur.*—Sulphur in any form can be tested by fusing a mineral containing it with sodium carbonate on charcoal. The melt is crushed on a silver coin and moistened. A brownish-black spot is produced—*Hepar test.* The melt also colors an alkaline solution of sodium nitrocyanide violet.

*Chlorine.*—Chlorine can be detected when a mineral powder is fused in a bead of microcosmic salt saturated with copper oxide. The flame becomes distinctly blue. The micro-chemical test is also good. Silver nitrate is added to an ammoniacal solution of a chloride and is left in the dark to evaporate. The resulting octahedrons of silver chloride have a high index of refraction and become clouded and violet when left in the light.

*Fluorine.*—To test for fluorine, the mineral is fused with salt of phosphorous in a small glass tube. The tube is etched near the melted material. The mineral can also be heated with concentrated sulphuric acid in a platinum crucible on the cover of which a drop of dialyzed silica adheres. This drop is later removed and placed on an object glass covered with Canada balsam and some sodium salt is added. The characteristic crystals of sodium fluosilicate are formed upon evaporation if fluorine were present.

Finally, the test for *water* must be mentioned Attention must be called to the fact that with many minerals, very careful and extended drying is necessary to remove all the hygroscopic water. The best test for water is carried out in the following manner. A narrow glass tube about 10 cm. long is drawn out at one end into a capillary and dry air is drawn through it while heating. Then the capillary is closed by fusion and the rock powder introduced into the other end of the tube which is likewise closed. During this process care must be taken that no moisture is introduced into the tube from the burner gas. Upon heating the powder in the sealed tube, whatever water is present can be driven into the capillary containing a small quantity of some dry dye. The dye is dissolved by the drop of water as it condenses and imparts an intense color to the drop.

### b. Special Reactions

Special reactions can be applied either to isolated grains or directly to thin sections. If the slide is to be subjected to chemical investigation it is left uncovered, or if covered, the cover-glass can be removed by warming it slightly. The section itself must then be thoroughly cleaned from Canada balsam by washing with benzol. For certain reactions, such as heating tests, etc., the rock section must also be removed from the object glass. This can be accomplished by heating gently to melt the Canada balsam, after which the section is washed for some time in benzol. In most cases the whole section is not subjected to chemical tests at one time, but only a portion of it is used, reserving the rest of it for other reactions. The cover-glass is cut between the two portions with a diamond cutter and, if the section also is to be removed from the object glass, it is cut through at the same place. In some cases the cover-glass is removed and the section covered with liquid Canada balsam. Then the particle to be isolated is focused under the microscope and a perforated cover-glass is placed over it so that the hole in the glass falls directly over the grain to be studied. If a reaction with hydrofluoric acid is to be made the cover-glass can be replaced by a platinum foil. The section must be left for a long time to dry and then the balsam must be thoroughly washed out of the small

Certain chemical reactions serve to clarify rock sections because they dissolve out those constituents which make it clouded or nontransparent. Such substances are chlorite, zeolites and other scaly decomposition products, or iron oxide which is present as a finely divided pigment. They can be removed by separating the section from the object glass and digesting it for a long period with dilute hydrochloric acid. If the section is impregnated with graphite or carbonaceous material, it is clarified by roasting on a platinum foil. A wet method for removing carbonaceous material is most favorable under certain conditions. e.g., in the study of the organic structure of coals. The section is treated for a long period with chlorous acid, page 150, which dissolves the carbonaceous matter. Graphite cannot be removed in this way.

The observation of etch figures has often been suggested as a means of investigating thin sections, but no reliable results can be obtained in this way. Etch figures may, however, be useful to distinguish between amorphous substances and those which crystallize in the cubic system because the latter would give regularly bounded figures.

**Staining Methods.**—The staining methods, which play so important a rôle in organic microscopy, are only used occasionally in the investigation of thin sections because only a few minerals in their natural condition would absorb the stains and those that do are principally thick, scaly to fibrous aggregates of good cleavable minerals, but even they can scarcely be differentiated or recognized in this way. Usually, before a mineral in a thin section is stained, it is treated on the object glass with dilute acid until it has been so altered that it is covered with a gelatinous precipitate. This gelatinous material absorbs the stain evenly and retains it so that it cannot be washed out. After the etching action, which is always only superficial, the acid must be thoroughly washed away before the stain is applied or it may be destroyed. The section is placed in an evaporating dish filled with distilled water to which a few drops of a solution of Congo red or malachite green or any other permanent dye have been added. If it is left to stand for several hours, the dye is absorbed quite evenly by the gelatinous precipitate. It is then thoroughly washed in running water, dried, and covered again with Canada balsam.

Certain silicates dissolve in hydrochloric acid and the silica separates in a gelatinous condition, covering the thin section. A thin film of dilute hydrochloric acid is put on the mineral in the thin section so that the etching will take place only on the surface and the whole mineral will not be dissolved. This reaction is characteristic for nepheline, which is otherwise often very difficult to recognize in the ground mass of a basaltic rock. But plagioclase and scapolite rich in lime, sodalite, melilite, wollastonite, chlorite, serpentine, zeolites, and certain rock glasses give the same reaction, so that the conclusion that nepheline is present is only warranted if, after it has been colored, the mineral shows the characteristic cross section of nepheline.

Aluminium fluosilicate, resulting by etching aluminium silicates with hydrofluoric acid, is also a gelatinous substance well adapted to such color tests. It is especially serviceable for differentiating between feldspar and quartz in very fine grained aggregates. Hydrofluoric acid is allowed to act for a short time on the section and then it is entirely removed by heating on a water bath. The stain is absorbed by the gelatin formed on the feldspar while the quartz is not colored at all. In this case, it is best to use dilute alcohol to wash the section. Other silicates of aluminium that are attacked by hydrofluoric acid, e.g., cordierite, can be distinguished from quartz or from silicates containing no aluminium in this manner. By careful operation the feldspars can be differentiated by these tests because orthoclase is more difficultly attacked than the plagioclases and, among the latter, those richest in lime are the most easily attacked.

Haüyne, containing calcium sulphate, can be determined by the gypsum crystals formed on its surface when it is treated with dilute hydrochloric acid and dried. Characteristic hopper-shaped growths of salt also appear with the gypsum. The salt crystals are seen alone under the same conditions on sodalite, noselite and nepheline. A characteristic reaction has been found for certain minerals in a modification of this test. If, e.g., an aluminium silicate containing chlorine (sodalite and scapolite) or sulphur (laznrite) is treated with a solution of silver nitrate in dilute hydrofluoric acid, the gelatin is impregnated in the first case with silver chloride, which becomes brown when treated with a photographic developer, and in the second case with black silver sulphide. In this manner these elements that are not common in silicates can be detected

**Precipitates on Thin Sections.**—A dilute nitric acid solution of silver nitrate can be used to test for chlorine in such minerals as apatite. Apatite can also be determined by a localized lemon-yellow precipitate which tends to form in a wreath around the apatite grain when it is treated with a concentrated nitric acid solution of ammonium molybdate. Heating should be avoided in this reaction because then the silica is easily dissolved out of the surrounding minerals and gives rise to a very similar precipitate of ammonium silicon molybdate.

There are numerous precipitation reactions by means of which the various carbonates, which cannot be distinguished by their optical properties, can be differentiated. Linck's solution is a solution of ammonium phosphate in dilute acetic acid. If a thin section containing carbonates is treated with it, calcite will be entirely dissolved out, while dolomite is slowly covered with crystals of magnesium ammonium phosphate arranged in characteristic aggregates. A dilute solution of copper sulphate becomes brilliant blue upon the addition of calcite, but with dolomite it remains unchanged. Calcite rapidly precipitates colored gelatinous alumina from a solution of alum or neutral aluminium sulphate, containing also *brilliant green* or *fuchsine*. A coating of ferric hydroxide forms on calcite in solutions of ferric salts and this coating can eventually be colored black by ammonium sulphide. Dolomite remains completely unaltered for a long time in both of the above cases, but it gives the same reactions upon heating. Calcite cannot be distinguished from aragonite by any of the above reactions, but the tests by which they can be differentiated are very interesting. If the minerals are finely powdered and boiled with a dilute solution of cobalt nitrate, calcite remains perfectly colorless while aragonite becomes bright violet. If boiled long, ten minutes or so, calcite is colored slightly, but in the meantime aragonite has turned dark violet. A solution of ferrous ammonium sulphate can be used to distinguish between calcite and aragonite, and this reaction can be carried out on a thin section. If a drop of the cold solution is placed on the slide, calcite becomes rust colored, while aragonite turns dark blackish-green.

Metallic iron occurs now and then as a constituent of rocks. It can be detected by a copper sulphate solution in which it becomes coated with metallic copper, or by Klein's solution which turns deep blue.

It is quite evident that all these precipitation reactions can be carried out on single isolated grains. This is of great importance in the case of such minerals as scapolite, which is present only in very small quantities and is very difficult to recognize.

**Alteration by Calcination.**—Attempts are frequently made to *produce characteristic changes in minerals by calcining the* section. Thus zeolites, brucite, hydromagnesite and cancrinite become cloudy when heated a little and their optical properties are somewhat changed. If the slide is heated to redness and afterward treated with silver nitrate, brucite and hydromagnesite will be coated with a dark brown film of silver hydroxide. Other hydrous minerals such as chlorite, serpentine, etc., must be calcined at very high temperatures for some time before they become cloudy. They turn brown first and at higher temperatures black, due to the oxidation of iron.

Numerous minerals containing iron change their color when moderately heated in an oxidizing flame. Thus, olivine becomes *brownish-red and quite pleochroic; light-colored hornblende* assumes the color and absorption of basaltic hornblende. Chlorite changes in a similar manner. Epidote and orthorhombic pyroxenes become darker when heated very slightly, while the monoclinic pyroxenes free from sodium darken only at very high temperatures, and those rich in sodium and iron melt easily to a black glass. Some varieties of colorless cordierite can be made blue and pleochroic by slow and careful heating, but they lose their color again if heated higher. Many members of the sodalite group are colored an intense blue by heating in air while, with other members, this change takes place only when *heated in sulphur vapor. Finally, the calcination test can be used to detect aluminium in a thin section. It is heated with* cobalt solution, then washed with dilute acid, and the blue color is observed in reflected light. This serves to distinguish talc from sericite.

The calcination process can be used to distinguish between carbonaceous substances or graphite and ores in a rock section. It is always well to treat the section with hydrochloric or nitric acid before and after heating, because the organic substance is very frequently intergrown with iron ore. Graphite and carbonaceous material both burn off more easily if they are in a finely divided state.

## 2. Physical Methods of Investigation

**Determination of the Specific Gravity.**—Specific gravity is the most important physical property, aside from the optical properties, that can be used to determine a mineral. The different methods, which the physicists employ to determine it, require for the most part, too much time. The accuracy of measurement with a hydrostatic balance or a pycnometer is not at all commensurate with the small degree of purity generally possessed by the rock minerals. Further, it is necessary, for such accurate determinations of specific gravity, to have a considerable amount of pure material available, which is often impossible. We must be contented with less accurate methods, but this has the advantage that the results can be obtained even with a very small grain of a mineral and the measurement possesses a sufficient degree of accuracy for our purpose.

The method generally employed in petrography to determine the specific gravity consists in putting a small splinter of the mineral in question into one of the heavy liquids described on pages 156 to 159. The liquid is gradually diluted until that point is reached at which liquid and grain have the same specific gravity, so that the grain remains suspended in any part of the liquid when it is agitated and is not driven up or down. If a crystal, which is apparently homogeneous, is broken into fragments, it will be found impossible to bring all these pieces into a state of suspension at the same time, but a medium grain will be suspended, while some will sink slowly and others will rise. These various fragments of one and the same crystal appear to have different densities. The phenomenon depends upon the fact that there are minute inclusions, cleavage cracks, etc., in the mineral and these are not constant throughout the crystal, but are different in the different fragments.

Cleavage cracks, gas bubbles, and liquid inclusions lower the specific gravity of a mineral, while inclusions of heavy minerals raise it. In general then, the specific gravity is most approximately obtained in a solution in which part of the grains float, while the others sink. The density of the liquid is then obtained by means of an aerometer, the best form of which is the *Westphal balance,* Fig. 177.

The two arms of the balance beam are in equilibrium. The pointer on the arm J plays exactly on the point opposite it when the hydrometer, usually prepared in the form of a thermometer, is suspended from E by a fine platinum wire. If the thermometer is immersed in water at 4° C., it is evident that it will be buoyed up and the balance will be thrown out of equilibrium. The buoyant force is equal to the weight of the volume of water at 4° C., displaced by the thermometer when it is immersed. If a weight $m$, equal to the weight of this volume of water, is suspended with the thermometer at E, the balance will again return to a state of equilibrium.

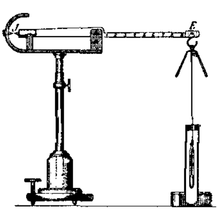


FIG. 177.—Westphal Balance.

The balance is supplied with four different weights in the form of riders and these are calibrated according to the volume of water at 4° C. displaced by the hydrometer. They correspond to 0.01, 0.1, one and three times the weight of it. In addition the balance beam is *divided into ten equal parts so that* the specific gravity of a liquid can be measured accurately to the third decimal place and can be estimated to the fourth. Thus, it can be measured far more accurately than is necessary when the impurity of the mineral is considered.

The specific gravity of the heavy liquids that are employed changes quite rapidly with a change in temperature, so the whole determination must be carried out at a temperature as nearly constant as possible. If this is not possible, the temperature, at which the mineral fragments were brought into suspension and that at which the specific gravity of the liquid was determined, must be taken. The error introduced by the change of temperature can be eliminated by considering the coefficient of expansion of the liquid. It is quite useless to make an extra effort to work at constant temperatures because the temperature variations ordinarily experienced do not affect the specific gravity of a mineral and only the changes in the liquid need to be considered. The expansion and contraction of a heavy liquid can be demonstrated best by bringing a crystal into suspension in a heated room and then placing the vessel in a cool room. After a short time the crystal rises again and floats. If the vessel is placed near a stove the crystal will be seen to sink rapidly. It is also to be noted that a crystal fragment turns upon its sharp edge when the specific gravity of it and of the liquid are about the same. This is an indication that further dilution must be continued extremely slowly and carefully. If the proper point is exceeded and the crystal begins to sink, the density must be increased again by the addition of the concentrated liquid.

It is not necessary at this time to consider any apparatus for determining the specific gravity of soluble substances because petrographers rarely have to deal with such minerals. Furthermore, the solvent effect of the organic liquids, which are used, and of the solutions of inorganic salts is extraordinarily variable. If one group of liquids cannot be used because of its solvent action on a mineral, another can be employed in almost all cases. On the other hand, minerals with a higher density than the heaviest liquid obtainable are not rare. The method of procedure then is to knead a mass of wax and minium thoroughly in such proportions that the specific gravity shall be about 2.5. The mineral is pressed into a weighed amount of this mass called the float. The amount of the float is so chosen that the specific gravity of the combination amounts to about 3.0. If $g$ equals the weight of the float and $p$ its specific gravity, $g'$ the weight of the mineral and P the specific gravity of the combination, the specific gravity of the mineral $p$, can be calculated from the formula $p' = \frac{g'P}{g + g' - P\,g/p}$. Fine feathery tongs of thin glass threads can be made and used as floats. The mineral grain is fastened in the tongs. In either case it is absolutely necessary not to use too small a fragment of the mineral because in that case the error introduced becomes too large.

Another apparatus for determining the specific gravity of liquids is based upon the law that the heights of columns of liquids retaining equilibrium in communicating tubes, are inversely proportional to their specific gravities. If the liquid to be determined is in one arm of the tube and water in the other, the difference in height of the columns gives the specific gravity of the liquid directly. This apparatus can also be arranged to make separations according to specific gravity.

**Determination of Hardness, Cleavage, etc.**—Now and then it is advantageous to determine the hardness of a mineral. However, the small grains that are obtainable are too small to make a hardness test by hand. A thin bar of lead is planed on one end. An indicator of known hardness is chosen from the scale of hardness and one surface is polished. The mineral grains, whose hardness is to be determined, are placed on this surface. Then the lead bar is pressed against it firmly and moved back and forth. The grains sink into the soft lead and are held firmly as if in a setting and are moved about over the polished surface. If the grains are harder than the indicator, fine scratches will be observed on the surface by the aid of a lens. The more accurate methods used in physics for determining the hardness of substances are of no consequence in the case of rock-forming minerals. It may be mentioned that the hardness of a mineral or a rock, *i.e., its resistance to being scratched,* is often confused with its resistance to abrasion. There are soft minerals that can be but slightly abraded. They are tough like serpentine. Then there are others that are very hard, but because of their brittleness, are more easily worn away than would be expected from their hardness. Quartz is one of this kind.

The determination of the hardness and the tendency to abrasion of a mineral is frequently greatly influenced by cleavage, because, parallel to the cleavage, scratching as well as abrasion encounters less resistance. Cleavage is nearly always quite evident in a thin section because the minerals are shattered more or less along their cleavage planes during the process of grinding. The degree of cleavage can be easily estimated in a mineral cross section by the number of the cleavage cracks, and whether they are long and straight or not. Compare Part I, p. 44. The cleavage form and the cleavage planes can be determined from the angle which the cracks make with each other in a thin section, but care must be taken to determine the cleavage only in sections perpendicular to the cleavage planes. Those are sections in which the cracks do not shift sideways when the focus of the microscope is changed from the upper to the lower surface of the mineral. An example of this is the distinction of pyroxene, with a prismatic cleavage of approximately 90°, from amphibole with a prismatic cleavage of about 124°. A section of pyroxene cut obliquely to the cleavage can show exactly the cleavage angle of hornblende and vice versa.

The production of a percussion figure is of special interest in the investigation of micaceous minerals. A minute scale of the mineral is placed on a smooth cork and a vertical needle is arranged in a support over it so that it can move up and down freely. The needle is struck a sharp blow with a watch spring and driven into the plate. A series of hexagons can be observed around the hole thus produced. See the mica group, p. 302. The angles of the hexagons are bisected by quite straight cracks of which two, lying diametrically opposite each other, are more pronounced than the others and are called the *principal rays*. The direction of these principal rays corresponds to the plane of symmetry of mica.

The study of magnetism is confined, for the most part, to the effect of a mineral on a magnetic needle so mounted as to be delicately sensitive. Only a very few minerals affect it naturally, particularly magnetite and pyrrhotite. All minerals rich in iron will affect a magnetic needle after they have been fused. Polar magnetism also occurs in rocks, but the distribution of the two poles is usually very complicated and apparently without any regularity. Conductivity of electricity is not often used in studying rock minerals, but is valuable to distinguish between graphite and coal. Graphite, fastened in zinc, becomes coated with metallic copper in a copper sulphate solution.

CHAPTER X

# Development of Rock Constituents

**External Form.**—The outlines of the rock-forming minerals are extremely simple. Well developed crystals, the outlines of which are generally not very sharp, are quite rare and, when they do occur, they are simple and do not show combinations of many faces. Rock constituents crystallographically developed in this manner, as the phenocrysts of the porphyries, Fig. 178, or the garnets of a mica schist, are termed *automorphic* (Greek *autos*, self; *morphe*, form) or *idiomorphic* (Greek *idios*, own). A partial crystallographic development is observed far more frequently. Feldspar in granite shows plainly its own crystal development next to the quartz, but not to the mica. This is called *hypidiomorphic* development (Greek *hypo*, almost). The most frequent case is that in which the mineral grains lie beside each other without any indication of crystallographic form. Such a granular aggregate is said to be *xenimorphic* (Greek *xenos*, foreign) or *allotriomorphic* (Greek *allotrios*, foreign). This type of development is seen most plainly in granular limestones and may be observed macroscopically.

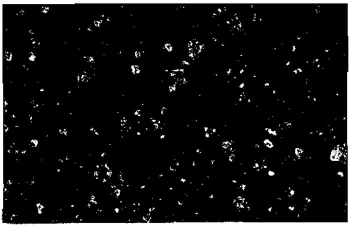


FIG. 178.—Quartz Porphyry, Rochlitz, Saxony.

Under the microscope also, these three types of development can be sharply differentiated from each other, as Figs. 179 to 181 show. In Fig.

180 the development of the quartz, the lightest material in the cut, is very distinctive. It fills up the spaces between the other constituents and obtains its form entirely from them. It is designated as *interstitial* material or *mesostasis* (Greek *mesos*, middle; *stasis*, mass).

FIG. 179.—Porphyric Structure. Granite Porphyry, Ernsthofen, Odenwald.

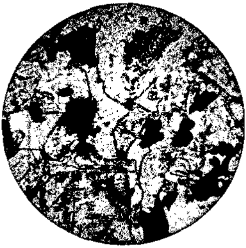


FIG. 180.—Hypidiomorphic Structure. Quartz Diorite, Schwarzenberg, Vogesen.

After F. Berwerth.

Rocks do not in all cases consist entirely of crystallized constituents. Sometimes amorphous substances make up part of the rock. This is sometimes rock glass formed from the magma, occurring either as a subordinate base or as a prominent constituent. Sometimes it is deposited from an aqueous solution and is then usually opal. Naturally these substances never possess characteristic forms.

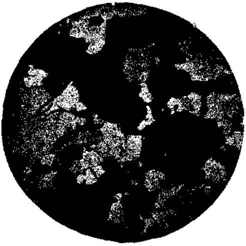


FIG. 181.—Allotriomorphic Structure. Quartzite, Perosa, Cottic Alps.

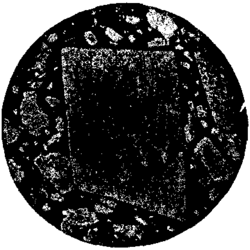


FIG. 182.—Sharp crystals, Uralite and Plagioclase in Uralite Porphyry, Predazzo, Tyrol.

It may be said that the smaller the amount of a constituent in a rock and the smaller the individuals, the more perfect is the crystallographic development. Those minute crystals occurring as accessory components of the eruptive rocks, like zircon, xenotime, apatite, monazite, and chrysoberyl, which are only present in very small quantites and belong to the oldest period of solidification of the rock, are often as well developed as models and sometimes show an abundance of faces. Likewise small crystals of feldspar, pyroxene, etc., which have separated from the glassy ground mass of an eruptive rock, sometimes have quite sharp forms. Larger individuals are not so apt to show this, either because they did not have a good development originally or because they have later been partly redissolved. The smaller crystals are not so liable to resorption.

The size of the rock-forming constituents is quite variable. Especially large dimensions are observed only in pegmatites, which are scarcely to be considered as rocks in the narrower sense. Feldspar crystals are found in them with edges several meters long and mica plates as big as a table. In rocks, mineral individuals as large as a head or fist are quite scarce; those whose largest dimension is one or more centimeters are more common. Even these are more apt to be found among the phenocrysts of porphyric rocks. The dimensions are usually smaller in granular rocks from a diameter of about 1 cm. down to individuals which cannot be seen with the naked eye. The granular rocks may be medium granular, or fine granular, or may appear to the naked eye to be *aphanitic*. The ground mass of porphyric rocks is generally macroscopically aphanitic and often under the microscope is composed of such minute individuals that a very thin section and strong magnification are necessary to resolve it. The minutest rock constituents, often well bounded crystallographically, which are so small that they appear in the slide as specks, are called *microlites* (Greek *micros*, small). This name was originally given to a rod-like formation which was afterward called *belonite* (Greek *belone*, arrow heads).

The crystallographic habit is in general quite characteristic for any one species. Apatite develops in needles; mica is tabular; epidote is elongated parallel to the *b* axis; hornblende parallel to the *c* axis; and many feldspars parallel to the *a* axis, Fig. 183, p. 184. In thin sections the cross sections have a characteristic form and a distinguishing principal zone, the optical character of which aids in determining the mineral. This is found in column $\text{Ch}_z$ in the table at the end of the book. Acicular or thin tabular minerals give mostly lath-shaped cross sections. Other minerals, e.g., quartz or calcite are developed more nearly isometrically. Their cross sections show no characteristic elongation and they have no principal zones, Fig. 184. In other cases, e.g., corundum and topaz, the individuals are sometimes elongated parallel to one crystallographic axis and sometimes to another, and the optical character of the principal zone varies accordingly.

The mineral individuals of a rock are frequently simple crystals. If they are well bounded crystallographically, the form of the crystal can generally be inferred from the outlines of several sections differently orientated. However, too much importance should not be given to the appearance of one or more cross sections. The predominant section of a mineral developed prismatic or tabular is in both cases lath-shaped. The laths from prismatic crystals have a width about equal to the thickness of the crystal, while those from tabular crystals are much broader.

Fig. 183.—Crystals with Principal Zone Grachyte, Nolles. (After Berwerth.)

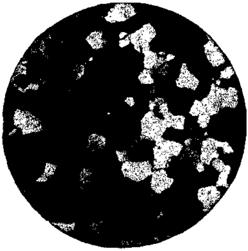


Fig. 184.—Crystals without Principal Zone. Quartzite, Steiermark.

*Such minerals, as apatite, often give six-sided sections which have no effect* on polarized light and even in convergent polarized light cannot be readily distinguished from isotropic minerals. Again in a great number of rocks including some igneous types, tabular or acicular crystals of uniaxial minerals are all arranged parallel so that they extinguish four times when rotated between crossed nicols, but as a uniaxial figure cannot be obtained, these are often mistaken for biaxial minerals.

**Twinning.**—Twinning is exceptionally widespread in rock-forming minerals. It can be recognized partly in the form of the section. In cubic twins and in uniaxial twins, in which the optic axes are parallel, this is the only way to recognize them. If reëntrant angles cannot be seen, the twinning will not be observed in rocks, even though it is very widespread, as in the case of quartz. *Cruciform* twins, Fig. 185, and *juxtaposition* twins, Fig. 186, show readily in the external form. In *penetration* twins this indication is lacking and is never observed where the rock constituents do

Twins of uniaxial crystals with their optic axes oblique to each other and twins of biaxial crystals can generally be recognized in polarized light. In the first case, the two individuals separated by a sharp plane extinguish *differently*, and in the second case even though the elasticity axes are parallel the two parts will show different interference colors. This is particularly notable in cyanite. In such cases as epidote where the twinning plane is very nearly parallel to the bisectrix of an optic angle, that is, almost 90°, the twinning may not be apparent.

Besides simple twinning, repeated twinning or lamination is as common in rock-forming minerals as it is in other minerals. It is rarely observed in cubic minerals, but is very frequent in hexagonal (calcite), tetragonal (rutile), orthorhombic (cordierite), monoclinic (diallage), and triclinic minerals (plagioclase). The two series of differently orientated individuals are intergrown with each other in a more or less regular manner in the form of lamellæ, Fig. 187. In the crystal systems of higher symmetry several series of lamellæ may cross, producing a lattice effect. These lamellæ are of the same shape and the twinning is parallel to the different faces of one form. Such is the case with calcite twinned parallel to $-1/2$ R. In the crystal *systems of lower symmetry*, this lattice structure may appear, but is due to the presence of two series of lamellæ twinned according to different laws. Albite, Fig. 188, is a good example of this, where albite and pericline twinning occur together. Twinning lamination may be caused by the effect of pressure on a mineral. This can be demonstrated with calcite which possesses the property of gliding. In other cases, particularly in the plagioclases, which are so important to petrographers, this is positively not the case as is shown in the schist belt of the Central Alps. Here some of the rocks have been greatly deformed locally, but the plagioclases show almost no lamination.

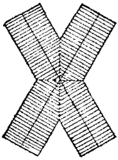


FIG. 185.—Penetration Twin with Inclined Axis. Staurolite.

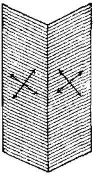


FIG. 186.—Monoclinic Twin. Diopside.

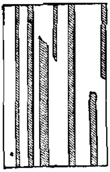


FIG. 187.—Twinning Lamination.

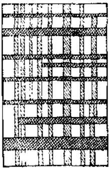


FIG. 188.—Lattice Lamination.

Plagioclase.

**Aggregates.**—The occurrence of several individuals of a mineral together is called an *aggregate*. Minerals, which have no characteristic principal zone generally form granular aggregates, while those with prismatic or acicular development tend to form columnar to fibrous aggregates, such as are macroscopically apparent in *sillimanite* intergrown with quartz. *Minerals* possessing a tabular habit develop scaly or flaky aggregates. Finely divided aggregates of colorless, low double refracting minerals appear as homogeneous individuals in a thin section in ordinary light, but their true nature becomes apparent in polarized light, if they are not isotropic substances, because the various parts extinguish differently—*aggregate-polarization.* If the aggregates are very fine an even illumination will be observed between crossed nicols with low magnification and this will not be affected by rotating the stage. Only with high power objectives is it possbile to resolve such aggregates into their constituent parts. This phenomenon is quite apparent in dense aggregates of sericite or talc.

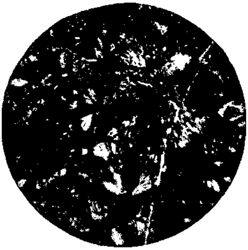


FIG. 189.—Liparite. Glashüttental, Hungary.

FIG. 190.—Oolite, Vilstal, Algän.

The most important of the fibrous or scaly aggregates are those in which the various individuals are arranged in a radiating manner around a point or a line—*spherulites* or *axiolites.* Such structures are characteristically developed in eruptive rocks that are rich in silica and have solidified rapidly. The spherulites, Fig. 189, correspond in general to a eutectic mixture of quartz and feldspar. Analogous structures are by no means rare in secondary depositions in cracks of the rocks, e.g., in chalcedony or aragonite. They constitute the formation known as oolite, Fig. 190. In organic nature the spherulitic development is sometimes quite marked, e.g., in the skeletal portions of foraminifera. In these, axiolites predominate, e.g., in the cross sections of nummulites. Frequently the radial structure is lost and a granular aggregate is developed in its place by recrystallization. The outer form and sometimes also the concentric structure may be preserved during this process. It gives rise to a *granospherite*, Fig. 191. Distinctions can be made in the character of the granular aggregates. Both end members of an even grained, granular rock show the mineral grains simply lying beside each other—*mosaic structure*, Fig. 192,—or very intimately dovetailed with each other, Fig. 193.

FIG. 191.—Granospherite. Recrystalized Oolite.

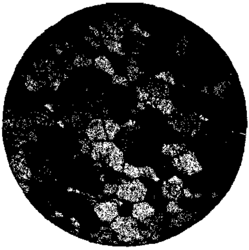


FIG. 192.—Marble (Ordinario), Carrara, Italy.

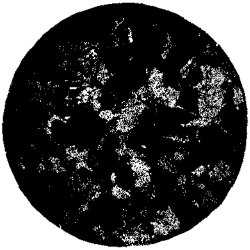


FIG. 193.—Marble (Statuario), Carrara, Italy.

FIG. 194.—Zonal Plagioclase in Pitchstone. Cunardo near Lugano. (After E. Cohen.)

**Growth and Solution.**—The composition of a magma gradually changes during the course of crystallization. This gives rise to zonal development in isomorphous minerals, particularly in the plagioclases and pyroxenes, Fig. 194, in which twinning, if it is present, continues unchanged through all zones. In pyroxenes rich in sodium and titanium various pyramids are so grown together as to produce an *hourglass structure,* Fig. 195. It is noteworthy that this appearance, which has been shown to be dependent upon a gradual change of the chemical composition of the crystallizing mass, occurs but exceptionally in contact rocks and, if it does occur, the law of zonal construction may be just reversed. In eruptive rocks this law seems to be constant, e.g., in the plagioclases where the outer zones are always richer in silica.

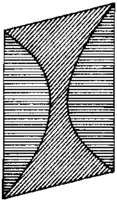


Fig. 195. — Hourglass Structure in Pyroxene.

Fig. 196.—Skeletal Crystals of Olivine.

Various phases in the process of the formation of rocks may be recognized from the development of the rock constituents as has been thoroughly established in the Allgemeine Gesteinskunde by E. Weinschenk. Only the external forms will be described here. The crystallization of a mineral is more complete if it takes place slowly from a very dilute solution. In the glassy eruptive rocks, which have cooled suddenly, incomplete crystallizations are frequently observed. The growth on the edges and corners is most noticeable and the faces remain as more or less deep indentations—*ruin-like* development. Crystal skeletons may result which are hard to define crystallographically, but

Fig. 197.—Skeletal Crystals in Pitchstone. (From Arran.)

are sometimes quite regular, Fig. 196, and at other times grow in variously shaped structures not unlike organic forms. The exact nature of them cannot be determined in most cases, Fig. 197. The last series of growth forms is very simple. In obsidian, *crystallites*, Fig. 198, which cannot be determined, are frequently found. They may appear as dark points—*globulites*—which may be grouped together like a string of pearls—*margarites*—or in irregular bunches—*cumulites*. Sometimes they are dark rods—*baculites*—or curved fine hair-like forms—*trichites*. These often form star-shaped aggregates, Fig. 198, *f*.

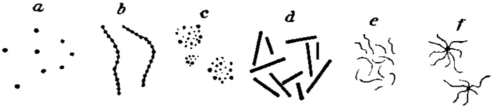


FIG. 198.—Crystallites.
a Globulite, b Margarite, c Cumulite, d Baculite and e and f Trichite.

Other irregularities in the form of the constituents of eruptive rocks are, unlike those already described, of a secondary nature, and are caused by the solvent action of the magma on the crystals which have formed in it. This is naturally observed most commonly in porphyric rocks in which the physical conditions have been intensely changed during the process of crystallization. The phenomenon, which is called magmatic corrosion or resorption, is rarer in rocks rich in glass than in rocks poor in glass, because in the latter the process of solidification has been slower and more time given to the solution process. The external form is often considerably changed. The corners and edges are rounded, and deep indentations made in the faces until finally only an irregular fragment of the crystal is left, Fig. 199. These

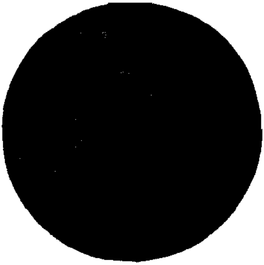


FIG. 199.—Corroded Quartz.

phenomena are especially pronounced in quartz, olivine and the minerals of the sodalite group.

Chemical changes also result under these conditions. Minerals of the amphibole and mica groups containing hydroxyl suffer molecular rearrangement in which opaque iron oxide separates out and a black magmatic border is produced. This process may continue until finally a more or less sharply defined speck, showing aggregate-polarization, is left in place of the original crystal. They are very difficult to determine, but in the tuffs of such eruptive rocks, which preserve the material in the first stages of its occurrence, the unaltered mineral is often seen in large quantities.

It is noteworthy that the accessory minerals in granular lime stones, especially the silicates, often show surface characteristics analogous to magmatic resorption so that they appear to have been partly fused.

**Cleavage, Parting, and Mechanical Deformation.**—The significance of cleavage in the determination of rock-forming minerals has already been pointed out. The more complete the cleavage the straighter and finer do the cleavage cracks appear in microscopical preparations and, if the cleavage is perfect in colorless low double refracting minerals as in feldspar, it is often quite difficult, even when the condensing system of lenses is lowered as far as possible, to recognize the cleavage cracks distinctly. It may, however, be noted that they often become visible in polarized light especially with the gypsum test plate. If the cleavage is less perfect, the cleavage cracks are not so straight, do not extend all the way across the section, and are readily recognizable.

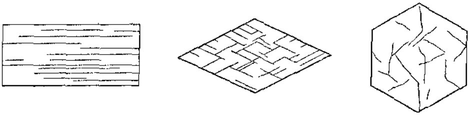


FIG. 200.—Perfect FIG. 201.—Distinct FIG. 202.—Imperfect.

Cleavage.

The number of cleavage cracks appears to have no connection with the character of the cleavage. Brittle minerals show a larger number in general than those that are less brittle even though the latter have a more perfect cleavage. In rocks which have been shattered by orogenic processes, cleavage is particularly noticeable. Figs. 200 to 202 show the difference in general appearance of perfect, distinct, and imperfect cleavages.

*Fibrous* cleavage is characteristic in cyanite and gypsum, and may be recognized by an aggregation of extremely fine lines in one place on the section. *Parting* faces appear different from the ordinary kind of cleavage because they are regular and straight, as in diallage.

Besides these appearances, based on the inner structure of the rock-forming minerals, cracks, which are more or less straight and of an incidental nature, are to be observed in the thin sections of many minerals. In garnet, for example, a checked or cracked appearance is extremely widespread and the short cracks cut through the whole section in the same manner without any relation whatever to the orientation of the garnet individuals. Long needles, e.g., of apatite or sillimanite, tend to show a distinct cross fracture which could easily be confused with cleavage. Such crystals are very easily divided by breaking and even the movement of a liquid stream of lava is sufficient to break a prismatic or tabular feldspar crystal and the parts may be found in a thin section in close proximity to one another

It is more difficult to explain the fact that some minerals, e.g., pyroxene in unaltered andesite, do not show complete extinction but appear to be compressed into columns that extinguish differently, i.e., they possess *undulatory extinction*. This can only be caused by fracturing which has resulted during the crystallization of the magma and is called *protoclase*. Analogous disturbance of the optical behavior is far more common in plutonic and in all possible metamorphic rocks. Certain brittle constituents often show a wavy or undulatory extinction in which uniaxial crystals, e. g., quartz, frequently become biaxial. This very readily changes into fracture and the grains of quartz or of olivine appear as an aggregate of columnar crystals, which show the extinction directions slightly different, but sharply separated, so that the mineral under certain conditions appears quite fibrous.

FIG. 203.—Mortar Structure in Quartz.

The columns, further, may be cross fractured and along the contact surfaces of the grains a fine friction material is formed. Homogeneous quartz grains are changed to a very fine aggregate of particles so intimately dovetailed into each other that they still form quite a compact sand. This is seen around the larger grains and is called *mortar structure,* Mörtelstruktur, Fig. 203.

It is not certain how much of this mechanical deformation is due to stresses dominant during crystallization and how much is due to orogenic pressure acting at a later period. However, the whole phenomenon is generally termed *cataclase.*

This deformation often produces a real characteristic appearance in minerals with a good cleavage. Individuals of hornblende, for example, may be divided up into cleavage prisms so that they behave in cross section like a packet composed of rhombs. Minerals with gliding planes like mica split parallel to these under the influence of orogenic pressure, and calcite under the same conditions assumes a fibrous character due to very fine twinning lamination. These minerals are, however, far more flexible than the ones first mentioned, especially mica and calcite, and to a less degree feldspar also. They can be bent and crumpled considerably without fracturing, Figs. 204 and 205, but finally when the action becomes too great they also are deformed in the same manner as quartz, i.e., assume the Mörtelstructur.

FIG. 204.—Bent Mica Plates, Mica Schist.

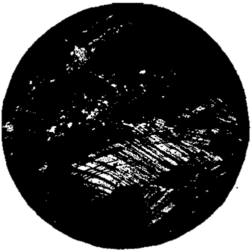


FIG. 205.—Marble with Bent Lamellæ.

**Intergrowth and Inclusions.**—Regular and irregular intergrowths of various minerals are widespread. It is necessary to distinguish between *poikilitic* intergrowth and *peripheral* development. In the first case two homogeneous minerals mutually penetrate each other. Pegmatitic intergrowth of quartz and feldspar, graphic granite, Fig. 206, and perthitic intergrowth of various feldspars (see feldspar group) are typical examples. Peripheral growth is most frequent in related minerals as orthorhombic and monoclinic pyroxenes, monoclinic and triclinic feldspars, or hornblende and pyroxene. It is also known in

FIG. 206.—Graphic Granite from Jekaterinburg, Ural.

minerals that are not at all related to each other, in gabbros where ilmenite is frequently surrounded by a halo of biotite and olivine by a halo of hypersthene or garnet, etc.

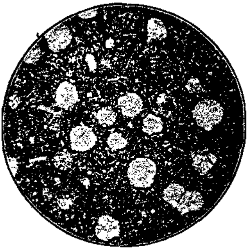


FIG. 207.—Ocellary Structure, Leucitophyre Ölbrück, Eifel.

FIG. 208.—Quartz Eye with a Halo of Glass Rich in Microlites. Basalt, Neuhaus, Oberpfalz.

The borders around certain minerals often show characteristic phenomena. For example, in volcanic glasses, a dark colored fringe may be seen around feldspar crystals and a lighter colored one around pyroxene. This is especially noticeable in leucite rocks where acicular crystals of aegirine grow around the larger leucite individuals, *ocellary structure*, Fig. 207, or in eclogites in which the garnets protrude into their surroundings like pseudopods. Among such appearances, which are classed together as *concentric structures*, the quartz lenses of basic eruptive rocks, Fig. 208, are especially noteworthy but they have an entirely different origin.

Crystal inclusions are distinguished from intergrowths, when the foreign mineral that is included in another crystal is less in quantity or possesses its own crystal form against the including substance, as quartz in hornblende in Fig. 209. The inclusions may be variously orientated or they may be arranged parallel to some crystallographic direction of the including mineral. Single grains of various minerals may also be included by another. In all these cases the relations between the inclusion and the including mineral are undoubtedly not so intimate as in the case of an intergrowth. Gas, liquid, and glass inclusions are also observed but their characteristics have been briefly described in part I, page 48.

FIG. 209.—Perforated Hornblende Granulite, Ampe, Ceylon.

The ability of various rock constituents to take up inclusions is quite variable. It is quite subordinate in quartz but plagioclase occurring right beside it, often shows abundant inclusions. This is also particularly noticeable in garnet, cyanite, staurolite, calcite, etc., where the quantities of inclusions may be so large as to exceed the mass of the including mineral.

The significance of the inclusions as to the conditions of the formation of rocks was early recognized, especially in the case of liquid inclusions in the quartz of granites, which point to an *hydatopyrogenic* origin.

With a low magnification, cloudy bands may be observed penetrating the quartz grains of granite without any reference to the orientation of the grains. With stronger magnification they are resolved into swarms of thousands of the most minute liquid inclusions with gas bubbles often in extremely violent motion. The liquid is sometimes water, or an aqueous solution, and sometimes liquid carbon dioxide. The latter is best tested by heating the preparation above the critical temperature of carbon dioxide, i.e., above 31° C. At this temperature the gas bubble disappears suddenly accompanied by a violent disturbance of the liquid, and the liquid inclusion becomes a gas inclusion. It can also be proved analytically that it is really carbon dioxide.

Liquid inclusions do not always have such small dimensions. Large irregular cavities filled with liquid are sometimes seen in olivine crystals in peridotites. In contact rocks the liquid inclusions frequently fill negative crystals, i.e., cavities with the same shape as the crystal, and of considerable size. They are sometimes apparent macroscopically in quartz crystals, and particularly in halite.

Liquid inclusions are found especially in minerals in plutonic rocks and in contact rocks, and these minerals do not often contain glass inclusions. Glass inclusions are characteristic for extrusive rocks, and it may also be observed that when they are included in light minerals, they are darker and in dark minerals lighter than the glassy basis of the rock itself. The form of glass inclusions is sometimes irregular, sometimes oval, or in the form of negative crystals with rounded edges. Their dimensions are never as small as those of liquid inclusions, but they rarely exceed microscopic size.

Inclusions of pure glass, are found mostly in acid and intermediate extrusive rocks and even also in such rocks in which the glassy basis has been completely devitrified by secondary alteration. Sometimes, however, the alteration has effected the glass of the inclusions and their character can only be recognized by the outer form. Corresponding to the greater ease with which basic magmas crystallize, real glass is less ofteu observed as an inclusion in basic rocks, the glass tending to be more or less filled with microlites which cloud it. Such products are better termed *slag* inclusions. In lava, which has solidified rapidly, they entirely fill the plagioclase individuals and in leucite crystals they cause a characteristic appearance by their radial or zonal arrangement, Fig. 210.

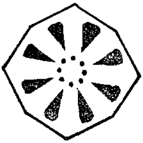


FIG. 210.—Leucite with Slag Inclusions.

The arrangement of the inclusions is often very characteristic. Aggregations in the center or in border zones are especially prevalent, as is also zonal arrangement. The plagioclases are frequently built up of zones alternately rich and poor in inclusions. In garnet the inclusions are sometimes orientated parallel to crystallographic directions and sometimes tangential to them. In certain pyroxenes, in olivine, and in the labradorite of gabbros, brown flakes and rods, which are perhaps ilmenite, *are regularly arranged and often cause a metallic chatoyancy in* the mineral visible to the naked eye. The arrangement of graphitic dust in certain minerals of contact rocks is especially typical, particularly in andalusite. The variety known as chiastolite presents the appearance shown in Fig. 211. In other minerals, which are likewise often rich in inclusions, as cyanite or staurolite, no regularity in the arrangement of the inclusions is to be noted.

One type of arrangement of inclusions, which is classed with the characteristic structures of contact rocks, is especially interesting. If a contact schistose rock is cut across the schistocity and observed in thin section an irregular crystalline aggregate appears. However, the bands of inclusions are often interwoven in the principal constituents and reveal the original schistocity with all its contortions very plainly. This is called *helicoidal* structure. In cordierite hornfels, Fig. 212, these bands consist of sillimanite, biotite, and ilmenite, in other cases of graphite dust, and in still others of small quartz grains, but in spite of the varying composition the general appearance remains the same and they are therefore extremely characteristic.

FIG. 211.—Chiastolite in Chiastolite Schist Gunildrud on Ekernsee, Norway. (After E. Cohen.)

FIG. 212.—Helicoidal Structure. Cordierite Gneiss, Bodenmais.

A large amount of inclusions in certain constituents, especially the larger ones, is characteristic for contact rocks. Such is particularly the case in garnet, in which sometimes the center of the crystal is a compact mass of inclusions surrounded by a ring of garnet, *perimorph*, Fig. 213, and sometimes the irregularly arranged inclusions constitute the greater part of the crystal and are interwoven with a network of fine veins of the including mineral, *sieve* structure, Fig. 214. The external form of such crystals so rich in inclusions may be perfectly normal.

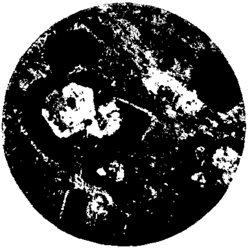


Fig. 213.—Garnet Perimorph. Eclogite, Kleinitz in Grosvenedig.

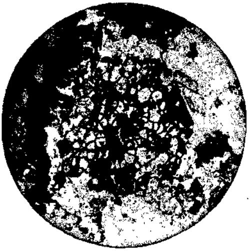


Fig. 214.—Sieve Structure. Mica Schist, Zopetspitze, Grosvenedig.

The occurrence of pleochroic halos must be mentioned. They occur around inclusions of certain minerals containing zirconium, tin, titanium, and some of the rare earths, when included in certain other minerals, see Table 19, No. IV.

They may be best observed when the direction of strongest absorption of the including crystal is parallel to the vibration direction of the polarizer and then they appear as quite small zones not sharply separated from the surrounding mineral, Figs. 215 and 216. The pleochroic halos show a much stronger absorption of light than does the rest of the crystal, yellow to deep brown colors being *especially common*. If, on the other hand, the direction of least absorption is parallel to the polarizer the phenomenon almost completely disappears. The form of the halo varies greatly and is dependent upon the form of the inclusion. It is very significant that other minerals than those included in Table 19, e.g., the needles of apatite in biotite, Fig. 216, do not show such halos. Pleochroic halos may be of a secondary origin, e.g., when augite, which does not show them, alters to hornblende. In

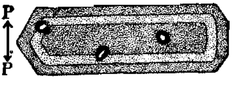


Fig. 215.

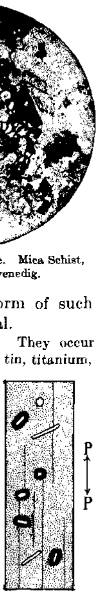


Fig. 216.

Pleochroic Halos around Inclusions of Zircon in Tourmaline. Biotite.

general the optical properties of a crystal are quite strongly modified in the pleochroic halos. The indices of refraction are raised, the double refraction may become much lower or may be raised considerably, and in biaxial crystals a stronger dispersion of the optic axes is generally to be observed in the halos. All these phenomena do not indicate that the coloring is due simply to an organic pigment but much more that it is due to an isomorphous mixture in which the elements, that are predominant in the inclusions, play a considerable rôle. The ease with which these halos can be destroyed by heating does not in any way oppose this view for that is a common property of silicates colored dark by a content of titanium, e.g., melanite, and also of numerous occurrences of dark rutile, cassiterite, zircon, etc.

*Pseudomorphs.*—Alteration of rock-forming minerals is exceedingly common, but very frequently the form and also a considerable portion of the original mineral remains unchanged indicating clearly the origin of the pseudomorphs. Most of the pseudomorphs are not the result of the action of ground waters. Pseudomorphs due to weathering are comparatively rare. The most of these occurrences are to be ascribed to the post-volcanic action of magmatic waters. They are, therefore, most important in eruptive rocks and in regions where they have effected contact metamorphism. These regions are the characteristic habitats of pseudomorphs.

Pseudomorphs, which exhibit a new composition in an old form, sometimes consist of a newly developed, homogeneous crystal, e.g., uralite. In *most cases, however, they are composed of a dense aggregate* which may still show the cleavage and structure of the original mineral, thus hastite, or may form an irregular cluster, which presents the phenomenon of aggregate polarization in polarized light, e.g., liebenerite.

*An important group of alterations belongs in this class, in which simple* molecular rearrangement takes place without change of chemical composition—*paramorphs.* One of the most important chemical geological processes belongs here. It is the very widespread transformation of aragonite into calcite in the fossilization of organic lime skeletons. Sometimes the original structure is retained, while at other times it is completely obliterated during the process. The transformation of minerals free from water into those containing water is especially frequent. There are two processes of this kind which take place very extensively, e.g., the formation of gypsum and of serpentine. An increase of volume takes place which produces great geological disturbances and its effects are even noticeable on a small scale in the fracturing of the surrounding minerals, which are traversed by radial cracks, Fig. 217.

Alteration begins for the most part on the border and progresses into the interior along the cleavages and gliding planes, expanding these more and more until a peculiar network results, Fig. 218, within which a residue of the original mineral, still unaltered but greatly clouded, is often preserved. In the normal case the newly developed substance is confined strictly to the border of the original crystal, but the texture of the altered rock may be recognized excellently, *palimsest* structure. The former shape is lost in the newly developed minerals only when the alteration is especially extensive and general. Secondary formations develop abundantly beyond the former borders of the minerals and the texture of the rock is more and more confused. In exceptional cases the alteration begins in the middle of an individual, but only when the crystals are zonal and the nucleus is more susceptible to alteration, as in the plagioclases of eruptive rocks.

One must guard himself against confusing alteration products with inclusions. Corresponding to the manner of formation, alteration products have a form dependent upon cleavage cracks and other discontinuities in the crystal. They form a more or less regular network in a crystal which has suffered alteration, but single constituents of the secondary substance lack characteristic form. Inclusions, however, can have definite forms and may be in definite orientation bearing no relation to the cleavage cracks. They do not form continuous veins but are in small sharply defined crystals, *which are completely imbedded in an unaltered clear transparent mineral.*

FIG. 217.—Radial Cracks in Plagioclase produced by Serpentinization of Olivine.

FIG. 218.—Mesh Structure in Serpentinized Olivine. Trogen near Hof, Fichtelgebirge.

**Directions for the Use of the Descriptive Section.**—The optical properties of rock-forming minerals are taken as a basis for the presentation in the descriptive portion and in the accompanying tables. A thorough knowledge of the methods of determining these properties, as is set forth in Part I, must be presupposed and the following paragraphs will only recapitulate the points particularly important in the use of this portion.

It may be remarked that, in so far as the transparent minerals are concerned, the presentation of the properties in the descriptive section will only supplement the statements in the tables so that both must always be used jointly. The arrangement in the text is the same as in the tables and *the number after the name of* each mineral in the descriptive section indicates the page of the tables where the mineral is to be found and, vice versa, the number in the first column of the tables refers to the page in the text giving the description of the mineral.

The systematic classification of rock-forming minerals must be different from that used in mineralogy because of the methods used to determine them. A chemical system, which mineralogists find so useful, has no significance in this case. The classification, which is adhered to in this text, has proved to be especially valuable and divides minerals into four groups:

1. Opaque minerals.
2. Isotropic minerals.
3. Uniaxial minerals.
4. Biaxial minerals.

This classification is based upon those properties which can generally be determined quickly and positively by simple methods. In certain cases some difficulties are encountered, especially by a beginner, because of the overlapping of the groups, but an experienced observer will soon overcome this. For example, hematite and ilmenite are found in the column of opaque minerals, but in certain instances they occur in fine transparent double refracting scales. Chromite is also quite frequently transparent with a brown color. On the other hand, some minerals from the other three groups are often so deeply colored that they do not transmit light except in the thinnest sections, as certain varieties of rutile or lievrite, and cossyrite. They may be distinguished from opaque minerals, however, by an entire lack of metallic luster in reflected light. This is especially so with the last two minerals.

Certain of the isotropic minerals are not isotropic in all cases. Such are perovskite, garnet, leucite, and analcite. However, these generally show a well characterized regular structure of several double refracting parts so that one, with experience at least, will scarcely ever be in doubt as to how to classify it. Some double refracting minerals may also be present, whose birefringence is so small that they could be overlooked in a cursory examination of a section, e.g., apatite, eudialyte, zoisite, etc. Optical anomalies are very common in uniaxial substances and they generally appear biaxial with a small optic angle in convergent light. There are also biaxial minerals in which the optic angle is nearly zero and they give the impression of being uniaxial, thus, mica. Any scheme of classification based upon a series of external features will show such discrepancies, but, as already remarked, they can be easily overcome and with a little practice any one can readily apply the division into these four groups.

That property which is first apparent, viz., refraction, is used as a basis for further subdivision of the transparent minerals, so that in each of the three groups the minerals are generally arranged according to the decreasing index of refraction. However, this principle is carried out only on general lines because there are no means of measuring the index of refraction of a mineral embedded in Canada balsam accurately. The necessity of treating various isomorphous groups as units gives rise to numerous deviations because there are sometimes great differences in the indices of refraction of various members of such a group, but this will scarcely ever give rise to confusion.

The observation of the relief of a mineral in a thin section gives a clue to the position in which that mineral is to be found in the table. Table No. 3 can be used for an approximate classification of the mineral.

The index of refraction is generally given to the third decimal place, which is unreliable in many cases. The determinations of various investigators often show variations of several units in the third decimal place, even in minerals which have a comparatively simple composition. In minerals belonging to an isomorphous series of many members, the variations in the determinations are much greater, e.g., almandine from Silberbach in the Fichtelgebirge, $n = 1.761$; from Falls in the Fichtelgebirge, $n = 1.770$; from India, $n = 1.791 - 1.800$. Three values are given for blue spinel from Ceylon, $n = 1.719$; $n = 1.720$; and $n = 1.726$. It seems useless, therefore, to give values to the fourth decimal place.

Table 18 gives a tabulation of the minerals treated in this text according to their double refraction and the interference colors dependent upon it, as arranged by Michel-Lévy and Lacroix. The values given there represent the difference between the maximum and the minimum indices of refraction, i.e., $\gamma - \alpha$, and generally are the mean where several values are to be found. The apparent extreme values are given only where the variations in the double refraction are especially large, as in chloritoid and titanite. The table may be used in the following manner. The thickness of the section is measured (see Part I, page 45) and then a cross section is sought as nearly parallel to the optic axis or to the optical plane as possible. This can be tested in convergent polarized light. The interference color of the section gives a very accurate means of determining the mineral. If, for example, by means of the low yellowish-white interference color of a section of quartz properly orientated, the thickness of the slide is found to be 0.03 mm., while another mineral, which is also colorless, shows yellow of the second order for its highest interference color, the vertical line corresponding to this color is followed to its point of intersection with the horizontal line corresponding to the thickness 0.03 mm. The diagonal through this point gives the double refraction of the mineral in question, which in this particular case is approximately 0.030. The distinction between the few minerals to which the investigation has thus been limited, can be made from a more careful study of the other optical properties.

The color of a mineral is highly characteristic and useful in its determination. Table 18 is arranged according to this principle. Many minerals, which are macroscopically colored, are entirely colorless in thin section and in all cases the thinner the section the lighter the color and more difficult is it to determine. The cause of the color varies greatly. Sometimes a characteristic relation to the chemical composition can be recognized, as in the pyroxenes and amphiboles. Sometimes the color changes without any apparent variation in the chemical composition. In this case, the color is produced by an admixture of an extremely small amount of highly colored material as seen in garnet. In a third case, microscopic investigation reveals the fact that *inclusions are the cause of color, e.g., haüyne and bronzite.* The color in this case is quite variable and many such minerals are only colored occasionally. The color is not always uniform in one section of a crystal. Zonal alternations or a very irregular speckled distribution of the color are very common.

The presence or absence of pleochroism is likewise a highly characteristic feature. The comparative depths of color, i.e., absorption, which appears along certain axes, is quite constant for a mineral group, and for this reason the absorption symbols are usually given in the tables. The colors of different axes, on the other hand, vary within wide limits and are only given where they are more or less constant.

A number of minerals are included in this part which occur *only rarely as rock constituents.* They are distinguished from the more important by smaller type. The most of these are not encountered by a beginner and are only observed in the course of advanced study.

Only those relations are considered which are of value to petrographers. All purely chemico-mineralogical and otherwise theoretical considerations are omitted. Likewise, the crystallographic development, which is of subordinate significance in the determination of rock-forming minerals, is only discussed in a cursory manner. Complicated crystal drawings are avoided and in *their place are numerous optical sketches for various minerals.*

In explanation of the figures it may be said that *a*, *b*, *c* are the crystallographic axes; $\mathfrak{a}$, $\mathfrak{b}$, $\mathfrak{c}$ are the principal vibration directions; $\alpha$, $\beta$, $\gamma$ are the corresponding indices of refraction; A and B are the optic axes.

A circle with a cross indicates the point of emergence of the optic axis of a uniaxial mineral. The point where an optic axis emerges from a biaxial mineral is indicated by a curve, printed heavily where the dispersion is great. These indicate by their position and distance apart the location of the axes in the section in question. The apparent optic angle is often indicated on an important crystal face or cleavage face, if it is parallel to the optic plane and this may be a characteristic property of the mineral.

The possibility of confusing various minerals is only considered in their descriptions when the slight differences in the optical properties might be easily overlooked. For example, the minerals perovskite and melanite are sometimes difficult to distinguish in spite of the great difference in the indices of refraction, *because they are very much higher than that of Canada balsam.* Nepheline and apatite, on the other hand, are not considered as similar minerals, although their indices of refraction are nearly the same, but the difference can readily be observed because they both lie in the neighborhood of that of the Canada balsam.

## CHAPTER XI

# Descriptive Section

*As already mentioned, the best classification of rock-forming* minerals embraces the following four groups: 1. Opaque Minerals. 2. Isotropic Minerals. 3. Uniaxial Minerals. 4. Biaxial Minerals. Those properties which are first apparent in microscopical investigation are made the basis for this classification. A classification according to crystal systems seems to be less commendable because it is not always possible to determine the system in a thin section, especially in the case of hexagonal and tetragonal minerals. Such a classification would also necessitate a division of the most important isodimorphous groups, which can be treated as a whole in the classification proposed.

## I. Opaque Minerals

Included with the opaque minerals are those which are ordinarily not transparent in thin section. They have more or less of a metallic luster macroscopically and in reflected light under the microscope. Since from their nature further optical determinations are impossible, microscopic distinctions cannot be made safely if they have the same surface color, and are without crystal form.

Some opaque minerals are cubic and some hexagonal. If they possess crystal forms, those belonging to the first system show three-,four- or six-sided cross sections which are isometric, while the typical sections of those of the other systems are hexagonal or lath-shaped, corresponding to a thin tabular development.

### Pyrite

Pyrite ($FeS_2$) occurs in perfectly bounded crystals of various dimensions consisting usually of a cube *a* striated by a pyritohedron *e*, or in combination with it, Fig. 219, page 205. It also occurs in large segregations and concretions, sometimes as a cementing material, and in irregular grains and fine veins as an impregnation in rocks.

It dissolves in nitric acid but hydrochloric acid scarcely attacks it. Hardness, 6.5; sp. gr., 5. Its brass yellow color is always apparent in a thin section. The ease with which it weathers to red or brownish-red ferric hydroxide varies in different localities and causes the rock to decompose very rapidly, for example Alaunschiefer. Pyrite occurs everywhere. When it is present as a constituent of eruptive rocks it is usually of secondary origin and its occurrence is accompanied by many other decomposition phenomena, such as kaolinization, propyllitization, and the formation of greenstone. It is frequently found also in all kinds of contact rocks, sometimes in large crystals which are greatly deformed if the rock was under great pressure, and sometimes in massive deposits as a constituent of the contact zone. It occurs in clastic rocks, principally in the form of concretions in clay slates, and in coal. It is often confused with the more bronze colored pyrrhotite and the more yellowish-green chalcopyrite, *but it can be distinguished from both of these by* its superior hardness.

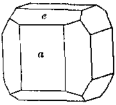


FIG. 219.
Cube and Pyritohedron.

### Pyrrhotite

Pyrrhotite (FeS), as a rock constituent, is found principally in small grains or in larger dense masses and, in unaltered gabbros, occasionally in tabular crystals. It is easily dissolved by acids. H. = 4; sp. gr. = 4.6 Usually strongly magnetic. Its color is bronze brown, but it is generally tarnished or entirely altered to rust. It is found as a primary constituent often containing nickel in basic eruptive rocks, and in green schists and amphibolites derived from them; also in contact limestones. It often forms comparatively large, dense irregular masses.

### Chalcopyrite

Chalcopyrite ($CuFeS_2$) is quite rare as a true rock constituent. It is found associated with other sulphides as a constituent of basic eruptive rocks and green schists, derived from them, and in granular limestones. It never shows crystal form. It is usually in very irregular grains in which well developed crystals of pyrite have grown. The distinction by means of the greenish-yellow color of chalcopyrite is then very easy. H. = 4; sp. gr. = 4.2. It gives a copper reaction.

### Galena

Galena (PbS), associated with sphalerite, is not a rare constituent of contact-metamorphic limestones. *Occasionally it occurs in well developed*

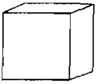


FIG. 220.—Cube.

cubes, Fig. 220, but more often it is in grains which have a light lead gray color and an extremely brilliant metallic luster. *It generally shows very perfect cubical cleavage* in reflected light. It is soft and often has a smeared border, like graphite. This with the color gives it the *appearance of molybdenite but it differs from the tabular* individuals of molybdenite in being more compact. H. = 2.5; sp. gr. = 7.5. Soluble in nitric acid with separation of sulphur.

### Metallic Iron

Metallic iron is rare in terrestrial rocks and occurs only in angular grains. It is always alloyed with nickel which may predominate, as in awaruite. *It is easily soluble in acids and decomposes Thoulet's and Klein's solutions.* In the latter case intense blue tungstic acid is formed. It precipitates metallic copper from copper solutions. H. = 4; sp. gr. = 7.8. Strongly *magnetic, but shows no polarity. It rusts easily in moist air.* While it has only been observed on the earth as a rare constituent of the most basic eruptive rocks, it is known to occur extensively in meteorites.

## Magnetite

Magnetite ($Fe_3O_4$), which often contains *titanium—titanium magnetite*—is a universal constituent of rocks. It occurs sometimes in octahedral crystals, Fig. 221, or twins, Fig. 222, sometimes in delicate crystal skeletons, and sometimes in irregular grains or compact masses. It dissolves easily in hydrochloric *acid especially upon addition of a little potassium iodide* (distinction from hematite, titanite, graphite, etc.). H. = 6; sp. gr. = 5.2. Strong magnetism, but not polar. Quite resistive to weathering, and is, therefore, only rarely surrounded by a border of rust, and is found commonly in secondary deposits—magnetite sand. It appears black with a variable strong metallic luster. The simplest means of isolating it is with a magnet. It may be distinguished in this way from other similar black opaque ores and from graphite. It is widely dis-

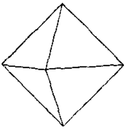


FIG. 221.—Octahedron.

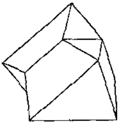


FIG. 222.—Twin. Spinel Law.

seminated in the eruptive rocks, particularly in the basic ones. It is usually one of the first minerals to crystallize and so is frequently included in the other constituents, especially in the colored minerals. Black ores are very frequent in the form of fine dust in the ground mass of such rocks. Although this is probably mostly magnetite, it has been called *opazite* because of the difficulty of determining it positively. It is quite as frequent in all other groups of rocks.

In gabbros black compact ores, which are to be considered partly as titanium magnetite and partly as ilmenite, are often surrounded with a homogeneous fringe of biotite. Aggregates of magnetite grains are widely disseminated in extrusive rocks, usually mixed with augite, which sometimes shows the form and cleavage of hornblende or biotite quite plainly, and is probably produced by magmatic resorption of them. Intergrowth with ilmenite is not at all rare. In such cases the magnetite can be dissolved with hydrochloric acid.

### Chromite

Chromite [$Fe(Al.Fe.Cr)_2O_4$] is found exclusively in olivine rocks in sharp octahedral crystals, Fig. 221, page 206, or in compact masses often of considerable size. It is one of the oldest products of crystallization and is very frequent in sharp crystals as inclusions in olivine with which it is almost universally associated. Acids attack it with great difficulty. H. = 5.5; sp. gr. = 4.5. Macroscopically, it is brownish-black with only a weak metallic luster, which appears more greasy under the microscope. In thin section it is frequently transparent with a brown color particularly on the edges. Its index of refraction is about 2.1. It is unaffected in the alteration of olivine to serpentine because it is so resistive. A brilliant green pleochroic halo of chromeocher is often to be observed around the crystals of chromite in serpentine. It is easy to isolate because of its high specific gravity and its resistance to reagents, and it can be tested by the bead reactions.

## Hematite

Hematite ($Fe_2O_3$) sometimes occurs in compact masses or in crystals with an uncommonly brilliant metallic luster, Fig. 223. They are always opaque in thin section, and appear steel gray to iron black in reflected light. Sometimes it is in thin hexagonal plates which are transparent and red. In the form of fine dust, hematite is the most frequent red pigment of rocks. It is difficultly attacked by hydrochloric acid, but the more finely divided it is, the more readily is it dissolved. It is not magnetic when not

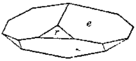


FIG. 223.
Hematite Crystal.

intergrown with magnetite. H. = 6.5; sp. gr. = 5.25. Streak red to reddish-brown. It is very resistive to weathering but is now and then transformed to rust.

*Compact nontransparent hematite is found in all kinds of rocks. In eruptive rocks, it is more frequent in the acid varieties into which it is often introduced by fumaroles.* Thin yellowish-red plates with properties like those of mica, which without further investigation have been identified as hematite, are found as orientated inclusions in feldspar. They give rise to the red metallic chatoyancy, as in *sunstone* (*Sonnenstein*). It is not positively determined whether these are hematite, but the well developed platy crystals with brilliant metallic luster in reflected light, which are so widespread in contact rocks, positively do belong to hematite. The thinner individuals are transparent with deep red color and have strong negative double refraction and weak pleochroism, $\varepsilon$ yellowish; $\omega$ brownish-red. Hematite is known as a red pigment in all rocks from granite to clay slate and is especially frequent in a group of acid porphyries and porphyrites that have been devitrified and appear felsitic. No characteristic properties can be recognized in it even with the strongest magnification and so this pigment sometimes, with a yellowish or brownish color, is better known as *ferrite*.

## Ilmenite

Ilmenite [$(Fe, Ti)_2O_3$] is more frequently found in crystals than compact. Two varieties can also be distinguished in this mineral. One has a weak metallic luster, is iron black, and occurs in tabular crystals or in dense compact masses; the other is micaceous, brown transparent, and has a submetallic luster. Both types have a great tendency to grow in skeletal forms. Perhaps the ocherous brown pigment, e.g., in the plagioclases of certain gabbros, may be referred to ilmenite.

It behaves like hematite toward acids and the magnet. H. = 5.5; sp. gr. = 4.8 to 5.2. Unlike hematite it is frequently decomposed and is then real characteristic. It is coated with a clouded film of leucoxene, white in reflected light, consisting of a mixture of various titanium minerals and at the same time the cleavage, which is not very apparent in the fresh mineral, becomes plainly visible. Ilmenite may finally be entirely replaced by leucoxene. Alteration into homogeneous individuals of titanite or rutile, or zonal growths with these minerals are not rare. It is found principally in eruptive rocks and of these it favors the basic and those rich in sodium. The micaceous type with not very strong double refraction, optically negative, ε brown, ω yellow, is confined to the porphyric eruptive rocks. Perhaps the orientated brown tabular inclusions, which produce the metallic chatoyancy of diallage, hypersthene, etc., belong to this mineral.

## Graphite

*Graphite (C) is found in granular limestones rarely crystallized* in hexagonal plates with a brilliant metallic luster and steel gray color. It generally forms shredded or flaky aggregates, which have a great tendency to parallel intergrowths with altered mica, Fig. 224. If it is treated with nitric acid and heated on a platinum foil, it swells up into voluminous worm-like particles. In other rocks the individuals are more compact and of even size and have an egg-shaped cross section in the slide. Such varieties are denser and do not show the flaky character of graphite to the naked eye. They do not swell when heated with nitric acid. For this reason it has been considered as an individual mineral called *graphitite*. Graphite is a widely disseminated black pigment of crystalline schists. As such it is as fine as dust and a crystallographic development cannot be observed even with the strongest magnification. This is designated as *graphitoid*, and is considered as a transition product to amorphous coal. The properties of these three types of graphite are too similar to permit a separation to be made, especially since they are related by all possible transition stages.

FIG. 224.—Graphite in Graphite Gneiss from Pfaffenreuth near Passau.

Graphite is completely insoluble in acids and molten alkalies. If it is melted with metallic potassium, and ferrous and ferric salts are added with some hydrochloric acid, Berlin blue is frequently obtained. This is a proof of a small content of nitrogen in the graphite. In a mixture of fuming nitric acid and potassium chlorate, it is oxidized to graphitic acid, which *crystallizes in golden yellow, metallic, hexagonal plates.* They are optically negative and have a strong double refraction. The *coarser flaky varieties of graphite* burn *very difficultly* but when finely divided it burns quite easily. It is a good conductor of heat and electricity. Rocks rich in graphite feel cold. When held in a zinc holder, it precipitates metallic copper from a solution of copper. H. = 1; sp. gr. = 2.3. The borders of its cross sections never appear sharp on account of its softness. It is smeared over the entire section in fine powder during the process of grinding so that its distribution is often recognized with difficulty. This property is one of the best characteristics of graphite compared with hematite and ilmenite, which are similar minerals. It is also distinguished from them by its insolubility and its ability to burn. The brilliant metallic luster of flaky aggregates produced by a very perfect cleavage parallel to the base, becomes more and more obscured in the more compact varieties. However, the grayish-black streak always remains brilliant except in the finest varieties.

Graphite is rare as a primary constituent of eruptive rocks, but *if present, is mostly in the form of thick lumps. Altered* limestones and schists are its true habitat. It results in these partly by contact-metamorphic alteration of organic matter and partly by some sort of fumarolic action, which greatly alters the rock at the same time. In such rocks its characteristic associate is rutile. The dust-like variety of graphitoid is distinguished from coal to which it is very similar by its electrical conductivity and its reaction for graphitic acid. Elementary analysis seems to be quite useless to distinguish between graphite and coals with high fixed carbon. This is partly on account of the organic impurities consisting chiefly of hydrous silicates, which graphite nearly always contains, and partly on account of an almost constant content of nitrogen in graphite. It is not even lacking in the best crystallized varieties, e.g., the coarse crystalline graphite from Ceylon.

### Carbonaceous Matter

*Carbonaceous matter is the black pigment of numerous sedimentary rocks.* Shapeless grains are found in the thin sections of gray to black clay slates and coal slates, and in gray to black limestone, but a fine opaque dust is more frequent. This impregnates the whole rock evenly and makes microscopic analysis of it very difficult. Nothing is known about the chemical constitution of this material which may cause the black color of coal. It contains oxygen, hydrogen, and a small quantity of nitrogen, besides carbon evidently in variable proportions. It must not be considered as established that a series of gradual transitions from a sedimentary occurrence, rich in oxygen, hydrogen, and nitrogen to a compound poor in them exists, as it was attempted to show in certain phyllites and in *schungite* interbedded in layers of compact coal. The analyses, which were designed to show that such was the case, were not made on material properly selected but on very impure formations and a certain amount of the hydrogen and oxygen reported could easily be explained in this way. The analyses which show a very small content of nitrogen are those of the purest varieties of graphite. Moreover, the methods of determining nitrogen in an elementary analysis are not reliable. All conjectures concerning the chemical properties of such transition members are entirely without foundation.

Many of the opaque carbonaceous substances are at least partially soluble in potassium hydroxide and become colored brown. All are soluble in a mixture of potassium chlorate and fuming nitric acid and give rise to a brown liquid. This appears to be the only characteristic reaction to distinguish them from graphite. At present it is by no means a settled question whether pure amorphous carbon or a compound closely related to it occurs in the black constituents of rocks, which also appear as sooty films on bedding planes and cleavage faces of the sediments in various formations, or whether the carbonaceous material is itself a definite compound or a series of compounds, or whether or not they are definite compounds at all.

Finely divided black ores appear very similar to carbonaceous material. They can be distinguished by treating the slide with hydrochloric or nitric acid, which dissolve the ores and then by heating to redness which destroys the coal. These processes are often necessary before microscopical investigation can be carried out on the slide.

**The dark color of sediments does not depend entirely upon carbonaceous matter. Frequently, other organic compounds with a brown to yellow color and resinous luster occur in the sediments along with carbonaceous**

matter, which is always opaque. These compounds are called *bituminous matter* and represent a series of oxidation products of hydrocarbons. Their constitution is likewise unknown but they give to a rock in which they occur in great quantities a brown shiny streak. They are at least partially soluble in benzol or xylol and are destroyed by a mixture of potassium chlorate and nitric acid.

Finally, there are organic ingredients in sedimentary rocks, which cannot be observed microscopically but can be recognized by the unpleasant odor, which they produce when the rock is struck—for example, stink stone. They are doubtless the most resistive of all organic compounds and remain unchanged even under the most intense metamorphic alteration, which transforms the other kinds into graphite. They are only changed in the zone lying next to the eruptive contact. Then a delicate rose-red coloring matter results from the vile smelling substance, which, together with the character of the odor, indicates that they are *indol* derivatives, especially *skatol*.

## 2. Isotropic Minerals

Amorphous substances and cubic crystals are optically isotropic. The former are not minerals in the narrower sense because they do not have a definite stoichiometric constitution. As *they are sometimes predominant and sometimes subordinate* as rock constituents, their characteristic properties must be included in this discussion.

Cubic crystals are distinguished from them by a regular structure which is indicated in the straight edges, cleavage, or the *arrangement of inclusions. The structure is sometimes so concealed* that it is not seen in direct observation but it can still be determined by the formation of etch figures.

FIG. 225.—Principal Cross Sections of Cubic Minerals.

Isotropic minerals are dark between crossed nicols and produce no interference figure in convergent polarized light. Optical anomalies of various sorts are very common and are recognized by spotted illumination, by lamination, or by a regular division of the crystal into segments that extinguish differently.

Cubic minerals generally develop in the form of cubes, octa hedrons, and dodecahedrons, and therefore their cross sections are commonly isometric and three-, four-, or six-sided. The tetragonal trisoctahedron is rarer and its cross section is usually eight-sided and more or less rounded. Distortions of any of the forms give rise to variations in the shape of the cross sections. Twins according to the spinel law are not at all uncommon. Only the simplest forms are known as cleavage fragments. Cleavage parallel to the cube and octahedron is frequent and perfect, while that parallel to the dodecahedron is rare and usually imperfect. Fig. 225 shows the forms of the cross sections of minerals in the cubic system as well as the principal kinds of cleavage.

### **Perovskite** (1)

Perovskite occurs as a rock constituent either in minute, light brown, octahedral crystals and skeletons of crystals, or in larger compact grains with a dark color. It is yellowish in reflected light and has an adamantine luster. The smaller crystals are usually optically normal but the larger ones consist of a system of interpenetrated double refracting lamellæ. Inclusions and decomposition are not known. It is widely disseminated in basic eruptive rocks associated especially with melilite. It is also known in certain contact rocks. It is infusible before the blowpipe. It is distinguished from various minerals that resemble it, picotite, melanite, etc., by its higher index of refraction, which causes the high metallic luster in reflected light, and by the reaction for titanium.

A large number of rare cubic minerals appear very similar to perovskite under the microscope with respect to the index of refraction, color, and geological occurrence. Such are pyrochlore, beckelite and pyrrhite, which crystallize predominantly cubical and are yellowish in color, also brown zirkelite, reddish koppite, knopite, which usually shows optical anomalies, and dysanalyte with its metallic luster, being almost opaque in thin section. All these minerals are local constituents of cruptive rocks and pegmatites rich in soda, but are found also in grains in the contact rocks lying next to these. Oldhamite, CaS, also occurs in meteorites but it is not observed except in specially prepared sections because it decomposes in water.

### **Sphalerite** (1)

Sphalerite is a widespread constituent of rocks, occurring in irregular grains associated with opaque sulphides. It is light yellow to brownish, and appears very much like rutile and was almost always determined as such until recently. It is distinguished from rutile by a more perfect cleavage and its isotropic behavior toward light.

Sphalerite may also be confused with the rare isotropic minerals mentioned under perovskite with which it is associated in contact rocks, especially in limestone. It can only be determined positively by a blowpipe. It gives a film of zinc oxide when fused with sodium carbonate on charcoal.

### Garnet Group (1)

*The minerals of the garnet group are widespread rock constituents.* They are sometimes well developed crystals, and sometimes rounded or irregular grains. The most frequent crystal form is the rhombic dodecahedron, Fig. 226, and the tetragonal trisoctahedron, Fig. 227, is less common. Combinations of these two forms, Fig. 228, also occur. Their dimensions vary greatly and every gradation from microlites to crystals as large as a fist are found. Individuals of intermediate sizes are most common and they are macroscopically visible. Almandite and the lime garnets often form perimorphs. Alterations that are comparatively rare, in which chlorite, amphibole, or biotite are formed at *the expense of the garnet, appear similar to these.*

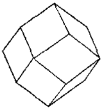


FIG. 226.
Dodecahedron.

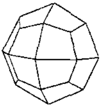


FIG. 227.
Tetragonal Trisoctahedron.

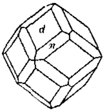


FIG. 228.
Combination.

Cleavage parallel to the dodecahedron is at most only suggested, Fig. 225, *e* and *f*. But on account of its brittleness the garnet crystals are usually quite full of short jagged cracks that do not indicate any crystallographic orientation.

Optical anomalies are common but are confined mostly to the group of lime garnets free from titanium and to the manganese garnets. This consists of a division of the crystal into segments, that are optically different, and often also of a zonal structure due to the growth of layers with very strong but variable double refraction. The division into segments always corresponds to one of the crystal forms present. The crystal then appears to be composed of as many pyramids as there are faces to that form and each face is the base of a pyramid whose apex lies in the center of the crystal. The double refraction of these segments is quite variable and may exceed that of quartz. They are biaxial, optically positive often with strong dispersion, $\rho < v$, and $2v = 56^\circ$ to $90^\circ$. Anomalous interference figures are frequent. Each one of these segments is usually not very homogeneous but is built up of differently orientated parts that are more or less irregularly bounded, so that the character of the optical anomalies stands out prominently and can readily be distinguished from normal double refracting substances.

The dodecahedron is the most frequent form of garnet crystals and, therefore, the optical structure is usually the so-called dodecahedral structure. Fig. 229 shows a section parallel to the dodecahedron face and Fig. 230 shows one out of the middle of a crystal parallel to an octahedron face. A similar development occurs now and then in almandite unaccompanied by optical anomalies, and is due to the arrangement of inclusions, or to breaking parallel to the pyramids of growth.

Almandite is the most widespread member of the garnet group. The larger crystals are macroscopically transparent and wine red, and are termed *precious* garnet, while the more frequent red to yellowish-red varieties clouded by inclusions or cracks, are called *common* garnet. Both varieties are pale reddish in thin section. Almandite is always isotropic. It is an accessory constituent of *all eruptive rocks with the exception of the most basic ones.* It is characteristic for granulite. It is more common and frequent as an essential constituent of various groups of contact rocks. It is usually macroscopically visible. Concentric structures often develop around almandite and these tend to extend outward from a compact grain into the surrounding minerals like pseudopods. The larger, well defined crystals are easily removed from rocks having abundant mica, while they are apt to be broken in rocks with little mica.

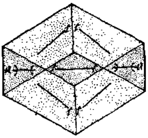


Fig. 229.—Segments in Garnet.

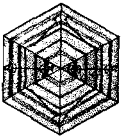


Fig. 230.—Garnet with Optical Anomalies. Section Parallel to Octahedron.

The mineral is sometimes altered to chlorite or hornblende, and in aplites and pegmatites, in which almandite is the most characteristic accessory constituent, round flakes of biotite are seen which contain a residue of garnet from which the biotite was formed. Almandite is quite resistive to weathering and is, *therefore, often found in secondary deposits. It is used as a* substitute for emery. A very fine skeletal development has been observed in clastic rocks but nothing more is known about this formation. *Almandite has the greatest tendency to crystallization of all rock-forming minerals* and is, therefore, frequently filled with inclusions. Almandite crystals, perforated like a *sieve, are the most characteristic features of contact rocks.* In rocks rich in quartz the garnet itself takes a small part in the composition of such a structure, Fig. 214, page 197. It also occurs in *the most beautiful perimorphs in such rocks, Fig. 213,* page 197.

The manganese garnet, *spessartite*, is very similar to almandite in its occurrence as a rock constituent but is much rarer. It is common, especially in pegmatite dikes. It forms also a principal constituent of the whetstone schists of the Ardennes mountains but occurs in minute colorless individuals.

Fig. 231.—Pyrope with Kelyphite Border in Serpentine from Karlstetton, Lower Austria. (After Cohen.)

Pyrope, usually containing some chromium, is confined to the olivine rocks and their derivatives, the serpentines. It generally shows rather indistinct crystal form, which appears to be hexahedral. Its individuals can be recognized distinctly macroscopically by the blood red color. It is distinguished from almandite by being poor in inclusions and cracks and, therefore, often transparent—*cinnamon-stone.* The occurrence of a fine fibrous, radial border of *kelyphite* is especially distinctive, Fig. 231. It sometimes consists of hornblende minerals but is more often a mixture. It often completely replaces the pyrope. This border is considered a product of magmatic resorption of pyrope, that has already been formed, by a magma rich in magnesium. Pyrope is also found in secondary deposits in comparatively large grains, which are cut as semiprecious stones—Bohemian garnet.

Hessonite, rich in iron, and topazolite of the lime garnet series are found almost exclusively in crevices and other forms of secondary development within rocks, especially in serpentine. Light green topazolite, *demantoid*, is sometimes found in disseminated crystals. These minerals are also the most important *constituents of skarn, which accompanies magnetite ore deposits.* Emerald green uwarowite, an optically anomalous lime garnet containing chromium, is likewise confined to crevices in serpentine. Grossularite and hessonite poor in iron are widely disseminated constituents of contact-metamorphic limestones and lime-silicate hornfels. The former is entirely colorless in thin section, and the latter is light reddish, brownish, or greenish, the color being entirely independent of the chemical composition. *Light reddish, excellently bounded microlites of lime garnet* often fill the plagioclase crystals of the granite of the Central Alps in such a manner that the rock has a reddish tinge. When these garnets occur in limestones, they have a crystallographic form but are often rounded in a peculiar manner as though they had been slightly fused on the surface. In other rocks they form granular aggregates without distinct crystal form. Lime garnets poor in iron are easily fusible, and those rich in iron fuse with difficulty.

The lime garnets have fewer inclusions than almandite, but perimorphs are encountered in them. Evidences of alteration are almost entirely lacking. On the other hand, a structure consisting of different zones is very common.

The members of the lime garnets containing titanium play a special rôle. They are macroscopically black with a pitchy luster but in thin section are brown and built up of zones in which *the intensity of the color varies depending upon the variations in* the content of titanium. These garnets occur especially in eruptive rocks rich in sodium and their contact formations, and are usually well developed and always poor in inclusions. They are named according to the increasing content of titanium—*melanite, schorlomite* and *ivaarite,* the latter containing about 15 per cent. $TiO_2$. The cause of the black color of *pyrenäite,* which occurs in the contact rocks of the Pyrenees, is to be sought not in these garnets but in finely divided graphite.

The silicates almandite, pyrope, and hessonite form isomorphous mixtures only in exceptional instances. The garnet of eclogites, which corresponds apparently to normal almandite, is such a mixture in which almandite predominates. Dense splintery aggregates of grossularite are noteworthy in olivine rocks and serpentine. They occur in lumps or form a part of the so-called saussurite. Similar formations of hessonite occur on the contact of dikes containing hessonite, with olivine or serpentine rocks. The latter have been shown to be alteration products of the olivine rock itself.

Almandite and pyrope are not easily confused with other minerals because of the reddish tint which is always plainly seen even in the thinnest sections. Colorless or greenish lime garnets resemble the spinels, especially when they are in small individuals, and when the crystal form is lacking they can only be distinguished by a chemical test. They can be differentiated from periclase, which they likewise simulate, by the imperfectness of the cleavage. Titanium garnets may be confused with picotite or perovskite, but the garnet usually has the zonal structure. Chemical reactions will give the necessary confirmation. Double refracting lime garnets are so similar to vesuvianite and to the low double refracting members of the epidote group, especially when the garnet is in fine grained aggregates, that a differentiation is not possible.

### Spinel Group (1)

The minerals of the spinel group (compare magnetite and chromite, page 206) occur in sharp octahedral crystals and twins according to the spinel law, Figs. 221 and 222, page 206, without cleavage, and less often in irregular grains. They are always optically normal. They are the hardest and most resistive rock-forming constituents and are, therefore, scarcely ever altered and are frequently found in secondary deposits.

Chrome spinel, *picotite,* forms minute crystals nearly everywhere in olivine with which it, like chromite, is always associated. It often shows no crystal form when it occurs as an independent constituent of peridotite. It is macroscopically black with a submetallic luster, but under the microscope the metallic luster is not seen. It is brown in transmitted light but usually lighter than chromite to which it is exactly similar except for the hardness. The iron spinels, *pleonaste* and *hercynite,* are black as is also the zinc spinel, *kreittonite,* which occurs in certain ore deposits and is very similar to the others, being distinguishable from them only chemically. They have dull luster, green streak, and are green and transparent in thin section. *Common* spinel is red, green, blue or violet to the naked eye, but is always colorless in thin section. It is a characteristic product of contact metamorphism particularly in granular limestones and dolomites. It can be recognized macroscopically, and on account of its dearth of inclusions and lack of cleavage, it is clear and transparent—*precious spinel.* Iron spinel is also found in other rocks, such as granulites and lherzolites. It is mostly in the outer border zone of the eruptive rock in schlieren and is often mixed with other contact minerals. *It is undoubtedly a residue of resorbed inclusions* of the neighboring rock. The minutest microlites of colorless spinel are found in the so-called fritted rocks and only the high index of refraction serves to determine it. Spinel can be easily isolated in all cases on account of its resistance to reagents. The distinguishing of the spinels *from perovskite and garnet is discussed* under those minerals. The lack of cleavage and its chemical behavior distinguish it from periclase.

### Periclase (1)

*Periclase is not a rare constituent of contact-metamorphic limestones.* It is usually in small octahedrons with rounded surfaces. They are macroscopically colorless to greenish-brown. When fresh it is easily recognized by the cleavage, Fig. 225, *c*, page 212, and the index of refraction. It is usually strongly altered to scaly aggregates of brucite, e.g., in predazzite, or of serpentine. In these the original cleavage is sometimes retained.

### *Boracite* (1)

Boracite is a rock-forming mineral now and then, but is confined to the rock-salt formations. It occurs in gypsum and abraum salts in well developed tetrahedral crystals that are macroscopically recognizable. They are colorless to light green, often possessing an abundance of faces. Under the microscope it appears very much like leucite from which it is distinguished by its higher index of refraction and its mode of occurrence.

### Rock Salt

Rock salt as a rock constituent is not observed in thin sections prepared with water and is, therefore, not included in the tables. H. = 2; sp. gr. = 2.2. Perfect cubical cleavage, Fig. 220, page 206. It is without crystal form and is soluble in water giving a salty taste, $n = 1.544$. It often occurs in pure, very coarse granular aggregates that are colorless, deep blue, red or yellow, and rich in liquid inclusions, or in fibrous masses in crevices, or finally in fine impregnations in salt clays. It also occurs as incrustations on lava rocks and as small cubes in liquid inclusions in quartz.

### Leucite (1)

Leucite is found almost exclusively in white, perfectly developed tetragonal trisoctahedrons, Fig. 227, page 214, in eruptive rocks rich in alkali, especially the leucitophyres, leucite tephrites, etc. In these rocks it frequently forms large, brittle, and checked crystals, but in leucite basalt it is only in the form of microlites. Aggregates of orthoclase and nepheline in the form of large leucite crystals are found in leucite syenites and the rocks produced by differentiation of such a magma.

The outlines are usually rounded. Skeletal development and magmatic resorption are not rare. Small crystals are always optically normal but larger crystals consist of complicated lamellar twinning intergrowths and penetration of such a character that a highly characteristic structure is observed in polarized light, as is shown in Fig. 232. When heated to 600° this anomalous structure disappears but returns again upon cooling.

The frequency of inclusions is an especially characteristic property of leucite. They consist of crystallized minerals, slag, or colorless to brownish glass, arranged in a regular manner either zonal or radial, Fig. 210, page 195. Needles of various minerals, arranged tangentially around the crystals of leucite, are often observed, *ocellary* structure, Fig. 207, page 193. It is often altered because it is so readily attacked. Besides the pseudomorphs referred to above those of analcite and other zeolites are widespread.

FIG. 232.—Twinning Lamination in Leucite.

It would be very easily overlooked where it occurs in the form of microlites, but even they are distinguished from all other minerals by the arrangement of the inclusions. It could be confused with microcline when it forms compact aggregates that are optically anomalous, but its mode of occurrence is entirely different. If the optical anomalies, the crystal form, and the inclusions are lacking, distinction from analcite, sodalite, or from rock glass is scarcely possible.

## Glass (1)

Glassy material is found as a principal or subordinate rock constituent only in rocks which have solidified rapidly from the magma. These are the comparatively small eruptive dikes, which have branched out far from the vulcanic center, or the rocks poured out upon the surface and their tuffs, or those rocks or fragments which have suffered partial fusion, i.e., *fritting*. The glass occurring in rocks may have quite a variable composition, but the acid mixtures tend in general more to glassy development than do the more basic ones. Although in andesite, diabase and basalt, glasses are not lacking, still the series of quartz porphyry, rhyolite, and trachyte is much richer in rock glass.

Some of the glasses are free from water while others show an original content of water up to 8 or 10 per cent. The former are called *obsidian* and the latter *pitchstone*, while *perlite* with 2.5 to 5 per cent. of water is intermediate. The specific gravity is always low, rising to 2.4 in obsidian and 2.7 in basic glasses, and falling to 2.25 in those containing water.

The normal rock glasses have a chemical composition corresponding to that of crystalline rocks. They are principally products of rapid solidification of granitic rock magmas, but glasses with the composition of andesite and even trap and basalt are not altogether lacking although they are in general anomalous forms of development. It has been noted that partially or entirely resorbed inclusions have given rise to the formation of glass because the ability of the dissolving magma to crystallize has been lost through the chemical composition of the inclusions. The glassy development of basic rocks may also be referred to such phenomena. These glassy forms occur sometimes in rounded masses within normal rocks or on the contact with certain rocks, while they are entirely lacking with other rocks. Chemical analysis almost always shows variations from the normal composition in such cases.

The chemical behavior of rock glasses is quite variable according to the varying composition. In general, the glasses are more rapidly attacked by the atmosphere and are more easily dissolved by hydrofluoric acid than are most of the crystallized rock constituents. Most of the rock glasses are very little affected by hydrochloric acid, but now and then they gelatinize with hydrochloric acid, especially basaltic glasses rich in sodium. Rock glasses often appear to have double refraction in the neighborhood of inclusions. This is produced by strain and gives rise to the Brewster's cross, Part I, page 123. Obsidian sometimes forms the predominant constituent of rocks and in them only a few devitrification products occur. It is brittle and has a perfect conchoidal fracture, Fig. 233, vitreous luster, and is almost invariably dark grayish-black to pitch black in color. In thin section the color can often be plainly recognized, but it is sometimes entirely colorless and frequently filled full of trichites. Upon heating many varieties swell out into foamy masses, which are light gray to white and are called *pumice*. Pumice in the form of ejectamenta and bombs is often found in nature accompanying obsidian. The obsidians belonging to basic rocks, such as the bluish-black tachylite and the black hyalomelane, are heavy and have comparatively high indices of refraction. They are quite highly colored in thin section.

FIG. 233.—Conchoidal Fracture (1/2 Natural Size). Obsidian, Iceland.

Perlite is a rock glass, which is full of curved cracks throughout its mass, so that it breaks up easily into rounded fragments each of which has an onion-like structure. It usually has a lower specific gravity than obsidian because of these cracks, and is lighter colored macroscopically. Under the microscope the onion-like arrangement of the cracks presents an uncommonly characteristic appearance, Fig. 234. Pitchstone has a pitchy luster and is variously colored macroscopically. It may be green, yellow, red, or black. The pitchy luster may be due to an abundant development of microlitic crystallization. Crystal skeletons assume manifold forms in pitchstone.

Rock glasses often possess the appearance of decided flow structure. In these glasses variously colored bands mixed with each other in multifarious ways form the principal constituent. In other cases they flow around the large crystals that have separated out, Fig. 235, *eutaxite*, so that it appears as if the different parts were not miscible with each other even in the liquid condition. Alteration of beds greatly devitrified with those less so, and of porous with denser layers, is not rare in rock glasses. The phenomenon of devitrification is to be especially emphasized. The original glass, which is completely amorphous, is transformed into a crystalline aggregate called *microfelsite, felsite*, etc. The newly formed mineral aggregates—structureless combinations of quartz and orthoclase in the ordinary acid glasses, are considered to be the result of a long period of molecular rearrangement somewhat analogous to the transformation of the metals. The cause has also been sought in circulating waters, either of a meteoric or of magmatic character.

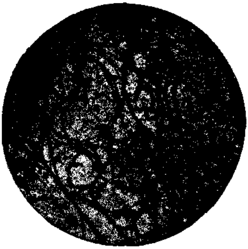


FIG. 234.—Perlite, Glashüttental near Schemnitz, Hungary.

FIG. 235.—Eutaxite. Microscopic Fluidal Structure in Pitchstone. Kastelruth, South Tyrole.

When the glass occurs in the form of fine films as a subordinate base between the crystalline constituents and is colorless, it is very hard to determine. It can scarcely be distinguished from nepheline or from zeolites, especially in those cases where a feeble double refraction is shown on account of strain. If it forms the residue from which the other constituents have crystallized, it is always richer in silica than the normal rock.

### Analcite (1)

Analcite is only known as a secondary rock constituent in druses and in pseudomorphs. It occurs in various types of soda rocks and is usually formed from sodalite, nepheline, and leucite. As a rock constituent it does not have its own crystal form. Crystals are only found in druses and cavities. Optical anomalies are present now and then, but they are mostly much weaker than in garnet. Analcite usually appears clear and transparent. Sometimes the cleavage cracks are quite plain, but frequently it does not possess these and then the determination is made in a chemical manner by testing for sodium. The double refraction also increases and it becomes clouded when heated. The mineral itself has, however, no characteristic microstructure and no striking properties. It is most easily confused with leucite, sodalite, and nepheline.

### Sodalite Group (2)

*The usual crystal form of the minerals of the sodalite group is* the rhombic dodecahedron, Fig. 226, page 214. The cross sections are therefore six-sided or quadratic, and often somewhat distorted. The edges are usually rounded and the faces are eaten out and corroded. Sodalite is found now and then in irregular grains, which is not the case with the other members of the group. The dimensions are usually not very small and microlites are entirely lacking. These minerals are easily recognized by the naked eye when they are colored. Colorless *fresh varieties may be easily overlooked, but they show plainly* on the fracture surface of the rock if they are clouded by incipient alteration. They then appear dull white or yellowish and are easily confused with altered feldspar from which they can be distinguished by the lack of cleavage and the typical isometric form of the cross section.

The sodalite minerals are found in rather basic soda rocks free from primary quartz and constitute the part most susceptible to alteration. They are frequently altered to natrolite, analcite, and other zeolites, forming aggregates like snowflakes—*Spreustein.* Alteration to dense aggregates of mica or to amorphous masses is also known.

Sodalite is disseminated throughout certain granular eruptive rocks and is macroscopically colorless, or at most very light blue or green, but in thin section it is always colorless. Haüyne is more often found in extrusive rocks and is sometimes colorless, while at other times it is gray, yellow, green, red, or deep blue. It is frequently speckled. Certain colorless occurrences have the property of taking on an intense blue color when heated. If such varieties are treated with hydrofluoric acid and silver nitrate they percipitate black silver sulphide, while sodalite becomes coated with silver chloride. Regularly arranged black bars with unknown properties are frequently observed in sodalite minerals. They have a tendency to congregate on the edge of the crystals and make them less transparent, Fig. 236. Such borders, which are quite small but entirely opaque, are observed especially around crystals, which have been greatly rounded and corroded by the molten magma. Ferric hydrate forms from these dark inclusions when the rock is weathered, and it colors the mineral yellowish to red. Other inclusions, ores, pyroxene, etc., are frequent, but glass is comparatively rare. If the crystal form is lacking, the regularly arranged inclusions together with the low index of refraction is often the only characteristic feature because they show very imperfect cleavage, which is at best only irregular cracks.

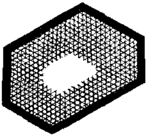


FIG. 236.—Hauyne with Regular Inclusions.

Differentiation of the various members is only possible chemically. The test for chlorine in sodalite has already been mentioned. If haüyne is treated with hydrochloric acid, gypsum crystallizes out. The same crystals are obtained from noselite if a trace of calcium carbonate is added to the solution. The index of refraction being lower than that of Canada balsam distinguishes them from other similarly appearing minerals, but that may give rise to confusion with zeolites, tridymite, or rock glass. They can, however, be positively differentiated from analcite and glass only by special chemical reactions.

Lazurite may be referred to briefly. It occurs in irregular grains forming the deep blue coloring constituent of lapis lazuli. It is a member of the sodalite group containing sodium sulphide and causes the blue color of the other members. Lapis lazuli is a contact rock containing also calcium-magnesium silicates and carbonates.

### Opal (2)

Opal, as a rock constituent, is not often visible macroscopically. It may be developed as precious opal with the characteristic play of colors or as dull colored common opal clouded by numerous inclusions. It is always secondary, filling crevices, or occurring in pseudomorphs after feldspar and other minerals. It is found especially in greatly altered eruptive rocks and their tuffs. It is not easy to ascertain to what extent opal occurs as a constituent of sedimentary rocks. The amorphous opal-like silica of organisms is very easily transformed into crystalline aggregates and, on the other hand, opal sandstones occur in such relationships that the formation of the mineral from thermal processes is highly probable. In rocks in which opal is not seen macroscopically it is observed in thin sections in finely divided, shapeless, and colorless impregnations which may be recognized only with great difficulty. This type of occurrence also shows all the earmarks of post volcanic alteration. It is always colorless under the microscope and may be recognized by its very low index of refraction. It often shows anomalous double refraction, Brewster's cross, and inclusions of tabular crystals of tridymite are extremely common. A microscopic differentiation from glass is often very difficult, although the low index of refraction is very distinctive. It can be determined positively by its solubility in potassium hydroxide. Even this reaction may give rise to error because numerous decomposition products containing aluminium also yield silica in potassium hydroxide.

### **Fluorite** (2)

Fluorite is rare as a real constituent of rocks. It is found in granite, especially in the facies altered by pneumatolytic processes—*greisen*—together with tourmaline, topaz, etc. It is also found as a constant associate of the zirconium silicates, that occur accessory in soda rocks. It is always in grains and is easily recognized when it is violet, but very difficult to find when it is colorless. *It is characterized by the fact that it has the* lowest index of the isotropic rock-forming minerals and also has a perfect cleavage, which usually causes a scaly appearance to the surface of the section.

## 3. Uniaxial Minerals

*The rock-forming minerals of the tetragonal and hexagonal* systems are sometimes long, sometimes short prismatic, with or without pyramidal terminations. Sometimes, they are developed tabular parallel to the base or are predominantly pyramidal or rhombohedral. Fig. 237 shows the most important types of

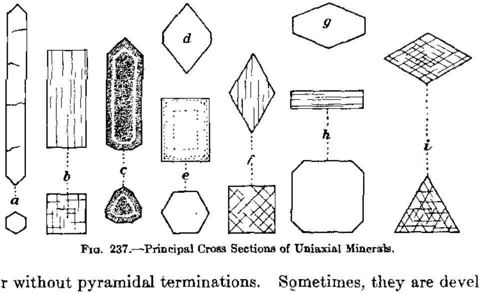


FIG. 237.—Principal Cross Sections of Uniaxial Minerals.

cross sections. In the prism zone they are either elongated or short, almost square rectangles with or without domatic forms on the long or the short side. Rhombic forms, with or without truncated corners, are also observed. In the first case the extinction is always parallel and perpendicular to the sides of the rectangle, while in the latter case the extinction direction bisects the angles of the rhombus.

A section orientated as nearly parallel to the optic axis as possible is found by choosing the one which, in parallel polarized light, shows the highest interference color of all the sections of the same mineral. This is also an indication of the strength of the double refraction. In convergent polarized light such a section shows a distribution of colors into curves simulating hyperbolæ. They are symmetrical with respect to two planes, and the color is lowered in those quadrants through which the optic axis passes and is raised in the other two quadrants with respect to the center of the field. The optical character of the principal zone, $Ch_z$, is the same as that of the mineral itself, $Ch_m$, because in uniaxial minerals with a prismatic development the optic axis and the axis of the principal zone coincide. If uniaxial minerals are tabular parallel to the base, the optic axis is perpendicular to the principal zone, and the character of the *principal zone is opposite to that of the mineral.*

Sections cut perpendicular to the optic axis remain dark when rotated between crossed nicols in parallel light and appear like isotropic minerals, but if the double refraction is not too small, as it is in apatite, such sections give an interference figure in convergent light. Their outlines are quadratic, or rarely eight-sided in tetragonal minerals, and six- or three-sided in hexagonal minerals. Occasionally where trigonal forms occur the sections are nine-sided. Such sections give the interference figure of uniaxial crystals in convergent light. In certain rock-forming minerals of this group optical anomalies are frequent. They may be shown only in convergent light by a spreading of the black cross upon rotation, or they may be noted in parallel light by the occurrence of double refracting segments in a basal section. Still these features are not as common as are the anomalies in isotropic minerals. The circular polarization in quartz is not observed in thin section.

In all cases the shapes of the sections show only the simplest forms and this is true to a still higher degree for the cleavage.

In the holohedral members, the cleavage is only parallel to prisms of the first and second order and to the basal pinacoid. In hemihedral forms rhombohedral cleavage in addition to the others is the most important. The character of the various kinds of cleavage is shown schematically in Fig. 237.

### **Rutile** (4)

Rutile is very widespread, but is only present in subordinate quantities. It is found in larger quantities only in association with certain intensely altered minerals. It sometimes shows good crystal form which is almost always long prismatic. Such development is apparent *even in the minutest microlites in clay* slates. It is sometimes found in rounded grains or in large compact masses that are visible to the naked eye and may be recognized by the blackish-red color and the submetallic to adamantine luster. Twins parallel to (101), P∞ with knee-shaped cross sections, Figs. 238 and 239, and those parallel to (301), 3P∞ with *heart-shaped cross sections, Fig. 240, are especially common* in the smaller individuals. In the compact masses twinning lamination according to the first law is observed. Here also prismatic cleavage, which is often lacking in crystals, appears as sharp cracks.

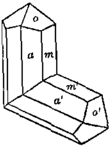


Fig. 238.—Rutile Twinned Parallel (101) P ∞.

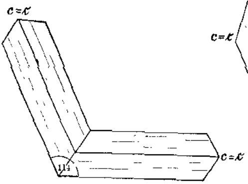


Fig. 239.

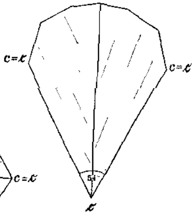


Fig. 240.

Rutile Twins.
Parallel (101) P ∞. Parallel (301) 3 P ∞.

*Sagenite* is a name given to a characteristic lattice structure of rutile needles crossing each other at an angle of about 60°. It is found as an inclusion in numerous micas, the asterism of which is often caused by it. It appears in this same form produced by the chloritization of biotite rich in titanium. Rutile accompanied by other titanium minerals is very frequently produced by the decomposition of bisilicates. Concerning pleochroic halos around inclusions of rutile in biotite, hornblende, cordierite, etc., see page 197.

Rutile has the highest indices of refraction and double refraction of all rock-forming minerals. Only the smallest microlites show brilliant interference colors, if they do not appear opaque on account of total reflection. In some varieties the extraordinary ray is strongly absorbed giving rise to a change in color. Sometimes pleochroism is entirely lacking, especially in the light yellow grains so widespread in amphibolite and eclogite. The larger compact particles are dark and usually strongly pleochroic. They show a submetallic luster in reflected light.

Primary rutile is rare in the eruptive rocks, but is widely disseminated in all groups of contact rocks. In them two types are frequently associated with each other. The one is in sharply developed crystals with a grayish-violet color, and the other is in rounded grains having a yellow or brown color. It often has a border with a crumbly appearance, which is white in reflected light and consists predominantly of titanite. This is called *leucoxene*. Rutile is sometimes intergrown with homogeneous titanite or ilmenite in various zonal arrangements. It is very widespread in sedimentary rocks because of its resistance to weathering. It occurs in the coarse mechanical sediments in the form of compact rounded grains, and in the fine sediments as needles that are doubtless *authigenetic*. These needles are very minute, often twinned and scarcely transparent. The most typical development of this formation appears to be present only in the extreme outer portion of a contact zone.

It is not attacked by the atmosphere nor by acid, except by hot concentrated sulphuric acid. It can be easily isolated by a mixture of hydrochloric and hydrofluoric acids. The test for titanium is made by fusing the residue in a bead of potassium bisulphate and dipping it in hydrogen peroxide when it becomes brownish.

Very dark colored rutile might be confused with opaque ores.

It can be distinguished by its adamantine luster in reflected light and its transparency, that is always to be noted upon careful observation. The light colored varieties were formerly often determined as zircon. It is distinguished from zircon by being always colored and by its higher double refraction, which also differentiates it from anatase. Distinction from the rarer minerals brookite, cassiterite, and goethite is very difficult, as these minerals, like rutile, give white of the higher order in a normal section and have an adamantine luster like it in reflected light. The safest method of differentiation is a chemical test, but the effect on convergent light is also distinctive in the case of brookite and goethite.

Rutile may be confused with perovskite and similar minerals on account of its high index of refraction, but perovskite, when it is anomalous, shows at best a very low interference color as does wurtzite, which is also included here. Confusion with sphalerite may occur, but that mineral never shows double refraction. Titanite finally does not have an adamantine luster in reflected light.

### **Anatase** (4)

Anatase as a rock constituent is frequently developed tabular, while sharp pyramidal forms are less common. Some typical cross sections are given, Fig. 237 *f*, page 225. It may also form granular aggregates. The individuals are mostly small, poorly developed, clouded, and have a speckled color,—blue, yellow or colorless. The stronger absorption of the ordinary ray is not often clearly discernable, and the same is true of the cleavage. It generally results from the alteration of other minerals containing titanium and is, therefore, found particularly in greatly altered rocks, in contact-metamorphic formations, as well as in those which have suffered decomposition by the action of mineralizers. It is very common in such rocks as a by-product in the alteration of bisilicates and it forms a part of the dense aggregate known as leucoxene. It is confused with zircon, from which it can be distinguished, however, by the speckled color and cloudy appearance, much higher indices of refraction, and the optical character. It is also similar to rutile, and titanite from which it is distinguished by its much lower double refraction, imparting to it brilliant interference colors in the section.

It may be remarked, parenthetically, that grains of corundum similar to anatase may be present in the section. These have been derived from the polishing or grinding material. The optical properties of these grains are similar to those of anatase. They are uniaxial, blue or yellowish, and pleochroic, but differ in the optical character of the principal zone.

### **Cassiterite** (4)

Cassiterite is a rare constituent of lithionite granite and the rocks in the vicinity of a contact with it. Crystals are not frequent in these rocks, but they have pyramidal development with characteristic twinning parallel to (101), P ∞ or they may be simple prisms. Grains are the most common. It is rarely colorless, but is yellow, brown, or more often deep red. In the last case it is strongly pleochroic in thin section. A zonal or speckled distribution of the color is common. If its determination is doubtful, especially if it is confused with rutile and anatase, the grains should be isolated with hydrofluoric and sulphuric acids and fused in a borax bead colored blue by copper oxide. A ruby-red color then indicates cassiterite. (See page 170.)

### **Wurtzite** (4)

Wurtzite is found together with sphalerite and is intergrown with it in clustered incrustations. It is similar to sphalerite in color. Its distribution as a rock-forming mineral has not been definitely determined. It is distinguished from the minerals, which appear similar to it, rutile, goethite, and sphalerite, by its weak double refraction. Its solubility in acids is also distinctive.

### **Zircon** (4)

Zircon is one of the most widespread rock constituents, but is always present only in small quantities. It is macroscopically apparent only in pegmatites. The so-called zircon syenites, belonging to the soda series of rocks, are especially rich in it. The mineral is abundantly present in brown, red, or greenish cloudy crystals with an adamantine luster and forms an important constituent of the rock. As a rock constituent, it is always *microscopic and the individuals are in most cases very small.* It is entirely colorless in thin section. It is almost never wanting in the acid and intermediate members of the normal series of eruptive rocks and is one of the first minerals to crystallize in them. It is, therefore, in minute crystals that are as perfect *as models and often have an abundance of faces. It is less common* in basic eruptive rocks and is only exceptionally observed in peridotites and in the members of the soda rock series rich in alkali. It is found in all types of contact rocks, but it occurs more frequently in grains, which are well characterized by their high index of refraction and brilliant interference colors. It is nearly always present in sedimentary rocks, but mostly in clouded grains.

Zircon is not attacked by acids. When decomposed in rocks *it often shows characteristic zonal structure* in which clear and more or less clouded zones alternate, Fig. 241. In spite of this there is much doubt concerning the mineralogical and petrographical definition of the mineral. It is often very difficult to distinguish it from xenotime, which has a slightly higher double refraction and according to modern investigations is found to be as widespread in acid rocks as zircon. Because of their similar appearance and occurrence they can be differentiated positively *only by the Hepar reaction.* Besides that, *very different* varieties can be distinguished in macroscopic crystals of zircon. One variety with a normal specific gravity and quite a high double refraction seems to be related by gradual transitions with one whose specific gravity sinks to 4, and which is scarcely double refracting when entirely clear and homogeneous. It cannot be determined just how much this transition is based upon the taking up of water, as has been shown for the cloudy variety known as *malacon.* Little is known of the distribution of the varieties with low double refraction because the *mineral occurs in small amounts and is usually* overlooked, or is classed as a member of the epidote series.

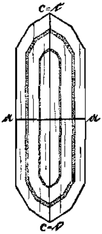


Fig. 241.—Zircon (Xenotime). Section Parallel to the Principal Axis.

Xenotime is frequently found by chemical investigations among the high double refracting individuals and is generally determined as zircon. Sometimes the zonal clouded crystals belong principally to xenotime. Under certain conditions it can be confused with colorless cassiterite, but the chemical reaction and higher double refraction of cassiterite, giving rise to white of the higher order in a normal section, serve to distinguish them. It is distinguished from titanite by a lower *double refraction. It can also be confused with monazite or* with colorless epidote, but convergent light shows the difference at once. Confusion with anatase and rutile was mentioned under these minerals. The occurrence of pleochroic halos around zircon individuals is noteworthy, see page 197. Very perfect cleavage is only clearly observed in the larger individuals and is almost entirely lacking in the ordinary microlitic forms.

### Xenotime (4)

**The distribution of xenotime in rocks cannot be ascertained with our present knowledge of it. It appears to be present first of all in acid eruptive**

rocks and in sedimentary rocks derived from them, occurring with or instead of *zircon*. *It is easily recognized when it occurs in short pyramidal* crystals, which are sometimes intergrown parallel with prismatic zircon crystals. It may form prismatic crystals itself like Fig. 241 and these can scarcely be distinguished from zircon. The higher interference colors, white of the higher order if the crystals are not too thin, and also the pleochroism ($\omega$ light rose-red, $\varepsilon$ pale yellowish), which closer observation reveals, make the recognition of isolated crystals possible, but in thin section both of these properties are not distinctly evident. The pyramidal crystals are usually greatly clouded by decomposition and in the prismatic crystals, which were simply called zircon, this turbidity is very common, particularly in the zonal development. Clear prismatic crystals are rarer. The Hepar test on carefully isolated material gives positive proof of xenotime. However, only fresh varieties give this reaction because the sulphuric acid disappears when the crystals become cloudy. It is difficultly fusible before the blowpipe, and if moistened with sulphuric acid it colors the flame bluish-green. It is slowly decomposed in a salt of phosphorous bead.

### Corundum (4)

Corundum shows varying habits. Short pyramidal crystals sometimes with a barrel shape, Fig. 242, and with distinct zonal structure, or thin tabular crystals parallel to the base are the common forms. Cross sections with a poor outline and pale speckled color are often difficult to determine, because they have no characteristic appearances except the high index of refraction. *The pleochroism is characteristic and is observed only* when the mineral has a deep blue color. The various other macroscopic colors are not seen in a thin section. A few twin lamellæ parallel to the rhombohedron are seen now and then. As a granular aggregate it forms the principal constituent of *emery*, which presumably represents a dike-like development in contact-metamorphic *limestones*. It is otherwise almost entirely a contact mineral and as such is most frequently developed tabular and accompanied by sillimanite, cordierite, spinel, etc.; or it occurs as the result of resorbed inclusions of aluminous rocks in eruptive rocks. These are the large blue crystals of *sapphire* occurring especially in pegmatites. It is also found in contact rocks as dark irregular masses of microscopic size produced by segregation. Corundum can be recognized by the naked eye in granular limestones and dolomites in which it appears brilliant red, *ruby*, but in thin section it is colorless. It is often necessary to isolate corundum from a rock to determine it positively. Its great resistance even toward molten carbonates of the alkalies makes its isolation easy. The presence of small grains of corundum in sections prepared with emery is mentioned because they often give rise to confusion. Corundum is distinguished from vesuvianite and apatite by its more brilliant interference

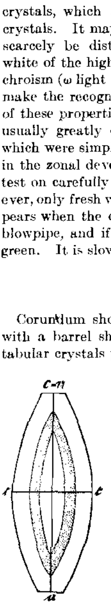


Fig. 242.—Barrel-shaped Crystal of Corundum.

colors. Light colored varieties of tourmaline can be very similar to it, but the latter shows a greater difference in absorption. Among the biaxial minerals it may be confused with those which are often blue like corundum, such as cyanite, sapphirine, lawsonite, zoisite, sillimanite, etc. Investigations in convergent light show the differences.

### Vesuvianite (Iodocrase) (4)

Vesuvianite is a typical contact mineral that occurs in well developed short prismatic crystals only in contact-metamorphosed limestones. In other contact rocks it forms irregular, elongated grains. It is macroscopically light green or yellow to brown in color, but in thin section it is colorless and transparent. Only those varieties containing manganese are colored distinctly reddish. It is decomposed by hydrochloric acid with difficulty and fuses before the blowpipe with intumescence to a greenish glass. After *fusion it gelatinizes with hydrochloric acid. The vesuvianites form a series* of isomorphous mixtures of which one end member, which usually predominates, is optically negative, and the other has a weak, positive, double refraction. Anomalous interference colors are therefore frequently observed in the intermediate members and the colors may be arranged in a zonal manner. The division of basal sections into regular biaxial fields is very common. Dense aggregates like nephrite, which occur in serpentine and produce a formation similar to saussurite, are noteworthy. In such an occurrence it is extremely difficult to recognize vesuvianite and distinguish it from grossularite, gehlenite or zoisite, and clinozoisite, since all these minerals have high indices of refraction and show anomalous interference colors. It is difficult to distinguish from apatite and this can often only be done by a chemical test. It appears similar to andalusite even when it has normal interference colors, but the biaxial behavior of the latter serves to differentiate the two.

### Gehlenite Group (4)

Gehlenite and melilite are apparently an isomorphous mixture of a calcium-aluminium silicate, which sometimes occurs pure in gehlenite, with a calcium silicate free from aluminium, that is not known in nature. Gehlenite forms rounded, short, prismatic crystals in contact-metamorphic limestones, and the length is usually quite the same as the thickness. Melilite occurs more frequently in poorly hounded, tabular crystals parallel to the base, and appears to he confined to basalts and tephrites. The former is macroscopically grayish, and in thin section always colorless. The latter is now and then colored yellow by its content of iron and the extraordinary ray is absorbed more than the other—*humboldite.* The latter also occurs in large irregular particles which are entirely perforated by leucite crystals. The negative double refraction diminishes with a decrease in the content of aluminium and those poorest in aluminium are optically positive. Between these extremes there is a series of mixtures, which show anomalous interference colors in the most typical manner.

Both minerals are easily altered and the melilite particularly is often coated with a dull hazy film. The mineral itself is also clouded considerably. It may pass over into a fibrous aggregate with a strong double refraction, the fibers standing perpendicular to the basal pinacoid. Melilite often shows the characteristic appearance of having its sections crossed by numerous thin glass pegs arranged parallel to the principal axis. These penetrate into the crystals from both sides and often spread out like funnels in the interior. Such an appearance is called *peg structure*, Fig. 243. Cleavage is often entirely lacking in such sections, but in other cases it is seen in a few sharp cracks running perpendicular to the principal axis. Perovskite is a characteristic associate of melilite. Gehlenite is often very similar to vesuvianite even in varieties with anomalous interference colors—*fuggerite*—and to zoisite and clinozoisite, and is often only to be distinguished from them positively by treatment with hydrochloric acid. Melilite was formerly determined as feldspar or as nepheline, but is distinguished from them by the higher index of refraction, the dull appearance in reflected light, and the chemical properties, particularly the ease with which it is dissolved in acids, and the high content of calcium.

FIG. 243.—Peg Structure in Melilite. Melilitebasalt, Oahu, Sandwich Islands. (After E. Cohen.)

In certain contact rocks in the Fassatal, gehlenite is replaced by fuggerite, a mineral with a similar composition. It is likewise tetragonal and occurs in tabular crystals. It is isotropic for sodium light and therefore has deep blue anomalous interference colors. It has a more perfect basal cleavage. Sp. gr. = 3.18. It is soluble in acids with the separation of powdered silica.

### Tourmaline (4)

A group of complex silicates containing boric acid is included under the name of tourmaline. Lithia tourmaline, macroscopically very pale, in thin section colorless, scarcely ever occurs as a real rock constituent and is distinguished from the strongly colored green, blue or brown magnesia tourmalines, which are mostly light colored in thin section. The iron tourmaline containing titanium, *schorl*, is, like most silicates containing titanium, macroscopically black with a pitchy luster. It is highly colored in thin section and is characterized by a very strong absorption of the ordinary ray. It is the most important member of the series as a rock constituent.

Schorl is often in zonal crystals built up of layers with different intensities of color. The hemimorphic development of the crystals, the ends of which are shown diagrammatically in Figs. 244 and 245, is rarely apparent, but the three- to nine-sided cross sections, Fig. 246, are very characteristic. The tourmalines that are light colored in thin section are especially widespread in granular limestones and are often found in large, well developed crystals with yellowish, greenish, bluish or brownish color, but these are often difficult to recognize because of the comparatively small difference in absorption. In other rocks the blue varieties form ragged particles without any indication of crystal form. Radial aggregates—*tourmaline suns*—are very widespread. It is often noted also that a crystal of dark tourmaline is well bounded on one side and on the other side it is grown into a fibrous aggregate of light colored tourmaline.

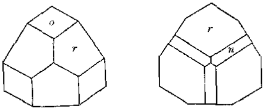


FIG. 244. FIG. 245.

Opposite Ends of a Tourmaline Crystal.

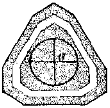


FIG. 246.—Tourmaline Cross Section.

The optical properties vary within wide limits. The indices of refraction and the double refraction appear to be highest in the members rich in titanium. The indices and the double refraction increase in the pleochroic halos, see page 197.

The dark colored varieties are sufficiently distinguished in all cases from the numerous and widespread members of the mica and amphibole groups and from apatite, with which they have been confused, by the strong absorption perpendicular to the principal zone and by the trigonal cross sections. The minerals with light color and low absorption, which are difficultly recognizable, are very similar to andalusite, staurolite, lawsonite, forsterite, and corundum, but by more careful observation the stronger absorption of the ordinary ray can be observed even though it is only seen in traces. Epidote often shows a similar orientation of the absorption. In this case the usual speckled appearance of the interference colors of epidote and its cleavage serve to differentiate them. Investigation in convergent polarized light is helpful here as in most of the other cases.

*In any case the resistance of tourmaline to reagents allows it to* be easily isolated and it can be determined by its reaction for boron, see page 169.

Only schorl is known as a primary constituent of eruptive rocks and it sometimes occurs as an accessory constituent of granitic rocks, especially the aplites. Otherwise tourmaline is the most distinctive mineral of pneumatolytic processes, and its formation can nearly everywhere be shown to be connected with such processes. It is therefore always found where they have been most intensely active. Besides in the pegmatites, it is found especially in the vicinity of tin ore veins and certain copper ore dikes, where the whole rock has been tourmalinized. It occurs also in the kaolin deposits.

The distribution of tourmaline in contact rocks of all sorts must be especially emphasized. It is never lacking in all the various kinds of formations which owe their origin to contact-metamorphic alteration by granitic rocks, even though the *granite itself contains no trace of tourmaline.* Tourmaline sometimes occurs in very large individuals, e.g., in the schist zone of the Central Alps where the crystals are macroscopically apparent, but even in these rocks it is more common in separate, minute microlites, which could be easily overlooked unless one accidentally observes a typical cross section or finds a prismatic crystal with the characteristic absorption perpendicular to the principal zone. Tourmaline is everywhere present in this form in gneisses, mica schists, amphibolites, green schists, hornfels, and Knotenschiefer and it is found in distinctly developed individnals in the remotest parts of the contact zone. Here no alteration can be recognized in the external appearance of the rock itself, and under the microscope the action of contact metamorphism can only be discerned by the formation of tourmaline and the development of small, clay slate needles—*rutile.*

## **Apatite** (5)

Apatite is everywhere present as a rock constituent, but in small quantities and nearly always in minute individuals. It occurs in acid eruptive rocks in well developed crystals with a long, prismatic to needle-like habit, Fig. 247. In basic rocks and, especially in those rich in sodium, it forms large, rounded crystals that are short and thick, and in contact rocks and sediments it forms rounded grains. Apatite as a rock constituent can only be seen macroscopically in exceptional cases. It appears as crystals with a brilliant luster in certain camptonites and may likewise be observed as light blue grains in marble. Radial aggregates—*phosphorite*—frequently colored dark by organic substances, are found in numerous sediments as large concretions.

Apatite is always one of the first products to crystallize in eruptive rocks and is, therefore, largely included in the other constituents, especially the dark ones. It is strikingly contrasted with the other minerals by its colorless lath-shaped or six-sided cross sections, Fig. 216, page 197. Gas, liquid, and glass are observed as inclusions in apatite. It is not often colored and the colored varieties are confined to eruptive rocks. It may be grayish-blue, brown, or brilliant orange, with a strong absorption parallel to the principal zone. Six-sided sections do not give a distinct interference figure, because of the low double refraction. Weathering and disintegration of the rock usually leave the apatite unaffected. It is therefore found very widespread in soils, which owe their content of phosphate to the great dissemination of apatite microlites.

Fig. 247. Apatite.

In many instances apatite can only be distinguished positively from vesuvianite, zoisite, or from other colorless double refracting grains belonging to orthite (allanite) by chemical tests for phosphoric acid. Low double refraction and the negative character of the principal zone distinguish it from tremolite, sillimanite, etc.

Fig. 248.—Slide of a Bone with Perfectly Retained Structure from the Permian Wichita Beds of Texas.

Bone substance, consisting predominantly of calcium phosphate, is to be appended to apatite. It likewise has a low double refraction and occurs in fine fibrous aggregates that are imperfectly radial. Within them the organic structure is often perfectly retained and shows itself in the nutrition canals, etc., Fig. 248.

### Rhombohedral Carbonates (5)

The rhombohedral modifications are the only carbonates that occur as actual rock constituents. The others are found principally as secondary depositions in crevices and as organic remains. The diagenetic transformation of these into calcite is explained in the Allgemeine Gesteinskunde by E. Weinschenk, page 118. Calcite is one of the most widespread rock-forming minerals. It forms the principal constituent of extensive formations and constitutes whole mountain chains. Dolomite is likewise quite widespread, while the other carbonates treated here, magnesite, siderite, and smithsonite, are more of local importance.

It is noteworthy that calcite seldom forms crystals in rocks. They do occur in minute, isolated rhombohedrons in the central granite and are here undoubtedly grown into the quartz as a primary constituent. Other than this it is always a secondary constituent of eruptive rocks produced by the alteration of silicates of lime. Pseudomorphs of calcite after plagioclase or augite, and even after olivine, are found in greatly altered occurrences. It is especially frequent under such conditions as an impregnation in the rocks, which it may penetrate in large veins in which the calcite is granular, or fibrous or the ground mass of a porphyric rock may be entirely impregnated with fine aggregates of calcite, which frequently possess a radial, fibrous structure.

Dense sedimentary limestones consist predominantly of irregular, granular aggregates of calcite. The individuals are usually clouded with inclusions and vary greatly in size. They are often transformed into larger grains with greater clearness by recrystallization. The organic structure is often distinctly retained in such a formation, Fig. 249. Only rarely do the limestones fail to show crystalline aggregates under the microscope, as for example in the *Solenhofener* schists, which are considered as a brackish water formation. Radial,


Fig. 249.—Crinoid Limestone with Lattice Structure. Vilstal near Pfronten, Algän.

fibrous oolites, sometimes with onion structure, are found in limestones. They often lose their structure by secondary processes and then they consist of small spheres of granular calcite, Figs. 190 and 191, pages 186–187.

Calcite shows its best development in the various groups of contact rocks, as in lime-mica schist and in calcium-silicate fels. In some of these rocks it forms the principal constituent as in marble, while in others it occurs in subordinate particles as in the two rocks mentioned above. It never shows crystal form, but is always in granular aggregates and all the other rock constituents are well crystallized in it, while in those occurrences rich in silicates the calcite takes on the character of interstitial material. Pure marble lying next to the contact is often quite coarse grained, the individuals measuring as much as an inch in one dimension and these tend to be colored sky blue. All gradations are found from this down to formations that are macroscopically entirely non-crystalline. Under the microscope a very regular texture of crystalline grains of calcite is observed. It sometimes shows mosaic structure and sometimes the grains are intimately dovetailed into each other, Figs. 192 and 193, page 187. The individual grains are sometimes clouded with fine graphite dust and then are somewhat pleochroic with the darker color in the vibration direction of the ordinary ray. The perfect cleavage parallel to the unit rhombohedron, Fig. 250, which is difficult to observe in the denser aggregates, shows plainly in this type in a series of sharp cracks. Very frequently, but not always, numerous twinning lamellae parallel to $-\frac{1}{2}R$ are seen, and these are often parallel to but one face of that form. They are to be explained by the gliding of the calcite under the influence of pressure, and have probably resulted during the mechanical operations of the grinding. The small number of lamellæ in Figs. 192 and 193 is remarkable, and is very distinctive because the marble from Carrara is considered as a type of dynamo-metamorphic limestone.

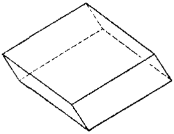


FIG. 250.—Rhombohedron

Undoubtedly the twinning lamellæ are increased everywhere where the marble has been subjected to orogenic stresses after recrystallization had taken place, and such occurrences consist entirely of fibrous grains in which the manifold bending indicates the high degree of plasticity of calcite, Fig. 205, page 192. This mineral also breaks under too high a pressure and dense shattered aggregates with great solidity are developed from granular marble. This is well illustrated in the ivory marble with its excellent cataclastic appearance.

The great difference in the indices of refraction for the two principal vibration directions can be distinctly shown under the microscope with one nicol. It is also the cause of the brilliant interference colors, which the twinning lamellæ crossing the section obliquely often show; compare Part I, page 87. In a normal section calcite gives a pale white of the higher order between crossed nicols. Cross sections in which the cleavage cracks form an equilateral triangle show an interference figure distinctly even with a low-power objective. With a higher objective a black cross is obtained surrounded by numerous colored rings but these are often disturbed by interbedded twinning lamellæ.

Dolomite is distinguished from calcite by its greater tendency to develop its own crystal form. If it is intergrown in calcite it usually shows rhombohedral cross sections. Aggregates consisting principally of dolomite show the mosaic structure much more distinctly than calcite, and this may pass over into a fine drusy granular structure like sugar. The dovetailed structure is also found in pure dolomites but it is rare. It forms wormlike intergrowths in calcite in a few occurrences of *eozoon canadensis.* The higher indices of refraction and double refraction compared with calcite cannot generally be determined in an ordinary section. The lack of twinning lamellæ parallel to $-1/2R$ is typical, for that is not a gliding plane in dolomite. In place of that, however, twinning parallel to $-2R$ occurs in numerous lamellæ so that is not a good means of differentiation although generally there are fewer twinning lamellæ in dolomite than in calcite. Furthermore, they are seldom so greatly deformed. The greater absorption of the ordinary ray is more easily noted than in calcite.

Dolomite is also found as a secondary formation in altered eruptive rocks and may be in pseudomorphs or as fine impregnations in the ground mass. If the content of iron which is always present has not given rise to the formation of rust, and also in the rare cases where it occurs in radial fibrous form filling out crevices, dolomite can only be determined by a chemical test. Dolomite rocks of the sedimentary formations generally show a more distinct crystalline texture than limestones, and are often penetrated through and through by veins of calcite. The numerous cavaties, which appear macroscopically and are covered with small dolomite crystals, are especially characteristic. Under the influence of contact metamorphism the dolomites form granular, and often pure, white dolomite marble, which is usually finer grained than the equivalent limestones, and like the limestones show transitions into silicate fels. Granular dolomite with excellent mosaic structure weathers very frequently to a sandy mass consisting of small rhombohedrons, *dolomite ash.*

Magnesite is much rarer and only of local importance. If it results as a by-product of serpentinization it is found in well developed unit rhombohedrons containing considerable iron. They are intergrown in serpentine, chlorite fels, pot stone, etc. It forms granular pseudomorphs after olivine in certain melaphyres and in sagvandite. Larger homogeneous masses, which occur within the metamorphic limestones in the border zones of the Central Alps have a very coarse-grained texture and consist of flat rhombohedrons, $-1/2R$, with dimensions of about an inch. This form occurs very distinctly in pinolites streaked with layers of clay slate. These varieties also contain iron in considerable amounts and they, therefore, assume a rusty appearance upon weathering. Snow-white aggregates of magnesite, free from iron, are just the opposite of those above. They are dense like porcelain, have a conchoidal fracture, and form veins in serpentine and, if it can be detected microscopically at all, they show a spherulitic texture.

Siderite is sometimes yellowish and weakly pleochroic in thin sections. It occurs locally in extensive deposits, and in geological association with magnesite it forms coarse to medium grained masses within the granular limestones of the Central Alps. It is also found as a constituent of carbonaceous iron rock occurring in bedded deposits. It is fine granular and filled with carbonaceous particles. It occurs also in the form of fibrous and spherulitic concretions—*spherosiderite.* This name is also used for radial fibrous incrustations of iron carbonate in crevices of trap rock.

For the other modifications of calcium carbonate, see aragonite under the *biaxial minerals. Ktypeite* has been found in rocks, especially as a constituent of a few pisolites. It has a specific gravity of about 2.65 and $n$ about 1.55. $\gamma-\alpha=0.020$, optically uniaxial, positive. *Conchite,* which is quite similar to aragonite in many respects but is undoubtedly not the same, is of interest because it forms the principal constituent of shells of living mollusks and many other lime organisms. Its geological significance depends upon its slight stability, especially upon the ease with which it is transformed on the one hand into calcite and on the other into dolomite under the influence of solutions containing magnesium. Sp. gr. $=2.85$, $\alpha=1.523$, $\gamma=1.662$, $\gamma-\alpha=0.139$. Optically uniaxial, negative, but frequently shows a distinct opening of the cross in convergent polarized light.

Concerning the distinction of the carbonates among themselves and from other similar minerals, it may be mentioned that in the normal fresh occurrences a differentiation of the rhombohedral carbonates from each other is not possible in a thin section by simple optical investigations. The special reactions thoroughly discussed on page 175 must be used here. The same is true for conchite and the orthorhombic series of carbonates of which only aragonite occurs as a constituent of rocks and is found but rarely. It almost always forms fine fibrous aggregates, which cause great difficulty in the determination of the optical properties even in convergent polarized light. The carbonates often appear very similar to titanite, but observation of the index of refraction always gives a positive distinction. The carbonates can always be positively determined in thin sections by the effervescence with cold or warm acid.

### **Eudialyte** (Eucolite) (5)

Eudialyte forms rounded crystals or irregular grains and can always be recognized macroscopically by its reddish color. It is usually colorless in thin section. The optical character is variable in one and the same cross section. Parts that are weakly doubly refracting and optically positive, *alternate with those that are isotropic or have a negative double refraction,* eucolite. These sections do not show anomalous interference colors. The members that are optically negative are often distinctly colored in thin *section and show weak absorption,* $\omega > \varepsilon$. *The mineral has only been found* in nepheline syenite. It can be distinguished from apatite by the fact that the eudialyte grains are always considerably larger.

## Scapolite Group (5)

The scapolites form an isomorphous series with quite variable optical properties. The calcium-aluminium silicate, *meionite,* forms one end member and a sodium-aluminium silicate, *marialite,* the other. The former has higher indices and double refraction. *Dipyre, couseranite,* etc., are intermediate members but they are all referred to in general as scapolite because the distribution of the various members has been very little studied.

The scapolites show crystal form only in contact-metamorphosed limestones. In them, prismatic crystals are macroscopically visible, but in spite of that, they are difficult to recognize; see cross sections *b* and *d*, Fig. 237, page 225. Otherwise only granular or columnar aggregates are observed in which the cleavage sometimes appears distinctly. Alteration to micaceous minerals with characteristic mesh structure is frequent as is also alteration to homogeneous individuals of colorless chlorite—*leuchtenbergite.* Special reactions for scapolite, page 174, can be made only on fresh material, because the content of chlorine is lost in the process of weathering. The usual occurrence of these minerals is in contact rocks and they are often so filled with carbonaceous inclusions that they are non-transparent. By metamorphism black crystals may be developed with an appearance similar to that of chiastolite, *couseranite,* or white knots with excellent sieve structure may be formed. If alteration phenomena also appear, it is very difficult to recognize the mineral. It occurs, furthermore, as granular aggregates in metamorphosed diabases and gabbros, especially in the vicinity of the Norwegian apatite dikes. It is likewise found in various rocks called scapolite gneiss but they do not have the composition nor the geological significance of a gneiss. They are mostly normal contact rocks. Scapolite often plays a rôle analogous to that of tourmaline in the contact formation of granites and particularly in that of basic eruptive rocks. Its lack of characteristic optical properties obscures an accurate conception of its distribution which is undoubtedly not unimportant.

The scapolites are most frequently confused with quartz and feldspar. The positive optical character of quartz and the biaxial property of feldspar distinguish them. Cordierite appears quite similar to the members with low double refraction but it has no cleavage in addition to being biaxial. The special reactions referred to above are the safest since the optical properties are so variable.

### **Alunite** (5)

Alunite forms cube-like rhombohedrons and occasionally basal tabular crystals and flaky aggregates. The cleavage appears distinctly both macroscopically and microscopically. It is only found as an alteration product of acid extrusive rocks which have been subjected to the action of solfataras. It is distinguished from diaspore, which accompanies it, by its lower indices of refraction, and from quartz by the cleavage and high double refraction, and this latter property also distinguishes it from the feldspars.

### **Beryl** (5)

Beryl is a rare constituent of certain granites and their contact formations, and occurs in poorly bounded prismatic crystals. It is more frequent in large, clear or clouded crystals in pegmatites. It is usually visible macroscopically and is generally sky blue in the eruptive rocks, and sap green—*emerald*—in contact formations. It is sometimes light blue under the microscope. However, it is usually quite difficult to determine the poorly defined individuals with any degree of accuracy, and principally, because of its similarity to quartz, it is generally overlooked, if it only occurs in microscopic individuals. It is distinguished from quartz by the negative character of the double refraction.

### **Brucite** (5)

Brucite is rare but is found in micaceous flaky aggregates in altered rocks rich in magnesium. It is characterized by its tombac brown, anomalous interference colors, which indicate a very low double refraction that approximates that of chlorite. It can often only be distinguished from chlorite by treatment with silver nitrate when the brucite becomes colored deep brown. Its radial, scaly pseudomorphs after periclase in contact limestones—*predazzite*—*and its coarse flaky occurrence in crevices in serpentine* are especially noteworthy. It is distinguished from the micas by the negative character of the principal zone and its easy solubility.

## **Quartz, Chalcedony and Tridymite** (5)

Quartz is one of the most important rock-forming minerals. It plays an important rôle in all groups of rocks. If it has crystal form it is the hexagonal bipyramid alone, Fig. 251, or *in combination with a very subordinate prism.* The *crystal.*

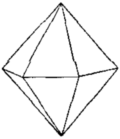


FIG. 251.—Quartz.

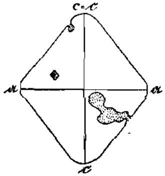


FIG. 252.—Quartz Section Parallel to the Principal Axis.

are originally sharply developed but the edges and corners are often considerably rounded and the faces greatly corroded forming irregular, tubular indentations now filled with the rock mass, Fig. 252 and Fig. 199, page 189. Sections parallel to the principal axis have rounded, rhombic outlines with an angle of about 100°. Perpendicular to the principal axis the sections are six-sided, Fig. 237*e*, page 225. Quartz is found principally with this development in quartz porphyry and rhyolite, and it contains a few glass inclusions filling negative crystals. The same development is also seen, but less distinctly and more rounded, in aplites and dike granites, in certain binary granites and granulites, Fig. 253, and likewise in lime-mica schists.

Rounded crystals of quartz are found in basic eruptive rocks and they may be present as numerous minute individuals penetrating the basic constituents, Fig. 209, page 194, especially in certain gabbros, or they may be in large shattered individuals surrounded by a border of hornblende or augite needles arranged radially to the quartz—*quartz-augen*, Fig. 208, page 193. These are seen in lamprophyres and diabases. In the latter case the origin of the quartz can nearly always be distinctly traced to the shattered neighboring rock. Most frequently all indications of crystal form are lacking in the quartz. In most granites, syenites, diorites, etc., it fills the interstices between the other constituents, Fig. 180, page 182. Minute liquid inclusions, arranged in rows, are especially common in this type. They penetrate through the sections as cloudy bands and pass from one grain over into the neighboring one unchanged. They are the cause of the clouded, milk-white color of certain occurrences of quartz. Others contain abundant microscopic needles, apparently rutile, and still others are colored red by small flakes of iron oxide.

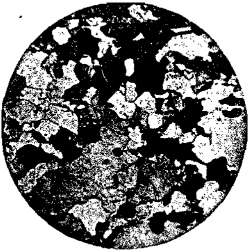


FIG. 253.—Granulitic (Aplitic) Structure. Granulite, Curunegala, Ceylon.

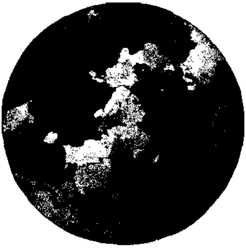


FIG. 254.—Dentated Quartz. Perosa, Cottic Alps.

In contact rocks quartz generally forms an uniform mosaic in which the grains may simply lie in contact with each other, Fig. 184, page 184, or they may be intensely dovetailed into one another, Fig. 254. Again they may form suture joints, but not grow together as in *itacolumite,* Fig. 255. Helicoidal structure is found in the quartz aggregates in contact rocks. Lines of inclusions of carbonaceous substance or sillimanite, etc., corresponding to the original schistosity of the rock, wind about through the aggregates.

Quartz does not suffer any alteration by weathering and, therefore, occurs always entirely fresh in secondary deposits. In clastic rocks it is sometimes angular, Fig. 256, and sometimes rounded. Frequently it is observed, that the fragments have grown into crystals by the addition of secondary silica—*crystal sandstone,* Fig. 257. In rocks containing but little quartz, the mineral is often found in well developed short prismatic crystals. These may be homogeneous or they may be brownish, due to organic substance—*stink quartz.* They may be red to yellow, colored by iron hydroxide, or they may be colorless, clouded, or limpid. These occurrences are undoubtedly of secondary origin, formed in place, and, for the greater part at least, have been derived from the siliceous portion of organic skeletons which are known to be very soluble. Quartz also occurs as a secondary formation in granular or radial, columnar aggregates. It may be in pseudomorphs after other minerals in certain eruptive rocks and their tuffs, or it may be a siliceous cement as in crystal sandstone, where it occurs as an enlargement of the original

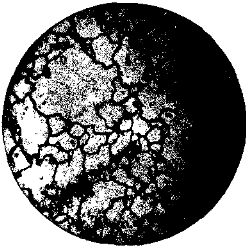


Fig. 255.—Itacolumite. Ouro Preto, Brazil.

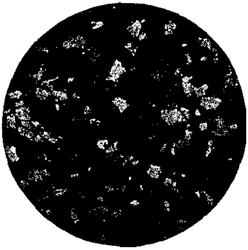


Fig. 256.—Clastic Structure. Sandstone, Schramberg, Black Forest.

clastic grains, or again it may occur in dense aggregates in silicified tuffs cementing the rock constituents. In the last case, however, quartz is frequently replaced by other modifications of silica. In fritted sandstone it often has properties resembling perlite. Inclusions in it are fused to glass. Quartz is extremely brittle and is, therefore, unlike any other mineral, an indicator of the degree of dynamic action that has modified the rock. Under the influence of pressure, the appearance of cataclastic or mortar structure, Fig. 203, page 191, is most distinctly developed. It frequently becomes biaxial under these conditions.

Quartz is characterized macroscopically by its concoidal fracture with somewhat of a greasy luster and its great hardness.

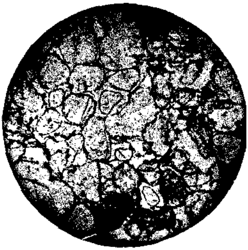


FIG. 257.—Clastic Structure Crystal Sandstone. Erbach, Odenwald.

FIG. 258.—Micropegmatite.

In rocks quartz is generally light smoky gray, but occasionally due to inclusions of (1) hematite flakes it is red, or of (2) magnetite dust grayish-blue, or of (3) chlorite or hornblende green. A light blue color, which sometimes occurs, cannot be explained by microscopic investigation. Under the microscope quartz shows an irregular outline and is always colorless. Twinning, which is also common in rock-forming quartz, cannot be recognized in thin section. Graphic intergrowths of microscopic dimensions of quartz and orthoclase are very widespread, particularly in the ground mass of porphyric rocks, Fig. 258. They are called *micropegmatites.* Sharp, angular sections of clear quartz are sharply delineated against the clouded feldspar, presenting a hieroglyphic appearance. Frequently the intergrowth becomes more and more indistinct and passes over into an irregular fibrous formation, *granophyre*, inclining to genuine spherulites, Fig. 189, page 186. It may become still more irregular and so fine that it has no effect upon polarized light whatever, *microfelsite*. An intergrowth similar to the micropegmatite occurs in which the parallel individuals of quartz penetrating the feldspar have worm-like sections—*quartz vermicule—myrmecitic intergrowth*, Fig. 259. The feldspar is plagioclase. Both kinds of intergrowths are typical structures for eruptive rocks.

FIG. 259.—Quartz Vermiculé.

Quartz is easily confused with several other minerals, which like it, are colorless and have a low double refraction. It is most similar to nepheline, which, however, has a lower double refraction and is soluble in hydrochloric acid. It resembles optically negative beryl and the various zeolites, which can be distinguished from it by cleavage, solubility, and in many instances the biaxial behavior. Scapolite is distinguished by its negative double refraction and cleavage, and cordierite by its biaxial properties and frequent pleochroic halos. The feldspars can be distinguished in general by cleavage, indices of refraction, and biaxial behavior. This last property becomes the most important earmark for plagioclase in contact rocks where cleavage, twinning, etc., are lacking. In order to establish its distribution compared with these minerals, the special reactions cited on page 174 can be employed to best advantage.

A large number of fibrous, siliceous minerals, occurring in radial aggregates or having an onion-like structure or both of these together and penetrated by opal, have been shown to be rock-forming minerals. They are found as concretionary masses in crevices and air holes in eruptive rocks, as a cement in their tuffs, and as a cementing material in sediments. Chalcedony is the best characterized member of this group. It has a somewhat stronger double refraction and negative principal zone, and the acute bisectrix of a very small optic angle lies perpendicular to this zone. *Quartzine* and *lussatite* are similar to it. They are biaxial with a small optic angle, but are positive and have positive principal zones. A variety known as *lutezite* is distinguished from the others by an oblique extinction of the fibers, while *pseudochalcedony* is distinguished by the negative character of the principal zone and of the mineral. Distinction from zeolites similar to it is only possible chemically.

Tridymite is more characteristic. Very small tabular crystals with an hexagonal outline are clustered together and the little plates overlap each other like shingles on a roof. It shows division into segments in polarized light, and in convergent polarized light it gives a badly distorted, biaxial interference figure. The very low index of refraction is its most distinctive feature, causing it to appear in thin section with decided relief. It occurs particularly in acid eruptive rocks, rhyolite and trachyte, but not as a primary constituent. It is of secondary origin produced by fumaroles and is, therefore, not uniformly distributed, but is segregated in individual clusters. It is also found in a few fritted sandstones.

### Nepheline (6)

Nepheline is never found in association with quartz and it occurs entirely in the basic soda rocks of the series from nepheline syenite to theralite, and from phonolite to basalt. Two types can be distinguished. The one is fresh, has a vitreous luster and is limpid in thin section. It is called *nepheline*. The other is macroscopically reddish or greenish with a greasy luster and it is called *elaeolite*. The latter is distinguished under the microscope by being less fresh. It is filled with inclusions and decomposition products of various sorts but it is by no means to be considered as an independent mineral species. In coarse granular rocks the mineral can be distinctly seen macroscopically in the last mentioned form and the same variety is also observed by the naked eye in nepheline porphyry. On the other hand, the fresh form is not so readily observed partly because the individuals are smaller and partly because they are *clear, colorless, and transparent*. Rocks, which contain nepheline in fine particles, frequently show a characteristic greasy luster.

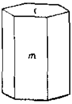


FIG. 260. Nepheline.

When nepheline shows distinct crystal form its habit is short, thick prismatic, Fig. 260. Its cross sections are short rectangular to six-sided, Fig. 237 *e*, page 225. Frequently inclusions of pyroxene needles are arranged in a zonal manner. It is usually without distinct cleavage. Even the variety known as elaeolite forms such individuals in rocks rich in nepheline. Characteristic for the shapeless particles of elaeolite are the irregular, clouded bands of decomposition products, and the inclusions of scales of brownish-red ferric hydroxide or of needles of aegirine. Likewise, the large grains of the clear, transparent type are easily recognized by the index of refraction which agrees almost exactly with that of Canada balsam. However, when the dimensions are very small, as in numerous nepheline basalts, or finally, when it occurs only as a fine cement of colorless substance between the other constituents, it can only be identified with an approximate degree of accuracy by gelatinization with hydrochloric acid and the formation of cubes of salt. It can only be positively distinguished from zeolites and rock glass, if in addition to this the etched grains show cross sections of a typical form after they have been stained.

The fact that nepheline is confined to the soda rocks helps to make it more easily recognized because it is almost always accompanied by bisilicates rich in sodium and, when these are present, *it is always well to look for nepheline. Its similarity to* the zeolites must, however, not be lost sight of. Numerous colorless minerals have been confused with nepheline. Apatite is distinguished by the higher indices of refraction, quartz and cordierite by the higher double refraction, scapolite by both of these properties, and sanidine by a lower index of refraction.

Nepheline is one of the most easily attacked of the rock constituents. *Alteration into zeolites such as analcite, hydronephelite,* and natrolite is especially common—*Spreustein.* In certain rocks pseudomorphs of matted mica after nepheline are found and these have received the name *liebenerite* or *gieseckite.*

### **Apophyllite** (6)

Apophyllite is rare and like all the zeolites is only known as a secondary product mostly in basic eruptive rocks. The mineral is characterized in thin section by an extremely low double refraction, the occurrence of anomalous interference colors, and a very perfect cleavage. It is a very rare mineral as a rock constituent.

### **Chabazite** (6)

Chabazite is also found among the zeolitic decomposition products of silicates containing lime. It occurs in cavities and crevices in basic eruptive rocks and is found often in splendidly developed limpid crystals. It occurs as a rock constituent in the same kind of rocks, but is usually poorly developed and difficult to distinguish from the other zeolites.

### **Cancrinite** (6)

Cancrinite is confined to the soda rocks. It is sometimes associated with nepheline after which it also forms pseudomorphs. It sometimes replaces nepheline. It appears macroscopically in poorly bounded grains and scaly aggregates with a yellow to reddish color, and is distinguished by its good prismatic cleavage. Recently, rhombohedral crystals have been observed in tephrites. Under the microscope its individuals are colorless and have inclusions of iron hydroxides, etc.

The mineral is easily distinguished from all other rock constituents by its low indices of refraction and brilliant interference colors. The identity of the mineral can also be proved by treating the section under the microscope with warm hydrochloric acid, when the development of small bubbles of carbon dioxide can be observed. If the preparation is heated, the mineral becomes cloudy. Alteration is the same as in nepheline. Cancrinite fuses before the blowpipe with intumescence to a vesicular glass.

### **Hydronephelite** (Ranite) (6)

Hydronephelite and ranite, which is distinguished from it by a small content of lime, are the most frequent alteration products of nepheline. They are observed in confused flaky aggregates in pseudomorphs after nepheline—*Spreustein.* They can only be recognized with any degree of accuracy under the microscope in sections perpendicular to the $c$ axis in convergent polarized light, and in all cases they are difficult to distinguish from the other zeolites, which are associated with them in the composition of spreustein.

## 4. Biaxial Minerals

When the rock-forming minerals of the orthorhombic, monoclinic and triclinic crystal systems show distinct crystal form they possess prismatic or tabular development. Pyramidal forms alone rarely occur, but they are frequent as terminations on prismatic crystals. Pyramid faces also have no significance as cleavage directions. Fig. 261 gives the principal types of cross sections observed.

In the orthorhombic system, sections parallel to the $a$ and $c$ axes are more or less lath-shaped with a square or a domatic end. Sections parallel to a macropinacoid are quadratic when there are but two end faces, and rhombic when the development is that of a prismatic form. When both of these types of forms occur in combination, the sections are six- to eight-sided. It is significant that the prism angle of numerous orthorhombic minerals, and the same is true for monoclinic and triclinic crystals, approaches 90° or 120°, and their cross sections are similar to those of tetragonal and hexagonal minerals. Quite frequently crystals with a lower symmetry are observed simulating the symmetry of a higher class. In the lath-shaped cross sections of the orthorhombic crystals the extinction is usually parallel and perpendicular to the edges, and the same is true for the sections across the front of the crystal, if its form is determined by the basal pinacoidal faces. If a prismatic form predominates in such a section, the extinction is symmetrical.

Monoclinic minerals are sometimes prismatic parallel to the axis of symmetry or in the direction perpendicular to it. Sometimes they are tabular parallel to the basal pinacoid or the plane of symmetry, and occasionally to the macropinacoid. In the prismatic type all the sections with parallel extinction are lath-shaped, while those with oblique extinction are much shorter and have four-, six- or eight-sided outlines. If the prism axis is perpendicular to the direction of the axis of symmetry, the sections with parallel extinction may show all of the forms referred to in the orthorhombic crystals, while the sections with oblique extinction appear elongated and have unsymmetrical end faces. Minerals in the monoclinic system, developed tabular parallel to the base, have lath-shaped cross sections, which may show parallel or oblique extinction, while sections parallel to the base are nearly always regular six-sided. Among the minerals on which the plane of symmetry predominates, all sections with parallel extinction are lath-shaped, while those with oblique extinction are rhombic or irregular six-sided.

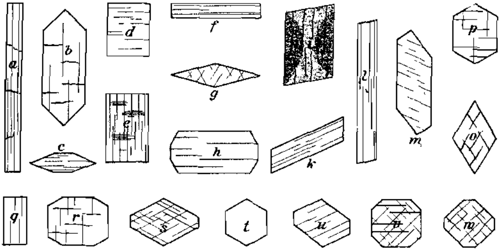


FIG. 261.—Principal Cross Sections of Biaxial Minerals

The triclinic minerals, which are not abundant as rock constituents, are very similar to the monoclinic in form. Generally it is quite difficult to establish the membership of the variously orientated cross sections in the triclinic system.

Sections of a biaxial mineral parallel to the plane of the optic axes give the highest interference colors of all sections. Such a cross section must be sought to determine the value of the double refraction by means of the interference colors, and one can be assured of the proper orientation by the behavior in convergent polarized light (see Part I, page 118). It is also useful to find a cross section parallel to the plane of the optic axes to determine the directions of extinction of monoclinic minerals, because in many monoclinic substances the axial plane lies in the plane of symmetry, and it is in this latter plane that the extinction angle must be determined. Sections of biaxial minerals perpendicular to one of the bisectrices give interference colors which under all circumstances are lower than those of a section parallel to the plane of the optic axes. The colors in the one case are about half as high as in the other, and they are about the same in both sections perpendicular to the acute or obtuse bisectrix if the optic angle approaches 90°. The interference color in a section perpendicular to the obtuse bisectrix is always the higher, and it is the more like that of a section parallel to the optic plane, the smaller the acute optic angle. The interference color is *very low in a section perpendicular to the acute bisectrix if the optic angle* is small, even though the double refraction of the mineral itself is high. This phenomenon is especially interesting in the investigation of micaceous minerals in the form of powder. In consequence of the perfect cleavage only small flakes are found and these are perpendicular to the acute bisectrix of a small optic angle. The best example of this is muscovite. It is optically negative, and in certain occurrences, $\gamma-\alpha=0.042$. Therefore the interference colors in a section parallel to the axial plane are quite brilliant in the thinnest slides. $\beta-\alpha=0.039$ shows that in a section perpendicular to the obtuse bisectrix the interference colors are quite the same as in the first section. On the other hand the double refraction in a cleavage plate is *quite different,* $\gamma-\beta=0.003$. *Distinct interference colors appear only in* very thick plates.

Biaxial minerals with a small optic angle cannot always be positively recognized even in sections perpendicular to the acute bisectrix, because of the frequency of optical anomalies in uniaxial minerals. It is not possible to make a distinction in sections quite oblique or parallel to the acute bisectrix. It was noted in Part I, page 118, that in minerals with a large optic angle and high indices of refraction the optic axes cannot be seen in convergent polarized light even in sections perpendicular to the acute bisectrix, with a dry system of lenses, because the axes are totally reflected. The determination of the optical character of such a mineral is only possible in oblique sections according to the method described in Part I, page 115. Even this method is not always reliable, especially when the optic angle is nearly 90°, as in olivine and plagioclase. It is quite evident that the determination of the optical properties is more positive and can be made in more sections where the optic angle is large than where it is small, because most of the sections in the former case will show a good characteristic interference figure.

The position of the plane of the optic axes relative to the principal zone is a valuable characteristic in determining a mineral. The plane is sometimes *parallel and sometimes perpendicular to the principal zone.*

The size of the optic angle is different for various colors. For this reason, if an interference figure is rotated into the 45° position with respect to the planes of vibration of the nicols, a fringe of color will be seen around the vertices of the hyperbolæ. It is sometimes yellow on the convex side and blue on the concave, and sometimes the reverse. In the first case the optic angle is greater for red than for blue, and the dispersion formula is $\rho>\upsilon$. In monoclinic and triclinic minerals, the bisectrices for various colors do not generally coincide. Inclined dispersion is the most frequent in the monoclinic rock-forming minerals (see Part I, page 111). Strong dispersion of the optic axes or of the bisectrices becomes apparent in many sections even in parallel polarized light by the occurrence of anomalous interference colors.

When biaxial minerals show pleochroism three color axes can be distinguished corresponding to the three principal vibration directions. In the orthorhombic system these two sets of axes coincide. In the monoclinic system the two color axes lying in the plane of symmetry may be oblique to the principal vibration directions, while in the triclinic system there is no regularity in the position of either set of axes. In both cases the differences are quite small. An accurate orientation of the mineral section in convergent polarized light should always precede an accurate determination of the pleochroism.

### **Brookite** (7)

Brookite occurs as a rock constituent in small rather elongated plates with domatic terminations, but it is a rare constituent and is always in small amounts. It is of secondary origin formed by the alteration of silicates containing titanium, especially of biotite in granite and quartz porphyry, and it is also often found in clastic rocks. It is always accompanied by rutile and anatase. It is brown and transparent under the microscope. It shows no pleochroism on the broad face and has an adamantine luster in reflected light. The crossed position of the optic planes for green and red is characteristic. It can be noted by observing the tabular crystals in convergent polarized light. The mineral can be determined by its adamantine luster in reflected light and high indices of refraction as well as high double refraction. Observations in convergent light distinguish it from rutile, cassiterite and pseudobrookite. It is distinguished from goethite principally by chemical tests.

### **Goethite** (Needle Iron Ore) (7)

A few remarks concerning goethite must be made here. Its occurrence in thin needle-like inclusions in various other minerals has been proved, but it is scarcely ever observed as a rock constituent on account of its similarity to rutile, brookite, etc. Fine fibrous aggregates of velvet blend are easily recognized in ore deposits, but otherwise it can only be positively determined by chemical tests.

The mineral, which was originally called goethite, is quite different from needle iron ore and it is now called *ruby mica*. Its composition is the same as that of goethite, but it occurs in short, rhombic, tabular crystals with very perfect cleavage parallel to the broad face and perfect cleavage perpendicular to it, and in addition it has a fibrous fracture. It is red to yellowish-red pleochroic, has high indices of refraction and comparatively low double refraction. 2V is not far from 90° for all colors in the same plane. Many of the red inclusions producing the red color or aventurine chatoyancy of minerals belong to this type.

Fine grained to scaly aggregates of brown iron hydroxides with brilliant interference colors are widely observed as pseudomorphs after pyrite. It cannot be positively determined whether they belong to goethite or not. The same is true for brown iron ore—*limonite*— $2Fe_2O_3 . 3H_2O$, which under certain conditions forms similar aggregates. It is fibrous with perfect cleavage in the direction of the fibers and has a positive principal zone and negative double refraction. It has high indices. $\gamma - \alpha = 0.05$. 2V is very large. It is brown to yellow pleochroic $\mathfrak{b} > \mathfrak{c} > \mathfrak{a}$.

### **Pseudobrookite** (7)

Small rectangular tabular crystals of pseudobrookite are but rarely found in the recent eruptive rocks and their tuffs. It is quite similar to brookite, but is usually deeper colored and is probably always secondary, formed by fumaroles. It is red, transparent under the microscope only when it is extremely thin and is weakly pleochroic. It is distinguished from brookite, goethite and wurtzite, which appear quite similar to it in ordinary light, by the depth of color and observations in convergent light.

### **Sulphur** (7)

Sulphur as a rock constituent is confined on the one hand to volcanic rocks and is then either a by-product in alumstone or a binding material in tuffs of volcanic ash. It is difficult to recognize in the latter case, but can always be determined by its ability to ignite and by the odor given off upon combustion. On the other hand, it is found in sediments especially in gypsum and in organic deposits in which it is apparent even macroscopically. Its microscopic distribution has been very little investigated.

### **Baddeleyite** (7)

Up to the present time baddeleyite is only known in basic granular soda rocks. The cross sections are usually elongated and show twinning lamination. They are pleochroic, being green parallel, and brownish perpendicular to the principal zone. It has perfect cleavage and is characterized beyond question by its high indices of refraction and double refraction.

## **Titanite** (7)

Titanite is always only an accessory constituent of rocks, but it may be so concentrated locally that it assumes considerable importance. It is distributed throughout all rocks with the possible exception of pure magnesium silicate rocks. It has a great tendency to be associated with hornblende. Its crystallographic habit is quite variable. In granite and related rocks the envelope form, Fig. 262, predominates. It gives a sharp

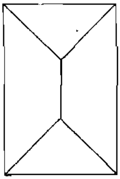


FIG. 262.—Envelope Form of Titanite.

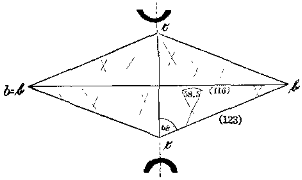


FIG. 263.—Titanite. Horizontal Cross Section through Fig. 262.

rhombic cross section, Fig. 263, caused by the predominance of $\{\bar{1}123\}$, $2/3\,P\breve{2}$. In soda rocks it has sharp angular prismatic development with $\{011\}$, $P\breve{\infty}$ predominating. Individuals of the first type generally belong to *grothite.* It is macroscopically dark brown and is often quite distinctly colored, generally reddish, in thin section and is pleochroic. Those of the second type resemble more the yellow *sphene,* which is colorless in thin section. Twinning parallel to the basal pinacoid is not rare. It often divides the rhombic cross sections in halves and it also occurs in the form of lamellae.

The mineral is further found in grains, which are frequently elongated especially in schistose rocks. Minute rounded particles may be assembled together, *insect eggs,* and the finer grained these are the more clouded they appear. Titanite is also widespread as *a border around other titanium minerals* and as *pseudomorphs* after them. It occurs especially with anatase as the principal constituent of leucoxene.

The cleavage is usually developed only in a very few cracks and it is very characteristic that these are generally not parallel to the edges of the crystals, Fig. 263. The optical properties vary within wide limits, but the high indices of refraction and double refraction together with the strong dispersion of the optic axes afford good marks of recognition. Deep colored varieties can be confused with rutile under some conditions and the colorless or light colored ones with cassiterite or xenotime from which a distinction is very difficult, if it cannot be made by the interference figure. This cannot always be done on account of the small optic angle of titanite. In this case a chemical test for calcium, made upon the isolated material, is necessary to make a positive distinction. It is easily distinguished from anatase, zircon, epidote and monazite by the much lower double refraction of these. See page 242 concerning confusion with calcite.

### **Lievrite** (Ilvaite) (7)

Lievrite is found in large masses in some ore deposits and in more isolated individuals in contact rocks. It forms pseudomorphs after the bisilicates in soda rocks. It is also encountered with fine hair-like development in the pores of trachytes and is known as *breislakite.* Its determination is made very difficult by the fact that it is almost entirely nontransparent but, on the other hand, it is favored by its solubility in hydrochloric acid and the micro-chemical test for calcium as well as by its fusibility. *Anigmatite* is similar to it, see page 294.

### Monazite (7)

Monazite is a widespread constituent of granitic and syenitic rocks, especially aplites and pegmatites, and the schists injected by them, but it is always only sporadically present. It occurs in tabular to prismatic crystals, Fig. 264, which have separated early from the magma. It is very easily confused with zircon and epidote in thin section, but observation with the spectroscope readily distinguishes them. The characteristic absorption bands of neodymium and praseodymium, page 168, characterize monazite. Cleavage plates show an almost symmetrical position of the positive bisectrix of a small optic angle. Since it is quite resistive to weathering, it is found also in clastic rocks, especially in sand stones, but it is frequently clouded and generally forms rounded grains.

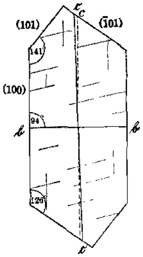


FIG. 264.—Monazite. Section Parallel Plane of Symmetry.

### Låvenite (7)

When låvenite occurs in irregular grains it is often difficult to distinguish from epidote. In most of the prismatic crystals the position of the optical plane parallel to the principal zone can be determined. It is reddish-brown or yellow macroscopically and in thin section it is quite distinctly colored. Twinning lamellæ parallel to {100} are frequent. One of the axes emerges from a cleavage plate obliquely. It is always fresh.

*Woehlerite* is very much like låvenite. It is also monoclinic, but is somewhat lighter colored and has lower double refraction. It forms larger individuals, which are usually tabular parallel to {100} and have twinning lamination parallel to the same form. The extinction angle is about 43° and that, together with the position of the optical plane perpendicular to the plane of symmetry, is the distinctive characteristic. The obtuse bisectrix, which is negative, is seen in laminated cross sections. It is more easily attacked by hydrochloric acid and is more difficultly fusible than låvenite. Both minerals are confined to the soda rocks, but are widely distributed in them in isolated grains or crystals, accompanied by other zirconium silicates and violet fluorite.

Another silicate containing zirconium and titanium, not unlike låvenite, has been observed in jagged needles that are frequently greatly honeycombed and often twinned, in certain phonolites and is called *hainite*. Monoclinic? It cleaves parallel to a direction perpendicular to the positive bisectrix of a large optic angle with strong dispersion $\rho > v$. Negative character of the principal zone. Extinction angle up to 16°. Index of refraction about 1.7. $\gamma - \alpha$ about 0.012. Pleochroism light yellow to colorless.

### Chrysoberyl (7)

Chrysoberyl undoubtedly plays no subordinate rôle among the constituents that are constant, but are only present in extremely small amounts in acid eruptive rocks, especially in aplites, pegmatites, and in schists injected by them. It is very difficult to determine it, when it occurs in small isolated crystals because of its optical properties which are unusually variable. It sometimes has a large optic angle with a weak dispersion, and often the optic angle is 0° for red and 90° or over for violet. It often shows anomalous interference colors in consequence of the great dispersion.

### **Epidote Group** (8)

The *epidote group is one of the most difficult to recognize of all* the rock-forming minerals, partly because of the great similarity in the optical properties of the various members, which are quite different chemically and crystallographically, and partly because of the enormous differences displayed by *compounds, chemically very closely related* to each other. Minerals of this group with an extremely low double refraction are distinguished from those which show medium to very strong double refraction. *There are types in the first class, which* show the highest degree of anomalous interference colors, and others that are scarcely observable in thin section and give a pure gray of the first order.

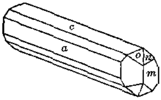


FIG. 265.—Epidote.

All the minerals considered here are developed prismatic with a *tendency to a long, tabular growth. In the monoclinic* members the principal zone is that of the axis of symmetry, Fig. 265, and the orthorhombic members, contrary to custom, are set up accordingly, so that the principal zone is that of the transverse axis. Sharply bounded crystals are rare. The predominating cross sections of the principal zone are mostly rounded on the ends. Corresponding to their development, the monoclinic members show chiefly sections with parallel

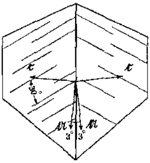


FIG. 266.—Section through a Twin of Epidote.

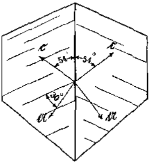


FIG. 267.—Section through a Twin of Orthite.

extinction. In transverse sections it is not easy to distinguish monoclinic from orthorhombic members. The extinction direction is almost parallel to the trace of the front pinacoid in many epidote minerals, which is usually also the twinning plane. The two halves or the lamellæ of which such crystals are constructed extinguish at about the same time, Fig. 266.

*Orthite* (*allanite*) shows a characteristic difference in this respect. Its extinction angle referred to this direction is very considerable, Fig. 267, and its twins therefore appear most distinctly in polarized light. It is noteworthy, however, that when crystal form or twinning are lacking, and the extinction is measured from the cleavage cracks, which are few in number but very sharp, both varieties show about the same extinction, 30°.

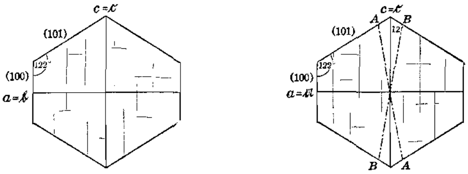


Fig. 268.—Zoisite α, Fig. 269.—Zoisite β,

Section Parallel (010).

There is a difference here in the axes of elasticity. In epidote and clinozoisite the axis of elasticity which forms this angle with the cleavage direction is that of the least velocity 𝔠, while in orthite it is the direction of the fast ray, 𝔞.

Figs. 268 to 273 show the usual development of the most important members of the epidote group together with their most important optical properties. In the normal members of the series the plane of the optic axes lies perpendicular to the direction of elongation. This is one of the most important means of distinguishing epidote from the pyroxenes and other minerals, which otherwise possess similar properties. In each of the subdivisions of the members with low double refraction, there are those in which the position of the axial plane coincides with the trace of the cleavage. In the first group transverse sections of the prismatic individuals are parallel to the axial plane and, therefore, show the highest interference colors. In these sections also, twinning appears most distinctly. In the other group such transverse sections show the obtuse bisectrix and have medium interference colors.

The minerals of the epidote group are very frequently intergrown with each other partly in a very regular, zonal manner, so that the content of iron, and with it the double refraction, decreases from the center toward the edge, or vice versa. Alternating zones also occur. In other cases the center may be one of the zoisites which grows into a monoclinic member toward the edge. One of the most characteristic features of orthite is an enveloping growth of clinozoisite. In such cases the following parallelism of elasticity axes is to be noted:

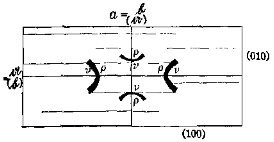


*Fig. 270.—Zoisite α: Axial Plane Parallel Cleavage. Zoisite β: Axial Plane Perpendicular Cleavage. Section Parallel Base.*

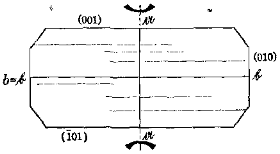


*Fig. 271.—Clinozoisite and Epidote.* Section Parallel (100).

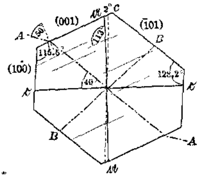


Fig. 272.—Clinozoisite,

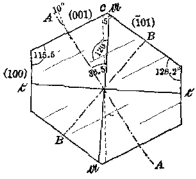


Fig. 273.—Epidote,

Section Parallel Plane of Symmetry.

| zoisite α | zoisite β | clinozoisite, epidote, orthite. |
|---|---|---|
| γ | γ | α |
| β | α | γ |
| α | β | β |

The crystallographic orientation of the members of the group referred to above is taken from these observations. In other cases the intergrowth is entirely irregular and the various members penetrate each other. The great differences in double refraction of the members thus intergrown often give rise to the brilliant speckled appearance of the sections in polarized light, and this does not occur in any other series of minerals.

Zoisite and clinozoisite are scarcely ever distinctly seen macroscopically, but rocks in which they participate in the composition to a great degree have a light yellowish- or grayish-green tint. Epidote itself with its pistachio green color—*pistazite*—is often seen macroscopically. It is the most frequent yellow pigment of crystalline rocks and as such is in a fine state of division. Normal zoisite and clinozoisite are colorless in thin section. Monoclinic epidote rich in iron is quite light, usually yellowish, with strong absorption parallel to the principal zone. The intensity of the color and the pleochroism are increased by heating to redness in air. A deep brownish-yellow color appears in an unroasted section of the members with the highest double refraction and the highest content of iron, but this seems to be a rare occurrence. Similarity to låvenite appears in the most highly colored members.

There is a series of members containing chromium which are macroscopically almost emerald green. In this series *chrome zoisite* and *chrome epidote* can be distinguished, and there are also varieties corresponding to clinozoisite. These minerals are deeply colored in thin section and the pleochroism ($\mathfrak{a}=\mathfrak{c}$ light green, $\mathfrak{b}$ deep orange) can be noted in occurrences that have such a low double refraction that they scarcely affect polarized light. The color and strength of the double refraction are in no way related to each other.

The whole series can be distinguished also in the members containing manganese. *Thulite* corresponds to the zoisites. It is macroscopically rose-red and has a distinct color in thin section; $\mathfrak{a}$ yellowish, $\mathfrak{b}$ red, $\mathfrak{c}$ rose. It usually has anomalous interference colors. A series with varying intensity of color and strength of double refraction leads to manganese epidote—*piemontite*. It appears blackish-red macroscopically and it is characterized in thin section by deep color and strong pleochroism. It is often the cause of the deep red color of rocks, especially in altered porphyrites, e.g., in *porfido rosso antico*, and in phyllites. Next to hematite it is the most important red pigment of crystalline rocks. It often appears not unlike dumortierite, but is distinguished from it by a different optical orientation.

Finally *orthite* or *cerium epidote*, *allanite*, is to be mentioned. It usually shows good crystal form in the granular eruptive rocks, and these as well as the isolated grains are characteristically enveloped by clinozoisite. It has a brown, sometimes also blood red, color and is strongly pleochroic with a high double refraction, $\gamma-\alpha$ = up to about 0.3. Isolated black grains with a pitchy luster, surrounded by a red border, are frequently observed macroscopically. It is noteworthy that these deep colored orthites are not infrequently transformed into an amorphous yellowish to red gum-like mass, a phenomenon which numerous minerals containing cerium show. The color of orthite is very much lighter in the soda rocks, contact rocks, and injected schists. In thin section it is light brownish, greenish-yellow, or light violet, probably due to titanium. Some individuals are indeed colorless. The double refraction is decreased in such occurrences to about 0.002, and the index of refraction of these lighter colored members also seems to be much lower, about 1.70 or less. The determination of small prisms is thus often extremely difficult. They often show normal interference colors and are then nearly always determined as apatite. Sometimes they are characterized by brilliant anomalous colors.

There are many reasons for classing these small crystals as orthite. Frequent zonal growths with clinozoisite point to their membership in the epidote group. The appearance of pleochroic halos is often observed near them, and this is distinctive for all occurrences of orthite, and, finally, the transverse sections nearly always show twinning with the orientation of Fig. 267, page 258. Hence there can be no doubt of their relation to orthite. It may be mentioned that in spite of the high content of rare earths, spectroscopic investigation of orthite usually gives no results.

The following table gives a classification of the phenomena described and can be used to differentiate these minerals.

| | Double refraction | Interference color | Position of optical plane | Optic angle | Extinction |
|---|---|---|---|---|---|
| Zoisite $\alpha$. | Low. | Anomalous. | ∥ cleavage and principal zone. | Medium. | Approximately or entirely parallel. |
| Zoisite $\beta$. | | Normal. | ⊥ cleavage and principal zone. | Small. | |
| Clinozoisite. | | Strongly anomalous. | | Very large. | |
| Epidote. | High. | Normal speckled. | | | |
| Orthite. | Medium to low. | Anomalous or normal. | Variable. | Variable. | Oblique 36°. |

The great difficulties encountered in making an accurate determination of the epidote minerals can be seen from this classification. A distinction is quite important where the members are of considerable size and to some extent well developed. Much practice is required to distinguish the various members, where the minerals occur in dense aggregates as in the saussurite, which is macroscopically greenish-gray and has a splintery fracture, or where they are in sharply defined microlites grown in plagioclase as is generally the case in the central granite. If cleavage plates of these minerals can be investigated, it is noted that in epidote rich in iron an axis emerges slightly oblique to the cleavage face. In clinozoisite it is more oblique and cleavage plates of the zoisites show no characteristic interference whatever.

Distinction of the two zoisites, which are not positively orthorhombic but possibly crystallize triclinic, from clinozoisite, which is certainly monoclinic, is made difficult by the fact that the latter has an extinction almost parallel to the vertical axis. The degree of abnormality of the interference colors is the safest means of differentiation. It is pure gray in zoisite $\beta$, distinct bluish-gray in zoisite $\alpha$, and brilliant Prussian blue in clinozoisite. Investigation in convergent polarized light also aids to distinguish them. Thorough study shows that clinozoisite is by far the most widespread of the low double refracting members, which were formerly simply classed together as zoisite. Zoisite $\alpha$ is rather frequent, but zoisite $\beta$ is quite rare as an independent rock constituent.

Concerning the geological distribution of these minerals, it may be said they belong to the most typical formations of contact rocks rich in aluminium and calcium, and as such are found especially abundant in amphibolites, chlorite schists, green schists, and eclogites, in which they are regularly mixed with the other minerals or are separated in lighter colored layers. They are observed less frequently in mica schists, but in them they have a tendency to occur in knots rich in graphite, which are macroscopically black. As already mentioned they form a constituent of saussurite, which occurs in pseudomorphs after plagioclase rich in calcium. In it these pseudomorphs are usually very poorly developed and the structure of the saussurite is so matty that the individual grains cannot be separated from each other even under the microscope. Since numerous other minerals with high indices and low double refraction, frequently also with anomalous interference colors, such as vesuvianite, garnet, gehlenite, prehnite, etc., take part in the formation of these aggregates, the question whether saussurite really belongs to the epidote minerals must remain unsettled.

The low double refracting members occur alone in some rocks, especially in amphibolites and saussurites. In other rocks, however, they are in zonal intergrowth with epidote, which is richer in iron and has a higher double refraction. In numerous chlorite schists, eclogites, etc., epidote entirely replaces the other members. In lime-silicate fels rich in aluminium, lime mica schist, etc., epidote is in general more frequent than the other members. These rocks pass over into yellowish epidote fels or *epidosite*. In the latter rock, epidote is observed here and there in crystals well bounded on all sides, while in other occurrences it, like the others, shows good faces at best only in the zone of the axis of symmetry. Sections parallel to the *a* axis generally appear as rounded tapering laths.

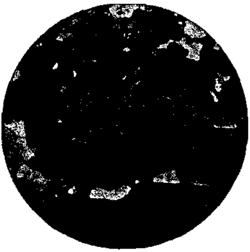


Fig. 274.
Plagioclase with Microlites of Clinozoisite.
Central Granite, Mösele, Zillertal.

The widespread occurrence of abundant sharply defined microlites of clinozoisite in the plagioclase of the central granite is very noteworthy. Fresh glassy feldspar consisting mostly of oligoclase is often so abundantly filled with these microlites without any orientation that the rock shows a yellowish-green tint macroscopically, and extremely thin sections are necessary to make the formation transparent at all. Fig. 274 gives a representation of this phenomenon, which differs greatly from all forms of secondary.development and can only be designated as an original formation. It represents a typical feature of piezocrystallization. Besides this, clinozoisite and epidote are encountered in much larger grains as primary constituents of acid eruptive rocks. They are generally confined to the border zone of the intrusive and represent constituents taken up from the neighboring rock. The zoisites are also found in intruding aplites and pegmatites. They occur in large crystals in pegmatites, which intrude the eclogites of the Fichtelgebirge, and in microscopic individuals in the aplites, which intrude the amphibolites of Mount Grossevenedig. They are much more frequent in the eruptive rocks, where they are secondary. The alteration of bisilicates into chlorite is almost always accompanied by the formation of greater or smaller amounts of epidote in irregular grains. If this form is but weakly colored it appears similar to anatase, which occurs under like conditions but is distinguished from the latter by much lower indices of refraction. The manner of occurrence of manganese epidote has already been referred to and likewise that of orthite. Aside from the extinction and the frequent occurrence of pleochroic halos in the neighborhood of orthite, it is characterized by the fact that it is always only a subordinate and purely accessory rock constituent.

Minerals of the epidote group are not infusible and the richer they are in iron the more easily they fuse. Orthite is distinctly attacked when fresh by hydrochloric acid, but the other members resist the acid unless they have previously been roasted to drive off water and then they gelatinize readily.

Confusion of epidote minerals with numerous others has already been referred to many times, thus with vesuvianite, etc., in saussurite where a separation is not possible. Light colored epidote is often not unlike the pyroxenes. They have numerous cleavage cracks parallel to which lies the optical plane, while in epidote it is perpendicular. In låvenite also the optical plane lies in the principal zone. Olivine often appears similar to epidote, but it never has the speckled interference colors and generally has no distinct cleavage cracks. It also turns deep brown upon roasting and gelatinizes readily with hydrochloric acid. The isolated occurrence and spectroscopic investigation distinguish monazite. Confusion of low double refracting members with apatite has been mentioned above. When no morphological distinction can be found, apatite can be determined by its solubility in dilute nitric acid and its reaction for phosphorus. Brown orthite often appears not unlike basaltic hornblende. It shows a smaller difference in absorption than does the hornblende and the position of the optical plane transverse to the principal zone. Further than this the border of clinozoisite and epidote around the individuals of orthite, which are always isolated, is exceedingly characteristic.

### **Staurolite** (8)

Staurolite is a typical mineral of the contact rocks, particularly those formed by piezocontact metamorphism. It is rarely found in the granites, but is found in the clastic rocks in consequence of its great resistance to weathering. It sometimes occurs in quite large, well developed, flat prisms and twins, in which the individuals interpenetrate each other at 90° or 60°, Fig. 275. They are dark brown in color. Sometimes the borders are very irregular. Smaller microscopic *individuals usually have a much poorer form*, but in general the prismatic development is distinct. The larger crystals are usually filled with inclusions like a sieve. They may be penetrated by quartz in an *irregular manner or in a helicoidal manner* as shown in Fig. 276. Graphite dust is observed in them much the same as in chiastolite. Microscopic individuals tend to be purer, but are difficult to determine on account of their poor development.

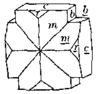


Fig. 275.
Staurolite Twins.

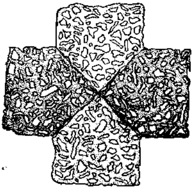


**Fig. 276.—Staurolite Twin Filled with Quartz Inclusions.**

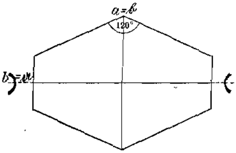


**Fig 277.
Staurolite Cross Section.**

Sections corresponding to Fig. 277 are the most characteristic for the mineral. It is distinguished from the yellow varieties *of tourmaline or from colored epidote by the lower double* refraction and by the orientation of the absorption, which is strongest in the direction of the principal zone. Now and then pleochroic halos are present in the mineral. It can be easily isolated because of its insolubility even in cold hydrofluoric acid. It is strongly attracted by an electro-magnet and is infusible before the blowpipe.

### **Diaspore** (8)

Diaspore has been positively recognized only as a decomposition product *in completely altered rhyolites, in the spreustein of nepheline syenites, in* kaolin, in emery, and in other rocks bearing corundum. Its distribution other than this cannot be determined. Small crystals of it are rounded and rather elongated plates. Sharp cracks occur parallel to the direction of the *a* axis. It is occasionally colored and is then pleochroic. Its insolubility allows it to be isolated. The development and negative character of the principal zone distinguish it from sillimanite. Higher double refraction and a good cleavage distinguish it from andalusite; parallel extinction and the lack of fibrous fracture from cyanite, and the double refraction and cleavage from sapphirine. It is most similar to lawsonite. Aside from its indices and double refraction, it may he distinguished from lawsonite by its infusibility.

### **Cyanite** (Disthene) (8)

Cyanite forms broad, tabular individuals usually poorly bounded with oblique four- or six-sided cross sections. It often occurs with a light blue macroscopic color and perfect cleavage. It is also found in certain piezocontact rocks in radial aggregates or sheaves, which are macroscopically black and entirely filled with graphite dust—*rhaetizite.* Twins are very widespread, the macropinacoid being the twinning plane. *Closely assembled cracks representing fibrous fracture parallel* to the base are frequently observed, especially in bent sections. These are perpendicular to the sharp cracks representing cleavage parallel to the macropinacoid and to the less regular cracks of the cleavage parallel to the brachypinacoid. A light bluish tint can frequently be discerned in thin sections. Pleochroism can also be recognized if some care is exerted. Deeper colors are rare and a mottled appearance is characteristic of their presence.

*Cleavage plates parallel to the macropinacoid* are nearly perpendicular to the negative bisectrix of a large optic angle, Fig. 278. The axial plane forms an angle of about 30° with the cleavage cracks parallel to the brachypinacoid. This makes the mineral easily distinguished from all other rock constituents. Cleavage plates from twins show a brilliant change of color in parallel polarized light, but no difference in extinction. The *fact that macropinacoidal sections of twins show different colors* in the two halves, but extinguish nearly at the same time, is the most characteristic feature of the mineral and prevents it from being confused with any other.

The principal field of distribution of cyanite is in mica schists where it *is frequently extremely rich in inclusions* of other minerals. It is penetrated by microlites of rutile, tourmaline, and quartz grains in a sieve-like manner. It is often so filled with graphite dust that it appears almost nontransparent. Then its determination in thin section is extremely difficult. In eruptive rocks, especially in cyanite granulites and in pegmatites, it is macroscopically visible and *in thin section it is poor in inclusions* and often distinctly blue. The most beautiful occurrences of the mineral —*paragonite schists*—belong here. It is frequently associated with staurolite in *such rocks and is often in parallel growth* with it.

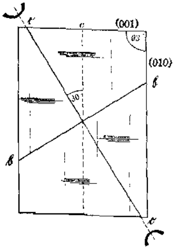


FIG. 278.
Cyanite, Cleavage Plate.

In thin section it is quite similar to a whole series of minerals, such as sillimanite, andalusite, topaz, colorless epidote, diaspore, lawsonite, sapphirine, serendibite, and finally light blue hornblende. *It is distinguished from all of* them by its fibrous fracture, the oblique extinction in sections perpendicular to the negative bisectrix or in the cleavage plates and by the nearly parallel extinction of macropinacoidal sections of twins.

### **Sapphirine** (8)

Sapphirine has been positively determined only in rocks from Greenland forming masses in gneiss and having the character of contact rocks. It may be found widely disseminated in the eclogites. The properties of sapphirine in thin section are not very distinctive. It may be discovered if it is blue or bluish-green, but its determination is very difficult if it is colorless or occurs as poorly bounded tabular crystals in parallel, scaly aggregates or those which are very imperfectly radial. It must be isolated with hydrofluoric acid in such cases, but even then it can be identified only with difficulty. It may be confused with all the minerals mentioned under cyanite. Lack of cleavage distinguishes it from most of them. It is distinguished from serendibite by lack of twin lamination, from corundum by its biaxial properties, and from cordierite by its much higher indices of refraction.

### **Serendibite** (8)

This mineral has only been found in the skarn-like border between a pegmatite and limestone in Ceylon. The lack of cleavage, typical twinning lamination, large extinction, and the pleochroism—from nearly colorless to sky blue or indigo—are sufficient indication of its presence.

### **Prismatine** (Kornerupine) (8)

Prismatine and kornerupine, which is closely related to it, are rare minerals in pegmatites and are associated with sapphirine. In thin section they are very similar to sillimanite in form and habit, but may be distinctly separated from it by the negative character of the principal zone. They are distinguished from apatite by higher double refraction, from tremolite and the brittle micas by parallel extinction in all sections, and from andalusite by the small optic angle.

### **Astrophyllite** (9)

Astrophyllite is not rare in soda rocks as an accessory constituent. It is macroscopically visible in micaceous individuals that are brittle and bronze colored or in star-shaped groups. In thin section it appears as laths with a perfect cleavage and strong pleochroism. It is distinguished from micas by its high indices of refraction, from the brittle micas by its high double refraction, and from yellowish-brown hornblende by the perfect cleavage, which shows only in one direction in sections parallel to the front pinacoid.

## Brittle Mica Group (9)

Many micaceous minerals are classed together under the term of the brittle micas. They are distinguished from mica and other flaky, micaceous minerals by greater hardness, decidedly higher indices of refraction and lower double refraction.

The following table is arranged to show a comparison of the properties of these minerals.

| | Index of refraction | Double refraction | Extinction | Optic angle |
|---|---|---|---|---|
| Astrophyllite... | High. | High. | Parallel. | Medium large. |
| Brittle micas... | | Medium to low. | Oblique. | Quite large. |
| Margarite...... | Quite high. | Low. | | Large. |
| Mica.. ........ | Low. | High. | Parallel. | Very small to medium large. |
| Chlorite........ | | Low. | | Very small. |
| *Clinochlore*..... | | Medium. | Oblique. | *Medium* large. |
| *Hydrargillite*... | | | | Small. |
| Talc........... | | High. | Parallel. | |
| Pyrophyllite.... | | | | Medium large. |
| Kaolin......... | | Low. | Oblique. | Large. |

They possess a distinct cleavage parallel to the basal pinacoid and one or more imperfect cleavages transverse to that. The optical properties of the brittle micas are not very constant. Differences in index of refraction are uncommonly distinctive and the differences in double refraction are not small. The *optical character is sometimes positive and sometimes negative.* The color is likewise quite variable. Some are colorless, while others are more or less deeply colored, and then pleochroic. They show *stronger absorption of the ray vibrating perpendicular to* the cleavage, which is uncommon for micaceous minerals.

Certain varieties of chloritoid are undoubtedly triclinic. In cleavage plates of such varieties the optical plane lies unsymmetrical to the percussion figure. Other varieties approach the hexagonal system in their behavior. The specific gravity varies within just as wide limits. Most of the brittle micas are not attacked by acids, but some are comparatively easily dissolved—*ottrelite.* Chemical analysis does not point to a common formula for the brittle micas so that the question of the relationship of the members must remain open. The two members given in the tables represent the end members of the series with *ottrelite, brandisite, clintonite, sismondine, masonite, seybertite,* etc., arranged intermediately. Nothing is known about the relative delimitations of these in rocks.

The brittle micas are widely disseminated constituents in contact rocks, especially in cases of piezocontact metamorphism and are found but rarely in the inner contact zone, e.g., in the coarse crystalline silicate fels in the Fassatal and in certain eclogites, etc. On the other hand, they are the most characteristic constituents of the outer contact zone and their principal field of distribution is in such rocks as phyllites. They appear macroscopically in the phyllites in elongated or disc-shaped knots—ottrelite—and occasionally also in sheaf-like and radial aggregates. They may be recognized by the greenish-black color and brilliant luster.

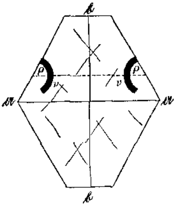


Fig. 279.—Chloritoid, Cleavage Plate.

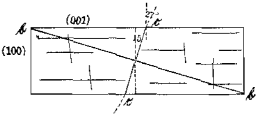


Fig. 280.—Chloritoid, Section Parallel Plane of Symmetry.

Abundant inclusions are usually observed under the microscope, especially in the knots. These are often penetrated with quartz grains, giving them the sieve structure or filled with graphite dust until they are nontransparent. Zonal structure, hourglass development, and abundant twinning lamination are often observed. Index of refraction, double refraction, and particularly the pleochroism of the larger individuals, are very important properties but, nevertheless, they are frequently confused with cyanite. The large tabular cross sections of the latter show more distinct cleavage than the basal sections of the brittle micas. Cyanite is also characterized by a larger optic angle. The brittle micas are often confused with bluish-green hornblende from which they can only be distinguished by observations in convergent light, particularly in cleavage plates, Fig. 279.

The brittle micas, as microscopic constituents, are much more widespread than the larger individuals. The development is such that they can hardly be determined positively. The normal occurrence is in small irregular particles, grouped in radial aggregates, in which the graphite content of the rock is so concentrated that they are nontransparent. These individuals, which often cannot be seen at all until after they have been roasted in an oxidizing flame, are quite light colored and sometimes entirely colorless. Twinning and cleavage can scarcely be recognized in them. They are constituents which can be determined more by the general character of the rock than by the properties of the mineral itself. They can be easily isolated from the rock because they are quite heavy and are not attacked very much by hydrofluoric acid.

### Margarite (9)

Margarite is undoubtedly much more widespread than it has been shown to be up to the present time. It is a constant associate of emery and is also found in contact rocks rich in alumina. It is distinguished from mica by the index of refraction and double refraction, and from colorless chlorite by the former property. It can scarcely be distinguished from the brittle micas in thin section except by the very large optic angle. A lower hardness can be observed on the larger isolated individuals.

## Olivine Group (9)

Olivine, or peridote, is by far the most frequent mineral of the olivine group. Forsterite and monticellite are rare and confined to contact-metamorphosed rocks. Fayalite, ferrous silicate, in crystals often with tridymite and alone in compact, dark brown masses, is characteristic in certain rocks and is probably of pneumatolytic origin. Chemically, the members are quite similar, but their optical properties vary greatly. The indices of refraction and the double refraction, likewise the positive optic angle, increase very appreciably with the content of iron, while the double refraction is very much lowered by the content of calcium, as noted in monticellite. Members rich in iron fuse more easily than those poor in iron.

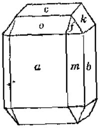


FIG. 281.
Olivine Tabular.
Parallel (100).

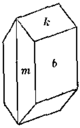


FIG. 282.
Olivine Tabular
Parallel (010).

Olivine with an average content of ferrous iron of from 11–13 per cent. is the most important member of the group. Hyalosiderite is much richer in iron. Olivine is characteristic of the most basic eruptive rocks. It seldom possesses crystal form in the granular rocks of the peridotite series except when numerous individuals are intergrown poikilitically in pyroxene. The same is true in gabbro, norite, and trap. On the other hand, it is one of the first products to form in porphyric rocks, especially in melaphyre and basalt, and less often in andesite, and then it is well bounded crystallographically. It is also found in large amounts in certain soda rocks. A mineral, which appears quite similar and is widespread in contact rocks, has a much lower content of iron and is classified as *forsterite*. In general the crystals are short prismatic parallel to the vertical axis or tabular parallel to the macropinacoid, Fig. 281. They are less often tabular parallel to the brachypinacoid, Fig. 282, and that particularly in mixtures rich in lime. They show poorly defined cleavage cracks parallel to the direction of elongation and the plane of the optic axes is perpendicular to them, Fig. 283. Faces and edges are generally rounded and corroded, and indentations filled with the solidified magma are not rare, Fig. 284. Basal sections are generally eight-sided and show two unequal cleavages perpendicular to each other, Fig. 285. The mineral is not often prismatic, except when it is rich in lime. Then the principal zone is parallel to the $a$ axis and is positive. Olivine is

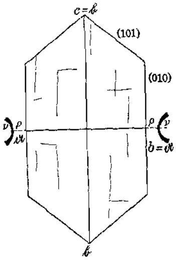


Fig. 283.—Olivine, Section Parallel (100).

Fig. 284.—High Index of Mineral in Canada Balsam.

occasionally found with a skeletal development as a constituent of the ground mass in rocks poor in olivine and containing abundant glass. Then it shows domatic or swallow-tail forms and various thread-like growths, Fig. 196, page 188.

It may be remarked that olivine is present in numerous rocks of the basalt series in large sharp angular fragments and grains. These can be referred to the inclusions of olivine fels which occur in these rocks. The entire olivine content of the rock may be traced back to crushing of these inclusions. In this form it is not equivalent to the other constituents of a basalt.

Olivine is macroscopically bottle green (*hyalosiderite* reddish-brown to golden yellow) and has a distinctive conchoidal fracture. Under the microscope it is almost colorless, and transparent, but when heated in air it always becomes reddish-brown. The ray vibrating parallel to the vertical axis is then less strongly absorbed. Hyalosiderite shows this property when fresh. Sometimes twinning is noted probably parallel to {011} and this can also be developed in the form of laminations. It is very brittle and frequently shows the cataclastic structure under the influence of mountain-forming processes.

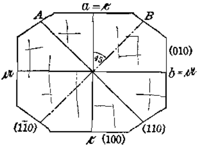


Fig. 285.—Olivine, Basal Section.

Its characteristic associate is chromite, which nearly always occurs as small, sharp crystals included in the olivine. Inclusions of other opaque ores and apatite are also found in olivine. Likewise, the little brown tabular crystals, which are regularly arranged and are so characteristic in hypersthene, occur in olivine of certain gabbros so abundantly that the mineral appears black macroscopically and in thin section it is scarcely transparent. Glass and slag inclusions are not rare in basaltic rocks, and liquid inclusions are found in peridotites as well as in the olivine fels bombs of basalts.

In certain gabbros olivine is surrounded by a wreath of amphibole arranged radial to the grain. If it borders on feldspar this wreath is composed of common hornblende, but otherwise it is tremolite. All of the olivine may finally be replaced by a confused fibrous aggregate of tremolite—*pilite*. This is frequently considered to be a result of dynamometamorphism and is genetically entirely different from serpentinization. It may be noted as contradictory to this hypothesis that tremolite is the most frequent by-product in the formation of serpentine.

*Fig. 286.*
Hyalosiderite Border around Olivine, Limburgite. Limburg on Kaiserstuhl.

In basaltic rocks olivine appears to be generally richer in iron and often shows a brilliant brown border of hyalosiderite with a stronger double refraction, Fig. 286. Similar borders seem to be of secondary origin, the olivine having been altered *into a yellow to reddish-brown substance consisting of parallel* fibers with very high indices of refraction. This has been described as goethite, but does not correspond to it in all of its properties. It probably is another ferric hydroxide. Alteration into scaly aggregates of talc or granular aggregates of carbonate, which is frequently very poor in magnesia, is noticed especially in melaphyres. Now and then biotite also results. By far the most frequent alteration of olivine is into serpentine, which is generally accompanied by a separation of iron ores. It gives the rock a green color, *veined or streaked with various shades* of red, brown, black, etc.

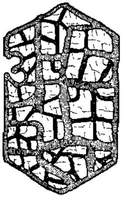


Fig. 287.—Olivine Beginning Alteration to Chrysotile, Mesh Structure.

Two kinds of serpentine formations are distinguished in olivine. One begins on the border of the crystals and in the cleavage cracks and forms parallel fibrous aggregates perpendicular to them. It is called fibrous serpentine or chrysotile. New cracks result from the increase in volume accompanying the change and these are filled with fine fibrous aggregates of serpentine. This gives rise to the typical mesh structure shown diagrammatically in Fig. 287, and as it appears in thin section, Fig. 218, page 199. Checked olivine may be present within the meshes or this may be entirely changed to a compact aggregate of serpentine.

In other rocks, *stubachite*, one may note that the fresh olivine is crossed by numerous lamellæ of flaky serpentine—*antigorite.* These are mostly orientated parallel to {011} and form a system of laths cutting each other at an angle of about 60°, Fig. 288. The angular parts of the olivine lying between them alter into irregular, scaly aggregates of antigorite beginning at the laths and progressing outward. When serpentinization is complete, the intersecting lamellæ produce the so-called *lattice structure.* In both these cases the process of serpentinization cannot be looked upon as a weathering process; see Allgemeine Gesteinskunde, page 152. Sometimes alteration of olivine, very rich in iron, produces a flaky aggregate of serpentine orientated in a simpler manner. It has a rust brown color and is called *Iddingsite,* see under serpentine.

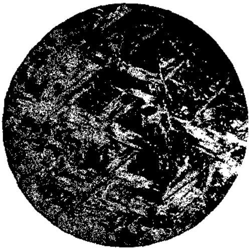


FIG. 288.—Olivine Intergrown with Antigorite. Lattice Structure.

The significance of fayalite as a rock constituent has not been investigated very much, but it is known principally in druses and in mineral veins. Possibly some of the formations called hyalosiderite belong to it. At any rate olivine in lamprophyric rocks is often very rich in iron on the border having brownish color and showing increase in the double refraction.

Titanium olivine is quite similar to it. It is macroscopically dark brown and yellow to orange in thin section. It is probably monoclinic, but occurs in grains laminated by twinning and these appear similar to chondrodite. $\alpha=1.669$, $\beta=1.678$, $\gamma=1.702$. $\gamma-\alpha=0.033$, $2V=63°$, $\rho<v$, $\mathfrak{a}$ orange, $\mathfrak{b}=\mathfrak{c}$ light yellow. Sp. gr. $=3.25$. They can only be distinguished by the difference in extinction in sections showing twinning lamination and the optical orientation of such a section, as shown in Figs. 289 and 290.

*Forsterite* has only been observed in contact-metamorphosed limestones and dolomites. It is widely disseminated in them, but is generally not macroscopically visible. When the carbonate predominates it forms rounded, colorless crystals, often containing quite large inclusions of iron spinel and calcite. If it or other silicates are the principal constituents, it forms irregular grains with the properties of olivine. *Eozoon* results by serpentinization which takes place in the ordinary manner and is quite widespread.

*Monticellite* is analogous to forsterite in its distribution, but is much rarer. The lower double refraction is especially noteworthy and distinguishes it from all other olivine minerals. It forms isolated, colorless rounded crystals in contact limestones and these often show incipient serpentinization.

Confusion of *titanium olivine* with chrome chondrodite has already been mentioned. Forsterite, colorless olivine, and monticellite often appear quite similar to diopside, but the latter shows sharper cleavage cracks, larger extinction, and has the optical plane orientated parallel to the principal zone. They can be distinguished from colorless humite only by a somewhat stronger dispersion of the optic axes if the cleavage does not appear. If the cleavage shows distinctly the optical plane in humite lies parallel to it, in the olivine minerals perpendicular. In other cases the olivine is distinguished by its solubility in hydrochloric acid and by its ability to assume a brown color, which increases with the content of iron, when it is roasted in an oxidizing flame. This latter property can serve also to distinguish olivine from forsterite and monticellite.

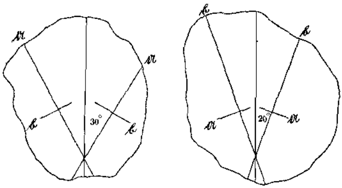


FIG. 289.—Chondrodite, FIG. 290.—Titanium Olivine,

Optical Orientation with Respect to the Twinning.

## Pyroxene Group (10)

Orthorhombic and monoclinic pyroxenes frequently occur in parallel or lamellar intergrowths. The triclinic members play no rôle among rock-forming minerals. From this fact the orientation of the orthorhombic pyroxenes in the table is so chosen that the acute prism angle lies to the front and the transverse axis is the shorter diagonal, although this is not the usual position. Prismatic cleavage is nearly always distinct and if other cleavages are present the one parallel to the front pinacoid tends to be the most perfect. It occurs particularly in orthorhombic pyroxenes and in diallage. Cleavage plates of the former parallel to this face are parallel to the optic plane, while those of the latter are almost perpendicular to an optic axis showing quite strong dispersion. A large extinction angle

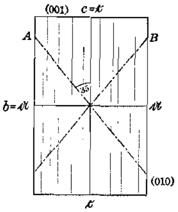


Fig. 291.—Enstatite,

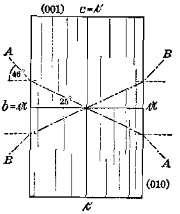


Fig. 292.—Hypersthene,

Section Parallel (100).

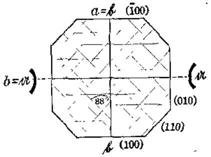


Fig. 293.—Enstatite and Hypersthene,

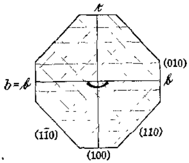


Fig. 294.—Diallage,

Cross section.

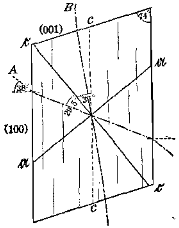


Fig. 295.—Diopside (Diallage),

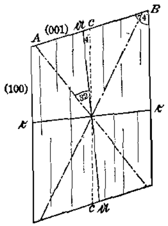


Fig. 296.—Aegirine,

Section Parallel Plane of Symmetry.

characterizes the monoclinic pyroxenes with the exception of those rich in sodium. They are further distinguished from the orthorhombic members by a much higher double refraction and by pleochroism, which is particularly typical for orthorhombic pyroxenes. It is also noteworthy that, unlike the amphibole group, the double refraction increases with the content of sodium. The pyroxenes can be isolated quite easily from rocks by hydrofluoric acid because they are very slowly attacked by it. One of the most important means for determining all pyroxenes is the very good cleavage parallel to the prism forming an angle of approximately 90°. This distinguishes them from the amphiboles with a more perfect prismatic cleavage forming an obtuse angle.

### (a) Orthorhombic Pyroxenes

Enstatite and bronzite are low in iron and may show various shades of brown macroscopically. Hypersthene is high in iron and is black. They form large irregular individuals in the granular rocks of the gabbro-peridotite series and in the olivine fels inclusions in basalt, but hypersthene is not so common as the others. They show very perfect cleavage parallel to the macropinacoid, but always in displaced cracks, and generally have a metallic shimmer caused by parallel orientated inclusions of brown tabular crystals and laths (ilmenite?). This passes over into golden yellow upon beginning alteration into serpentine—*bastite*. Macroscopically, they are generally various shades of brown, but in thin section only those members rich in iron are colored, and then they show characteristic pleochroism, but no distinct difference in the intensity of the colors. Very frequently an indistinct twinning lamination occurs, which passes over into the formation of fine fibers. Likewise lamellar intergrowths with diallage can be distinctly discerned even in sections showing parallel extinction, because of the different optical orientation of orthorhombic and monoclinic pyroxenes.

Well developed crystals, invisible macroscopically, are widely disseminated in porphyrites and andesites, and in these hypersthene generally predominates. The crystals are short prismatic with rounded pyramidal ends and in the vertical zone they are principally bounded by the end faces, Fig. 293. They are often rich in inclusions of light colored glass or slag. In these the cleavage is only prismatic and pleochroism becomes a characteristic property. Parallel intergrowths with monoclinic pyroxenes are found in which the latter form a shell around a center of the orthorhombic variety. Glass inclusions and the rounding of the edges are frequent, but orientated inclusions and fibrous structure are lacking. A second generation of hypersthene in microlitic development is observed now and then in the ground mass of andesitic rocks.

Alteration is comparatively frequent, especially that into serpentine which affects the orthorhombic pyroxenes, particularly when they occur as constituents of serpentinized olivine rocks. An analogous alteration is also observed in the crystals in porphyries. A parallel, scaly aggregate of antigorite is formed progressing from the transverse cracks outward, and the faces, parallel to which antigorite possesses perfect cleavage, lie parallel to the macropinacoid of the pyroxene. Cleavage plates of the pseudomorphs—bastite—thus formed, are perpendicular to the acute bisectrix and the optic angle varies as is characteristic for serpentine. The names *diaclasite*, *protobastite*, etc., refer to masses of serpentine with pyroxene which is still fresh. Hornblende is formed now and then at the expense of orthorhombic pyroxene in granular rocks.

Aside from the parallel extinction, orthorhombic pyroxenes are distinguished from the monoclinic members by a much lower double refraction and from aegirine by the positive character of the principal zone. They are distinguished from andalusite, olivine, etc., by a more distinct development of the cleavage and by the character of the principal zone, which is positive in orthorhombic pyroxenes, negative in andalusite, and variable in olivine.

### (b) Monoclinic Pyroxenes

Monoclinic pyroxenes, free from sesquioxides, are called diopside normally. It is one of the most characteristic minerals in contact rocks rich in lime and occurs in short prisms or grains, which are macroscopically light grayish-green or less often sap-green. It is found in eclogites, as *omphazite* containing a little aluminium and in certain peridotites as *chrome diopside* containing chromium. It is sometimes blackish-green in *hedenbergite* rich in iron, which occurs only in the silicate aggregates known as *skarn*. The mineral is generally colorless in thin section, but may show a pale greenish tinge. The deeper colored varieties are also green under the microscope and hedenbergite is deep green, but shows no pleochroism. The presence of pleochroism, except in the case of fassaite, seems to be connected with the presence of alkali silicates.

Pyroxene similar to diopside is found in acid eruptive rocks from granite to diorite—*malacolite*—and especially in the basic differentiation products from minette to kersantite. In certain varieties of trap, a diopside occurs along with common augite, described below, but it is distinguished by a high content of magnesia—*salite*. A very small optic angle is observed in these occurrences.

In general they form short prismatic crystals, Fig. 297, or tabular crystals parallel to the orthopinacoid, Fig. 298. The cleavage shows quite distinctly in thin section. They are more or less crystallographically bounded even where the common augite forms the interstitial material. The form of the pyroxenes in the extrusive rocks of the acid and intermediate series is quite similar to the above. Pyroxenes are found as phenocrysts especially in andesites. Diallage includes those varieties which are distinguished from diopside by a low content of alumina. It shows basal parting macroscopically as well as parting parallel to the orthopinacoid, and also twinning laminations parallel to it. It has a metallic chatoyancy and the individuals, which occur particularly in gabbro and peridotite, are quite distinctly visible macroscopically. Under the microscope it is often somewhat pleochroic and aside from its occasional fibrous properties, is marked by the regular arrangement of small, brown, tabular inclusions, mentioned under bronzite. It is not to be considered as an independent mineral species.

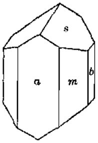


FIG. 297.—Augite, Short Prismatic.

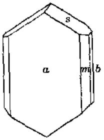


FIG. 298.—Augite, Tabular Parallel (100).

*Fassaite*, which is chemically quite closely related to diallage, plays a peculiar rôle. It is found principally as a constituent of contact rocks, but is also quite important in monzonites. It corresponds to aegirine, described below, in its optical properties, especially in the pleochroism and strong inclined dispersion, but differs greatly in chemical constitution. The sharp pyramidal habit exhibited by the crystals in an extraordinary manner is distinctive for it.

There is a series of gradual transition members from diopside to common or basaltic augite, the latter being characterized by a higher content of alumina. The mineral is always black macroscopically, but under the microscope it generally has only a very pale, brownish tint and is not normally pleochroic. Common augite is disseminated first of all in the basic eruptive rocks, and in porphyric rocks it often occurs in two generations and the first of these often forms phenocrysts of considerable size. The occurrence of diabase augite as interstitial material, Fig. 299, is especially distinctive. The formation of twins is quite common in common augite, especially in the form of isolated lamellæ. Juxtaposition and penetration twins are also found and the hourglass structure, which is frequently observed, is also looked upon as complicated twinning. The twinning lamellæ are arranged parallel to $\{100\}$ and, therefore, in a pyramidal section they lie oblique to the cleavage parallel to the prism faces, Fig. 300. Many kinds of forms of growth, crystal skeletons, etc., are found in glassy eruptive rocks.

FIG. 299.—Augite as Interstitial Material. Diabase. Arran, Scotland.

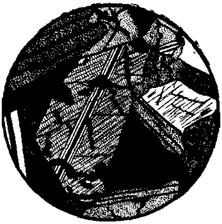


FIG. 300.—Simple Twinning Lamellæ in Augite.

A very large extinction angle is a characteristic of this augite and it shows particularly in comparison with the hornblende, which occurs as a border around such augite. If the small content of titanium, which is usually present, increases a distinct violet color generally appears in thin section. Such titanium augites are somewhat pleochroic. The ray vibrating parallel to *b* is colored deep violet. Sections with the most oblique extinction show the least pleochroism. Locally, reddish to brownish-red colors are observed, and these can be referred to a content of manganese. However, some occurrences of greenish or brownish augites assume that color when roasted in air. The color of augite is rarely yellow.

Alteration in diopside and augite is very widespread. In the first case the decomposition gives rise to fibrous scaly aggregates, which are generally considered to be serpentine, but which scarcely belong to it. Augites rich in aluminium are generally changed to chlorite. Low doubly refracting aggregates of it are congregated on the borders and in cleavage cracks of the individuals, and give rise to the formation of the greenstone facies of augite rocks. They are usually penetrated by grains of epidote and calcite, and frequently also by small needles of hornblende. They inclnde small individnals of titanite, anatase, and opaque ores. It is noteworthy that this alteration is everywhere accompanied by the formation of pyrite. Sometimes an aggregate of quartz with carbonates and rust occurs instead of the green minerals in a rock that is entirely decomposed and changed to *wacke*. This kind of alteration appears in its entire distribution to be a direct antithesis to the first.

*Uralite* is an especially interesting pseudomorph. It is generally green, but sometimes bluish hornblende in the form of augite. It was generally considered as a product of paramorphism, but it is a typical product of pneumatolytic hydatogenic activity in which anhydrous augite passes over into hornblende containing an hydroxyl. This is frequently accompanied by an intensive alteration of its entire composition. In porphyric rocks—*uralite porphyrite*—the form of the augite is perfectly retained and the formation of fibrous hornblende attacks the whole crystal without change of form. In granular rocks on the other hand, e.g., in uralite gabbro, the newly developed hornblende grows like brushes spreading out over the crystals so that uralitization, which frequently goes hand in hand with saussuritization, entirely obscures the structure of the rock.

Although the alteration first mentioned is interpreted as weathering, *the latter type is a typical result of dynamometamorphism*, see Allgemeine Gesteinskunde page 151. Recrystallization from magmatic waters may be the cause, and it cannot be doubted in the alteration to *seladonite* where an augite rock free from potassium is transformed into a green silicate rich in potassium. This occurs in a very characteristic manner in the melaphyres of the Fassatal.

*Augite is itself not rare as a secondary product, and forms* the principal constituent of resorbed residues of hornblende or mica in extrusive rocks. It is a typical product of crystallization from a magma after its extrusion upon the surface and the dark minerals formed during the intratelluric period of the magma are aggregates of augite grains mixed with opaque ores.

Diopside is often uncommonly plastic when subjected to orogenic pressure, and its prismatic individuals are frequently greatly bent. Augite and diallage are more inclined to the development of cataclastic structure, which strangely enough occurs just as perfectly developed in young eruptive rocks, which have not suffered any kind of deformation, and is therefore a protoclase.

*The members of the series containing sodium, leading from* augite or diopside to aegirine, are confined to the soda rocks, and are characterized as a whole by distinct pleochroism, which in the normal occurrences alternates between yellow and green shades, and is deeper green the richer they are in sodium. If they contain titanium, as is frequently the case in basalts, they show a violet color principally in the direction of $\mathfrak{b}$. The titanium augites containing sodium are strongly pleochroic and the hourglass structure, mentioned on page 188, is especially conspicuous in them. The members containing sodium, as a whole, frequently show fine zonal development in which the very narrow zones alternate with each other in an extremely regular manner. *Sometimes a more or less intensely corroded and irregular grain* is surrounded by shells, which are crystallographically well defined. In the soda rocks it may be observed that in the poorly bounded pyroxenes, which are frequently tabular parallel to the front pinacoid, the core is almost colorless, non-pleochroic, and is manifestly closely related to diopside. Toward the border it passes into aegirine augite and finally the outer zone is aegirine. Intergrowths with hornblende are not at all rare but then, unlike the augite, hornblende containing sodium is in the center and the pyroxene grows around it.

With reference to extinction the monoclinic pyroxenes differ from each other in a distinctive manner. From diopside to common augite, and from this to aegirine, the angle between the positive bisectrix and the vertical axis becomes constantly greater, Fig. 301.

The soda pyroxenes show crystal form particularly in the porphyric rocks in which they occur in two generations. The large phenocrysts often show tabular development parallel to {100} while the second generation is always richer in sodium and is fine acicular showing a radial development. In other cases, the latter type forms short irregular specks, which are often so intergrown with small nepheline crystals that they are scarcely transparent. The *soda pyroxenes, especially acmite,* which is generally spear-shaped, show extremely irregular forms, but not to the same degree as the corresponding amphiboles. Manifold crystal skeltons are found in glassy rocks. It cannot be positively determined whether the forms of growth illustrated on page 188 are aegirine or hornblende.

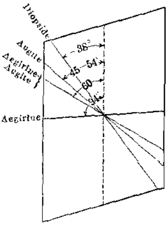


Fig. 301.—Extinction of Monoclinic Pyroxenes.

Sodium augite and the titanium augites, belonging to it, are characterized by a strong inclined dispersion, as a result of which sections parallel to the plane of symmetry give an extremely incomplete extinction, and in sections perpendicular to the optic axis very brilliant anomalous interference colors are seen. The *difference in this respect from diopside is notable.* It has a very small dispersion and, therefore, its extinction in the plane of symmetry is very complete. Alteration of the soda pyroxenes is rare. Sometimes aggregations of opaque ores, which are difficultly determinable, occur in place of them in entirely decomposed keratophyres.

Although in general a regular relationship between the optical properties and the chemical composition of monoclinic pyroxenes cannot be denied, yet investigations to determine the chemical composition merely from the optical properties lead to rather negative results. Minerals of the aegirine-augite series, which are designated as *fedorowite* or *violaite,* are in a way not to be considered as an independent species, but chemical analysis shows great deviations from what would be expected from the optical properties. The pyroxene group is built up in too complicated a manner in contradistinction to the plagioclase group, in which such conclusions appear to be well justified.

Colorless pyroxenes are most frequently confused with olivine or epidote, but are distinguished from both by the position of the optical plane with respect to the zone of cleavage. The colored members are sometimes very similar to common hornblende and, if the depth of color is the same in each, the absorption of the latter in the principal zone is stronger. The extinction is less with the exception of aegirine, which can be recognized however by its sap green color, higher double refraction, and the negative character of the principal zone. Under certain circumstances, the cleavage angle of pyroxene approximates that of hornblende in oblique sections. If these sections have parallel extinction the optic plane lies in the bisector of the acute cleavage angle in pyroxene and, in general, in the bisector of the obtuse cleavage angle in hornblende.

Soda pyroxenes poor in iron or free from iron are comparatively rare as rock constituents. They are macroscopically white to green, but under the microscope generally colorless. *Jadeite* ($NaAlSi_2O_6$) belongs especially to this group. It occurs only in fine columnar masses with properties like saussurite, in the serpentine from Burmah, Turkestan, etc., but is widely known from the stone age when it was worked up. It is easily distinguished from the similar *nephrite* by its low fusibility. Further, *spodumene* must be mentioned. It occurs as a constituent of pegmatite in clear beautifully colored crystals, emerald green *hiddenite* and rose-red *kunzite*, and as a constituent of other rocks, of granites and injected schists, in poorly developed grayish-green needles, which are purely accessory.

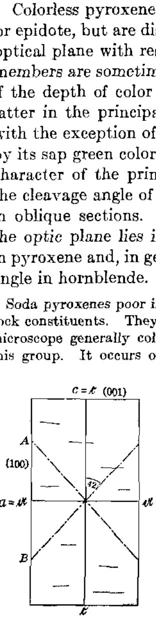


FIG. 302.—Lawsonite, Section Parallel (010).

### **Lawsonite** (10)

Lawsonite has been found as a constituent of certain eclogites. It forms large lobated particles in them without any characteristic microstructure. The mineral is also suspected in certain occurrences of saussurite, but the determination does not seem to be reliable because of the lack of characteristic properties of the mineral and its poor development, which all the minerals in saussurite show. In such aggregates confusion with hornblende or prehnite is natural, but it is distinguished from the other minerals of the aggregate by much stronger double refraction. Lawsonite is distinguished from hornblende by its constant parallel extinction and *the direction of the cleavage cracks in macropinacoidal sections and prehnite* is distinguished by the characteristic rosette arrangement in its cross sections. Stronger double refraction and positive character of the principal zone distinguish it from andalusite and the position of the optical plane parallel to the cleavage from wollastonite, while the distribution distinguishes it from both.

## **Amphibole Group** (11)

The minerals of the amphibole group have a very perfect cleavage parallel to the prism making an angle of about 124°. They always show a *prismatic development*, Fig. 303, but may be short, thick forms like the crystals of pargasite or basaltic hornblende, or the grains of common hornblende. They may be long, needle-like and fibrous, as is often the case in the light green hornblendes of green schists and the secondary aggregates in diabase. The crystal form is nearly always observed in the principal zone and consists of the prism and clinopinacoid. The amphiboles have a tendency to show a defective development on the ends, when they occur as phenocrysts in porphyries. Compare with aegirine for the occurrence of very delicate crystal skeletons in certain pitchstones. Zonal structure and parallel growths of various members of the series are observed, although they are not numbered among the character-

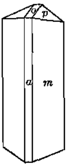


Fig. 303. Hornblende, Usual Combination.

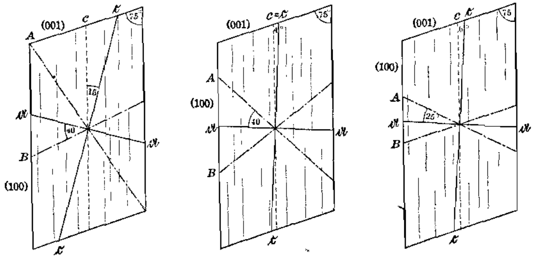


Fig. 304. Actinolite,

Fig. 305. Basaltic Hornblende,

Fig. 306. Glaucophane,

Section Parallel Plane of Symmetry.

istic features as is the case with the soda pyroxenes. See under pyroxenes for parallel growth with them.

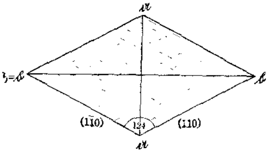


Fig. 307.—Cross Section of Hornblende.

Unlike the pyroxenes, with which they can be confused in color, index and double refraction, the amphiboles have a very small extinction angle of from 0° to 25° with the exception of the rare group of cataphorites. This is shown in Fig. 308 in which the relationship of $c: \mathfrak{c}$ is diagrammed for the most important members. This angle has a very small value in the amphiboles free from alkali, but in soda hornblende the angle $c:\mathfrak{a}$ is small. The minerals of the amphibole group are generally deep colored and show various colors even in thin section. With the exception mentioned above, the ray vibrating in the principal zone is most strongly absorbed. The plane of the optic axes is nearly always parallel to the plane of symmetry. Only in the case of blue hornblendes rich in sodium are these two planes perpendicular. The chemical composition of the minerals belonging in this group is quite variable and is in general analogous to that of the pyroxenes, but differs from them in the content of the hydroxyl, which is never absent. In consequence of this fact, the deep seated rocks are the ones which contain the hornblende, while augite takes its place in the extrusive rocks. It is further observed that hornblende is changed to augite by the action of heat, *magmatic resorption*, while hydrochemical processes have the opposite effect and form uralite. The specific gravity and indices of refraction are lower in hornblende than in the pyroxenes, which have an analogous composition, but the amphiboles are more strongly magnetic.

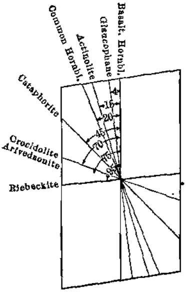


Fig. 308.—Extinction on Monoclinic Amphiboles.

**Pleochroic** halos with brown colors are common. They are also observed in uralite but not a trace of them can be found in the original pyroxene. The index and double refraction are higher in the halos.

The amphiboles are not difficultly fusible and those rich in sodium even belong to the most easily fusible minerals. Green hornblende turns brown upon roasting gently, and it assumes the absorption and optical orientation of basaltic hornblende.

*Anthophyllite* and *gedrite*, which are considered orthorhombic because of the parallel extinction, are found sporadically in amphibolites and are predominant in anthophyllite schist. They are also found in certain serpentines. They form flaky, columnar or tufted aggregates, and less often small acicular crystals. They possess a brownish color. Alteration into talc and serpentine is known.

Tremolite usually appears in fine radiating needles with white or pale greenish color. These occur in granular limestone and dolomite, or in serpentine. In the latter rock there are all possible transitions from tremolite to actinolite, which is always distinctly green macroscopically, and in thin section it is generally somewhat colored, but is scarcely pleochroic. Both types are sometimes found in larger prisms. The occurrence in serpentine, which is uncommonly widespread, especially in the microscopical development, must be looked upon as a secondary by-product in the formation of serpentine. Sometimes the transition from olivine direct to such aggregates of amphibole with spherulitic structure or that similar to snow crystals is observed—*pilite*. An analogous development also occurs in nephrite, which is usually light green, macroscopically, and consists of a dense mat of actinolite needles. It represents the toughest of all rocks. Its occurrence is also connected with serpentine. Poorly developed individuals of tremolite and actinolite are often bent by mechanical stresses and are crushed into isolated columns, which show a parquetry appearance in

FIG. 309.—Distorted Actinolite in Serpentine, Rifflkees, Stubachtal, Salzburg.

cross section, Fig. 309. It is most similar to the normal occurrence of prehnite and is distinguished by the obtuse angle of the fragments. These minerals also form fibrous individuals and pass over into asbestos.

Macroscopic varieties, with a sap green color, which are often extremely fine fibrous and generally contain some alumina and occur as pseudomorphs after diallage, are called *smaragdite*. In thin section it is colorless to light green and often shows the structure and inclusions of diallage quite distinctly.

Among the amphiboles free from alumina, grünerite $(FeMg)SiO_3$ *is remarkable because of its similarity to epidote.* $n=1.7$. $\gamma-\alpha=0.03$–$0.056$. $\mathfrak{a}=\mathfrak{b}$ colorless, $\mathfrak{c}$ light yellow. Sp. gr. $=3.3$. $c:\mathfrak{c}=15°$. $2E=95°$. Optically positive. Usually shows twinning lamination parallel to the orthopinacoid. Brownish *cummingtonite,* $(MgFe)SiO_3$, may also be mentioned. $\mathfrak{a}=\mathfrak{b}$ light yellow, $\mathfrak{c}$ light brownish. $c:\mathfrak{c}=15°$ and $\gamma-\alpha=0.022$. The petrographical importance of these is but little known.

*Edenite,* an *amphibole poor in iron and rich in alumina,* is macroscopically light green, but generally colorless in thin section. It cannot be distinguished from those already described. It is found in isolated, rounded and greatly corroded crystals with a short prismatic development in granular limestones and lime-silicate fels together with pargasite, which is richer in iron and is macroscopically darker, being green, or brown to black. It *forms the transition to common green hornblende rich in alumina* and ferrous iron. The latter appears blackish-green macroscopically. It is found in compact, rarely elongated, prismatic grains in the acid and intermediate rocks of the normal series, and shows well developed crystals in the porphyric forms of these. Very strong absorption is always distinctly observed, and isolated twinning lamellæ parallel to the orthopinacoid are not rare. *In contact rocks the cross sections of hornblende often* show a bluish-green color and transitions to *carinthine,* which is deep bluish-green in thin section, are observed especially in the sheaf-like aggregates of the Garbenschiefer. Hornblende showing a similar development is very widespread in amphibolites in which it sometimes forms short shreds and sometimes parallel columnar aggregates with frayed ends—*sedgy hornblende. The latter form of development is very similar to the* uralite pseudomorphs after augite found in numerous basic eruptive rocks. In such rocks the mineral is often very light colored and is developed in long needles. It is then very difficult to distinguish from similar occurrences of actinolite without making a thorough chemical investigation. The stronger absorption of the ray vibrating in the direction of elongation is nearly always distinctly observable in common hornblende. Green hornblende with such a development is, along with chlorite, the most frequent green pigment of schistose rocks.

A brownish-green variety of hornblende occurs in place of the green in porphyrites. The crystals are short prismatic and the ray vibrating parallel to *b* is very distinctly brownish. This passes over into pure brown varieties rich in ferric iron, which are lighter or deeper colored corresponding to the content of iron. The lightest colored varieties of common, brown hornblende are macroscopically brownish-black, and they replace the green entirely in deep seated basic rocks, e.g., in gabbro. When hornblende is primary in such rocks it belongs to the brown variety. Secondary processes analogous to the formation of uralite alter the brown, primary hornblende into secondary green, sedgy hornblende. Tonalite and certain granulites are the principal acid rocks which contain brown hornblende. It is also found as phenocrysts in numerous porphyric rocks and is especially characteristic for certain lamprophyres in which small needles of brown hornblende are the principal constituent of the ground mass. They are always replaced by augite in the ground mass of extrusive rocks.

If titanium dioxide also occurs in varieties rich in iron, the mineral is macroscopically jet black and has a pitchy luster. The cleavage faces are exceptionally brilliant and in thin section the absorption in the principal zone is more complete, while the extinction diminishes to 0°. This series is designated as *basaltic* hornblende and contains up to 5 per cent. $TiO_2$. It is widespread in numerous extrusive rocks in which the crystals are long or short prismatic, and are well developed. They are frequently zonal with a light center and darker borders. They show twinning parallel to the orthopinacoid most frequently and this sometimes appears as isolated lamellæ or as two equal parts of twins. The indices and double refraction are considerably higher than that of the other amphiboles. On the border it often shows a zone with stronger absorption. It has resulted from the action of the magma on the mineral after it was formed—magmatic border. This leads to magmatic resorption in which pseudomorphs of augite and magnetite after hornblende are formed. Finally even the form is destroyed. Thus, in the tuffs, large crystals of basaltic hornblende are present but in the extrusive rocks specks very rich in iron are found as a residue from them. The varieties richest in titanium, 6-7 per cent. $TiO_2$, are called *Kärsutite.*

Amphiboles containing aluminium and ferric oxide suffer the same alterations as common augite, but not to the same extent. A distinction is made between chloritization, which is always accompanied by the formation of epidote, carbonates, and titanium minerals, and the alteration into quartz, carbonates, and rust. Amphiboles, like the pyroxenes, are resistive to acids. All green members assume a brown color and stronger absorption when heated in air. Those members richer in iron show the optical properties of basaltic hornblende after roasting.

There are many members of the amphibole group that are rich in sodium. Two groups may be distinguished. The one is poor in ferric iron and rich in alumina and occurs chiefly in contact rocks, especially in eclogites. The other is rich in ferric iron and is distributed principally in the rocks of the soda series.

There are transition members from common, green hornblende to carinthine, which is macroscopically bluish-black, and in thin section is deeply colored. The bluish-green color of the ray vibrating in the direction of elongation is characteristic for it. It passes over into *glaucophane* or *gastaldite,* which is a very delicate blue in thin section. The latter minerals are characteristic constituents of eclogites and rocks embedded in them. The columnar individuals with a dark violet blue color are often macroscopically visible. They are best recognized in thin section by the blue color and the splendid pleochroism. Zonal structure is found in them and some of the zones may have a very low double refraction. It is not uncommon to see the center entirely colorless with a low double refraction and small extinction, and surrounded by a brilliant blue envelope. *Crocidolite,* which is externally not unlike glaucophane, but is always fibrous and richer in iron, often occurs as a secondary development in crevices in amphibolites and related rocks. It is distinguished by a comparatively high double refraction. It has a larger extinction angle than the other soda hornblendes rich in iron, and the character of the principal zone is different. The ray vibrating in the principal zone is the most strongly absorbed, as is the case in nearly the whole hornblende group. It is remarkable that the same phenomena are seen in crossite and in the other soda hornblendes in which the optical plane is transverse to the plane of symmetry, and the optic normal forms an angle of 25° or less with the vertical axis. Even in this case the principal zone absorbs the rays most strongly.

Another series branches off from the basaltic hornblende. It consists of soda amphiboles rich in ferric iron. *Barkevikite,* which stands next to it, is quite rich in titanium. It is brown and can only be distinguished by the larger extinction, $c:\mathfrak{c}=$about 14°. It is found especially in nepheline syenites. A characteristic series of amphibole minerals, *cataphorite,* seems to be related to barkevikite. They are rarer, have larger extinction, $c:\mathfrak{c}=30\text{–}60°$, and a peculiar reddish color. They are distinguished from all the other amphiboles by strong absorption transverse to the principal zone, $\mathfrak{b}$ deep brownish-red to violet, $\mathfrak{c}$ yellowish-green, $\mathfrak{a}$ reddish-yellow, $\mathfrak{b}>\mathfrak{c}>\mathfrak{a}$. Cataphorite is very frequently surrounded by *arfvedsonite,* which is free from titanium and distinguished by a bluish-green color. Like the amphiboles free from sodium, it shows strong absorption in the principal zone, but this corresponds to the direction $\mathfrak{a}$. Arfvedsonite is likewise a widespread constituent of soda rocks and is often surrounded by a border of aegirine.

Pure sodium iron silicate, *riebeckite,* occurs particularly in soda granites. The absorption in the principal zone is almost complete even in very thin sections. It forms irregular shreds that look quite like tourmaline, and were formerly determined as such. Aside from the cleavage, it is distinguished by the fact that it absorbs the light in a different direction, i.e., riebeckite has stronger absorption in the principal zone. Alteration of this amphibole, like that of the pyroxenes, leads to the formation of blurred specks rich in opaque ores.

Anthophyllite, tremolite, and edenite, as well as very weakly double refracting occurrences of glaucophane, are generally colorless in thin section. Actinolite, pargasite, and common green hornblende are green; carinthine and arfvedsonite are bluish-green; glaucophane, crocidolite, crossite, and riebeckite are blue; grünerite and cummingtonite are yellowish; common brown hornblende, basaltic hornblende, and barkevikite are brown, while cataphorite is reddish to violet.

The extinction angle is as follows, Fig 308, page 288; $c:\mathfrak{c}$ for anthophyllite and gedrite 0°; basaltic hornblende 0–10°; glaucophane 4–6°; barkevikite and brown hornblende 12–14°; actinolite, pargasite 15–18°; green hornblende 20—25°; cataphorite 30–60°; crocidolite 65–70°; arfvedsonite and crossite 76°; riebeckite 85–86°. Unlike the pyroxenes the double refraction and the strong dispersion of the optic axes decrease in those members rich in ferric iron and sodium.

The extraordinarily manifold properties of the minerals of the amphibole group give rise to numerous confusions especially with the pyroxenes. Aside from the difference in the cleavage angle, by which they can be distinguished in basal sections, they vary also in other properties. The pyroxenes have larger extinction, and when they are deeply colored, show less absorption than the amphiboles. Tremolite is similar to sillimanite, but the latter has parallel extinction in all sections, a very small optic angle, and simple cleavage in one direction transverse to the principal zone. It is also similar to wollastonite and epidote in which the optical plane is perpendicular to the principal zone, to diaspore which has a negative principal zone, to cyanite which is distinguished by the acute bisectrix being perpendicular to the cleavage, and to lawsonite which always shows parallel extinction and becomes cloudy upon heating and fuses quite easily. Cleavage plates of the latter are parallel to the optical plane. Green hornblende is quite like tourmaline, but the latter has a stronger absorption perpendicular to the principal zone. It also resembles chlorite, which has much lower indices and double refraction, and chloritoid in which the optical plane lies transverse to the principal zone. Brown hornblende frequently resembles tourmaline; also orthite, staurolite, and acmite, but the last three are characterized by higher indices of refraction and weaker absorption. It is also like biotite which has lower indices of refraction, and also has the optical plane transverse to the principal zone and the interference figure is nearly uniaxial and appears symmetrical in cleavage plates. Blue hornblende is also often confused with tourmaline, and in rare instances it is similar to chloritoid.

Triclinic *aenigmatite*, or *cossyrite*, is included in the amphibole group but does not really belong to it. It forms prismatic crystals and grains showing twinning laminations parallel to the brachypinacoid. It has a less perfect cleavage parallel to the prism making an angle of 114°. It occurs in eruptive rocks rich in sodium. Minute individuals are found in the ground mass of basalts and are formed here by refusion of basaltic hornblende. Hardness is 5.5 and sp. gr. 3.8. The axial plane is nearly parallel to the brachypinacoid, and on it c:𝔠 is 45° f*. On the macropinacoid it is 4°, 2E = 60°; positive; 𝔠 blackish-brown or almost opaque, 𝔟 deep brown, 𝔞 lighter reddish-brown; very high indices of refraction. Aenigmatite is attacked by hot hydrochloric acid and fuses easily, forming a black glass. It is similar to lievrite in both these properties, but is more transparent.

### Dumortierite (11)

*Dumortierite is found in pegmatites and occurs also as minute needles or tufts in certain contact rocks. The needles are recognized by their* intense color and strong pleochroism. It forms penetration twins according to the aragonite law. It is surrounded by a pleochroic halo when it is included in cordierite. It gives an opalescent bead with microcosmic salt. Stronger absorption in the principal zone distinguishes it from piemontite and tourmaline, and the direction of the cleavage in basal sections differentiates it from hornblende. It is decolorized by heating, whereas hornblende becomes brown and fuses. Its distribution has as yet not been investigated to any great extent.

### Axinite (12)

Axinite is a rare product of contact metamorphism or of pneumatolytic activity, especially in coarse-grained dikes occurring in granite—*limurite.* If it has crystal form the cross sections are wedge-shaped. If crystal form is lacking, it is very easily overlooked because it possesses few characteristic properties. Color and pleochroism are generally very delicate. It can be easily isolated and then it gives the greenish boron flame upon fusing.

### Rinkite (12)

Rinkite is found as an accessory mineral in various soda rocks, especially in nepheline syenite, and is associated with other rare minerals such as mosandrite, låvenite, etc., and is generally penetrated by fluorite. It is rapidly decomposed by hydrochloric acid even in a slide, and silica containing titanium separates out. It fuses easily with intumescence and gives off fluorine. The positive bisectrix is nearly perpendicular to the cleavage plates, this being the best property to use for its determination. It is often transformed into yellowish, clouded aggregates.

### Sillimanite (12)

Sillimanite forms colorless needles without terminations, and these are often finely shredded and have a silky luster macroscopically. Radial aggregates, that are only transparent in thin section, are called *fibrolite.* It is found in contact rocks in helicoidal bands wound in various ways and penetrating through

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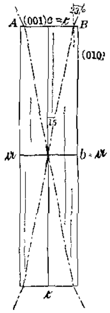
* f. = front.

the other constituents of the rocks. Elongated sections are narrow lath-shaped *and often bent, or fractured transversely.* Basal sections only show good forms where the individuals are isolated. They are then extremely characteristic, Fig. 311. It is disseminated principally in contact rocks rich in aluminium, in certain gneisses, and as isolated needles in granite. Alteration is not known.



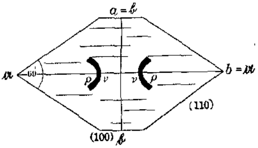


FIG. 310. FIG. 311.

*Sillimanite*, Section
Parallel (100). Parallel (001).

Concerning the microscopic distinction from apatite or tremolite, see those minerals. The positive character of the principal zone distinguishes it from andalusite and prismatine, parallel extinction from chloritoid, as also the position of the optical plane parallel to the cleavage, *and the absence of twinning laminations.*

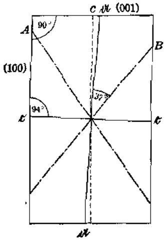


FIG. 312.—Datolite, Section Parallel Plane of Symmetry.

**Datolite** (12)

Datolite is only known as a secondary formation, chiefly in cavities in basic eruptive rocks. Its distribution as a rock constituent has not been investigated, but it may occur in certain contact rocks. It forms granular or *fibrous aggregates parallel to the b axis—botryolite.* In the latter the axial plane lies *transverse to the fibers. It fuses* before the blowpipe to a clear glass and colors the flame green. The powder has a strong alkaline reaction even before fusing. Datolite is best determined by separating it from the rock powder with heavy liquids, *its specific gravity being 2.9,* and then treating it with hydrochloric acid. Alcohol is then poured upon the residue and if datolite was present it will burn with a greenish flame.

### **Mosandrite** (12)

Mosandrite is found as an accessory constituent in nepheline syenite in small tabular crystals associated with rinkite, etc., and penetrated by fluorite. It is brittle and, therefore, generally checked. Lath-shaped cross sections show twinning laminations. The mineral is often changed into earthy brown to opaque aggregates. *Johnstrupite* is very similar to it but has lower indices of refraction. Mosandrite is easily fusible and forms a light colored bead. It gives a dark red solution with hydrochloric acid and evolves chlorine. Strong inclined dispersion of the axes in cleavage plates distinguishes it from rinkite.

### **Barite** (Heavy Spar) (12)

Barite forms granular or platy, rarely fibrous, aggregates without distinct borders. They occur now and then filling crevices and cavities in rocks, as cement in sandstone, and particularly as concretions in marl and sand. These concretions are frequently filled with inclusions of sand, etc., and consist of imperfect, tabular crystals arranged in rosettes. If it forms the predominant cement of a rock, it is recognized by the great weight of the same. Cleavage plates of the mineral are perpendicular to the negative obtuse bisectrix. If it occurs in subordinate amounts, it is easily overlooked. Its distribution as a rock constituent is, therefore, not accurately known. Aside from a different flame reaction, it is distinguished from celestite by a comparatively small optic angle and from quartz, feldspar, and similar colorless rock constituents by higher indices of refraction and insolubility in hydrofluoric acid.

## **Andalusite** (12)

Andalusite is generally found in short, prismatic, rounded crystals in which very frequently the cleavage cannot be recognized. The individuals tend to arrange themselves in divergent radial groups or fingered aggregates. It is colorless in thin section or speckled with a pale reddish color, and is then pleochroic. It is found now and then in parallel intergrowths with sillimanite. The arrangement of graphite inclusions is especially characteristic—*chiastolite*, Figs. 313 and 314, also Fig. 211, page 196.

Andalusite is very frequently altered to a compact aggregate of mica, but these pseudomorphs can be recognized by the arrangement of the graphite inclusions. If this arrangement becomes more and more irregular and the outer form quite imperfect, these elongated mica aggregates filled with graphite dust are extremely difficult to determine. They are widely distributed in contact rocks and form a large part of the knots that appear macroscopically in such rocks. In most favorable cases a few unaltered, but corroded residues point to the original andalusite. Its chief distribution is in contact rocks rich in aluminium. Andalusite is the lightest of the three modifications of aluminium silicate. It is, therefore, absent in rocks which have been formed under high pressure, especially in the contact rocks of the Central Alps.

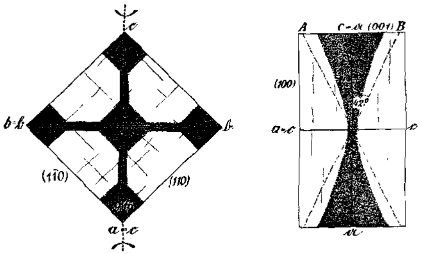


FIG. 313. FIG. 314.

Andalusite, Section Parallel to

(001) (010)

The negative character of the principal zone affords a distinction of colorless andalusite from sillimanite, and the lower double refraction together with the orthorhombic properties of all sections distinguishes it from diopside. Red andalusite may appear similar to hypersthene but they have opposite characters of the principal zone. It may also be confused with piemontite in which the optical plane lies transverse to the cleavage.

### Lazulite (12)

The petrographical importance of lazulite has been very little investigated. Good crystals of it have been found in quartz veins in phyllites and in impregnations in granular limestone—*bluespar*. High double refraction, absence of cleavage, and its pyramidal form distinguish it from other blue minerals.

### Carpholite (12)

Carpholite is known as a fibrous, secondary formation in crevices in altered rocks. Weaker absorption in the principal zone distinguishes it from most other yellowish minerals except tourmaline, which is uniaxial, and epidote in which the optical plane lies transverse to the cleavage.

### Prehnite (12)

Prehnite belongs to those minerals whose petrographical importance is but little known. It is found in radial, flaky aggregates in cavities in eruptive rocks, or in compact aggregates as a constituent of saussurite,—*lotrite*. It is also quite widespread as an alteration product of feldspar. No other mineral shows such variable properties as prehnite, and it can only be identified by the rosette structure in thin sections, which is extremely characteristic. Double refraction, normal and anomalous interference colors, position of the optical plane, size of the optic angle, and the lattice structure vary in the different occurrences, so that even though the mineral can be determined macroscopically it presents many difficulties under the microscope.

### Celestite (12)

Celestite is analogous to barite as a rock-forming mineral, except that it rarely forms individuals so rich in inclusions. See under barite for its distinction from that and other similar minerals.

### Aragonite (13)

Aragonite is a rare constituent of rocks, but it occurs in columnar aggregates which are very difficult to distinguish from fibrous calcite. The principal characteristics by which it can be determined when accurate observation of the interference figure is not possible, are the lack of cleavage and the special reaction with cobalt solution, page 175. It is probably quite widespread as an original constituent of rocks, but it has been very extensively transformed into calcite. Aragonite itself is found only in secondary deposits from hot springs, particularly as *onyx*.

### Wollastonite Group (13)

Wollastonite forms columnar to flaky individuals in which the axis of symmetry is the axis of elongation. Cross sections parallel to it are lath-shaped, and those perpendicular to it are somewhat elongated along the orthopinacoid and are bounded by from six to eight faces. The cleavage cracks are all parallel to the axis of symmetry, and in transverse sections two systems of very perfect cleavage cracks nearly at right angles are seen along with another set that is less distinct, Fig. 315. Twinning parallel to the orthopinacoid is very common. It is recognized in transverse sections by the extinction. Wollastonite is chiefly characteristic for granular limestone. In feldspar-bearing rocks it is only found in the neighborhood of such formations. When it occurs in eruptive rocks, it is probably the result of resorbed lime inclusions or it may form pseudomorphs after anorthite. *The moistened powder gives an alkaline reaction. It fuses* before the blowpipe to a crystalline slag. The ease with which it is attacked by hydrochloric acid distinguishes it from numerous other minerals with which it might be confused if the cross sections are poorly developed. The mineral is always colorless but is well characterized by the position of the optical plane transverse *to the cleavage in sections showing parallel* extinction, the comparatively small optic angle with distinct inclined dispersion, and other optical and chemical properties. The lower indices of refraction and the solubility distinguish it from epidote minerals which are similarly orientated.

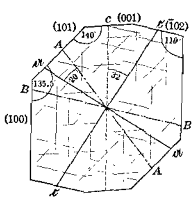


Fig. 315.—Wollastonite, Section Parallel Plane of Symmetry.

*Pectolite* is related to wollastonite. It occurs in fibrous, radial aggregates as a *secondary formation in crevices of eruptive* rocks rich in lime and in amphibolites derived from them, and now and then as an alteration product of feldspar in soda rocks. It is distinguished from wollastonite by the orientation of the optical plane parallel to the positive principal zone and the higher double refraction. Cleavage plates are almost perpendicular to the obtuse bisectrix.

*Rosenbuschite is still rarer. It forms colorless to yellowish, radial, fibrous* aggregates in nepheline syenites. In it the optical plane is parallel to the principal zone which is negative. It is characteristically accompanied by fluorite. It is distinguished from similar minerals by the negative character *of the principal zone and by its solubility.*

## Humite Group (13)

The minerals of the humite group cannot be distinguished from one another macroscopically and frequently also microscopically. They are found mostly in contact limestones or dolomites in rounded grains in which the cleavage is very poorly developed. They often show irregular cracks. Twinning lamination parallel to the basal pinacoid is common in chondrodite and clinohumite. If the humites are colorless, they are very similar *to olivine from which they can only be distinguished by the extremely* low dispersion and by the position of the optical plane, which is parallel to the cleavage in humite. The direction of extinction in the monoclinic members, showing cleavage cracks or twinning lamination also serves to distinguish them from olivine. See under olivine for the distinction between colored varieties and titanium olivine. The humites often pass over into serpentine with the formation of the mesh structure. Brucite also results from such alterations. They become white, but do not fuse before the blowpipe.

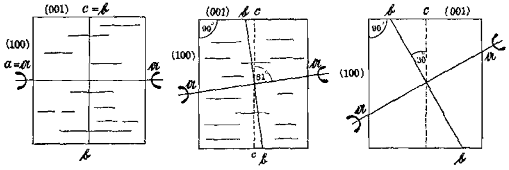


Fig. 316.—Humite, Fig. 317.—Clinohumite, Fig. 318.—Chondrodite,
Section Parallel (010).

## *Topaz* (13)

Topaz forms short, prismatic crystals and grains which show perfect cleavage in the elongated sections by the presence of a few very sharp cracks. Cleavage plates are perpendicular to the acute, positive bisectrix. The optic angle is generally quite large, but is variable. The mineral is also found in columnar or radial aggregates—*pycnite*—where it has been formed from other minerals by the activity of fumaroles, as in the topaz quartz porphyries, occurring in connection with tin ore veins. In these the character of the principal zone is positive. The mineral is known in the associated granites as a primary constituent, but otherwise it is always secondary and points to very intensive post-volcanic processes.

Topaz is always colorless in thin section and is distinguished from quartz by higher relief. Distinction from sillimanite may be very difficult, but the latter is characterized by higher indices and double refraction, and by the cleavage parallel to the principal zone. Topaz can be easily isolated from a rock on account of its high specific gravity and resistance to acids. It is infusible before the blowpipe, but turns white and at the same time flakes up.

## **Anhydrite** (14)

Anhydrite itself forms a rock consisting of granular, or less often columnar aggregates, that change easily into gypsum. It is often colored blue or red, macroscopically, but in thin section it is always colorless and has three cleavages differently developed. Its solubility in water is characteristic, and gypsum crystallizes out upon evaporation. It is very similar to muscovite in thin section but the latter has but one distinct cleavage. The mineral is confined to sedimentary rocks and is often found in very coarse-grained aggregates in the crevices of such rocks.

### **Mica Group** (14)

A very large series of minerals is characterized by an exceptionally perfect cleavage in one direction, so that they have a flaky or scaly appearance. The outer form of the small plates is almost without exception hexagonal. A table of the members of this group, that are important in rocks, can be found on page 270. The mica group is the most important of these.

The members of the mica group, which are important in rocks, are potassium mica—*muscovite*, magnesium micas—*phlogopite* and *biotite*, and the lithium micas, which are classed together under the name *lithionite*. The determination of the crystal system of mica is generally not possible by optical methods. Most of them show parallel extinction although they are monoclinic, and apparently uniaxial varieties are very common. If an optic angle can be determined distinctly, it may be observed that the negative, acute bisectrix coincides almost exactly with the vertical axis, while in the uniaxial varieties this is the direction of the optic axis.

Cleavage plates of mica are perpendicular or almost perpendicular to the acute, negative bisectrix. The true optic angle is small to medium large, from approximately 0° in most magnesium micas to 30–40° in normal muscovite, but rarely larger. In convergent light, therefore, the optic axes appear symmetrically within the field of vision. Transverse sections give brilliant interference colors in consequence of the high double refraction, and they extinguish almost exactly parallel to the numerous, sharp cleavage cracks. When such sections are colored, they are distinctly pleochroic. Basal sections are entirely different, making it difficult for the beginner to determine it. This variation aids the experienced observer, however, to recognize it. Such sections are either entirely dark between crossed nicols, or they show low interference colors corresponding to the small difference $\gamma-\beta$, which never exceeds 0.008. In addition to this, nothing is seen of the cleavage, and the colored members of the group are rarely pleochroic. However, in convergent polarized light a remarkably distinct interference figure is always obtained.

The optical plane sometimes lies perpendicular to the plane of symmetry—mica of the *first order*, Fig. 319, and sometimes in the plane of symmetry—mica of the *second order*, Fig. 320. Muscovite belongs to the first type and most of the biotites to the second. The orientation can be recognized by means of the percussion figure which is shown in the figures for all the minerals belonging in this group. Twinning is very widespread and generally parallel to the basal pinacoid. It is not often observed in transverse sections because of the parallel extinction, but it can be recognized in thick cleavage plates by means of the distorted interference figure. Micas are elastic and are perfectly flexible under the influence of orogenic stresses. They, therefore, occur in variously bent forms, Fig. 204, page 192. Now and then they are torn apart parallel to the gliding plane, which is transverse to the cleavage, and the alteration to chlorite proceeds outward preferably from such parting structures.

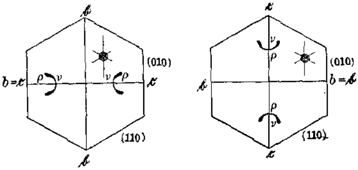


Fig. 319. Fig. 320.

Mica Orientated by Percussion Figure.
First Order. Second Order.

Colored micas always show great differences in absorption, and the browns possess this to a higher degree than the rarer greens. The rays vibrating in the cleavage plane are always the most strongly absorbed, and generally show no difference among themselves. For this reason cleavage plates are generally not pleochroic. Biotites with entirely anomalous properties occur in soda rocks, but they are very rare. Here, they have quite a large optic angle and quite an appreciable angle of extinction and also show a distinct difference in absorption between **𝔟** and **𝔠**.

In pleochroic halos, which are found in the micas in all rocks, the direction of the stronger, often complete absorption, is likewise parallel to the cleavage cracks. Indices of refraction and double refraction are higher in them.

The micas always contain the hydroxyl group. They are more widespread among the intrusive rocks than among the extrusive. In the latter they are often magmatically resorbed in a manner analogous to that described for hornblende. The specific gravity is high but they cannot be isolated by heavy liquids on account of their flaky development. See page 155 for a method of separating mica from other minerals. Members rich in iron are easily attracted by an electro-magnet. Light colored micas are only slowly attacked by hydrofluoric acid, but the darker ones are decolorized by hydrochloric acid and gradually lose their double refraction. The fusibility is quite variable from the difficultly fusible muscovite to the easily fusible lithia micas. It may also be noted that the micas like all aluminium silicates become blue when roasted with cobalt nitrate, and this is the only real positive reaction, without making thorough chemical tests, for distinguishing between mica and talc.

Muscovite, Fig. 321, is rare as a primary constituent of eruptive rocks. It occurs in very large crystals in granitic pegmatites and forms irregular flakes in binary granites, which are recognized macroscopically by the brilliant luster. It is also found abundantly in fresh plagioclase in the central granite. Here it forms minute, well-defined, and regularly arranged scales, which can only be considered as primary inclusions. The appearance of secondary mica, which may develop from any of the feldspars, is entirely different. It is sometimes in larger scales, which follow the cleavage cracks, etc., and form veins or bands with irregular properties. More often it is a dense, confused, scaly formation imbedded in the clouded substance of the feldspar or entirely replacing it. Similar aggregates, that are macroscopically always dense, occur as pseudomorphs after nepheline, scapolite, andalusite, etc. Their properties indicate that they belong to the sericites described below. Small flakes of muscovite are found also in

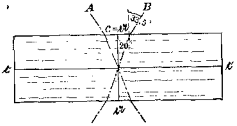


FIG. 321.—Muscovite, Orthopinacoid.

the ground mass of quartz porphyries that have been somewhat altered and they can only be secondary.

Muscovite is far more widespread in contact rocks, especially those formed by piezocontact metamorphism. It is shown in the Allgemeine Gesteinskunde, page 138, how mica schist occurs under these conditions in place of the normal hornfels. Muscovite is the most frequent cause of the schistose structure of the crystalline schists formed by contact metamorphism. When light mica occurs in isolated individuals that are poorly developed but are macroscopically distinct, the schistosity is generally very imperfect. This phenomenon is seen in many injected schists, especially in amphibolite and eclogite, but in the latter rock the mica does not appear to belong to muscovite, but is a mica whose properties have not been accurately determined.

*The mica in these rocks tends to bind itself into membranes with a silvery luster, which wrap around all the other rock constituents as in a mica schist.* In the phyllites these membranes become finer and finer and are folded in various ways, Fig. 322. Then the single flakes cannot be seen with the naked eye and the mica can only be recognized by the silky luster of the rock. Such fine, scaly aggregates of mica, related by a series of transition members to true muscovite, are called *sericite*. They have properties different from muscovite, chief among which are the smaller optic angle and a greater susceptibility to the action of acids.

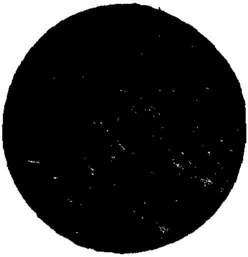


FIG. 322.—Folded Sericite Membrane. Quartz Phyllite, Sunk, Steiermark.

This mineral forms the principal constituent of a widespread series of sericite schists, that have extremely thin layers, and are mostly white with a silky luster. They are rocks in which a few phenocrysts of corroded quartz can be distinctly seen, Fig. 199, page 189. These can only be looked upon as altered quartz porphyry. Granite, gneiss, etc., suffer similar sericitization now and then, especially in the neighborbood of faults and when certain ore veins are formed in the crevices thus produced.

Rocks rich in sericite are apparently quite similar to fine, scaly talc, and this is increased by the greasy feeling of them. It is interesting to note that nearly all such occurrences were formerly designated as talc schists, and even to-day, sericite schists are generally included with talc schists. Aggregates of soda mica—*paragonite*—are outwardly very similar to sericite. They are well-known because of the content of staurolite and cyanite. They replace the granite pegmatites in the Central Alps. Nothing is known of a further distribution of this mineral. Dense light green or yellowish aggregates of mica with properties similar to soapstone are known in small masses in the schists of the Central Alps and in other places under analogous conditions. They are called *onkosine, prägratite, cossaite, damourite, margarodite*, etc., and consist of aggregates that are composed of various sorts of minerals which cannot be distinguished from sericite.

Muscovite is always a mica of the first order but is often in parallel intergrowth with biotite. Characteristic intergrowth with quartz resembling palm leaves occurs in pegmatitic rocks and called *mica palmé*. Alteration of muscovite is not known. It is therefore often found unaltered in clastic rocks, but without accurate investigation it can be confused with bleached biotite.

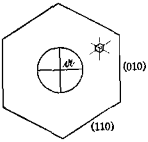


Fig. 323.
Biotite (Phlogopite), Cleavage Plate.

Phlogopite, Fig. 323, is a typical mineral of contact-metamorphosed limestones and dolomites, and occurs principally in rounded crystals or those elongated along the vertical axis. Macroscopically, it is usually very light brown. Large tabular crystals of commercial importance are found in the granite pegmatites, which cut through carbonate rocks. It is always colorless in thin section and distinguished from muscovite by the fact that it is usually nearly uniaxial, and that the cleavage cracks do not have a tendency to be so sharp. Oblique extinction is observed. Needle-like inclusions—sillimanite and rutile—tend to arrange themselves diagonal to the rays of the percussion figure and upon alteration, which occurs now and then, sagenitic intergrowths of rutile are seen along with scaly aggregates. The distribution of phlogopite in rocks is but little known.

Biotite is much more widespread. It is macroscopically brown to black and often has a bronzy luster. Dark green varieties are rarer. Deep reddish-brown *rubellane* of the básic, extrusive rocks is generally burned and strongly resorbed by the magma. A few rarer varieties are the micas of the first order—*anomite*—and these frequently have an extinction of 4–5°, and a somewhat larger optic angle. Most of the biotites are micas of the second order—*meroxene* and *lepidomelane*. The latter is particularly rich in iron and titanium, and the absorption of the rays vibrating parallel to the cleavage is almost complete in thin sections. In rarer varieties, which occur especially in the group of soda rocks, the optic angle is quite large, up to 35°, and at the same time an important extinction, up to 10°, makes its appearance. Transverse sections show distinct twinning laminations and a difference between the two rays vibrating nearly in the cleavage plane, $\mathfrak{b}$ golden yellow, $\mathfrak{c}$ reddish-brown.

Most of the biotites are brown in thin section with different degrees of intensity. Less often they are colored yellowish-brown, red brown or finally green, $\mathfrak{a}$ yellowish, $\mathfrak{b}=\mathfrak{c}$ green. Biotite is widely disseminated in eruptive rocks and contact rocks of all sorts. The best developed crystals, apparently hexagonal, are found in glassy extrusive rocks while in other extrusive rocks they are magmatically resorbed. They are the more resorbed the more crystalline the rock. Inclusions of apatite and zircon are frequent and the former are without, the latter with pleochroic halos, Fig. 216, page 197. Sagenitic intergrowths of rutile are also common. In granulitic rocks the cross sections are often completely perforated by rounded grains of quartz. The flakes themselves have rounded outline in contact rocks, and skeletal development is occasionally observed as well. They do not combine to form membranes as frequently as sericite does. They never form such fine crystalline films. On the other hand, biotite flakes pentrate the other constituents of a hornfels in a helicoidal manner and in schistose rocks, the flakes are often placed transverse to the schistosity. They are then often filled with graphite, etc., and do not show a thin tabular development, but often a distinct prismatic growth, Fig. 324, in contradistinction to the biotite flakes which lie in the structure plane of the rock.

It is found in parallel intergrowth with muscovite in binary granites, gneisses, etc., and with chlorite in the central granites. Perfect freshness of the biotite prevents confusion with the alteration of mica to chlorite, which is so common. It is often intergrown with hornblende and pyroxene, or a narrow homogeneous border surrounds an irregular grain of opaque ore, particularly in gabbro.

Alteration is very common. The simplest process is bleaching in which the mineral loses its color and fresh appearance, and passes over into a colorless mica with a somewhat lower double refraction. Chloritization is more frequent. Proceeding inward from the edges and along gliding planes, the mineral is changed to lamellar chlorite. The separation of titanium minerals, then quartz, carbonates, iron ores, epidote, etc., allow the process of alteration to be followed closely. Sometimes rutile is observed in the form of sagenite, the crystals intersecting each other at an angle of 60°. This rutile is a by-product of the formation of chlorite or the bleaching process. In certain cases almandine or olivine are altered into biotite.

FIG. 324.—Biotite, Transverse to Schistocity, Prismatic. Graphite Schist, Maurertal, Grosvenediger.

The lithionites are sometimes light, and sometimes dark colored. They are constituents of lithionite granite and can only be distinguished from muscovite or biotite by chemical reactions, especially the flame reaction, and by the greater fusibility. Dark lithia micas have a variable optic angle up to about 65°, and are micas of the second order. They are observed first of all in the lithionite granites, which occur in combination with tin ore veins, and they are here the principal micas. The colorless, as well as the brown, are often completely filled with pleochroic halos, which occur around inclusions of rutile, zircon, and cassiterite. Mica very rich in iron, macroscopically black—*raven mica*—is found in certain soda rocks.

See the introduction to this section for a distinction between the real micas and a series of minerals with a similar development. Special attention is called to the use of the cleavage plates in the investigation, for this is sometimes the only means of distinction, e.g., muscovite from pyrophyllite, although the latter has a much larger optic angle. Therefore the phenomena, which the cleavage plates of mica and micaceous minerals show, are considered first in the diagrams; see also the table. page 270. This method on the other hand does not give results in the case of dense aggregates of talc. Here chemical reaction, page 168, must find a place. Diaspore may appear similar to colorless micas on account of the coincidence of the interference colors, but it is characterized by higher indices of refraction. Also anhydrite, which has more than one cleavage not all equal, is similar to colorless mica. The most perfect cleavage planes of that mineral are perpendicular to the obtuse negative bisectrix. Minerals of the amphibole group, tourmaline, and orthite are confused with colored micas, but all these minerals have higher indices of refraction and poorer cleavages. The hydrofluosilicic acid reaction, page 163, is valuable under all circumstances for determining the micas.

Chrome mica—*fuchsite*—must also be mentioned. It occurs in emerald green flakes in contact rocks. It has a variable optic angle. $\mathfrak{a}$ pale sky-blue, $\mathfrak{b} = \mathfrak{c}$ siskin green.

*Seladonite* is appended to the mica group. It is an alkali silicate similar to mica and occurs as a rock constituent in basic eruptive rocks and tuffs. It is sometimes in the veins in them, sometimes as pseudomorphs after augite, and sometimes as an impregnation in the rock. It is dark green in color, has dense, earthy properties—*green earth*—and is very soft. Sp. gr. = 2.6–2.8. It is apparently uniaxial, negative, $\mathfrak{a}$ pale yellowish-green, $\mathfrak{c}$ deep green. Double refraction is somewhat lower than that of the micas. *Glauconite* with a similar composition is distinguished from it by its occurrence, which appears to be confined to the sedimentary rocks—*green sand*. It is found in small dark green spheres, which appear macroscopically like grains of gun powder and is often collected into masses as an agent of petrifaction, especially of foraminifera. Its structure is generally confused even microscopically. Distinct flaky, radial aggregates, showing marked pleochroism from light yellow to deep green, are rare. It is also negative but is biaxial, $2E = 30$–$40°$. $\gamma - \alpha = 0.020$. Both are difficultly soluble in hot hydrochloric acid. *Chrome ocher* appears very similar and is likewise brilliant green. It is nearly uniaxial, negative, $\mathfrak{a}$ yellowish to colorless, $\mathfrak{b} = \mathfrak{c}$ brilliant green. It is found particularly as a halo around chrome spinel in serpentine.

It is not determined whether the small greenish-yellow, radial, fibrous spheres with a perfect cleavage that occur in quartz schists and alum schists and are called *astrolite*, belong here or not. Aside from a lower double refraction, they possess properties very similar to mica. The number of names, which micaceous aggregates have received, is so large that they cannot be discussed in this text.

### Chlorite Group and Serpentine (14)

The minerals of the chlorite group in the narrower sense can but rarely be recognized macroscopically as rock constituents and are generally dark green. Perfect micaceous cleavage, low hardness and flexibility of the flakes are characteristic. They are generally so fine scaly that the individual flakes cannot be recognized distinctly. They have a somewhat parallel arrangement giving to the rock a soft velvety luster. The normal chlorites, i.e., those members of the series rich in iron, together with sedgy hornblende, constitute the most frequent green pigments of crystalline rocks, and numerous greenstones, greenschists, etc., owe their color to it. *Leuchtenbergite*, which is free from iron and colorless, is very rare and is scarcely ever visible macroscopically while the dark red to violet members containing chromium, *Cotschubeyite* and *cämmererite* or *rhodochrome* are confined to secondary formations in serpentines rich in chromite.

Distinction is made under the microscope between pennine, which is sometimes positive and sometimes negative, uniaxial with parallel extinction and frequently shows anomalous lavender blue to rust brown interference colors, and clinochlore. The latter has higher double refraction, is biaxial, and always positive. It shows normal interference colors and on account of its not insignificant oblique extinction it often shows twinning lamination according to the mica law in thin section. These minerals are very light in thin section, but are generally distinctly colored and, whether they are positive or negative, they show stronger absorption of the rays vibrating in the cleavage plane. Colorless cross sections of a mineral with properties similar to chlorite and often with quite anomalous interference colors appear occasionally in the rocks chiefly as a decomposition product of silicates poor in iron. It has been identified as leuchtenbergite. Cotschubeyite corresponds to clinochlore in its optical behavior while cämmererite frequently has anomalous interference colors and is similar to pennine. Both are hyacinth red parallel to $c=\mathfrak{c}$ and perpendicular to c deep violet. Deep blue chlorite, *erinite*, has been observed as a rock constituent. It is yellowish parallel to $c=\mathfrak{a}$ and cobalt blue perpendicular to c.

*Pleochroic halos with brown colors are common in chlorites.* Scarcely a trace of an interference figure can be observed in cleavage plates on account of the deep color and the low double refraction. When roasted in air the chlorites become deep brown and show great differences in absorption, but they fuse with difficulty. They can be etched out of rocks with hydrochloric acid, but leave gelatinous silica behind.

Coarse, scaly aggregates of chlorite are found as secondary veins in serpentine and as a facies of that rock. These aggregates frequently contain large crystals of magnetite and occur as irregular non-schistose masses. They consist principally of anomalous pennine which often has a radial flaky appearance, Fig. 325. The same species is also common as an alteration product of basic silicates and sometimes forms pseudomorphs after biotite. These are always penetrated by titanium minerals and have abundant pleochroic halos. Sometimes it forms irregular scaly aggregates, which have developed from hornblende or pyroxene; also from almandine, feldspar, etc. The same formation is found in greenstones and propyllites as a fine pigment throughout the whole rock. It is not definable optically and is called *viridite.* In piezocrystalline rocks, especially in the central granites, large poorly developed flakes of pennine are undoubtedly primary constituents. These often grow parallel with biotite, but are distinguished from secondary chlorites by a lack of by-products and by the perfect clearness of the mica.

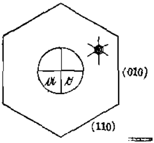


Fig. 325.
Pennine Cleavage Plate.

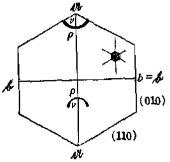


Fig. 326.

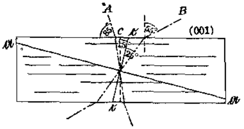


Fig. 327.

Clinochlore,
Parallel Cleavage. Parallel Plane of Symmetry.

The tabular individuals of chlorite occurring in green contact rocks of all kinds, amphibolite, eclogite, green schist and chlorite schist, belong chiefly to clinochlore, Figs. 326 and 327. It shows twinning lamination and normal interference colors. In denser formations approaching phyllites, a mineral similar to chlorite occurs but is distinguished from clinochlore by higher indices of refraction but they do not reach those of the brittle micas although they approach them.

The table, page 270, shows the distinction between the chlorites and other micaceous minerals. A series of dark green minerals, generally with low but sometimes with high double refraction, $\gamma-\alpha=0.02$, is appended to the chlorites. They are called *delessite*, *ripidolite*, etc., and some of them at least are chlorites rich in iron. Likewise silicates very rich in iron with the general habit of chlorite are found frequently as predominant constituents of sediments particularly of oolite. They are called *thuringite*, *owenite*, *chamosite*, etc., and form scaly cleavable aggregates with a specific gravity of about 3.2. They are similar to chlorite in all the optical properties, being negative with a small optic angle and having a positive principal zone.

The relations between the chlorite minerals and serpentine have as yet not been thoroughly determined. There is no doubt that flaky serpentine or *antigorite* is quite analogous to the chlorites in its optical behavior and the chemical composition of chlorite rich in magnesium has been explained by an isomorphous mixture of magnesium aluminium silicate called *amesite* with magnesium silicate, serpentine. Besides the serpentine minerals, which belong here, there is a fibrous serpentine or *chrysotile*, that has no relation whatever to the chlorite group.

The serpentine minerals are not known in individual crystals. All occurrences so designated are pseudomorphs. Antigorite in deep green, flaky masses and chrysotile in yellowish-green, fine, fibrous masses with a silky luster and fine enough to spin, are observed in crevices of serpentine consisting for the most part of very fine aggregates of that mineral. The principal field of distribution of the mineral is in those rocks, which are macroscopically compact with a fine splintery fracture and streaked with dark green or red, rarely with honey yellow.

The appearance of the two varieties of serpentine under the microscope is quite variable in spite of the similarity with respect to index and double refraction. Both are generally colorless in thin section and are therefore not pleochroic. If pleochroic varieties are thought to have been found, *villarsite*, chemical observation will not confirm it and the mineral is undoubtedly chlorite, which is so often mixed with serpentine. Figs. 328 and 329 show the optical constants of the two types of serpentine and in these the difference in habit appears distinctly. However, the question is by no means clear in all respects and there are undoubtedly forms of development in genuine serpentine, which could not be classified under either of the diagrams.

New names cannot be given to these dense aggregates simply because they have different habit as has been done in the antigorite varieties, *picrosmine, metaxite, picrolite*, etc., and likewise the microscopic forms of aggregation, e.g., the radial, which has lately given rise to the name *radiotine*, cannot be recognized as sufficient ground for evolving a new name.

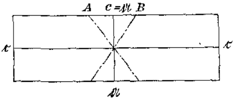


Fig. 328.

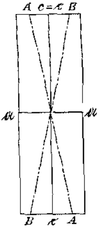


Fig. 329.

Optical Orientation of
Antigorite. Chrysotile.

Serpentine is undoubtedly very rare as a primary constituent of rocks. Antigorite as such has been mentioned and shown in Fig. 288, page 276. It occurs in parallel growth with olivine. If an olivine rock is intergrown with antigorite, which represents a typical formation of piezocrystallization, *stubachite*, later suffers more or less complete serpentinization by thermal processes, a very fine, scaly, irregular aggregate of secondary serpentine is developed between the lath-shaped crystals of the primary antigorite. The secondary serpentine is dense and compact and scarcely acts upon polarized light while the laths of fresh antigorite appear like a lattice in it, *lattice structure*, Fig. 330, and often fine, granular residues of olivine that are scarcely transparent are seen. This development is to be sure very typical, but by no means constant. It gives way to radial fibrous and confused, almost structureless masses. The various antigorite serpentines are characteristic for regions in which the rocks have been formed under the influence of piezocrystallization. They are predominant under such circumstances, but are exceptional under normal conditions.

The appearance of crysotile serpentine is unlike that of antigorite. It forms fibrous masses perpendicular to the edges and filling out the cracks of olivine thus causing the mineral to crack further and these cracks are again filled with fine fibrous aggregates. So the process goes on until the characteristic appearance of the mesh structure is seen, Fig. 331. Small grains of more or less clear olivine may be present in it or the whole may be altered to serpentine. In the veins of such fibrous serpentine there are generally two differents kinds of substances, which appear quite similar. On the outer border the axes of the fibers are positive and the middle portion is also fibrous with the crystals perpendicular to the sides of the vein, but the principal zone is negative.

Serpentine as a rock is always developed from peridotites. Other rocks, e.g., pyroxenite and amphibolite, never turn to serpentine. It is always a product of thermal activity, see *Allgemeine Gesteinskunde, page 152.* Now and then pyroxenes low in aluminium in such rocks are effected by this process of alteration and a pseudomorph of antigorite is formed from it, *bastite.* Generally, however, these minerals remain unchanged and in the serpentines of the Central Alps a few individuals of pyroxene constitute the only residue of the original rock and this gave rise to the opinion that the whole rock was an altered pyroxenite—pyroxene serpentine. By-products are very widespread in the formation of serpentine from olivine. Besides iron ores, which always occur, chlorite, talc and actinolite are formed. The latter material has been falsely considered as the parent substance of serpentine,—hornblende serpentine.

FIG. 330.—Serpentine with Lattice Structure. Hackbrettl in Stubachtal.

FIG. 331.—Serpentine with Mesh Structure. Trogen near Hof, Fichtelgebirge.

The pseudomorph formations are also formed in rocks in which olivine is a subordinate constituent as in the contact-metamorphosed carbonate rocks where the serpentine is generally poor in iron and is yellowish-green to sulphur yellow—*precious serpentine*—but it is sometimes dark green to pure black. The latter color is found especially in certain ophicalcites called *eozoon.* Besides forsterite, humite may be the parent material in such rocks and in both cases the serpentine shows the typical mesh structure. More rarely it is formed from periclase and the cubical cleavage shows even macroscopically. In the pseudomorphs the antigorite flakes lie parallel to the cube faces and overlap each other in such a manner that no double refraction can be observed in thin section. Fresh fragments of the original mineral are sometimes seen as small rounded inclusions in calcite grains.

Sometimes pseudomorphs after an olivine rich in iron are found in olivine-bearing porphyric plagioclase rocks. These have a cleavage like that of mica and are similar to bastite. They are distinctly green in thin section and pleochroic, $\mathfrak{c}$ green, $\mathfrak{b}$ and $\mathfrak{a}$ yellow. They also have quite a strong double refraction, $\gamma-\alpha=0.025$. They are serpentine very rich in iron. The color and pleochroism become more intense upon oxidation and when such pseudomorphs become brown they show very significant difference in absorption from brownish-red to yellowish $\mathfrak{c}>\mathfrak{b}>\mathfrak{a}$, *iddingsite* or *bowlingite.* Similar substances are found in the same rock occurring principally with the mesh structure and when they are brown the serpentines rich in iron can be made deeper brown and strongly pleochroic by roasting in the air. The common serpentines remain unchanged by this treatment so long as they do not lose their water. Serpentine can be distinguished from chlorite, which appears very similar to it, by roasting with cobalt solution when the latter becomes blue. Sometimes it is necessary to dissolve the serpentine out with hydrochloric acid in order to expose accessory minerals concealed in it.

*Black serpentine* mentioned above must be briefly described here. It occurs in many ophicalcites. In thin section, it generally forms a mass like graphite, but a few individuals are prominent from their larger dimensions. They show complete absorption even in the thinnest sections parallel to the principal zone and perpendicular to it they are completely colorless. Hydrosilicates containing nickel belong in this group. They occur as a secondary development in crevices in serpentine and represent one of the most important nickel ores, *numeite, genthite, pimelite,* etc. They are *fibrous scaly substances with brilliant green to yellowish-green color,* sp. gr. 2.6–2.9. Optically positive with medium double refraction and positive principal zone. They turn black before the blowpipe and are attacked by acids with difficulty.

### *Hydrargillite* (14)

Hydrargillite is formed occasionally in the decomposition of various *feldspars especially in the formation of bauxite. It has also been found in* spreustein and a few occurrences of emery. The aggregates appear fibrous in thin section and are extremely difficult to determine because various occurrences have different optical properties. Strong double refraction, negative principal zone and oblique extinction are characteristic and distinguish the mineral from brucite, kaolin, talc, muscovite, leuchtenbergite, etc., which appear similar to it. Diaspore occurs with it and is recognized by much higher indices of refraction. Chemical reactions, such as the blue color upon roasting with cobalt solution and the lack of silica, are sometimes employed to determine the diaspore.

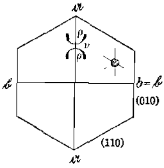


FIG. 332.—Hydrargillite, Cleavage Plate.

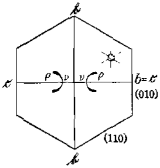


FIG. 333.—Talc, Cleavage Plate.

## Talc (15)

Talc as a rock-forming mineral has, by no means, the significance which geology in general ascribes to it. Most of the occurrences so designated are scaly aggregates of sericite as mentioned above. Talc has a much more greasy feel, but the two cannot be differentiated under the microscope. Chemical investigation alone furnishes a clue for the distinction and this may be either the hydrofluosilicic acid reaction, page 163, or roasting the mineral with cobalt solution, when sericite becomes brilliant blue.

Talc rocks in general consist predominantly of fine, confused, *scaly aggregates of talc, such as talc schists, soapstone, potstone,* etc. They are very soft and can be carved or turned, but upon roasting they attain a hardness greater than that of quartz. They are always anomalous formations, which have resulted from intense chemical processes sometimes in the neighborbood of the most acid eruptive rocks, the granites, and sometimes they have formed from the most basic rocks, the peridotites, in which frequently the whole rock is changed to talc without any residue. Rhombohedrons of magnesite, prisms of actinolite and microlites of rutile are frequently by-products occurring in the yellowish, grayish, or greenish aggregates of talc. Talc is found occasionally as a subordinate constituent in occurrences that scarcely deserve the name of rock, such as *listwänite* and *duelho*. It also occurs in magnesite and numerous serpentines.

### **Pyrophyllite** (15)

The distribution of pyrophyllite as a rock constituent cannot be estimated because it is very difficult to distinguish it from muscovite in thin section except that it has a larger optic angle. In cases of doubt a decision can be reached by means of the hydrofluosilicic acid reaction. It is sometimes formed as a by-product in the process of kaolinization and other similar replacement processes. It occurs in isolated scales and rarely in dense aggregates of *agalmatolite* similar to soapstone. When roasted with cobalt solution they become blue. It is more frequently found as a fine, scaly coating on clay slates in which it often occurs in silvery aggregates covering crevices or as an agent of petrifaction, of *grapholites*, *gümbelite*, for example.

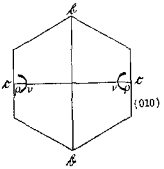


Fig. 334.

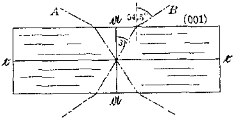


Fig. 335.

Pyrophyllite,

Cleavage Plate.

Macropinacoid.

### **Bertrandite** (15)

Limpid, tabular crystals of bertrandite have been found in certain pegmatites. It occurs also as a constituent of granites, aplites, etc., but is very difficult to determine on account of its great similarity to muscovite.

It is very difficult to find in any case because its specific gravity is about *the same as that of the principal constituents occurring in the rocks and* it cannot be separated. The hydrofluosilicic acid reaction is of value to distinguish it from muscovite.

### **Wagnerite** (15)

Wagnerite is probably much more widespread than it is at present supposed to be. It is only known as an associate of siderite in phyllitic rocks. Its optical properties are not very characteristic, but it may be isolated quite easily on account of its high specific gravity. The reaction for phosphate is a good test for it.

### **Kaolin** (15)

Feldspar rocks alter to kaolin by post-volcanic processes and the alteration affects the plagioclase first and later the orthoclase, while microcline resists it almost entirely. Kaolin forms extremely fine, scaly aggregates, which so far as is positively known, are always *porous and are scarcely ever observed in thin* section. The usual alteration products of feldspar, which cause the cloudiness that is so widespread in them, do not belong to kaolin as is commonly supposed, but are distinguished from it even in the densest aggregates by a much more brilliant interference color. It is probably sericite.

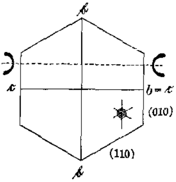


Fig. 336.

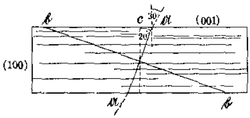


Fig. 337.

Kaolin,

Cleavage Plate. Plane of Symmetry.

When the presence of kaolin can be positively proved, the rocks are so much altered that the kaolin, which is easily suspended in water, can be isolated by simply washing and it can be identified by chemical tests. The mineral is quite important *as a constituent of secondary deposits of kaolin sandstone and* kaolin clay. It is by no means positively determined to what extent it occurs in plastic and non-plastic clays because the clay substance, that is always present in these sediments and is called kaolin, in many cases, does not prove to be kaolin by chemical analysis. The same is true for its distribution in the normal products of weathering and in soils, in which kaolin was assumed as a constituent, without further investigation. It is doubtful whether the scaly mineral in such occurrences can be distinguished from kaolin or not, although it differs from kaolin greatly in chemical composition, being an alkali mineral. Differentiation may be accomplished by an application of the method of Schroeder van der Kolk, Part I, page 38.

### **Nontronite** (15)

Nontronite is not a rare constituent of greatly altered eruptive and contact rocks. It may be formed from any mineral whether it bears ferric oxide or not, and occurs especially in rocks that have been so shattered that the inner texture is entirely porous. It sometimes forms a scaly sulphur yellow coating in crevices of rocks or it penetrates the whole rock in a regular manner and forms earthy pseudomorphs after it. Greenish-yellow masses with a choncoidal fracture and impregnated with opal, *chloropal,* are not rare in such cases. Nontronite is nearly always determined as epidote on account of its color and double refraction but is distinguished from it by much lower indices of refraction.

A mineral very similar to nontronite in appearance and optical properties is very common as a crust in crevices especially on the surface of rocks containing pyrite. This is *copiapite,* a basic ferrous sulphate, that is decomposed in water.

### **Hydromagnesite** (15)

Hydromagnesite is found in dense masses as pseudomorphs after minerals rich in magnesium and also in flaky or fibrous aggregates in crevices of rocks rich in magnesium. It generally shows twinning lamination similar to that of plagioclase. The aggregates are very fine, fibrous and irregular and can be recognized with difficulty. Effervescence shows its presence in a thin section if other carbonates are not present.

## **Cordierite** (15)

Cordierite forms crystals with short prismatic habit that are usually quite distinctly visible macroscopically in granites, quartz porphyries and other extrusive rocks, but become microlites in fritted sandstones. They are frequently in the form of penetration twins appearing in cross section as shown in Fig. 338. The edges are generally rounded and the crystals corroded *in varied manners. It is also found quite widespread in the* form of grains in clay slate hornfels, and these often show decided twinning lamination. A portion of the knotty aggregates in a spotted slate, *Knotenschiefer*, consists of poorly developed individuals of cordierite very rich in inclusions. In these rocks it is colorless in thin section and is frequently penetrated by long slender needles of sillimanite, Fig. 212, page 196. It also contains a large number of inclusions of rutile and zircon with typical yellow pleochroic halos in which the double refraction is lower, but the dispersion of the optic axes and the indices of refraction are higher and the ray vibrating parallel to c appears brilliant yellow.

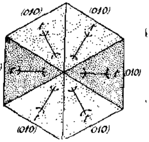


Fig. 338.—Cordierite, Section through a Trilling.

If such characteristic inclusions are lacking in colorless cordierite it is distinguished from quartz by observation in convergent light, by special chemical reactions, page 174, and by the beginning alteration of cordierite into greenish micaceous aggregates, which begins on the borders or at the inclusions. The pseudomorphs sometimes consist of parallel aggregates, *gigantolite*, and sometimes of irregular masses similar to snow crystals in polarized light, *pinite*. The pleochroic halos often remain as brown specks after the alteration. Cordierite often appears very similar to plagioclase on account of its twinning *lamination. If the characteristics mentioned above are lacking,* its determination in thin section may become very difficult. The hydrofluosilicic acid reaction affords positive proof of the mineral. When it occurs as a fresh constituent of extrusive rocks or in tuffs it is generally decidedly blue in thin section and then shows distinctive pleochroism. It becomes nontransparent before the blowpipe and melts with difficulty.

### Wavellite (15)

Wavellite is not rare in crevices of sedimentary rocks in which it forms perfectly radial aggregates. It has apparently resulted from decomposition *of organic phosphates. Its distribution has never been* determined microscopically, but the extraordinarily typical form of aggregation [illegible] tity

### Gypsum (15)

Gypsum is a prominent constituent of numerous members of the halite formations, but it is also found in sedimentary rocks other than these. Its origin from anhydrite can be determined in many cases. It is also found as a product of solfataras and sulphur springs and is sometimes formed from carbonate rocks or occurs as impregnations in volcanic tuffs. In the latter case it is generally accompanied by sulphur. Gypsum is often found as a secondary formation in the *iron caps* of sulphide ore deposits and in calcareous rocks where sulphides have been altered.

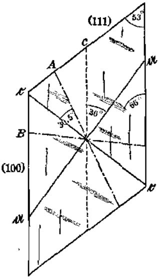


FIG. 339.—Gypsum, Plane of Symmetry.

Rocks consisting predominantly of gypsum are very soft and are generally crossed by numerous veins of fibrous gypsum. The color is white or gray, due to carbonaceous substance, or yellow to red, due to ferric hydroxide. If gypsum occurs as a subordinate constituent of rocks it can only be recognized when cleavage plates with pearly luster appear distinctly. It is difficult to determine under the microscope. Twinning lamination and fibrous fracture, which are distinctly visible in crystalline aggregates, are rarely observed in the denser varieties. Positive evidence of the presence of gypsum in rocks is obtained by leaching the rock with water when small microscopic crystals of gypsum are formed from the solution.

### Feldspar Group (16)

The feldspars are the most widespread rock-forming minerals. Accurate investigation of them is especially interesting on account of their importance because they form the basis for classifying the eruptive rocks. Separation of monoclinic orthoclase from triclinic plagioclase is far from sufficient for the modern petrographical classification. It is also recognized that a natural petrographical system founded on a chemical basis, is not possible without determining the exact properties of the feldspar. For these reasons many investigators have set about to determine the composition of these minerals in an optical way without the aid of chemical analyses, which at best require much time and are often not possible. Many methods, giving results in a more or less direct manner, have been worked out so that now an experienced petrographer can determine quite accurately with the microscope, the chemical properties of a plagioclase in thin section.

The dimensions of rock-forming feldspars are extremely variable. Orthoclase crystals several cubic meters in size occur in certain pegmatites, and crystals from the size of an egg to those the size of a man's head occur in granite porphyries. All possible dimensions are found from these down to the minutest microlites of very glassy rocks. The microlites are often so small that even in a thin section several individuals may overlap each other. The plagioclases develop into large crystals much less than orthoclase and in most instances they cannot be determined *macroscopically*.

The crystallographic development of orthoclase is in the main not very different from that of plagioclase. The combination occurring most frequently on adularia crystals, viz., a prism with a rear hemidome, Fig. 340, appears to be the typical form of an orthoclase and the cross sections are principally rhombic—*rhombporphyry*, Fig. 343. They are sometimes rounded and sometimes elongated like a lancet. Another type of development particularly common on orthoclase shows the above combination modified by the addition of a side pinacoid which truncates the sharp edges of the prism, Fig. 341. The basal pinacoid and a number of other end faces are often present. Fig. 178, page 181, shows the appearance of cross sections of the more isometric individuals. The side pinacoid may become more and more dominant in the combination and the crystals assume a thick or thin tabular habit. This is seen characteristically in cross

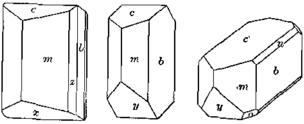


Fig. 340. Fig. 341. Fig. 342.

Usual Types of Feldspar Crystals.

sections of plagioclase rich in lime, Fig. 344. Finally a type elongated parallel to the *a* axis is quite widespread, Fig. 342. Cross sections of it appear quadratic in orthoclase and nearly quadratic in plagioclase, about 93°, Fig. 371, page 338, because of the equal development of the basal and side pinacoids.

The cleavage of the feldspars is about the same in the different members, but in thin section it occurs in various ways, according to the condition of the feldspar. A system of long sharp cracks, parallel to the base and less perfect ones parallel to the side pinacoid are seen in thin sections of the fresh unaltered occurrences of the Central Alpine granites and schists. Parting parallel to the orthopinacoid often appears more distinctly in fresh sanidine. Cleavage is less perfect in the clouded occurrences and is often indicated in thin section more by the arrangement of decomposition products than by real cracks. When the rock is crushed, the feldspars cleave very differently. In orthoclase cleavage plates parallel to the base predominate, while in plagioclase plates parallel to the side pinacoid are most common because of the lamellar development parallel to it. Microscopic investigation of these cleavage plates in parallel and convergent polarized light affords considerable data for determining the feldspar.

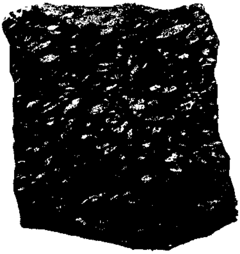


FIG. 343.—Rhombporphyry. Kolsaas near Cristiania.

FIG. 344.—Labradorite Porphyrite with Tabular Plagioclase.

Alteration is extremely common and those feldspars, that are colorless when fresh, assume a clouded appearance and often become deeply colored. In thin section the color can be seen to be due to inclusions. Orthoclase usually appears with deep red and brown colors while plagioclase is usually not so intensely colored and is more apt to be yellow or greenish. In zonal crystals the alteration often begins in the center and proceeds outward along the cleavage cracks or it attacks the various zones differently. The usual cloudiness is produced in orthoclase as well as in plagioclase by fine, scaly aggregates of sericite. Kaolin, on the other hand, is entirely independent genetically and is wholly a local alteration.

Mechanical structures are not very widespread in the feldspars. The occurrence of fractured feldspar crystals in normal extrusive rocks is characterized as *protoclase.* The twinning lamellæ of plagioclase are often bent by orogenic processes while orthoclase frequently assumes a lattice structure similar to microcline. Both may be crushed and assume the cataclase structure.

The feldspars are divided into two groups:

*a.* Alkali feldspars; orthoclase, microcline, anorthoclase.

*b.* Soda lime feldspars or plagioclase.

### a. The Alkali Feldspars

The alkali feldspars occur as rock constituents in three forms and two of these are monoclinic, orthoclase and sanidine. They are distinguished by the size of the optic angle which in orthoclase is very large and in sanidine is always much smaller and is often zero. Further, the plane of the optic axes in orthoclase is always perpendicular to the plane of symmetry and in sanidine it

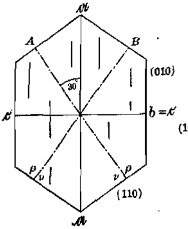


FIG. 345.

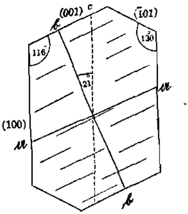


FIG. 346.

Orthoclase Cleavage Plates.

Parallel Base. Parallel Plane of Symmetry.

is *sometimes parallel*, Figs. *345 to 348*. *In the last case, strong* inclined dispersion of the optic axes is especially noticeable and this is characteristic for sanidine. When orthoclase is slowly heated, it may be noted that the optic angle gradually diminishes to zero and at about 500° the axes separate again in a plane perpendicular to the first. When heated for a long time at a temperature above 600° the orientation remains the same even upon cooling. The geological conclusions concerning the temperature at which the rocks are formed, drawn from this phenomenon, have been shown to be entirely intenable. Triclinic microcline *is the third form of alkali feldspar.*

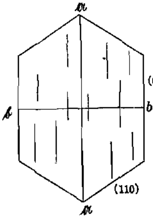


Fig. 347.

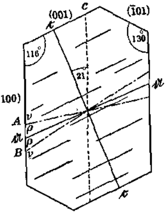


Fig. 348.

Sanidine, Cleavage Plates,
Parallel Base. Parallel Plane of Symmetry.

Orthoclase sometimes develops in well outlined crystals which *are generally distinctly visible macroscopically* and *may attain* considerable size, especially in granite porphyry. Sometimes the crystals *are somewhat rounded*. The *small microlitic* individuals in the ground mass of trachytes, etc., may have perfect crystallographic outline especially in rocks containing glass. The crystals show the variable habits sketched above. The cross sections are six-sided or rectangular to long lath-shaped. The last form is common, especially in the minute individuals in the ground mass of trachytes, etc. Fig. 183, p. 184, shows the lath-shaped cross sections of this type with fluidal arrangement and the brittleness of sanidine phenocrysts also appears distinctly in this figure.

Twins are extremely widespread and generally two individuals lie side by side separated by a more or less straight line. Twins according to the Carlsbad law are most common. The orthopinacoid is the twinning plane and the development may be such that this is also the composition plane, Fig. 349, or, as is more frequently the case, the two individuals are grown together with the clinopinacoid for the composition plane, Fig. 350. The Baveno is another, less common twinning law. Here the clinodome {011} is the twinning plane. This type is found particularly in the crystals developed. prismatic along the *a* axis. Fig. 351 shows a cross section of it. The two individuals are almost exactly at 90° to each other and therefore extinguish simultaneously, but equivalent vibration directions are crossed in them. Twinning parallel to the base and to other forms occur now and then but are generally very difficult to determine. Frequently the crystals show zonal development. Zonal arrangement of inclusions is often observed in fresh individuals. The zonal structure appears more distinctly when the crystals are weathered because the different zones alter differently.

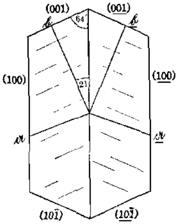


FIG. 349.—Carlsbad Twin, Section Parallel Clinopinacoid.

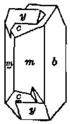


FIG. 350. Orthoclase, Carlsbad Twin.

Regular intergrowth of orthoclase with other minerals is frequent, above all with plagioclase. The latter may penetrate orthoclase throughout in parallel position so that a fine network of acid plagioclase with orthoclase results—*perthite*—Fig. 352, or the reverse may be true—*antiperthite.* A section perpendicular to that shown in Fig. 352 appears wholly fibrous even in ordinary light. In other cases a few irregular elongated spindles of plagioclase are regularly intergrown with orthoclase. Such intergrowths are widespread in purely microscopic dimensions—*microperthite*—and finally they become so fine that their presence can be recognized only by the imperfect extinction of

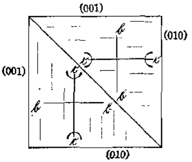


FIG. 351.—Baveno Twin, Section Parallel Orthopinacoid.

the cross sections—*cryptoperthite.* Orthoclase sometimes occurs as a border around plagioclase crystals, but the reverse of this is a rare occurence.

Graphic intergrowth of orthoclase and quartz is very important. Long parallel rods of quartz penetrate through the feldspar crystals and the cross sections of the quartz show an angular outline similar to writing, Fig. 353. This intergrowth is very frequent in aplites and in the ground mass of quartz porphyry, but often in microscopic dimensions. Then it is called *micropegmatite.* In many cases this becomes more and more indistinct. It forms an extremely fine aggregate often appearing somewhat radial—*granophyre*—until finally it passes over into a dense aggregate of particles that are only transparent in the thinnest sections and very little or no effect at all can be observed on polarized light—*microfelsite.*

*Fig. 352.—Perthitic Intergrowth of* Orthoclase and Plagioclase.

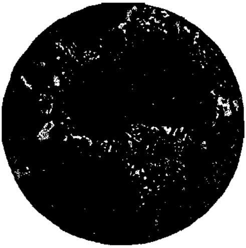


*Fig. 353.—Micropegmatite.* Aplite, Col de Tourmalet, Pyrenees.

In another kind of intergrowth of quartz with feldspar the cross sections of the quartz rods are rounded and worm-like—*myrmicoïdal* structure, Fig. 259, p. 248. This is beautifully seen in rounded grains in granite, granulite, and quartz diorite and in injected schists and it can frequently be positively proved that in this intergrowth the feldspar is a plagioclase.

Inclusions are not very common in orthoclase, but all of the other rock constituents may be found as inclusions in it. The phenocrysts of a granite porphyry may be quite rich in such foreign minerals. Biotite flakes and quartz crystals can be seen with the naked eye and these sometimes show the zonal arrangement. Liquid inclusions are comparatively rare. Glass and slag inclusions are observed abundantly in glassy extrusive rocks. The regularly arranged small red plates which cause the copper red iridescence of sunstone are also to be mentioned. They are generally considered to be hematite, but this has not been definitely proved.

Orthoclase, as a constituent of granite and quartz porphyry, is one of the most widespread minerals and is very important as a source of potassium for the soils. It is also very common in injected schists, but is rarer in contact rocks. It is only a subordinate constituent of clastic rocks in which it is rather fresh.

In central granite the orthoclase is entirely fresh and is characterized by a very perfect cleavage—*adularia*. The form known as *sanidine* is likewise often glassy, but it has a more concoidal fracture. Ordinary orthoclase is in a state of alteration, which sometimes begins on the edge, sometimes in the center and sometimes in certain zones. It gives rise to cloudy, scaly aggregates assembled chiefly along the cleavage cracks. Ordinary alteration gives rise to sericitic substances, the double refraction of which can be recognized even in the very fine, scaly particles. Kaolinization is a very different process from this and is entirely local. The aggregates resulting from it have scarcely any double refraction at all and are generally so crumbly that they are not observed in a thin section because they fall out during the grinding.

FIG. 354.—Microcline, Lattice Structure.

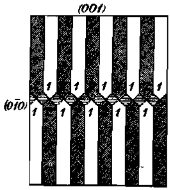


FIG. 355.—Microcline, Explanation of Lattice Structure.

Microcline is very similar to orthoclase macroscopically but they can be differentiated under the microscope by different behavior in polarized light. The former can always be recognized beyond a doubt by the characteristic twinning lamination known as lattice structure, Fig. 354. This distinctive property appears to be the result of lamellar twinning according to the albite law. The lamellæ do not lie side by side as in the case of the plagioclases, but cut each other in the manner shown in Fig. 355. The triclinic character of microcline appears on the cleavage plates which have an extinction of 15° and show an unsymmetrical interference figure, Fig. 356.

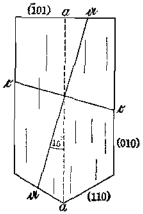


Fig. 356.—Microcline, Cleavage Plate Parallel Base.

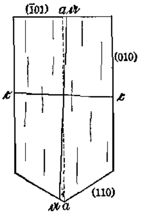


Fig. 357.—Anorthoclase.

The twinning mentioned for orthoclase is also observed on microcline and likewise the intergrowth with albite—*microcline perthite.* It is sometimes found in very large crystals occurring in pegmatites of the granite series or of the soda rocks. It often occurs with a very brilliant red or green color—*amazonstone.* *It is widespread as a rock constituent in granites and injected* schists but only the microscope reveals it as the last mineral to separate out. It only shows crystal form in the neighborhood of cavities. It is entirely lacking in extrusive rocks but the orthoclase of these rocks sometimes shows the microcline structure as a result of pressure. Microcline is also very common in granular soda rocks but its properties are much less regular.

Its great resistance to weathering is noteworthy. It is often found unaltered in soil and in kaolinized granite when the other feldspars have been entirely destroyed.

Soda orthoclase or anorthoclase is also triclinic, Fig. 357. It is confined to the soda rocks in which it replaces orthoclase. In some of these rocks it shows a characteristic rhombic form, previously mentioned, while in others it shows the same development as orthoclase. A brilliant bluish iridescence is quite common. It may be observed in thin section that anorthoclase is united to cryptoperthite by all possible transition stages. Twinning is exceptionally common. However, the lamellar structure according to the different laws is so fine that it only appears distinctly in thin section. The laminated sections do not have sharp boundaries between the parts and these finally grade over into homogeneous sections. The characteristic denticulated laths in the ground mass of certain soda trachytes, Fig. 358, are especially distinctive. Besides the above phenomena, anorthoclase is distinguished from orthoclase by a smaller extinction on the basal pinacoid and a larger extinction on the side pinacoid running up to 10°. It also has a smaller optic angle.

Fig. 358.—Soda Feldspar in Bostonite from Conny Island, Mass., U. S. A.

All alkali feldspars are not attacked by acids except hydrofluoric, but it dissolves them quite rapidly. They melt with difficulty. They are distinguished from the plagioclases by lower indices of refraction, even when the twinning lamination is lacking in the latter. Investigation of the powder immersed in benzonitrile ($n = 1.526$) is very useful to distinguish the feldspars. Orthoclase has lower indices of refraction in all directions than the liquid; anorthoclase and microcline are a little lower in one direction and only a trifle higher in the other; all the plagioclases have higher indices in all directions. The alkali feldspars are easily distinguished in thin section from quartz, cordierite, scapolite, nephelite, etc., by their indices of refraction being lower than that of Canada balsam.

### b. Soda-lime Feldspars or Plagioclase

The plagioclase group consists of crystallized triclinic mixtures of soda feldspar or albite, *Ab*, with lime feldspar or anorthite, *An.* It has as yet not been positively determined whether the plagioclases represent a continuous isomorphous series in which

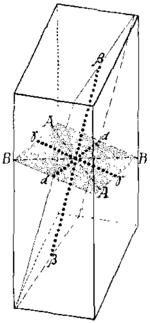


FIG. 359.—Albite.

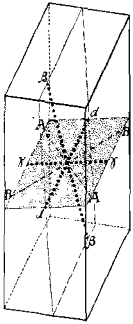


FIG. 360.—Oligoclase.

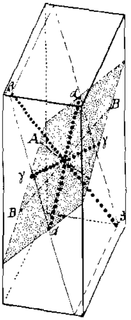


FIG. 361.—Andesine.

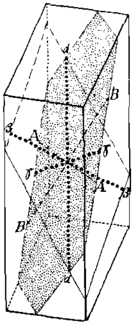


FIG. 362.—Labradorite.

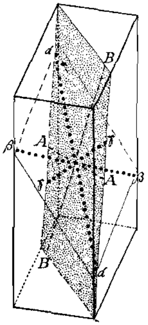


FIG. 363.—Bytownite.

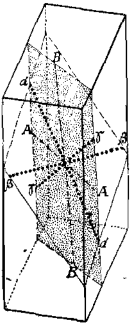


FIG. 364.—Anorthite.

the two silicates may grow together in any proportions, or whether only certain compounds with definite composition are formed. The latter appears the more probable. At any rate, certain types given in the table are much more common than mixtures that might be placed between them. Phenocrysts in porphyric rocks are well bounded crystallographically as are often the microlitic individuals of the ground mass, especially if the rock contains glass. The plagioclases show isometric forms only in the more acid rocks. In other rocks they are partly

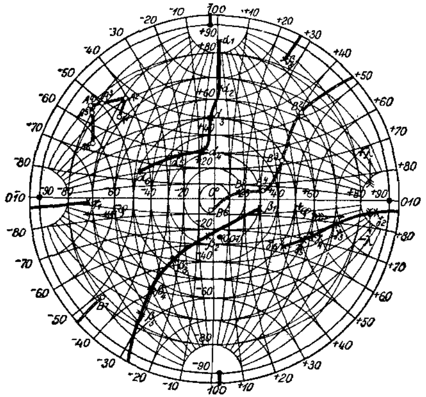


Fig. 365.—Stereographic Projection of the Optical Constants of the Plagioclases.

rismatic along the *a* axis and partly tabular parallel to the side inacoid, particularly in the more basic varieties. Their cross ections are predominantly lath-shaped, Fig. 366.

The basal and brachypinacoids, the two principal cleavage irections, form an angle of about 93½°. The base is grooved by egular parallel striations produced by the ever present twinning amination parallel to the brachypinacoid—*albite law,* Fig. 367. hese striations on the most perfect cleavage face are the only seful macroscopic distinction from orthoclase, if the latter does ot have its characteristic red or brownish color, which does not ccur in plagioclase. The twinning lamination is also the best characteristic under the microscope. It is rarely recognized in thin sections by the reëntrant angles, Fig. 368, but it shows up in polarized light by the different extinction of the lamellæ. If it is lacking, as is frequently the case in basic plagioclase of eruptive rocks and very often in contact rocks, the determination of the feldspar is very difficult. The lamination is quite variable, sometimes broad and sometimes narrow. The former appears to be the more common in plagioclase rich in lime and the latter in those consisting predominantly of soda. A fine system of lamellæ may alternate with one band which occupies most of the crystal. The section is regularly laminated in one case, and in the other, there are a few fine lamellæ, while the rest of the crystal appears homogeneous. Sometimes the stripes pass clear through the individual and sometimes they narrow down and pinch out entirely. Where orogenic pressure has acted on the plagioclase the lamellæ may be bent or broken and may be displaced.

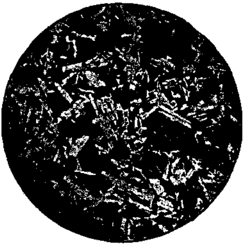


FIG. 366.—Lath-shaped Plagioclase in Trap, Reykjavik, Iceland.

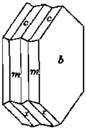


FIG. 367.—Plagioclase, Albite Twinning Lamellæ.

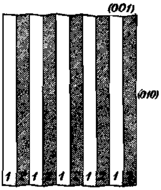


FIG. 368.—Twin Lamination after the Albite Law in a Section Parallel to the Macropinacoid.

In addition to this most frequent twinning there is often another, likewise lamellar, according to the *pericline law*. The *b* axis is the twinning axis. This second system of lamellæ crosses the first under variable angles, but approximates a right angle in the zone of the *b* axis, Fig. 371, page 338. Such polysynthetic twinning may be combined with one of the laws for orthoclase, most frequently the Carlsbad, and the appearance becomes quite complicated. Globular and star-shaped intergrowths of many individuals are found in certain rocks, particularly andesites and tephrites. By their regularity, they give the impression of a very complicated growth of twins.

The occurrence of isomorphous layers is extraordinarily frequent in intermediate eruptive rocks and is very troublesome in the exact determination of the plagioclase. The different zones, which are sometimes very narrow, extinguish differently. The center always consists of a more basic plagioclase than the outer zones. Twinning lamination continues undisturbed throughout all the zones. Irregular penetration of different plagioclases also occurs in eruptive rocks. Zonal structure is very widespread in contact rocks, but here the order is reversed and the center is more acid than the rest. See page 326 for intergrowths with orthoclase.

The plagioclases are always colorless in thin section. They are very fresh, particularly in unaltered extrusive rocks where they have the appearance of sanidine. This has been distinguished as *microtine*. Abundant inclusions of dark glass, often with zonal arrangement, are very common in glassy rocks. Most of the acid plagioclases in certain Central Alpine granites and tonalites are fresh and transparent, but they are often filled with a large number of microlites so that they appear clouded macroscopically and become transparent only in very thin slides. The microlites are well bounded crystallographically, Fig. 274, page 264, and generally they are orientated at random in the fresh mass of the feldspar. Sometimes they are muscovite, sometimes sillimanite or garnet, but in most cases they are members of the epidote group poor in iron. These plagioclases are light reddish in color when they contain garnet, but the epidote minerals produce a light greenish-yellow color.

Plagioclase is generally clouded in the eruptive rocks and its alteration is quite analogous to that of orthoclase except that plagioclase containing lime is more easily attacked, and epidote, calcite, chlorite, etc., frequently occur as by-products of the alteration. Pseudomorphs of hydrargillite after plagioclase have been found locally in greatly altered rocks and replacement by zeolite is not at all uncommon in soda rocks. Brown tabular microlites with parallel orientation occur as inclusions, particularly in basic plagioclase. These are often the cause of the chatoyancy. Such feldspars sometimes appear brownish-black macroscopically, but under the microscope they seem to be filled with dust. This appearance may also depend upon similar inclusions minutely divided.

The two end members of the plagioclase series are the rarest as rock constituents. Albite is the commonest representative of the series in granite pegmatites, in which it is the last mineral to crystallize. It occurs as a rock constituent in perthitic intergrowth with orthoclase, but aside from this it is a rare exception in granites. It occurs more frequently in acid members of the soda series, in which it is often the only feldspar. Clouded individuals of it are present in the corresponding extrusive rocks, especially in keratophyres. Oligoclase to andesine are the usual plagioclases in acid and intermediate eruptive rocks. Labradorite is sometimes quite widespread, for example, in monzonite. It is the typical feldspar of gabbro and trap, sometimes passing over into bytownite, but rarely into anorthite. In general, phenocrysts in porphyrites and andesites approach labradorite, while more acid plagioclase predominates in the ground mass.

Plagioclase is much fresher in contact rocks and is usually clear and transparent. Its lack of twinning lamellæ has been mentioned above. It shows good crystal form only in granular carbonate rocks in which isolated microscopic individuals of albite are very widespread, or in the lime-silicate fels formed near them. Here anorthite often forms large individuals. The Knoten in certain Alpine graphite schists are often composed of rounded crystals of albite. These are more commonly granular aggregates with beautifully developed mosaic structure, Fig. 369. They are often very rich in inclusions.

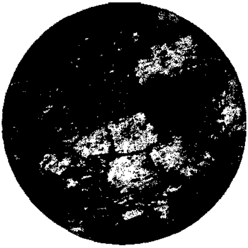


FIG. 369.—Albite in Green Schist. Tummelbachtal, Grossvenediger. Mosaic Structure.

Under the influence of piezocontact metamorphism, those plagioclases rich in lime decompose into calcium-aluminium silicates like clinozoisite, garnet, etc., and into a granular mosaic of clear plagioclase low in lime. The higher the pressure during the recrystallization the more the latter approaches albite. It is, therefore, almost always pure albite in the schistose masses of the Alps. Under lower pressure the plagioclase simply recrystallizes so that in the normal contact metamorphism of diabase the original lath-shaped crystals retain their outward form, but consist of a granular aggregate of the same feldspar.

Another type of alteration, effecting especially basic plagioclase in eruptive rocks, is quite analogous in its entire character to piezocontact metamorphism. This is saussuritization and is usually accompanied by uralitization of the pyroxene. Macroscopically the saussurite appears to have the form of the feldspar, but it has no trace of cleavage but consists of dense, hard, heavy aggregates with splintery to conchoidal fracture and is characterized by great tenacity. Its color is greenish or yellowish, passing over into almost pure white. It has a clouded appearance under the microscope even in very thin slides because of the small size of the irregular individuals with high indices of refraction. These minerals are most frequently members of the epidote and garnet groups poor in iron, vesuvianite, lawsonite, prehnite often penetrated by hornblende needles or flakes of chlorite. The host of all this aggregate seems to be plagioclase similar to albite. A definite conclusion concerning the composition of saussurite is very difficult because of the poor development of the various constituents and the similarity of their optical properties. Pseudomorphs of chlorite or talc after different feldspars are found locally as rare formations.

Acid plagioclase is effected by acids just as the alkali feldspars are. Basic plagioclase is readily attacked by hot hydrochloric acid and the richer in lime it is the more easily it is gelatinized. Acid members are rather difficultly fusible before the blowpipe and the basic are almost infusible.

In many cases it is desirable to determine the plagioclase accurately because of the importance of this mineral in the classification of the eruptive rocks. The most reliable means for this purpose is quantitative chemical analysis, but it requires a great deal of time and frequently enough pure material cannot be obtained for it. Determination of the silica content alone would be quite useful as will be seen from column 6, Table 16. The difficulty here is the same as in the preceding case.

A number of qualitative chemical tests can be made on small fragments that can be easily isolated in a pure condition from the rock, but they do not give very definite results. Thus attempts have been made to estimate the soda content of a feldspar by the color produced by the mineral in a flame or by the relative amounts of sodium fluosilicate and calcium fluosilicate in the residue after the mineral has been decomposed by hydrofluoric acid. The end members may be distinguished by their behavior toward hydrochloric acid. Determination of the specific gravity, column 7, gives better results than the above methods. A very pure minute grain can be used for this purpose.

A few of the numerous optical methods for the determination of the plagioclase are much more reliable than all the above tests. The optical orientation of the plagioclases is known in a general way, although there is some disagreement about minor details so that determinations by different methods have given different results. This does not appear to be due to the method used alone but is dependent, to a certain extent at least, upon *varying optical properties caused by uncontrollable contingencies.* Optical methods cannot replace quantitative chemical analysis if there is suitable material for it. They often give better results than the latter, however, under the conditions in which a petrographer finds them.

The optical properties of the plagioclases have been thoroughly investigated because of the importance of these minerals in the classification of the eruptive rocks. Figs. 359 to 364, page 331, and the projection in Fig. 365 give a general survey of these properties. A and B in these figures are the optic axes and $\alpha$, $\beta$, $\gamma$ are the principal vibration directions. The index 1, Fig. 365, refers to albite, 2 to oligoclase, etc., corresponding to the six figures 359 to 364. In general, mean values are used as the basis for construction so that there are small deviations from the true relationships, but a synopsis of the whole can be obtained from the figure.

It is understood that in all the determinations with these figures or with table 16 belonging to them, the orientation of the section, if it is not a cleavage piece, is determined much more accurately in convergent polarized light than in parallel light, but for other purposes only measurements in parallel polarized light yield good results. The optic angle of plagioclase is so large that its measurement and the determination of the optical character even with an immersion system give doubtful results. The dispersion is so weak that it cannot be positively determined in thin section. The double refraction is almost the same for all members except the most basic. These properties are therefore of no use to distinguish the different members of the plagioclase group.

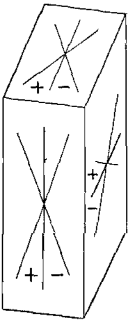


Fig. 370.—Sign of the Extinction in Plagioclase.

*The most important optical methods for determining them are the following:*

1. The oldest and simplest is the method of determining the extinction angle on cleavage plates parallel to P = {001} and M = {010}; see table 16,

columns 16 and 17. The significance of the sign in this determination is explained by Fig. 370. This method gives results rapidly if the individuals of plagioclase are large and fresh. It can also be used on very small individuals under certain circumstances. A small fragment of rock is crushed between two object glasses and the resultant fine sand is used for the investigation. The best cleavage is parallel to the basal pinacoid, but the cleavage plates are more often parallel to the brachypinacoid on account of the lamellar development of the crystal parallel to this face. The interference figures of such plates are not characteristic except for the end members.

2. All sections perpendicular to the brachypinacoid, i.e., the twinning plane of the albite law, show extinction of the individuals symmetrical to the trace of the twinning plane. Such sections may be recognized in a slide by the symmetrical extinction of the two parts. The maximum extinction in this zone, column 21, can be found approximately by measuring a large number of sections showing symmetrical extinction in a slide. These measurements give valuable results, particularly with minute individuals in the ground mass of extrusive rocks, provided that all the plagioclase cross sections do not have about the same orientation on account of flowage of the magma.

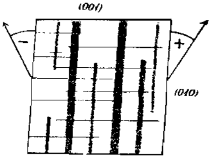


FIG. 371.—Orientation of a Plagioclase Crystal Elongated along the *a* Axis.

Sections perpendicular to the *a* axis, column 20, also have a special significance. These sections are rhombic, nearly quadratic, in outline on the small individuals due to equal development of the basal and brachypinacoids, Fig. 371. Cleavage parallel to the base and the albite twinning lamellæ are both perpendicular to these sections. The extinction on such sections is a splendid means for determining plagioclase microlites that can scarcely be determined by other methods. If the positive or negative direction of the extinction cannot be determined the results may have a two-fold meaning, at least with the acid plagioclases.

3. *Fouque Method.*—Determination of the extinction angle in sections in which the optical orientation can be easily and quite accurately determined by investigation in convergent polarized light, is very important. The best sections are those perpendicular to one of the two bisectrices, columns 18 and 19. Sections, orientated favorably enough, can be found quite readily with a little practice, in almost any slide. The index of refraction of the plagioclase is compared with that of the Canada balsam and then by studying the figures 359 to 364, an idea of the direction of the cleavage or twinning lamellæ in the section in question is obtained. Sections are then found corresponding to this conception, these showing an interference color about half as high as the highest

color possible in plagioclase. When a section is found as nearly perpendicular to a bisectrix as possible, its character is determined with a gypsum test plate, regardless of whether it is the acute or obtuse bisectrix. On sections perpendicular to the negative bisectrix, the angle between the optic plane and the trace of the twinning plane can always be measured. This is apparent in Figs. 359 to 364. Sections perpendicular to the positive bisectrix give the angle between the cleavage parallel to the base and the optic plane, while the twinning lamellæ are so oblique that they cannot be observed at all or are not very sharp. Column 18 gives the angles between the optic plane and the twinning lamellæ of the albite law and the values in column 19 are the angles between the optic plane and the cleavage parallel to the base. Both of these values together furnish a distinctive characteristic for a feldspar, while only one of them is not sufficient for the determination, in many cases.

4. In double twins where the albite and Carlsbad laws occur simultaneously, there are four conjugate extinction angles for the different parts in each section where these two laws appear distinctly. If 1 and 2 are the two individuals twinned according to the Carlsbad law, each contains albite lamellæ 1′ and 2′. Each member of the plagioclase series has a characteristic value for 2 and 2′ corresponding to a certain value for 1 and 1′. This can be deduced from the stereographic projection. To take this up in detail would lead too far for this text.

5. The mean value of a number of extinction angles, measured from the twinning plane on several random sections in a slide, also furnishes somewhat of an indication of the kind of plagioclase. Thus more than half of all sections of anorthite show an extinction between 31° and 50° and oligoclase between 0° and 5°. It follows from this that the twinning lamellæ are not distinctly seen in the latter case where the difference in extinction of the two parts is so small, while in the former case the twinning appears very distinctly.

6. As shown in Fig. 365, one of the optic axes in basic plagioclase is not very much inclined to the vertical axis. The point at which this axis emerges in each component of a double twin according to albite and Carlsbad laws can be determined from the interference figure if the section is not greatly inclined to the vertical axis. $\varphi$ and $\lambda$ can be determined from this with respect to the twinning plane and these values can be used to determine the plagioclase from Fig. 365 in which the values are indicated. Such sections of the members richer in sodium do not show the emergence of an optic axis. This method therefore has very little practical significance.

7. *Schroeder van der Kolk Method.*—One method, which often gives rise to good results, is based upon the difference in the indices of refraction for the different plagioclases. Whether the

plagioclase is acid, intermediate or basic can be very rapidly determined by comparing its index with that of Canada balsam. More accurate results can be obtained, especially with intermediate members, if the different elasticity axes of the plagioclase are compared with the two vibration directions of the quartz grains lying beside it, column 8, Table 16. This method is especially valuable for the investigation of rock powders, sands, and soils in which the minutest flecks of the feldspar are sufficient to obtain perfect results. A series of liquids can be arranged in well stoppered phials. The liquids must not decompose too easily and they must not be of such a nature as to be impaired very much by use. They are so chosen that the index of refraction of the liquid lies between those of two principal members of the plagioclase series. A grain of the feldspar to be investigated is placed upon an object glass in a drop of the liquid, the index of refraction of which has been previously determined. The cover-glass is laid on and the illuminating cone of light is narrowed down as much as possible. Then the index of refraction of the two vibration directions of the plagioclase is compared with that of the liquid.

The liquids used are organic because solutions of inorganic salts, described in Part I, page 37, change their indices rapidly upon evaporation. The purity of the liquids and therefore the indices of refraction are rather variable so that the indicators must be tested with a Bertrand refractometer and the true index determined before the series is made up. The values given below were determined by Weinschenk for liquids obtained from Bender and Hobein in Munich. The variations for different tests from other sources amounted to about ±0.002 to 0.004.

The following serve to distinguish:

Alkali feldspar from plagioclase: Benzonitrile......$n=1.526$
Albite from oligoclase: Eugenol..................$n=1.540$
Oligoclase from andesine: Bromtoluol............$n=1.550$
Oligoclase from andesine: Nitrobenzol............$n=1.552$
Andesine from labradorite: Anethol...............$n=1.558$
Labradorite from bytownite: Monobrom benzol....$n=1.560$
Bytownite from anorthite: Orthotoluidine.........$n=1.575$

It is necessary to carry out these investigations in sodium light on account of the strong dispersion of the liquids and the great difference in dispersion between them and the feldspars. The above indices are given for sodium light.

8. The Fedorow universal stage was originally constructed for determining the feldspars; see Part I, page 127. The universal stage is placed on the stage of the microscope, with its principal axis of rotation exactly parallel to the vibration direction of one of the nicols. The horizontal axis of the inner stage will then lie parallel to the other vibration direction. The thin section is placed on a small round object glass and fastened on the glass stage with a drop of glycerine. The feldspar to be investigated is centered and a plano-convex lens is placed over it and one under the stage, contact being made with glycerine. Then the glass stage is rotated until the trace of the twinning plane is parallel to the horizontal axis of the inner stage. Then it is rotated on this axis until the two individuals of the albite law have the same interference color, i.e., they extinguish symmetrically with respect to the twinning plane. The angle of rotation is read and plotted in the stereographic projection. Then the inner stage is rotated on both of its axes until one part of the twin remains dark when the nicols are rotated. The pole of the axis which emerges perpendicularly is read. The pole of the other optic axis is determined in a similar manner. The position of A and B and of $\alpha$, $\beta$ and $\gamma$ relative to the twinning plane in the albite law is thus determined and the plagioclase can be determined directly from that.

9. A Wallerant total reflectometer, Part I, page 40, can also be used to determine the plagioclase. The polarizer is pushed out and the critical angle of total reflection is measured.

### Biaxial Zeolites (17)

All zeolites are colorless of themselves, but they are sometimes colored yellowish-brown to red by inclusions of ferric hydrates or brownish by organic substances. They all have low indices of refraction, lower than Canada balsam. The double refraction corresponds somewhat to that of quartz. It is much lower in phillipsite and harmotome and unusually high in thomsonite. The latter does not appear similar to the other zeolites in thin section and can be determined as such only by its solubility in hydrochloric acid and by its becoming cloudy when slightly heated. Laumontite is another of the zeolites given in the table, which is somewhat peculiar. It gives up a part of its water at ordinary temperature and is, therefore, always cloudy. Some other zeolites show the same phenomenon.

The zeolites rarely form granular aggregates, but phillipsite and harmotome may. Most of them appear tabular like heulandite or radial like epistilbite and desmine. When they are macroscopically visible they nearly always show the latter form of aggregates and this together with the perfect cleavage is sufficient for the determination.

Since the indices and double refraction of the various zeolites are about constant, the optical character of the principal zone can be used to distinguish some of them, particularly natrolite from scolesite. The latter is also characterized by a small optic angle and strong dispersion of the optic axes. Mesolite stands between these two chemically and also takes an intermediate position with respect to the optical properties.

*Oblique extinction serves to distinguish monoclinic zeolites* from the orthorhombic. It is small in the minerals of the stilbite group and natrolite, medium in scolesite, laumontite and phillipsite and quite large in harmotome. Differentiation of the zeolites is, however, very difficult and their significance as rock constituents has by no means been determined.

All zeolites are typical products of thermal activity. They occur chiefly in amygdaloids, especially near the contacts of eruptive rocks and frequently form beautiful crystals. They are not rare as infiltrations in tuffs and are also found in sediments in the neighborhood of eruptive rocks. Whatever their occurrence, the principal associate is chalcedony and the other modifications of silica. The difficulty of distinguishing the zeolites from each other is increased by the presence of these minerals, which are very similar optically. The determination is much easier when they occur as secondary deposits in cavities than when they occur in decomposed soda rocks. In the latter case all kinds of zeolites occur in aggregates similar to ice flowers or in dense pseudomorphs after nepheline, leucite, sodalite minerals and feldspar. These are classed together as spreustein. Determination of the different zeolites is impossible in such an occurrence. They can be shown to be zeolites by their solubility in hydrochloric acid and by the cloudiness of the section when it is heated very gently.

## OPTICAL KEY FOR DETERMINING ROCK-FORMING MINERALS

**A. Determination of the Index of Refraction** *n* (of minerals imbedded in Canada balsam).

| | | | |
|---|---|---|---|
| 1. Relief and rough surface with the condenser as high as possible. | $n$ = about 2 and over. | 4. Relief only when the condenser is lowered to the limit. The band of light moves inward when the tube is raised. | $n$ = 1.6 to 1.55 |
| 2. Relief with the condenser lowered 1–2 mm. | $n$ = about 1.8 | 5. No relief whatever.............................. | $n$ = about 1.54 |
| 3. Relief only when the condenser is lowered still more. | $n$ = about 1.7 to 1.6 | 6. Relief with condenser very low. Band of light moves outward when tube is raised. | $n < 1.54$ |

***B. Determination of the Crystal System.***

| | | | | |
|---|---|---|---|---|
| 1. All sections remain dark when rotated between crossed nicols. (Exceptions due to optical anomalies: Speckled illumination, segmentation, lattice structure, but no regular double refraction. | (*a*) Without | crystal form, cleavage or other regular structure. | | **Amorphous** |
| | (*b*) With | | | **Cubic** |
| 2. Most or all sections are alternately light and dark when rotated between crossed nicols. Cross sections with the lowest interference colors or those that remain dark give a uniaxial interference figure in convergent polarized light except those in which the double refraction is too low and *those in which the cross opens a little anomalously.* | Sections with the least effect on polarized light have edges, cleavage or other regular structure at angles of | | 120°, 60° or 30° | **Hexagonal** |
| | | | 90° or 45° | **Tetragonal** |
| 3. All or most sections are alternately light and dark when rotated between crossed nicols. Sections with the lowest interference colors or those that do not become dark at all give a biaxial interference figure in convergent polarized light except those that are apparently uniaxial because of the small optic angle. | (*a*) Always parallel or symmetrical extinction | in those sections which give an interference figure symmetrical to a plane. | | **Orthorhombic** |
| | (*b*) Partly parallel, partly oblique extinction | | | **Monoclinic** |
| | (*c*) Always oblique extinction | | | **Triclinic** |

**ISOTROPI**

| Page | Group | Minerals | Chemical composition | Crystal system | Cleavage | Development | Sp. gr |
|---|---|---|---|---|---|---|---|
| 213 | | Perovskite | $CaTiO_3$ | C | (100) | Octahedral<br>Hexahedral<br>Granular | 4.0 |
| 213 | | Sphalerite | $ZnS$ | C | 110 | Granular | 3.9 to 4.2 |
| 214 | *Garnet Group* | **Almandine** | $Fe_3Al_2Si_3O_{12}$ | C | (110) | Dodecahedral<br>Less often tetragonal trisoctahedral<br>Granular | 4.0 to 4.3 |
| | | **Pyrope** | $(Mg\ Fe)_3Al_2Si_3O_{12}$ | | | | 3.75 |
| | | Grossularite | $Ca_3Al_2Si_3O_{12}$ | | | | 3.45 to 4.1 |
| | | **Topazolite** | $Ca_3Fe_2Si_3O_{12}$ | | | | |
| | | **Melanite** | $Ca_3Fe_2(Si\ Ti)_3O_{12}$ | | | | 4.3 |
| 218 | *Spinel Group* | Chrome spinel | $(Fe\ Mg)(Al\ Cr)_2O_4$ | C | | Octahedral<br>Granular | 4.1 to 4.5 |
| | | Iron spinel | $(Fe\ Mg)(Al\ Fe)_2O_4$ | | | | 3.9 |
| | | Spinel | $MgAl_2O_4$ | | | | 3.6 |
| 219 | | Periclase | $MgO$ Contains iron | C | 100 | Octahedral<br>Granular | 3.65 |
| 219 | | Boracite | $Mg_7Cl_2B_{16}O_{30}$ | C | | Hexahedral<br>Tetrahedral | 2.9 |
| 219 | | **Leucite** | $KAlSi_2O_6$ | C | | Tetragonal<br>trisoctahedral<br>Rounded | 2.5 |
| 220 | | Glass acid<br>basic | Variable | A | | | 2.25 to 2.7 |
| 222 | | **Analcite** | $NaAlSi_2O_6 + aq.$ | C | 100 | Granular<br>Tetragonal trisoctahedral | 2.20 |

MINERALS. TABLE 1

| Color | n | Solubility | Remarks |
|---|---|---|---|
| Gray<br>Violet<br>Brown | 2.38 | Only soluble in conc. sulphuric acid | Optical anomalies<br>Lamination |
| Yellow<br>Brown | 2.37 | Soluble in conc. nitric acid | Zinc coating on charcoal |
| Almost colorless to reddish | 1.76 to 1.81 | Difficultly soluble in hydrochloric acid<br>Easily attacked after melting | Often rich in inclusions<br>Siebstructure |
| Light red | 1.750 | | Kelyphite border |
| *Variable*<br>Frequently colorless<br>Reddish<br>Brownish | 1.750 to 1.784 | | Optical anomalies<br>Division into segments |
| Brown | 1.856 | | Zonal structure |
| Brown | approx. 2.0 | Not attacked by acids and molten alkali carbonate<br>Decomposed by potassium bisulphate | |
| Green | 1.750 | | |
| Colorless | 1.720 | | |
| Colorless<br>*Light green* | 1.736 | Difficultly *soluble* | Often altered to serpentine and brucite |
| Colorless | 1.667 | *Difficultly* soluble | *Optical anomalies*<br>Lattice structure |
| Colorless | 1.509 | Gives powdered silica with hydrochloric acid | Optical anomalies<br>Lattice structure<br>Inclusions |
| Colorless<br>Brownish | 1.49 to 1.63 | Variable | Often fluidal |
| Colorless | 1.488 | Forms gelatinous silica in hydrochloric acid | Optical anomalies<br>Segments |

**Explanation of the Tables.**

The first vertical column gives the page in the book on which the mineral is described. Under the heading "Chemical Composition" frequently only the principal constituents are given and the formula is simplified so that the chemical constitution of the mineral is expressed only in a general way. In the "Crystal System" column, A = amorphous, C = cubic, H = hexagonal, T = tetragonal, O = orthorhombic, M = monoclinic, Tr = triclinic. The symbols for the cleavage forms are written differently from the customary usage: a symbol in parenthesis indicates imperfect cleavage, without them only distinct cleavage, and underscored it is perfect cleavage. Sp. gr. = specific gravity, and *H at the top of a column is for hardness.*

The values given for specific gravity, index of refraction ($n$ or $\alpha$, $\beta$, $\gamma$) and double refraction are only average values and may vary greatly especially in mixed isomorphous groups. When such values have been accurately measured, as in the case of scapolite and epidote, the maximum and minimum are given.

Color also may vary within wide limits in one and the same mineral Only the colors that are most important for rocks are given in that column and then only those that can be observed in thin section. Pleochroism i even more variable than the regula color of the mineral. When it i characteristic and more or less constant it is indicated under the indices of refraction. Otherwise the *absorption formula, which is much mor* constant, is given. The character o the double refraction of the mineral i indicated under Ch*m* and that of th principal zone under Ch*z*.

In the column "Optical Orientation" the *b* axis is always given in biaxial crystals. It can then be seen at a glance whether the plane of the optic axes is parallel or perpendicular to the plane of symmetry in monoclinic minerals. The extinction angle is generally measured from the vertical axis; after the number indicates that it i

ISOTRO

| Page | Group | Minerals | Chemical composition | Crystal system | Cleavage | Development | Sp |
|---|---|---|---|---|---|---|---|
| 223 | **Sodalite Group** | **Sodalite** | $3NaAlSiO_4$ $+ NaCl$ | C | (110) | Dodecahedral<br>Granular | 2 |
| | | **Noselite** | $+ Na_2SO_4$ | | | | 2 |
| | | **Haüyne** | $+ (Na_2Ca)SO_4$ | | | | |
| 224 | | Opal | $SiO_2 + x$ aq. | A | | | 2 |
| 225 | | Fluorite | $CaF_2$ | C | 111 | Granular | 3 |

MINERALS.—*Continued.*

TABLE 2

| Color | $n$ | Solubility | Remarks |
|---|---|---|---|
| Colorless<br>Blue<br>(ellow, Green) | 1.483<br>1.495<br>1.504 | Form gelatinous silica with hydrochloric acid | *Regularly arranged* rod-like inclusions<br>Black corrosion borders<br>Often altered to zeolite<br>Difficultly fusible |
| Colorless | 1.46 | Soluble in potassium hydroxide | Index of refraction *variable*<br>Often anomalous double refraction |
| Colorless<br>Violet | 1.434 | With sulphuric acid it gives off hydrofluoric acid vapor | Phosphorescent when heated |

**Explanation of the Tables—Continued.**

toward the front or in the obtuse angle $\beta$; r means to the rear. The expressions "difficultly soluble" and "insoluble" refer to hydrochloric acid as a *solvent unless otherwise indicated*. The next column indicates the most important phenomena that are sometimes observed. Thus "optical anomalies" only means that the mineral is sometimes anomalous and not that it always occurs that way. The meaning of the various columns in table 15, which includes the feldspars, may be determined from the text. Remarks in *parentheses refer to rarer and differently* developed varieties except in the cleavage column as explained above and in the absorption column where the parentheses indicate that the absorption is not a characteristic ear mark of the mineral. $\rho \gg v$ or $v \gg \rho$ in the dispersion column indicates that the dispersion of the optic axes is extraordinarily strong.

ROCK-FORMING MINERALS, OTHER THAN THE CUBIC,
INDEX OF REFRACTION, DOUBLE

| Double refraction →<br>Index of refraction ↓ | | < 0.005 | to 0.010 | to 0.015 | to 0.020 |
|---|---|---|---|---|---|
| < 1.55 | + | Tridymite<br>Zeolites →<br>Apophyllite ↓ | Quartz<br>Gypsum | ← Zeolites | Hydromagnesit |
| | − | Nepheline<br>Apophyllite ↑ | Chalcedony<br>Cordierite<br>Zeolites → | ← Zeolites | |
| 1.55 to 1.60 | + | Pennine | Quartz<br>Chrysotile<br>Clinochlore → | Wagnerite<br>← Clinochlore | Alunite<br>Hydrargillite |
| | − | | Margarite<br>Beryl<br>Kaolin<br>Antigorite → | Scapolite →<br>← Antigorite | |
| 1.60 to 1.65 | + | Melilite ↓<br>Eudialyte | Celestite<br>Topaz → | Barite<br>← Topaz | Prehnite →<br>Pargasite |
| | − | Apatite<br>Melilite ↑<br>Eucolite | | Andalusite<br>Wollastonite | Tourmaline ↘<br>Monticellite ↓ |
| 1.65 to 1.70 | + | Zoisite<br>Thulite | Enstatite | Mosandrite | Lawsonite<br>Rinkite<br>Spodumene |
| | − | Riebeckite<br>Arfvedsonite<br>Orthite ↘ | Dumortierite<br>Gehlenite<br>Axinite<br>Margarite | Xanthophyllite<br>Prismatine | Monticellite ↑<br>Glaucophane |
| 1.70 to 1.80 | + | Clinozoisite →<br>Chloritoid → | Chrysoberyl<br>Staurolite<br>Serendibite | ← Clinozoisite<br>← Chloritoid | |
| | − | Vesuvianite<br>Sapphirine | Corundum | Epidote →<br>Cyanite →<br>Hypersthene | ← Cyanite |
| >1.80 | + | | Wurtzite | | |

CEPT THE FELDSPARS, ARRANGED ACCORDING TO
FRACTION, AND OPTICAL CHARACTER. TABLE 3

| 0.025 | to 0.030 | to 0.050 | to 0.075 | to 0.100 | >0.100 |
|---|---|---|---|---|---|
| te | Thomsonite | | | | |
| ite | | | | | |
| | | Anhydrite | | | |
| ite<br>.dite | | ← Scapolite<br>Pyrophyllite<br>Mica ↓ | Talc | | |
| hyllite<br>lite | Rosenbuschite | ← Prehnite<br>Pectolite<br>Humite | | | |
| ende<br>ite | Tremolite<br>Actinolite<br>Lazulite | Mica ↑ | | | Calcite<br>Dolomite<br>Magnesite |
| ite | Forsterite<br>Diopside<br>Jadeite | Olivine | | | |
| | | ↖ Tourmaline<br>Datolite | | | Aragonite |
| | Aegirine augite | Diaspore<br>Monazite | Astrophyllite | Xenotime | |
| | Låvenite<br>↖ Orthite | Piemontite<br>Aegirine | ← Epidote<br>Basaltic hornblende | | |
| | | | Zircon | Cassiterite<br>Pseudobrookite<br>Titanite → | Rutile<br>Brookite<br>← Titanite |
| | | Fayalite | Anatase | Goethite<br>Baddeleyite | Sulphur |

UNIAXIAL

| Page | Group | Minerals | Chemical *composition* | Crystal *system* | Cleavage | *Development* | Sp. gr. | H | Color |
|---|---|---|---|---|---|---|---|---|---|
| 227 | | **Rutile** | $TiO_2$ | T | 110<br>(100) | Prismatic<br>Granular | 4.25 | 6.5 | **Brow**<br>**Yellowi**<br>**Grayish-**<br>**violet** |
| 229 | | Anatase | $TiO_2$ | T | 111<br>001 | Granular<br>Tabular<br>Pyramidal | 3.85 | 6 | Colorle<br>Blue<br>Yellowi |
| 230 | | Cassiterite | $SnO_2$ | T | (100) | Granular<br>Pyramidal<br>Prismatic | 6.9 | 6.5 | **Yellow**<br>**Red-br**<br>to color |
| 230 | | Wurtzite | ZnS | H | $10\bar{1}0$ | Fibrous | 3.98 | 3.5 | *Yellow*<br>**Brown** |
| 230 | | **Zircon** | $ZrSiO_4$ | T | 110<br>(100) | Prismatic | 4.7 | 7.5 | Colorl |
| 231 | | Xenotime | $Y_2O_3$ phosphate containing $SO_3$ | T | 110 | Pyramidal<br>Prismatic | 4.6 | 6.5 | Colorl<br>Light<br>reddi |
| 232 | | Corundum | $Al_2O_3$ | H | | Granular<br>Pyramidal<br>*Tabular* | 4.0 | 9 | Colorl<br>Blu |
| 233 | | Vesuvianite | Calcium-aluminium silicate | T | | Short prismatic<br>Granular | 3.45 | 6.5 | Colorl<br>(Ros |
| 233 | **Gehlenite Group** | Gehlenite | $Ca_3Al_2Si_2O_{10}$ | T | 001 | Thick tabular<br>Isometric | 3.0 | 5.5 | Color<br>(Yello |
| | | Melilite | $Ca_4Si_3O_{10}$ | | | Thin tabular | 2.9 | | |
| 234 | **Tourmaline** | **Precious Tourmaline** | Aluminium silicate containing $B_2O_3$ | H | | Prismatic<br>Acicular | 3.0 to 3.25 | 7.5 | **Bl**<br>**Gre**<br>**Yello**<br>**Bro**<br>**Vio** |
| | | **Schorl** | | | | | | | |

MINERALS. TABLE 4

| $\alpha$ | $\gamma$ | $\gamma-\alpha$ | Chm | Chz | Solubility | Remarks | Minerals |
|---|---|---|---|---|---|---|---|
| 616 | 2.903 | 0.287 | + | + | Insoluble | Adamantine luster in reflected light<br>Frequently twinned and laminated<br>Absorption $\varepsilon>\omega$ | **Rutile** |
| 493 | 2.554 | 0.061 | − | (+) | Insoluble | Often adamantine luster in reflected light<br>Mottled color<br>Absorption $\omega>\varepsilon$ | Anatase |
| .997 | 2.093 | 0.096 | + | + | Insoluble | Adamantine luster in reflected light<br>Zonal structure<br>Absorption $\varepsilon>\omega$ | Cassiterite |
| >1.93 | | Low | + | + | Easily soluble in cold hydrochloric acid | Absorption $\varepsilon>\omega$ | Wurtzite |
| .931 | 1.993 | 0.062 | + | + | Insoluble | Sp. gr. = 4.0 in some varieties<br>Not decomposed in a bead of microcosmic salt | **Zircon** |
| .721 | 1.816 | 0.095 | + | + | Insoluble | Often decomposed in the rocks, then H = 4−5<br>Clouded | **Xenotime** |
| .760<br>ight<br>uish-<br>reen | 1.769<br>Blue | 0.009 | − | −<br>(+) | Insoluble | Mottled color<br>Absorption $\omega>\varepsilon$<br>Often zonal structure | Corundum |
| .701<br>to<br>.726 | 1.705<br>to<br>1.732 | 0.001<br>to<br>0.006 | − | − | Difficultly soluble in hydrochloric acid | Often anomalous interference color<br>Optical anomalies | Vesuvianite |
| | | | + | + | | | |
| .657 | 1.665 | 0.008 | − | | Form gelatinous silica with hydrochloric acid | Anomalous interference color | Gehlenite |
| .629 | 1.631 | 0.003 | − | + | | Peg structure<br>When colored $\varepsilon>\omega$ | Melilite |
| | | | + | − | | | |
| 620<br>to<br>651 | 1.640<br>to<br>1.685 | 0.017<br>to<br>0.034 | − | − | Insoluble | Weak absorption $\omega>\varepsilon$ | **Precious Tourmaline** |
| | | | | | | Strong absorption $\omega>\varepsilon$<br>Pleochroic halos | **Schorl** |

UNIAXIAL

| Page | Group | Minerals | Chemical composition | Crystal system | Cleavage | Development | Sp. gr. | H | Color |
|---|---|---|---|---|---|---|---|---|---|
| 236 | | **Apatite** | $Ca_5P_3O_{12}$ (Cl,F) | H | | Long prismatic Grains | 3.16 | 5 | Colorles<br>(Brown<br>yellow) |
| 238 | **Rhombohedral Carbonates** | **Calcite** | $CaCO_3$ | H | $10\bar{1}1$ | Granular Radial | 2.72 | 3 | Colorl |
| | | Dolomite | $CaMg(CO_3)_2$ | H | | Rhombo-*hedral* Granular | 2.95 | 4 | |
| | | Magnesite | $MgCO_3$ | H | | | 3.0 | 4.5 | |
| | | Siderite | $FeCO_3$ | H | | Granular Rhombo-hedral | 3.9 | 4 | Colorle<br>Yellowi |
| 242 | | Eudialyte (Eucolite) | Silicate containing $ZrO_2$ and $Ce_2O_3$ | H | (0001) | Grains | 3.0 | 5.5 | Colorle<br>(Reddi |
| 242 | **Scapolite Group** | **Marialite** | $Na_4Al_3Si_9O_{24}Cl$ | T | 110 | Prismatic Granular Columnar | 2.55 to 2.75 | 5.5 | Colorle |
| | | **Meionite** | $Ca_4Al_6Si_6O_{25}$ | T | | | | | |
| 243 | | Alunite | $KAl_3(OH)_6(SO_4)_2$ | H | 0001 | Rhombo-hedral | 2.7 | 4 | Colorle |
| 243 | | Beryl | $Be_3Al_2Si_6O_{18}$ | H | (0001) | Prismatic | 2.7 | 8 | Colorl<br>(Bluis |
| 244 | | Brucite | $Mg(OH)_2$ | H | 0001 | Tabular | 2.35 | 2.5 | Colorle |
| 244 | **Silica Group** | **Quartz** | $SiO_2$ | H | | Granular Pyramidal | 2.65 | 7 | Colorle |
| | | **Chalcedony** | | ? | | Fine fibrous | 2.60 | 6.5 | |
| | | **Tridymite** | | H | | Tabular | 2.3 | | |

| | $\gamma$ | $\gamma-\alpha$ | Chm | Chz | Solubility | Remarks | Minerals |
|---|---|---|---|---|---|---|---|
| 1 | 1.637 | 0.003 | − | − | Easily soluble | Absorption when colored $\varepsilon > \omega$ | **Apatite** |
| 7 | 1.659 | 0.172 | − | | Effervesces in cold acid | Twinning lamellæ parallel to $-\frac{1}{2}R$ frequent<br>(Absorption $\omega > \varepsilon$) | **Calcite** |
| 3 | 1.682 | 0.179 | − | | Effervesce in warm acid | (Absorption $\omega > \varepsilon$)<br>Index and double refraction increase with the content of iron | **Dolomite** |
| 5 | 1.717 | 0.202 | − | | | | Magnesite |
| 3 | 1.872 | 0.239 | − | | | Frequently altered to limonite | Siderite |
| 2<br>7) | 1.610<br>(1.620) | 0.002<br>(0.003) | +<br>(−) | | Gelatinizes with hydrochloric acid | Absorption when colored $\omega > \varepsilon$<br>Easily fusible | Eudialyte<br>(Eucolite) |
| 2<br>8 | 1.555<br>to<br>1.597 | 0.013<br>to<br>0.039 | − | − | Not attacked by hydrochloric acid | Precipitate of silver chloride when treated with HF and $AgNO_3$ | **Marialite** |
| | | | | | Easily decomposed by hydrochloric acid | | **Meionite** |
| 2 | 1.592 | 0.020 | + | | Difficultly soluble in sulphuric acid | Soluble in water after ignition | Alunite |
| 2 | 1.577 | 0.005 | − | − | Insoluble | Often apparently biaxial | Beryl |
| 0 | 1.581 | 0.021<br>(?) | + | − | Easily soluble | Anomalous interference colors<br>Brown with $AgNO_3$ | Brucite |
| 4 | 1.553 | 0.009 | + | + | Entirely soluble in hydrofluoric acid | Frequently cataclastic | **Quartz** |
| 2 | 1.543 | 0.011 | + | − | | Generally apparently biaxial 2V up to 40° | Chalcedony |
| 6 | 1.478 | 0.002 | + | − | | Frequently twins<br>Anomalous interference, segments 2E about 65° | Tridymite |

## UNIAXIA

| Page | Group | Minerals | Chemical *composition* | Crystal *system* | Cleavage | Development | Sp. gr. | H | Co |
|---|---|---|---|---|---|---|---|---|---|
| 249 | | **Nepheline** | $NaAlSiO_4$ | H | $(10\bar{1}0)$<br>$(0001)$ | Short prismatic<br>Granular | 2.60 | 6 | Colo |
| 250 | | Apophyllite | Ca, K silicate containing water | T | 001 | Scaly | 2.35 | 5 | Colo |
| 250 | | Chabazite | $CaAl_2Si_4O_{12}+6aq.$<br>Contains Na | H | $10\bar{1}1$ | Rhombohedral | 2.1 | 4 | Colo |
| 250 | | Cancrinite | $NaAlSiO_4+CO_2$ and aq. | H | $10\bar{1}0$<br>$(0001)$ | Columnar | 2.45 | 5.5 | Colo |
| 251 | | Hydronephelite *(Ranite)* | $HNa_2Al_3Si_3O_{12}+3$ aq. | H | $(10\bar{1}0)$ | Confused columnar | 2.25 | 5 | Colo |

IINERALS.—*Continued.*

TABLE 6

| | $\gamma$ | $\gamma-\alpha$ | Chm | Chz | Solubility | Remarks | **Minerals** |
|---|---|---|---|---|---|---|---|
| 8 | 1.542 | 0.004 | – | – | Gelatinizes easily with hydrochloric acid | Frequently altered<br>Optical anomalies | **Nepheline** |
| 5 | 1.537 | 0.002 | +<br>(–) | –<br>(+) | Forms powdered silica when treated with hydrochloric acid | Cloudy after ignition, *Anomalous* interference colors, Segments | Apophyllite |
| out 1.50 | | Low | –<br>(+) | | Gelatinizes with hydrochloric acid | Often anomalous interference Segments | Chabazite |
| 6 | 1.522 | 0.025 | – | – | Gelatinizes with weak effervescence in hydrochloric acid | Cloudy after ignition<br>Frequently altered<br>Pseudomorph after nepheline | Cancrinite |
| 4 | 1.496 | 0.012 | + | + | Gelatinizes with hydrochloric acid | Pseudomorph after nepheline<br>(Spreustein) | Hydronephelite<br>(Ranite) |

BIAXIAL

| Group | Minerals | Chemical composition | Crystal system | Cleavage | Development | Sp. gr. | H | Color | $\alpha$ | $\beta$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | Brookite | $TiO_2$ | O | 010 | Tabular ‖ *{100}* | 4.0 | 6 | Brownish-red<br>Yellowish<br>($\mathfrak{c} > \mathfrak{b} = \mathfrak{a}$) | 2.583 | 2. |
| | Goethite | $FeO_2H$ | O | 010 | Fine acicular ‖ {010} | 4.4 | 5 | Brown<br>Yellowish | Above | |
| | Pseudo-brookite | $Fe_4Ti_3O_{12}$ | O | (010) | Tabular ‖ {100} | 5.0 | 6 | Brownish-red<br>Hardly transparent<br>$\mathfrak{b} > \mathfrak{c} = \mathfrak{a}$ | | Ve<br>hi |
| | Sulphur | S | O | | Pyramidal<br>Granular | 2.05 | 2 | Yellowish | 1.950 | 2. |
| | Baddeleyite | $ZrO_2$ | M | 001 | Prismatic along the b axis | 6.0 | 6.5 | Greenish to brown<br>$\mathfrak{a} = \mathfrak{c} > \mathfrak{b}$ | High | |
| | Titanite | $Ca(SiTi)O_5$ | M | 110 (134°) | Flat prismatic ‖ {123} or {110}<br>Grains | 3.5 | 6 | Colorless<br>Yellowish<br>Reddish<br>($\mathfrak{c} > \mathfrak{b} > \mathfrak{a}$) | 1.888 to 1.913 | 1.<br>t<br>1. |
| | Lievrite | $HCaFe_2Fe Si_2O_9$ | O | (010) | Prismatic<br>Columnar<br>Fibrous | 4.0 | 6 | Usually transparent parallel to *a* only<br>Brownish-green | About | |
| | Monazite | $CePO_4$ | M | 001 | Thick tabular ‖ {100}<br>Grains | 5.15 | 5.5 | Colorless<br>Yellowish<br>Brownish<br>($\mathfrak{b} > \mathfrak{c} = \mathfrak{a}$) | 1.796 | 1. |
| | Låvenite | Silicate containing $ZrO_2$, $TiO_2$ $Nb_2O_5$ | M | (100) | Prismatic ‖c<br>Tabular ‖ {100} | 3.5 | 6 | Yellow to colorless<br>$\mathfrak{c} > \mathfrak{b} > \mathfrak{a}$ | Bright yellow | Ab<br>1.<br>Yel<br>is<br>gre |
| | Chryso-beryl | $BeAl_2O_4$ | O | (010) | Isometric grains | 3.73 | 8.5 | Light green<br>Colorless | 1.747<br>Reddish | 1.<br>Yel<br>is |

MINERALS. TABLE 7

| $\gamma$ | $\gamma-\alpha$ | Ch*m* | Chz | 2V | 2E | Disper-*sion* | Optical orien-*tation* | Solubility | Remarks | Minerals |
|---|---|---|---|---|---|---|---|---|---|---|
| .741 | 0.158 | + | − | Very small | | Crossed optic planes | $a=\mathfrak{c}$<br>$b=\mathfrak{a}(\rho)$<br>$b=\mathfrak{b}(\upsilon)$ | Insoluble | Pleochroism<br>Weak adamantine luster | Brookite |
| 2.5 | High | − | ± | Medium | | Crossed optic planes | $b=\mathfrak{a}$<br>$c=\mathfrak{c}(\rho)$<br>$a=\mathfrak{c}(\upsilon)$ | Difficultly soluble | Pleochroism brown to yellow Adamantine luster | Goethite |
| | High | + | − | Large | | $\upsilon>\rho$ | $a=\mathfrak{c}$<br>$b=\mathfrak{a}$ | Soluble in hot $H_2SO_4$ | Adamantine luster | Pseudo-brookite |
| .240 | 0.290 | − | | 70° | | | $a=\mathfrak{a}$<br>$b=\mathfrak{b}$ | Soluble in KOH | Opaque to Roentgen rays | Sulphur |
| | High | − | ± | 70° | | | $c:\mathfrak{a}=13°$ f<br>$b=\mathfrak{b}$ | Insoluble | Always twinned | Baddeley-ite |
| .978 to .054 | 0.090 to 0.141 | + | | | 45° to 60° | $\rho\geqslant\upsilon$ | $c:\mathfrak{c}=51°$ f<br>$b=\mathfrak{b}$ | Soluble in hot $H_2SO_4$ | Twins<br>Insect's eggs | **Titanite** |
| 1.89 | Un-known | + | + | | | | | Gelatinizes with HCl | Easily fusible to black magnetic glass | Lievrite |
| 1.841 | 0.045 | + | + | | 25° | $\upsilon>\rho$ | $c:\mathfrak{c}=4°$ f<br>$b=\mathfrak{a}$ | White residue with HCl | Spectroscopic test | Monazite |
| range | About 0.03 | − | − | 80° | | | $c:\mathfrak{a}=20°$ r<br>$b=\mathfrak{b}$ | Attacked with difficulty | Easily fusible<br>Twins | Låvenite |
| .756<br>Green | 0.009 | + | | 0° to 90° | | $\rho\geqslant\upsilon$<br>$\upsilon\geqslant\rho$ | | Insoluble | Dispersion extremely variable | Chryso-beryl |

**BIAXIAL**

| Page | Group | Minerals | Chemical composition | Crystal system | Cleavage | Development | Sp. gr. | H | Color | α | β |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 258 | Epidote Group | Zoisite α | $HCa_2Al_3Si_3O_{13}$ | O | 100 and (001) | Prismatic along the b axis Granular | 3.3 | 6 | Colorless Light reddish | 1.697 | 1.699 |
| | | Zoisite β | | | | | | | | | About 1.7 |
| | | Clinozoisite | | M | 001 and (100) 115½° | | 3.35 | 7 | | 1.718 to 1.731 | 1.720 to 1.754 |
| | | Epidote (Pistazite) | $HCa_2(AlFe)_3Si_3O_{13}$ | | | | 3.4 | | Yellowish Greenish $\mathfrak{c} > \mathfrak{b} > \mathfrak{a}$ | | |
| | | Piemontite | $HCa_2(AlFeMn)_3Si_3O_{13}$ | | | | | | Red Violet Yellow $\mathfrak{c} < \mathfrak{b} > \mathfrak{a}$ | Orange | Violet |
| | | Orthite (Allanite) | $HCa_2(AlFeCe)_3Si_3O_{13}$ | | | | 3.6 to 3.8 | 5.5 | Brown (Pale reddish) $\mathfrak{c} > \mathfrak{b} > \mathfrak{a}$ | | About 1.78 |
| 266 | | Staurolite | $HFeAl_5Si_2O_{13}$ | O | (010) | Prismatic Prism angle 129° | 3.6 to 3.8 | 7.5 | Yellow, Reddish brown $\mathfrak{c} > \mathfrak{b} = \mathfrak{a}$ | 1.736 | 1.741 |
| 267 | | Diaspore | $AlO_2H$ | O | 010 | Platy ∥ {010} | 3.5 | 6 | Colorless (Bluish) | 1.702 | 1.722 |
| 267 | | **Cyanite** | $Al_2SiO_5$ | Tr | *100*<br>(010)<br>001 | *Prismatic* ∥$\mathfrak{c}$ Tabular ∥ {100} | 3.6 | 4–7 | Colorless Bluish | 1.712 Colorless | 1.720 Pale violet |
| 268 | | Sapphirine | $Mg_5Al_{12}Si_2O_{27}$ | M | | Tabular ∥ {010} Granular | 3.5 | 7.5 | Very pale blue to bluish green | 1.706 Colorless | 1.709 Very |
| 269 | | Serendibite | Aluminium silicate containing $B_2O_3$ (CaMgFe)O | Tr | | Plates *Grains* | 3.4 | 7 | Blue *Pleochroic* | | About 1.7 |
| 269 | | Prismatine | $MgAl_2SiO_6$ | O | 100 (81°) | Prismatic Columnar Radial | 3.3 | 6.5 | Colorless Yellowish | 1.669 | 1.680 |

MINERALS.—*Continued.* TABLE 8

| $\gamma$ | $\gamma-\alpha$ | Chm | Chz | 2V | 2E | Dispersion | Optical orientation | Solubility | Remarks | Minerals |
|---|---|---|---|---|---|---|---|---|---|---|
| 702 | 0.005 | + | − | | 90° | $\upsilon \gg \rho$ | c = $\mathfrak{c}$<br>b = $\mathfrak{a}$ | | Anomalous interference color, Obscure twinning lamination | ***Zoisite α*** |
| | Very low | + | $\pm$ | | 50° | $\rho > \upsilon$ | c = $\mathfrak{c}$<br>b = $\mathfrak{b}$ | | | **Zoisite β** |
| 723 to 768 | 0.005 to 0.061 | + | $\pm$ | 80° | | $\upsilon \gg \rho$ | c : $\mathfrak{a}$ = 2° f<br>b = $\mathfrak{b}$<br>$\mathfrak{c}$:a about 30° | Gelatinize in HCl after melting | | **Clinozoisite** |
| | | − | $\pm$ | 70° | | $\rho > \upsilon$ | c : $\mathfrak{a}$ = 3° r<br>b = $\mathfrak{b}$<br>$\mathfrak{c}$:a about 30° | | | **Epidote** (Pistazite) |
| mine | | −<br>+ | +<br>− | Variable | | | c : $\mathfrak{a}$ = 2° to 7° r<br>b = $\mathfrak{b}$<br>$\mathfrak{c}$:a about 30° | | Speckled interference colors | Piemontite |
| | 0.002 to 0.030 | − | $\pm$ | 70° | | | c : $\mathfrak{a}$ = 36° r<br>b = $\mathfrak{b}$<br>$\mathfrak{a}$:a about 30° | Difficultly soluble in HCl | Surrounded by pleochroic halo | Orthite (Allanite) |
| 746 | 0.010 | + | + | 85° to 90° | | Weak $\rho > \upsilon$ | c = $\mathfrak{c}$<br>b = $\mathfrak{a}$ | Insoluble | Pleochroic halos<br>Twins | **Staurolite** |
| 750 | 0.048 | + | − | 85° | | $\upsilon > \rho$ | a = $\mathfrak{c}$<br>b = $\mathfrak{b}$ | Insoluble | | **Diaspore** |
| 728 ale lue | 0.012 to 0.016 | − | + | 82° | | $\rho > \upsilon$ | $\mathfrak{a}$ about ⊥ {100}<br>c : $\mathfrak{c}$ = +30° | Insoluble | Twinning ‖ {100}<br>Fibrous fracture ‖ {001} | **Cyanite** |
| 711 blue | 0.005 | − | | 69° | | $\upsilon > \rho$ | c : $\mathfrak{a}$ = 81° f<br>b = $\mathfrak{b}$ | Insoluble | Infusible | Sapphirine |
| | 0.006 | + | | Large | | | c : $\mathfrak{a}$ about 40° | Insoluble | Always twin lamellæ<br>Infusible | Serendibite |
| 682 | 0.013 | − | − | | 65° | $\rho > \upsilon$ | c = $\mathfrak{a}$<br>b = $\mathfrak{c}$ | Insoluble | Infusible | **Prismatine** |

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| Page | Group | Minerals | Chemical composition | Crystal system | Cleavage | Development | Sp. gr. | H | Color | $\alpha$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 269 | | Astrophyllite | Alkali iron silicate containing $TiO_2$ | O | 100 | Tabular Prismatic ‖b | 3.3 | 3.5 | Orange Brownish Red<br>$\mathfrak{a} > \mathfrak{b} > \mathfrak{c}$ | 1.678 Deep orange | 1<br>O |
| 269 | Brittle Micas | **Chloritoid** | Basic aluminium silicate containing (FeMgCa)O | Tr | 001 (110) | Tabular ‖ {001} Platy | 3.5 | 6.5 | Bluish-green Colorless<br>$\mathfrak{b} > \mathfrak{a} > \mathfrak{c}$ | Olive-green | 1<br>I |
| | | Xanthophyllite | | M | | | 3.1 | 5 | Colorless Light green<br>$\mathfrak{a} > \mathfrak{b} = \mathfrak{c}$ | 1.649 | 1 |
| 272 | | Margarite | $H_2CaAl_4Si_2O_{12}$ | M | 001 | Tabular Flaky | 3.0 | 4 | Colorless | | |
| 272 | Olivine Group | **Forsterite** | $Mg_2SiO_4$ | O | 010<br>(100) | Short prismatic ‖c<br>Grains | 3.2 to 3.6 | 7 | Colorless | | 1 |
| | | **Olivine** | $(MgFe)_2SiO_4$ | | | | | | | 1.661 | 1 |
| | | Fayalite | $Fe_2SiO_4$ | | | | | 6.5 | Yellow Brownish<br>$\mathfrak{b} > \mathfrak{c} = \mathfrak{a}$ | 1.824 | 1 |
| | | Monticellite | $CaMgSiO_4$ | | | | 3.2 | 5.5 | Colorless | 1.651 | 1 |

MINERALS.—*Continued.* TABLE 9

| $\gamma$ | $\gamma-\alpha$ | Chm | Chz | 2V | 2E | Dispersion | Optical orientation | Solubility | Remarks | Minerals |
|---|---|---|---|---|---|---|---|---|---|---|
| 1.733<br>Light yellow | 0.055 | + | + | Very large | | $\rho > \upsilon$ | $c = \mathfrak{b}$<br>$b = \mathfrak{c}$ | Difficultly soluble | Easily fusible<br>Star-shaped aggregates | **Astrophyllite** |
| Greenish-yellow | 0.003 to 0.015 | + | − | | 65° to 120° | $\rho \gg \upsilon$ | $c : \mathfrak{c} = 0°–15°$<br>$b : \mathfrak{a} = 0°–25°$ | *Insoluble* | Twinning after the mica law<br>Scarcely fusible | **Chloritoid** |
| 1.661 | 0.012 | − | + | | 0° to 25° | $\upsilon > \rho$ | $c = \mathfrak{a}$<br>$b = \mathfrak{b}$ | | | **Xanthophyllite** |
| | 0.009 | − | + | Large | | | $c : \mathfrak{a} = 6\frac{1}{2}°$<br>$b = \mathfrak{c}$ | Quite difficultly soluble | Twinning lamellæ | **Margarit** |
| 1.697 | *About* 0.03 | + | +<br>− | 85° | | Weak<br>$\upsilon > \rho$ | $a = \mathfrak{c}$<br>$b = \mathfrak{a}$ | Gelatinize slowly with cold HCl | Alteration into serpentine | **Forsterit** |
| | 0.036 | +<br>(−) | | About 90° | | Distinct<br>$\upsilon > \rho$<br>$(\rho > \upsilon)$ | | | | **Olivine** |
| 1.874 | 0.050 | − | | 50° | | $\rho > \upsilon$ | | | | **Fayalite** |
| 1.668 | 0.017 | − | | 38° | | $\rho > \upsilon$ | | | | **Monticellite** |

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| ge | Group | Minerals | Chemical composition | Crystal system | Cleavage | Development | Sp. gr. | H | Color | α | β |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 7 | Pyroxene Group | **Enstatite** (**Bronzite**) | $MgSiO_3$ * | O | 110<br>100<br>(010) | | 3.1 to 3.5 | | Colorless | 1.660 to 1.716 Red-brown | 1.665 to 1.725 Yellowish-brown |
| | | **Hypersthene** | $(MgFe)SiO_3$ | | | | | | Brown | | |
| | | **Diopside** | $(MgCaFe)SiO_3$ | | | | | 5.5 | Colorless Green Scarcely pleochroic | 1.671 to 1.699 | 1.678 to 1.706 |
| | | **Diallage** | | | | Short prismatic along *the c axis* | 3.3 | | Greenish Brownish | 1.679 Greenish | 1.681 Yellowish |
| | | Fassaite | | | | | | | Green | Green | Yellow-*green* |
| | | **Augite** | $(MgFe)\ (AlFe)_2$ $SiO_6$ | M | 110<br>87° | | | | Greenish Brownish | 1.698 to 1.706 | 1.704 to 1.712 |
| | | **Aegirine-augite** | | | | | 3.4 to 3.5 | 6 | Green Violet with content of $TiO_2$ | Green | **Bright green** |
| | | **Aegirine** (Acmite) | $NaFeSi_2O_6$ | | | | | | Sap green (Brown) | 1.763 Grass-green (Brown) | 1.799 **Light green (Light brown)** |
| | | Spodumene* | $LiAlSi_2O_6$ | | | **Prismatic** to tabular ∥ {100} | 3.1 | 6.5 | Colorless | 1.660 | **1.666** |
| | | **Lawsonite** | $H_4CaAl_2Si_2O_{10}$ | O | 010<br>001 | **Tabular** ∥ {001}<br>**Prismatic** ∥ c | 3.1 | 8.5 | Colorless | 1.665 | **1.669** |

MINERALS.—*Continued.* TABLE 10

| $\gamma$ | $\gamma-\alpha$ | Ch*m* | Ch*z* | 2V | 2E | *Dispersion* | *Optical orientation* | *Solubility* | Remarks | Minerals |
|---|---|---|---|---|---|---|---|---|---|---|
| 670 to 729 ray-een | 0.010 to 0.013 | + | | 77° to 90° | | $\upsilon > \rho$ | c = $\mathfrak{c}$<br>b = $\mathfrak{a}$ | Difficultly soluble even in HF | Infusible<br>For FeO = 10 %<br>2V = 90° | **Enstatite (Bronzite)** |
| | | — | | 90° to 50° | | $\rho > \upsilon$ | | | Difficultly fusible | **Hypersthene** |
| 700 to 727 | *0.029* | | | 59° | 109° | $\rho > \upsilon$ | c: $\mathfrak{c}$ = 39°–44° f<br>b = $\mathfrak{b}$ | | Difficultly fusible | ***Diopside*** |
| 703 enish | 0.024 | | + | | | | c: $\mathfrak{c}$ = 40° f<br>b = $\mathfrak{b}$ | | Twinning lamellæ and parting {100} and {001} | **Diallage** |
| een | 0.024 | + | | | | | c: $\mathfrak{c}$ = 45° f<br>b = $\mathfrak{b}$ | | Strong dispersion of the bisectrices | Fassaite |
| 723 to 728 | 0.022 to 0.025 | | | Variable | | | c: $\mathfrak{c}$ = 54° f<br>b = $\mathfrak{b}$ | | Frequently a few twinning lamellæ | **Augite** |
| enish-llow | | | | | | | c: $\mathfrak{c}$ = 60° f<br>b = $\mathfrak{b}$ | | Strong dispersion of the bisectrices | **Aegirine-augite** |
| 813 llow-sh een-sh) | 0.050 | — | — | 64° | | | *c: $\mathfrak{c}$ = 94° f*<br>b = $\mathfrak{b}$ | | Easily fusible | **Aegirine** (Acmite) |
| 676 | 0.016 | + | + | 60° | | $\upsilon > \rho$ | c: $\mathfrak{c}$ = 25°<br>b = $\mathfrak{b}$ | | Easily fusible with intumescence | Spodumene |
| 684 | 0.019 | + | | 84° | | $\rho > \upsilon$ | c = $\mathfrak{c}$<br>b = $\mathfrak{b}$ | Gelatinizes with HCl after melting | Easily fusible<br>Twins | Lawsonite |

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| Page | Group | Minerals | Chemical composition | | Crystal system | Cleavage | Development | Sp. gr. | H | Color | $\alpha$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 287 | Amphibole Group | Anthophyllite (Gedrite) | (MgFe)-$SiO_3$ containing $Al_2O_3$ | Containing hydroxyl | O (?) | 100<br>110<br>(010) | Columnar {110} = 124°<br>Flaky<br>Fascicular | 3.1 | 5.5 | Colorless<br>Light brownish<br>Reddish<br>($\mathfrak{c} > \mathfrak{b} > \mathfrak{a}$) | 1.633 |
| | | Actinolite (Tremolite) | (MgFeCa) $SiO_3$ | | M | 110<br>124°<br>(001) | Prismatic along the c axis | 3.0 | 5.5 to 6 | Colorless<br>Light green | 1.607 |
| | | Pargasite | (MgFeCa) $Al_2SiO_6$ | | | | | 3.1 to 3.2 | | Light green (Brownish) | 1.616 |
| | | Green hornblende | | | | | | | | Green, Bluish-green, Brownish-green<br>$\mathfrak{c} > \mathfrak{b} > \mathfrak{a}$ | 1.629<br>Yellowish |
| | | Brown hornblende | (MgFeCa) $(AlFe)_2$-$SiO_6$ | | | | | | | Brown<br>$\mathfrak{c} = \mathfrak{b} > \mathfrak{a}$ | Yellowish |
| | | Basaltic hornblende | Contains $TiO_2$ | | | | | 3.3 | | Red brown<br>Yellowish-brown<br>Deep brown<br>$\mathfrak{c} > \mathfrak{b} > \mathfrak{a}$ | 1.680<br>Yellowish-brown |
| | | Glaucophane | NaAl-$Si_2O_6$ | | | | | 3.1 | | Light blue | 1.621<br>Light yellowish |
| | | Crocidolite | | | | | Fibrous<br>Resembles asbestos | | | Light blue | Blue |
| | | Riebeckite | NaFe-$Si_2O_6$ | | | | Short prismatic<br>Irregular shreds | 3.4 | 5 | Deep blue<br>$\mathfrak{a} > \mathfrak{b} > \mathfrak{c}$ | Blackish-blue |
| | | Arfvedsonite | | | | | | 3.5 | | Bluish-green<br>$\mathfrak{a} > \mathfrak{b} > \mathfrak{c}$ | Greenish-blue |
| 295 | | Dumortierite | $Al_8Si_3O_{18}$ containing boron | | O | 100 | Acicular ∥ c | 3.3 | 7 | Violet<br>Blue | 1.678<br>Bluish-violet |

MINERALS.—*Continued.* TABLE 11

| | $\gamma-\alpha$ | Chm | Chz | 2V | 2E | Dispersion | Optical orientation | Solubility | Remarks | Minerals |
|---|---|---|---|---|---|---|---|---|---|---|
| 57 | 0.024<br>Variable | +<br>− | + | Very large | | $\upsilon>\rho$<br>$(\rho>\upsilon)$ | c = $\mathfrak{c}$<br>b = $\mathfrak{b}$ | Attacked with difficulty | Pleochroic halos | Anthophyllite (Gedrite) |
| 34 | 0.027 | − | | 80° | | $\upsilon>\rho$ | c: $\mathfrak{c}$ = 10°–20° f<br>b = $\mathfrak{b}$ | | Very weakly pleochroic at best | **Actinolite** (Tremolite) |
| 35 | 0.019 | + | | 55° | 97° | $\rho>\upsilon$ | c: $\mathfrak{c}$ = 18° f<br>b = $\mathfrak{b}$ | | Short thick prisms | **Pargasite** |
| 53<br>e-<br>vn<br>ep<br>en | 0.024 | − | | 84° | | $\upsilon>\rho$ | c: $\mathfrak{c}$ = 12°–20° f<br>b = $\mathfrak{b}$ | | Pleochroic halos | **Green hornblende** |
| vn | About 0.025 | | | | | | c: $\mathfrak{c}$ = 14° f<br>b = $\mathfrak{b}$ | | | **Brown hornblende** |
| 2<br>p<br>vn | 0.072 | | | 80° | | | c: $\mathfrak{c}$ = 10°–0° f<br>b = $\mathfrak{b}$ | | Magmatic resorption<br>Strong dispersion | **Basaltic hornblende** |
| 39<br>lue | 0.018 | | | 50° | 85° | | c: $\mathfrak{c}$ = 4°–6° f<br>b = $\mathfrak{b}$ | | | **Glaucophane** |
| st<br>r-<br>ı | 0.025 | + | | | 95° | | c: $\mathfrak{a}$ = 18°–20° f<br>b = $\mathfrak{b}$ | | Easily fusible | Crocidolite |
| ih-<br>n | 0.003 | − | − | | Very large | $\upsilon>\rho$ | c: $\mathfrak{a}$ = 5° r<br>b = $\mathfrak{b}$ | | Strong dispersion of the bisectrices | Riebeckite |
| sh-<br>n | Low | ? | | | Very large | | c: $\mathfrak{a}$ = 14° r<br>b = $\mathfrak{b}$ | | Very easily fusible | Arfvedsonite |
| 9<br>r- | 0.011 | − | − | 30° | 54° | $\rho\gtrless\upsilon$ | c = $\mathfrak{a}$<br>b = $\mathfrak{b}$ | Insoluble | Decolorised by strong ignition<br>Infusible | Dumortierite |

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| Page | Group | Minerals | Chemical composition | Crystal system | Cleavage | Development | Sp. gr. | H | Color | α | β |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 295 | | Axinite | Aluminium silicate containing boron | Tr | (110) | *Wedge shape*<br>Granular | 3.3 | 6.5 | *Colorless*<br>Light violet | 1.672<br>Colorless | 1.67<br>Ligh<br>viole |
| 295 | | Rinkite | *Cerium silicate* containing $TiO_2$ and Fl | M | 100 | *Thick* tabular ‖ {100} | 3.46 | 5 | Colorless<br>Yellowish<br>$\mathfrak{c} = \mathfrak{b} > \mathfrak{a}$ | 1.665 | 1.66 |
| 295 | | **Sillimanite** | $Al_2SiO_5$ | O | 100 | Acicular \| c | 3.24 | 6.5 | Colorless | 1.656 | 1.65 |
| 296 | | Datolite | $HCaBSiO_5$ | M | | Granular<br>Fibrous ‖ b | 3.0 | 5 | Colorless | 1.626 | 1.65 |
| 297 | | Mosandrite | Similar to rinkite. Contains $ZrO_2$ | M | 100 | Tabular ‖ {100} | 3.1 | 4 | Colorless<br>(Yellowish) | 1.646<br>(Greenish) | 1.64<br>(Brow<br>ish) |
| 297 | | Barite | $BaSO_4$ | O | 001<br>$\overline{110}$ | Granular<br>Platy ‖ {001} | 4.5 | 3.5 | Colorless | 1.637 | 1.63 |
| 297 | | **Andalusite** | $Al_2SiO_5$ | O | 110<br>91° | Prismatic ‖ c | 3.2 | 7.5 | Colorless<br>Reddish | *1.622*<br>Rose | 1.63<br>Color |
| 298 | | Lazulite | $H_2(FeMg)$<br>$Al_2P_2O_9$ | M | | Pyramidal | 3.0 | 5 | Blue | 1.603<br>Colorless | 1.62<br>Azur |
| 299 | | Carphulite | $H_4MnAl_2Si_2O_{10}$ | M | (010) | Acicular<br>Fine fibrous | 2.9 | 5 | Yellow | 1.62<br>Yellowish | |
| 299 | | **Prehnite** | $H_2Ca_2Al_2$<br>$Si_3O_{12}$ | O | 001<br>(001) | Tabular ‖ {001}<br>Fibrous<br>Rosettes | 2.9 | 6.5 | Colorless | 1.616<br>Very | 1.62 |
| 299 | | Celestite | $SrSO_4$ | O | 001<br>(110) | Granular<br>Fibrous | 3.95 | 3.5 | Colorless | 1.622 | 1.62 |

MINERALS.—*Continued.* TABLE 12

| $\gamma$ | $\gamma-\alpha$ | Ch*m* | Ch*z* | 2V | 2E | Dispersion | Optical orientation | Solubility | Remarks | Minerals |
|---|---|---|---|---|---|---|---|---|---|---|
| 1.681<br>Colorless | 0.009 | − |  | 72° |  | $\upsilon > \rho$ |  | Insoluble | Test for boron | **Axinite** |
| 1.681 | 0.016 | + | $\pm$ |  | 80° | $\upsilon \geqslant \rho$ | $c:\mathfrak{b} = 7°$ r<br>$b = \mathfrak{a}$ | Easily decomposed | Twinning lamellæ ∥ {100}<br>Fuses easily | **Rinkite** |
| 1.677 | 0.021 | + | + | 20° to 30° | 35° to 55° | $\rho \geqslant \upsilon$ | $c = \mathfrak{c}$<br>$b = \mathfrak{a}$ | Insoluble | Often very fine fibrous | **Sillimanite** |
| 1.670 | 0.044 | − |  | 74° |  | $\rho > \upsilon$ | $c:\mathfrak{a} = 4°$ r<br>$b = \mathfrak{b}$ | Gelatinizes readily in HCl | Test for boron | **Datolite** |
| 1.658<br>Light<br>ellow) | 0.012 | + | − | 70° |  | $\rho \geqslant \upsilon$ | $c:\mathfrak{a} = 2°$<br>$b = \mathfrak{b}$ | Easily decomposed | Twinning lamellæ ∥ {100}<br>Fuses easily | **Mosandrite** |
| .649 | 0.012 | + |  | 37° | 63° | $\upsilon > \rho$ | $a = \mathfrak{c}$<br>$b = \mathfrak{b}$ | Soluble in warm $H_2SO_4$ |  | **Barite** |
| .643<br>less | 0.011 | − | − | 84° |  |  | $c = \mathfrak{a}$<br>$b = \mathfrak{b}$ | Insoluble | Pleochroic halos<br>Chiastolite | **Andalusite** |
| .639<br>blue | 0.036 | − | − | 69° |  | $\upsilon \geqslant \rho$ | $c:\mathfrak{a} = 9°$ r<br>$b = \mathfrak{b}$ | Attacked with difficulty | Decolorizes giving off water upon ignition | **Lazulite** |
| lorless | 0.022 | − | + | 60° |  |  | $c:\mathfrak{c} = 3°$<br>$b = \mathfrak{a}$ | Attacked with difficulty |  | **Carpholite** |
| .649<br>riable | 0.033 | + | − | Variable |  |  | $c = \mathfrak{c}$<br>$b = \mathfrak{b}$ | Gelatinizes with HCl after melting | Optical anomalies<br>Parquet forms | **Prehnite** |
| .631 | 0.009 |  | + | About 90° |  |  | $c = \mathfrak{c}$<br>$b = \mathfrak{b}$ | Soluble only in hot $H_2SO_4$ | Fusible<br>Colors flame red | **Celestite** |

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| Page | Group | Minerals | Chemical composition | Crystal System | Cleavage | Development | Sp. gr. | H | Color | α | β |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 299 | | Aragonite | $CaCO_3$ | O | | Columnar ∥ c | 2.95 | 4 | Colorless | 1.530 | 1.6 |
| 299 | Wollastonite Group | Rosenbuschite | Silicate containing $ZrO_2$, $TiO_2$ $La_2O_3$ | M | 001<br>(100) | Radial ∥ b axis | 3.3 | 5.5 | Yellowish | | Ab<br>1. |
| | | Wollastonite | $CaSiO_3$ | | 001<br>100<br>$(\bar{1}02)$<br>$(\bar{1}01)$ | Columnar ∥ b axis | 2.85 | 5 | Colorless | 1.621 | 1.6 |
| | | Pectolite | $(CaNa_2H_2)$ $SiO_3$ | | 100<br>001 | Sheaf-like ∥ b axis | 2.8 | 4.5 | | | Ab<br>1. |
| 300 | Humite Group | *Humite* | $Mg_7(FOH)_2$ $Si_3O_{12}$ | O | 001 | Rounded grains | 3.1 to 3.2 | 6.5 | Colorless Yellowish | 1.607<br>to<br>.....<br>Yellow | 1.6<br>to<br>1.6<br>Col |
| | | Clinohumite | $Mg_9(FOH)_2$ $Si_4O_{16}$ | M | | | | | | | |
| | | Chondrodite | $Mg_5(FOH)_2$ $Si_2O_8$ | | | | | | | | |
| 301 | | **Topaz** | $Al_2SiO_4$ $(FOH)_2$ | O | 001 | Granular Columnar ∥ c axis | 3.4 to 3.6 | 8 | Colorless | 1.607 to 1.629 | 1.6<br>to<br>1.6 |

MINERALS.—*Continued.* TABLE 13

| $\gamma$ | $\gamma - \alpha$ | Ch*m* | Ch*z* | 2V | 2E | Dispersion | Optical orientation | Solubility | Remarks | Minerals |
|---|---|---|---|---|---|---|---|---|---|---|
| 1.686 | 0.156 | − | − | 18° | 31° | $v > \rho$ | c = $\mathfrak{a}$<br>b = $\mathfrak{c}$ | Readily soluble in HCl | | Aragonite |
| | About 0.026 | | − | About 90° | | | c:$\mathfrak{c}$ = 13° r<br>b = $\mathfrak{a}$ | *Readily* soluble in HCl | Easily fusible | Rosenbuschite |
| 1.635 | 0.014 | − | +<br>− | 40° | 70° | $\rho > v$ | c:$\mathfrak{a}$ = 32° r<br>b = $\mathfrak{b}$ | | Powder reacts alkaline | **Wollastonite** |
| | About 0.038 | + | + | 60° | | | c:$\mathfrak{a}$ = 5° f<br>b = $\mathfrak{c}$ | | Twinning lamellæ parallel to {100} | Pectolite |
| 1.639 to ..... less | 0.032 | + | | About 70° | | $v > \rho$ Very weak | c = $\mathfrak{b}$<br>b = $\mathfrak{c}$ | Gelatinize readily with HCl | Infusible | Humite |
| | | | | | | | c:$\mathfrak{b}$ = 9° f<br>b = $\mathfrak{c}$ | | Twinning lamellæ ∥{001} | Clinohumite |
| | | | | | | | c:$\mathfrak{b}$ = 30° f<br>b = $\mathfrak{c}$ | | | Chondrodite |
| 1.618 to 1.637 | 0.011 to 0.008 | + | + | 67° to 50° | 126° to 86° | $\rho > v$ | c = $\mathfrak{c}$<br>b = $\mathfrak{b}$ | Insoluble | Ch*z* formed by cleavage, negative | **Topaz** |

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| Page | Group | Minerals | Chemical composition | Crystal system | Cleavage | Development | Sp. gr. | H | Color | $\alpha$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 301 | | **Anhydrite** | $CaSO_4$ | O | $\underline{001}$<br>010<br>(100) | Granular | 2.95 | 3 | Colorless | 1.570 |
| 302 | **Mica Group** | **Muscovite** | Aluminium silicate with content of<br>$K_2O$ | M | 001 | Tabular ∥ {001} Scaly | 2.8 to 3.0 | 2.5 | Colorless | 1.562 |
| | | **Phlogopite** | $MgO$ | | | | | | Colorless<br>Light brownish<br>$\mathfrak{c} = \mathfrak{b} > \mathfrak{a}$ | 1.541 |
| | | **Biotite** | $MgO$<br>$FeO$ | | | | 3.0 to 3.2 | | Brown<br>Green<br>$\mathfrak{c} = \mathfrak{b} \geqslant \mathfrak{a}$ | 1.580 |
| | | **Lithionite** | $Li_2O$<br>$(FeO)$ | | | | 2.8 to 3.2 | | Colorless<br>Brown<br>$\mathfrak{c} = \mathfrak{b} \geqslant \mathfrak{a}$ | 1.562 |
| 310 | **Chlorite Group** | **Pennine** | $H_4(MgFe)_2$<br>$Al_2SiO_9$ | M | $\underline{001}$ | Tabular ∥ {001} Scaly to radial | 2.6 to 3.0 | 2.5 | Green, ∥ c light yellow<br>⊥ c green<br>Colorless | 1.576 to 1.585 |
| | | **Clino-chlore** | | | | | | | | |
| | | **Antigorite** | $H_4(MgFe)_3$<br>$Si_2O_9$ | O? | | Flaky | 2.5 to 2.7 | 3.5 | Colorless<br>Light greenish<br>Rarely green | 1.560 |
| | | **Chrysotile** | | | 110<br>About 130° | Fibrous | | | | |
| 316 | | **Hydrar-gillite** | $Al(OH)_3$ | M | $\underline{001}$ | Scaly<br>Fibrous | 2.4 | 2.5 | Colorless | 1.535 |

MINERALS.—*Continued.*

TABLE 14

| $\gamma$ | $\gamma-\alpha$ | Chm | Ch₂ | 2V | 2E | Dispersion | Optical orientation | Solubility | Remarks | Minerals |
|---|---|---|---|---|---|---|---|---|---|---|
| 1.614 | 0.044 | + | | 43° | 71° | $\upsilon>\rho$ | $\mathfrak{a}=\mathfrak{c}$<br>$\mathfrak{b}=\mathfrak{b}$ | *Difficultly* soluble in water | Readily altered to gypsum | **Anhydrite** |
| 1.603 | 0.041 | − | + | 30° to 50° | 55° to 90° | $\rho>\upsilon$ | $\mathfrak{c}=\mathfrak{a}$<br>$\mathfrak{b}=\mathfrak{c}$ | Attacked with difficulty but more easily the higher the content of Mg and Fe | Twin lamination parallel {001} generally not observed | **Muscovite** |
| 1.575 | 0.034 | | | | 0° to 25° | $\upsilon>\rho$ | $\mathfrak{c}=\mathfrak{a}$<br>$\mathfrak{b}=\mathfrak{b}$ | | Fuses with difficulty | **Phlogopite** |
| 1.638 | 0.058 | | | | 0° to 70° | $(\rho>\upsilon)$ | $\mathfrak{c}:\mathfrak{a}=0°$ to (10°)<br>$\mathfrak{b}=\mathfrak{b}$<br>$(\mathfrak{b}=\mathfrak{c})$ | | Pleochroic halos | **Biotite** |
| 1.606 | 0.044 | | | | 0° to 90° | $\rho>\upsilon$ | $\mathfrak{c}=\mathfrak{a}$<br>$\mathfrak{b}=\mathfrak{c}$ | | Readily fusible | **Lithionite** |
| 1.577 to 1.596 | 0.001 to 0.011 | +<br>(−) | −<br>(+) | 0° | | $\upsilon\geqslant\rho$<br>$(\rho>\upsilon)$ | $\mathfrak{c}=\mathfrak{c}\ (\mathfrak{a})$<br>$\mathfrak{b}=\mathfrak{b}$ | Gelatinize with HCl | Very variable optically<br>Anomalous interference colors<br>Pleochroic halos | **Pennine** |
| | | + | − | Variable | | $\upsilon\geqslant\rho$ | $\mathfrak{c}:\mathfrak{c}=0°–15°$ f<br>$\mathfrak{b}=\mathfrak{b}$ | | Pleochroic halos<br>Twinning lamellæ ∥ {001} | **Clinochlor** |
| 1.571 | 0.011 | − | + | | | Very weak $\rho>\upsilon$ | $\mathfrak{c}=\mathfrak{a}$<br>$\mathfrak{b}=\mathfrak{c}$ | | Pseudomorph after olivine<br>Normal interference colors<br>Very difficultly fusible | **Antigorite** |
| | 0.009 | + | + | Quite small | | | $\mathfrak{c}=\mathfrak{c}$<br>$\mathfrak{b}=\mathfrak{a}$ | | | **Chrysotile** |
| 1.510 | 0.025 | + | − | 0° to 40° | | $\rho>\upsilon$ | $001:\mathfrak{a}=65°$ f<br>$\mathfrak{b}=\mathfrak{b}$ | Soluble in hot $H_2SO_4$ | Twinning lamellæ ∥ {001}<br>Infusible | **Hydrargillite** |

BIAXIAL

| ge | Group | Minerals | Chemical composition | Crystal system | Cleavage | Development | Sp. gr. | H | Color | $\alpha$ | $\beta$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 6 | | **Talc** | $H_2Mg_3Si_4O_{12}$ | M | 001 | Scaly | 2.7 | 1 | Colorless | 1.539 | 1.589 |
| 7 | | Pyrophyllite | $HAlSi_2O_6$ | O | 001 | Radial Fibrous | 2.8 | 1 | Colorless | | 1.58 |
| 7 | | *Bertrandite* | $H_2Be_4Si_2O_9$ | O | 010<br>001<br>110 | Tabular ‖ {001} or {010} | 2.6 | 6 | Colorless | | 1.57 |
| 3 | | Wagnerite | $Mg_2FPO_4$ | M | | Prismatic | 3.0 | 5.5 | Colorless | 1.569 | 1.570 |
| 3 | **Kaolin Group** | **Kaolin** | $H_4Al_2Si_2O_9$ | M | 001 | Scaly | 2.5 | 2.5 | Colorless | | 1.55 |
| | | Nontronite | $H_4Fe_2Si_2O_9$ | | 001<br>(110) | | 2.7 | 2 | Yellow | Light yellow | About 1.6 Greenish- |
| | | Hydromagnesite | $Mg_4(CO_3)_3(OH)_2+3aq.$ | M | 010<br>100 | Columnar | 2.15 | 2 | Colorless | | About 1.54 |
| | | **Cordierite** | $Mg_2Al_4Si_5O_{18}$ | O | | Granular | 2.65 | 7 | Colorless<br>Light blue | 1.535<br>Colorless | 1.540<br>Blue |
| | | **Wavellite** | $Al_3P_2O_8+12aq.$ | O | 110 | Acicular Spherulitic | 2.4 | 3.5 | Colorless | | 1.526 |
| | * | **Gypsum** | $CaSO_4+2aq.$ | M | 010<br>(100)<br>$\bar{1}11$ | Granular Fibrous | 2.3 | 2 | Colorless | 1.521 | 1.523 |

MINERALS.—*Continued.* TABLE 15

| $\gamma$ | $\gamma-\alpha$ | Chm | Chz | 2V | 2E | Dispersion | Optical orientation | Solubility | Remarks | Minerals |
|---|---|---|---|---|---|---|---|---|---|---|
| .589 | 0.050 | − | + | 0° to 17° | Small | $\rho>\upsilon$ | $c=\mathfrak{a}$<br>$b=\mathfrak{c}$ | Attacked with difficulty | Similar to muscovite<br>Distinguished by cobalt solution | **Talc** |
|  | 0.041 | − | + | 62° | 109° | $\rho>\upsilon$ | $c=\mathfrak{a}$<br>$b=\mathfrak{c}$ | Soluble in hot $H_2SO_4$ | Similar to muscovite<br>Distinguished by hydrofluosilicic acid | Pyrophyllite |
|  | High | − | +<br>− |  | 75° | $\upsilon>\rho$ | $a=\mathfrak{a}$<br>$b=\mathfrak{b}$ | Insoluble | Infusible | Bertrandite |
| .582 | 0.013 | + | + |  | 26° | $\rho>\upsilon$ | $c=\mathfrak{c}$<br>$b=\mathfrak{b}$ | Easily soluble | Very difficultly fusible | Wagnerite |
|  | 0.008 |  | + | About 90° |  | $\rho>\upsilon$ | $c:\mathfrak{a}=20°$ r<br>$b=\mathfrak{c}$ | Soluble in hot $H_2SO_4$ | Infusible | **Kaolin** |
| llow | 0.02 | − | + |  | 60° |  | $c:\mathfrak{c}=6°$<br>$b=\mathfrak{b}$ | Gelatinizes with HCl | Fusible to black slag | Nontronite |
|  | About 0.02 | + |  |  | About 120° |  | $c:\mathfrak{a}\doteq33°$<br>$b=\mathfrak{c}$ | Easily soluble with effervescence | Twinning lamination ∥ {100} | Hydromagnesite |
| .544<br>lorless | 0.009 | − |  | Variable |  | $\upsilon>\rho$ | $c=\mathfrak{a}$<br>$b=\mathfrak{c}$ | Attacked with difficulty | Penetration trilling<br>Pleochroic halos | **Cordierite** |
|  | 0.025 | + | + |  | 50° | $\rho>\upsilon$ | $c=\mathfrak{c}$<br>$b=\mathfrak{a}$ | Soluble |  | Wavellite |
| .531 | 0.010 | + |  | 60° | 104° | Inclined | $c:\mathfrak{c}=54°$ f<br>$b=\mathfrak{b}$ | Difficultly soluble in water | $\{\bar{1}11\}$ Fibrous fracture<br>Twinning lamellæ | **Gypsum** |

**BIAXIAL**

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|
| Page | Group | Minerals | Chemical composition | Ab:An | %$SiO_2$ | Sp. gr. | Indices compared with quartz | $\alpha$ | $\beta$ |
| 321 | Feldspar Group | **Orthoclase** | $(K,Na)AlSi_3O_8$ | —— | 65% | 2.56 | ($\omega$ for quartz $=1.544$) | 1.519 | 1.524 |
| | | **Microcline** | | | | | $\left.\begin{matrix}\alpha\\\beta\\\gamma\end{matrix}\right\\} < \omega$ | 1.522 | 1.526 |
| | | **Anorthoclase** | $(Na,K)AlSi_3O_8$ | | | 2.58 | | 1.523 | 1.529 |
| | | **Albite** | $NaAlSi_3O_8$ ↓ | Ab | 68% | 2.62 | $\left.\begin{matrix}\alpha\\\beta\\\gamma\end{matrix}\right\\} < \omega$ | 1.532 | 1.534 |
| | | **Albite-oligoclase** | | $Ab_6An_1$ | 65% | 2.64 | | 1.534 | 1.538 |
| | | **Oligoclase** | | $Ab_4An_1$ | 64% | | $\gamma > \omega$; $\alpha < \omega$ | 1.537 | 1.541 |
| | | **Oligoclase-andesine** | | $Ab_2An_1$ | 60% | 2.65 | $\gamma = \varepsilon$; $\alpha = \omega$ | 1.544 | 1.548 |
| | | **Andesine** | | $Ab_3An_2$ | 58% | 2.67 | $\gamma > \varepsilon$; $\alpha < \varepsilon$ | 1.549 | 1.553 |
| | | **Labradorite** | | $Ab_1An_1$ | 55% | 2.69 | $\left.\begin{matrix}\alpha\\\beta\\\gamma\end{matrix}\right\\} > \varepsilon$ | 1.555 | 1.558 |
| | | **Labradorite-bytownite** | | $Ab_2An_3$ | 53% | 2.70 | | 1.560 | 1.563 |
| | | **Bytownite** | | $Ab_1An_4$ | 48% | 2.72 | | 1.564 | 1.569 |
| | | **Anorthite** | ↑ $CaAl_2Si_2O_8$ | An | 44% | 2.75 | ($\varepsilon$ for quartz $=1.553$) | 1.575 | 1.583 |

MINERALS.—*Continued.* TABLE 16

| 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $\gamma$ | $\gamma - \alpha$ | Chm | 2V | Dispersion about $\mathfrak{a}$ | Extinction Angles | | | | | | Minerals |
| | | | | | on 001 | on 010 | $\perp \mathfrak{a}$ | $\perp \mathfrak{c}$ | ⊥a | Zone ⊥010 | |
| 526 | 0.007 | − | 69° | $\rho > v$ | 0° | +5° | 0° | 5° | 0° | 0° | **Orthoclase** |
| 529 | | − | 88° | $\rho > v$ | +15½° | +5½° | 88° | 10° | | | **Microcline** |
| 530 | | − | 45° | $\rho > v$ | +2° | +9° | 88½° | 9° | | | **Anorthoclase** |
| 540 | 0.008 | + | 77° | $v > \rho$ | +4° | +19½° | 74° | 19½° | −15° | −16° | **Albite** |
| 542 | | + | 84° | $v > \rho$ | +2½° | +11½° | 84½° | 13° | −6° | −8° | **Albite-oligoclase** |
| 545 | | − | 88° | $\rho > v$ | +2° | +8° | 83° | 3° | 0° | +5° | **Oligoclase** |
| 552 | | − | 86° | $\rho > v$ | 0° | +½° | 75° | 5° | +4° | +10° | **Oligoclase-andesine** |
| 557 | | + | 88° | $v > \rho$ | −2½° | −8° | 68° | 7° | +13° | +19° | **Andesine** |
| 563 | | + | 77° | $v > \rho$ | −5° | −18° | 65° | 22° | +27° | +28° | **Labradorite** |
| 568 | | + | 77° | $v > \rho$ | −9° | −25° | 58° | 32° | +33° | +38° | **Labradorite-bytownite** |
| 574 | 0.010 | − | 80° | $\rho > v$ | −21° | −33° | 57° | 42° | +37° | +45° | **Bytownite** |
| 588 | 0.013 | − | 77° | $\rho > v$ | −37° | −36° | 55° | 48° | +43° | +56° | **Anorthite** |

BIAXIAL

| Page | Group | Minerals | Chemical composition | Crystal system | Cleavage | Development | Sp. gr. | H | Color | α | β |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 341 | Phillipsite Group | Phillipsite | $(CaK_2)Al_2$<br>$Si_5O_{14} + 5$ aq. | M | (001)<br>(010) | Spherulitic | 2.2 | 4.5 | Colorless | | >1. |
| | | Harmotome | $(BaK_2)Al_2$<br>$Si_5O_{14} + 5$ aq. | | | | 2.5 | | | 1.503 | 1.5 |
| | | Laumontite | $CaAl_2Si_4O_{12}$<br>+4 aq. | M | 010<br>110 | Prismatic | 2.4 | 3.5 | Colorless | 1.513 | 1.5 |
| | | Thomsonite | $(CaNa_2)Al_2$<br>$Si_2O_8 + 2\frac{1}{2}$ aq. | O | 010<br>(100) | Tabular ∥ {100} | 2.3 | 5 | Colorless | 1.497 | 1.5 |
| | Stilbite Group | Heulandite | $CaAl_2Si_6O_{16}$<br>+5 aq. | M | 010 | Platy ∥ {100} | 2.2 | 5 | Colorless | 1.498 | 1.4 |
| | | Desmine | $(CaNa_2)Al_2$<br>$Si_6O_{16} + 6$ aq. | | | Columnar ∥ c<br>Tabular ∥ {010} | 2.15 | 3.5 | | 1.494 | 1.4 |
| | | Epistilbite | $CaAl_2Si_6O_{16}$<br>+5 aq. | | | Radial<br>Fibrous | 2.25 | 4 | | 1.502 | 1.5 |
| | Natrolite Group | Natrolite | $Na_2Al_2Si_3O_{10}$<br>+3 aq. | M | 110<br>(89°) | Columnar ∥ c<br>Radial | 2.2 | 5.5 | Colorless | 1.478 | 1.4 |
| | | Mesolite | $\downarrow$<br>$\uparrow$ | | | | | | | | Ab<br>1. |
| | | Scolesite | $CaAl_2Si_3O_{10}$<br>+3 aq. | | | | 2.4 | | | | 1.5 |

## ZEOLITES.

## TABLE 17

| $\gamma$ | $\gamma - \alpha$ | Ch*m* | Chz | 2V | 2E | Dispersion | Optical orientation | Solubility | Remarks | Minerals |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0.003 | + | + | 70° | | Very weak | $c:\mathfrak{c} = 20°$<br>$b = \mathfrak{b}$ | Gelatinize with HCl | Readily<br>Fusible | **Phillipsite** |
| .508 | 0.005 | + | | 85° | | | $c:\mathfrak{a} = 60°$<br>$b = \mathfrak{b}$ | | Difficultly | **Harmotome** |
| .525 | 0.012 | − | + | | 55° | $\upsilon \gg \rho$ | $c:\mathfrak{a} = 70°$ f<br>$b = \mathfrak{b}$ | Gelatinizes with HCl | Decomposes in air with loss of water | **Laumontite** |
| .525 | 0.028 | | +<br>− | | About 90° | $\upsilon \gg \rho$ | $c = \mathfrak{a}$<br>$b = \mathfrak{c}$ | Gelatinizes with HCl | Fuses with intumescence | **Thomsonite** |
| .505 | 0.007 | + | − | | 0° *to* 50° | Crossed | c nearly $= \mathfrak{b}$<br>$b = \mathfrak{c}$ | Gelatinizes with HCl | Parallel aggregates | **Heulandite** |
| .500 | 0.006 | − | − | 33° | 52° | $\upsilon > \rho$ | $c:\mathfrak{a} = 8°$ f<br>$b = \mathfrak{b}$ | Give powdered silica with HCl | Often radial aggregates | **Desmine** |
| .512 | 0.010 | − | + | 40° to 70° | | $\upsilon > \rho$ | $c:\mathfrak{c} = 9°$ r<br>$b = \mathfrak{b}$ | | Twinned ‖ {100} | **Epistilbite** |
| .490 | 0.012 | + | + | 60° | 96° | $\upsilon > \rho$ | $c:\mathfrak{c} = 0°\text{–}5°$<br>$b = \mathfrak{b}$ | Gelatinize with HCl | Radial aggregates | **Natrolite** |
| | About 0.01 | | | | | | | | Twinning lamellæ ‖ {100} | **Mesolite** |
| | 0.008 | − | − | | 58° | $\upsilon \gg \rho$ | $c:\mathfrak{a} = 17°$ f<br>$b = \mathfrak{c}$ | | | **Scolesite** |

## TABLE 18

### ROCK MINERALS GROUPED ACCORDING TO COLOR.

**Grayish-violet:** Perovskite, tourmaline, rutile, titanium augite, cataphorite, axinite.

**Violet:** Dumortierite, piemontite, cotschubeyite, cæmmererite, fluorite.

**Blue:** Riebeckite, arfvedsonite, carinthine, dumortierite, chlorite (crinite), lazurite, tourmaline, glaucophane, haüyne-noselite, lazulite, chloritoid, serendibite, crocidolite, corundum, fuchsite, cordierite, anatase, cyanite, sapphirine, sodalite, beryl, diaspore.

**Green:** Green hornblende, aegirine, tourmaline, glauconite, seladonite, biotite, aegirine-augite, fassaite, chrome epidote, iron spinel, pargasite, brittle mica, chlorite, lime garnet, actinolite, diopside, baddeleyite, chrysoberyl, serpentine.

**Orange** and **Yellow:** Brookite, wurtzite, sphalerite, astrophyllite, biotite, brown hornblende, rutile, cassiterite, låvenite, humite group, staurolite, chrome epidote, rosenbuschite, monazite, glass, carpholite, baddeleyite, fayalite, nontronite, sulphur, epidote, grünerite, cummingtonite, tourmaline, apatite, melilite, lime garnet, anatase, titanite, rinkite, mosandrite, prismatine, siderite.

**Red:** Hematite, piemontite, chrome chlorite, thulite, hypersthene, cassiterite, cataphorite, titanite, andalusite, garnet, orthite, clinozoisite, manganvesuvianite, eudialyte, xenotime.

**Brown:** Lievrite, cossyrite, ilmenite, chromite, pseudobrookite, brookite, basaltic hornblende, biotite, lithionite, tourmaline, rutile, melanite, orthite, chrome spinel, perovskite, wurtzite, sphalerite, barkievikite, hyalosiderite, astrophyllite, fayalite, staurolite, brown hornblende, glass, baddeleyite, hypersthene, lime garnet, monazite, diallage, titanite, pargasite, anthophyllite, augite, brittle mica.

N. B. In a general way the minerals are arranged above according to diminishing intensity of color. Those at the beginning of a series are in some instances not very transparent while those at the end scarcely show any color at all in thin section. Rare varieties are introduced here when the

## TABLE 18.—*Continued.*

### I. INTERFERENCE FIGURES ARE OBSERVED IN CLEAVAGE PLATES.

1. **Uniaxial and Nearly Uniaxial:**

a. *Perpendicular to the optic axis:* Brittle mica ∓, eudialyte +, alunite +, phlogopite −, biotite −, pennine ±, brucite +, talc −, apophyllite +, heulandite +.

b. *Oblique to the optic axis:* Calcite, dolomite, magnesite, siderite, hydrargillite.

c. *Parallel to the optic axis:* Rutile, wurtzite, zircon, xenotime, scapolite, cancrinite.

2. **Biaxial:**

a. *Perpendicular to the acute bisectrix, approximate optic angle in parenthesis:* Brittle mica ± (not very large), margarite − (large), prehnite + (quite variable), topaz + (quite large, variable), celestite + (about 90°), muscovite − (about 70°), sericite − (about 25°), phlogopite and biotite − (very small), lithionite − (variable), clinochlore + (variable), antigorite − (variable), talc − (about 25°), pyrophyllite − (>100°), hydromagnesite + (120°), heulandite + (small), thomsonite + (about 90°), goethite + (crossed optic planes).

b. *Perpendicular to the obtuse bisectrix:* Zoisite $\beta$ −, astrophyllite −, anthophyllite −, pectolite −, barite −, anhydrite −.

c. *Parallel to the optic plane:* Zoisite $\alpha$, diaspore, lawsonite, sillimanite, humite, bertrandite, gypsum, laumontite, desmine, epistilbite.

d. *Slightly inclined to the acute bisectrix but perpendicular to the optic plane:* Monazite + (25°), baddeleyite − (very large), rinkite + (77°), cyanite − (very large), clinochlore + (variable).

e. *Greatly inclined to the acute bisectrix and perpendicular to the optic plane:* Hydrargillite, clinozoisite.

f. *Nearly perpendicular to an axis:* Epidote, diallage, wollastonite.

g. *Inclined to the optic plane:* Brittle mica, amphibole, augite, wavellite, kaolin.

### II. TWINNING LAMINATIONS.

(Those indicated with * do not often show lamination on account of the small extinction angle). Leucite, rutile, perovskite, calcite, dolomite, baddeleyite, zoisite, *clinozoisite, *epidote, orthite, cyanite, chloritoid, margarite, serendibite, diallage, rinkite, mosandrite, prehnite, wollastonite, pectolite, humite group, *mica, clinochlore, hydrargillite, gypsum, hydromagnesite, microcline, plagioclase, epistilbite, mesolite, scolesite.

## TABLE 18.—*Continued.*

### III. MINERALS THAT FREQUENTLY SHOW ANOMALOUS INTERFERENCE COLOR.

Chrysoberyl, clinozoisite, zoisite $\alpha$, pennine, gehlenite, melilite, vesuvianite, brucite, dumortierite, prehnite, lime garnet, chloritoid, fassaite, titanium augite, laumontite, sanidine.

### IV. PLEOCHROIC HALOS.

**Found in:** Amphibole, andalusite, chlorite, mica, cordierite, brittle mica, staurolite, tourmaline.

**Found around:** Dumortierite, orthite, rutile, titanite, xenotime, cassiterite, zircon.

### V. USUAL CRYSTALLOGRAPHIC HABIT OF NON-CUBIC MINERALS.

1. **Isometric** (pyramidal, thick tabular, short prismatic, granular): Anatase, cassiterite, xenotime, gehlenite, carbonates, scapolite, alunite, chabazite, quartz, nepheline, titanite, sulphur, monazite, chrysoberyl, diaspore, forsterite, olivine, fayalite, monticellite, axinite, rinkite, lazulite, barite, humite group, celestite, topaz, anhydrite, cordierite.

2. **Tabular:** Anatase, corundum, melilite, brucite, tridymite, apophyllite; brookite, pseudobrookite, serendibite, astrophyllite, cyanite, brittle mica, margarite, sapphirine, spodumene, axinite, mosandrite, micas, chlorite group, antigorite, bertrandite, hydrargillite, talc, kaolin, heulandite.

3. **Prismatic:** Rutile, cassiterite, zircon, xenotime, corundum, vesuvianite, tourmaline, apatite, scapolite, beryl, baddeleyite, lievrite, titanite, epidote group, lavenite, prismatine, staurolite, cyanite, pyroxene group, amphibole group, andalusite, aragonite, wollastonite group, wagnerite.

4. **Columnar** (acicular): Tourmaline, apatite, cancrinite, hydronephelite, gœthite, lievrite, acmite, tremolite, actinolite, sillimanite, datolite, dumortierite, aragonite, wollastonite group, topaz, celestite, hydromagnesite, desmine, natrolite.

5. **Fibrous:** Wurtzite, chalcedony, sillimanite, crocidolite, prehnite, carpholite, datolite, chrysotile, wavellite, hydrargillite, pyrophyllite, gypsum, zeolites.

### VI. CLASSIFICATION OF A FEW MINERALS ACCORDING TO *DECREASING MAGNETISM. (AFTER DOELTER.)*

Metallic iron, magnetite, pyrrhotite; ilmenite, lievrite, hematite; chromite, siderite, almandine, limonite, augite rich in iron, iron spinel, arfvedsonite; hornblende, augite poor in iron, epidote, pyrope; tourmaline, bronzite, vesuvianite, staurolite, actinolite, olivine, pyrite; biotite, chlorite, rutile; haüyne, diopside, muscovite, nepheline, leucite, dolomite, feldspars.

## TABLE 18.—*Continued.*

### VII. CLASSIFICATION OF ROCK-FORMING MINERALS ACCORDING TO SOLUBILITY.

1. **Insoluble in hydrofluoric acid:** Magnetite, chromite, hematite, ilmenite, graphite, carbonaceous substance, perovskite, spinel group, prismatine, astrophyllite, fluorite, rutile, anatase, cassiterite, zircon, xenotime, chrysoberyl, corundum, baddeleyite, tourmaline, serendibite, beryl, brookite, staurolite, diaspore, cyanite, chloritoid, xanthophyllite, sapphirine, axinite, sillimanite, dumortierite, andalusite, topaz, bertrandite.

2. **Attacked by hydrochloric acid with difficulty:** Hematite, ilmenite, sphalerite, boracite, garnet, vesuvianite, pseudobrookite, gœthite, titanite, orthite, ottrelite, lavenite, carpholite, lazulite, hydrargillite, labradorite.

3. ***With hydrochloric acid give powdered silica:*** Leucite, meionite, apophyllite, rinkite, mosandrite, anorthite, desmine, epistilbite.

4. **With hydrochloric acid give gelatinous silica:** Analcite, sodalite group, gehlenite, melilite, eudialyte, nepheline, hydronephelite, lievrite, forsterite, olivine, fayalite, monticellite, datolite, rosenbuschite, wollastonite, pectolite, humite group, chlorite group, serpentine, heulandite, natrolite, chabazite, phillipsite, harmotome, laumontite, thomsonite, mesolite, scolesite.

5. **Soluble in hydrochloric acid:** Pyrrhotite, wurtzite, magnetite, periclase, apatite, *calcite, *dolomite, *magnesite, *siderite, brucite, *cancrinite, monazite (white residue), wagnerite, wavellite, *aragonite, *hydromagnesite.
Those marked * evolve carbonic acid with effervescence.

6. **Soluble in caustic potash:** Opal (quartz), chalcedony, tridymite, sulphur, kaolin (white residue).

### VIII. CLASSIFICATION OF THE MINERALS ACCORDING TO THEIR FUSIBILITY BEFORE THE BLOWPIPE.

1. **Easily fusible (Kobell's scale 1–3):** Almandine, grossularite, lievrite, sulphur, låvenite, aegirine, aegirine augite, spodumene, glaucophane, riebeckite, arfvedsonite, crocidolite, axinite, rinkite, datolite, mosandrite, rosenbuschite, pectolite, lithionite, phillipsite, scolesite.

2. **Fairly easily fusible (3–4):** Pyrope, hessonite, topazolite, melanite, analcite, tourmaline, eudialyte, scapolite, elæolite, apophyllite, chabazite, cancrinite, hydronephelite, epidote group, astrophyllite, augite, fassaite, lawsonite, tremolite, actinolite, hornblende, prehnite, celestite, lepidomelane, anhydrite, nontronite, gypsum, anorthoclase, basic plagioclase, heulandite, desmine, natrolite, thomsonite, epistilbite.

3. **Difficultly fusible (4–5):** Boracite, sodalite, melilite, nepheline, monazite, chloritoid, fayalite, hypersthene, diopside, diallage, carpholite, wollastonite, muscovite, phlogopite, biotite, clinochlore, orthoclase, microcline, acid plagioclase, harmotome.

TABLE 18.—*Continued.*

4. **Only fusible on the edges** (5–6): Magnetite, sphalerite, wurtzite, *haüyne, noselite, fluorite, gehlenite, apatite, beryl, pseudobrookite*, baddeleyite, titanite, margarite, monticellite, hyalosiderite, enstatite, anthophyllite, barite, humite group, pennine, serpentine, cordierite, wagnerite.

5. **Infusible:** Perovskite, spinel, periclase, leucite, opal, rutile, anatase, cassiterite, zircon, xenotime, corundum, carbonates, alunite, brucite, quartz, chalcedony, tridymite, brookite, chrysoberyl, gœthite, serendibite, prismatine, staurolite, diaspore, cyanite, xanthophyllite, sapphirine, forsterite, olivine, sillimanite, dumortierite, lazulite, andalusite, aragonite, topaz, bertrandite, hydrargillite, talc, pyrophyllite, kaolin, hydromagnesite, wavellite.

## IX. FINE POWDER GIVES ALKALINE REACTION.

Albite, analcite, andesine, anorthite, apophyllite, axinite, biotite, bytownite, datolite, desmine, epidote, heulandite, hydronephelite, lime garnet, clinochlore, clinozoisite, labradorite, leucite, lithionite, margarite, microcline, muscovite, natrolite, nepheline, oligoclase, orthoclase, pennine, prehnite, serpentine, talc, tremolite, vesuvianite, wollastonite, zoisite.

## TABLE 19.

### X. ROCK-FORMING MINERALS ARRANGED ACCORDING TO SPECIFIC GRAVITY.

| | |
|---|---|
| Metallic iron | 7.8 |
| Galena | 7.5 |
| Cassiterite | 6.9 |
| Baddeleyite | 5.8 |
| Hematite | 5.25 |
| Magnetite | 5.2 |
| Ilmenite | 5.2–4.8 |
| Pyrite | 5.0 |
| Pseudobrookite | 5.0 |
| Zircon | 4.7 |
| Pyrrhotite | 4.6 |
| Xenotime | 4.6 |
| Chromite | 4.5 |
| Koppite | 4.5 |
| Barite | 4.5 |
| Melanite | 4.3 |
| Almandine | 4.3 |
| Pyrochlore | 4.3 |
| Goethite | 4.3 |
| Rutile | 4.25 |
| Chalcopyrite | 4.2 |
| Chrome spinel | 4.1 |
| Topazolite | 4.1 |
| Dysanalyte | 4.1 |
| Brookite | 4.1–3.9 |
| Sphalerite | 4.0 |
| Wurtzite | 4.0 |
| Lievrite | 4.0 |
| Perovskite | 4.0 |
| Corundum | 4.0 |
| Celestite | 3.95 |
| Iron spinel | 3.9 |
| Siderite | 3.9 |
| Anatase | 3.9 |
| Hessonite | 3.8 |
| Staurolite | 3.8–3.6 |
| Pyrope | 3.75 |
| Chrysoberyl | 3.7 |
| Periclase | 3.65 |
| Cyanite | 3.6 |
| Ardennite | 3.6 |
| Orthite | 3.6 |
| Spinel | 3.6 |
| Låvenite | 3.6 |
| Fayalite | 3.6 |
| Topaz | 3.6–3.4 |
| **Rohrbach solution** | **3.58** |
| **Diamond** | **3.5** |
| Chloritoid | 3.5 |
| Titanite | 3.5 |
| Sapphirine | 3.5 |
| Aegirine | 3.5 |
| Arfvedsonite | 3.5 |
| Triphyline | 3.5 |
| Hypersthene | 3.5 |
| Diaspore | 3.45 |
| Rinkite | 3.45 |
| Grossularite | 3.45 |
| Vesuvianite | 3.45 |
| Woehlerite | 3.4 |
| Barkievikite | 3.4 |
| Serendibite | 3.4 |
| Epidote | 3.4 |
| Augite | 3.35 |
| Astrophyllite | 3.35 |
| Prismatine | 3.35 |
| Jadeite | 3.35 |
| Clinozoisite | 3.35 |
| **Methylene iodide** | **3.32** |
| Zoisite | 3.3 |
| Diallage | 3.3 |
| Olivine | 3.3 |
| Bronzite | 3.3 |
| Basaltic hornblende | 3.3 |
| Axinite | 3.3 |
| Riebeckite | 3.3 |
| Dumortierite | 3.3 |
| Rosenbuschite | 3.3 |
| Diopside | 3.3 |
| **Klein's solution** | **3.28** |
| Cornerupine | 3.25 |
| Sillimanite | 3.25 |
| Forsterite | 3.25 |
| Tourmaline | 3.25–3.0 |
| Crocidolite | 3.2 |
| Fluorite | 3.2 |
| Andalusite | 3.2 |
| Monticellite | 3.2 |
| Fuggerite | 3.2 |
| Common hornblende | 3.2–3.1 |
| Humite | 3.2–3.1 |
| Chondrodite | 3.2–3.1 |
| Clinohumite | 3.2–3.1 |
| Fassaite | 3.2–3.0 |
| Biotite | 3.2–3.0 |
| Lithionite | 3.2–2.8 |

## TABLE 19.—*Continued.*

### X. ROCK-FORMING MINERALS ARRANGED ACCORDING TO SPECIFIC GRAVITY.—*Continued.*

| | |
|---|---|
| **Thoulet solution** | 3.18 |
| Apatite | 3.15 |
| Enstatite | 3.1 |
| Lazulite | 3.1 |
| Magnesite | 3.1 |
| Spodumene | 3.1 |
| Lawsonite | 3.1 |
| Euclase | 3.1 |
| Xanthophyllite | 3.1 |
| Anthophyllite | 3.1 |
| Glaucophane | 3.1 |
| Mosandrite | 3.1 |
| Eucolite | 3.05 |
| Actinolite | 3.0 |
| Phlogopite | 3.0 |
| Wagnerite | 3.0 |
| Datolite | 3.0 |
| Boracite | 3.0 |
| Cryolite | 3.0 |
| Phenacite | 3.0 |
| Margarite | 3.0 |
| **Acetylene bromide** | 3.0 |
| Dolomite | 2.95 |
| Carpholite | 2.95 |
| Aragonite | 2.95 |
| Anhydrite | 2.95 |
| Melilite | 2.9 |
| Prehnite | 2.9 |
| Pectolite | 2.9 |
| Tremolite | 2.9 |
| Chlorite | 2.9–2.6 |
| Conchite | 2.85 |
| Wollastonite | 2.85 |
| Paragonite | 2.85 |
| Muscovite | 2.85 |
| Iddingsite | 2.85 |
| Pyrophyllite | 2.8 |
| Anorthite | 2.75 |
| Scapolite | 2.75–2.6 |
| Bytownite | 2.72 |
| Calcite | 2.72 |
| Alunite | 2.7 |
| Beryl | 2.7 |
| Talc | 2.7 |
| Pennine | 2.7 |
| Clinochlore | 2.7 |
| Nontronite | 2.7 |
| Serpentine | 2.7–2.5 |
| Labradorite | 2.69 |
| Andesine | 2.67 |
| Quartz | 2.65 |
| Cordierite | 2.65 |
| Ktypeite | 2.65 |
| Glass | 2.65–2.2 |
| Oligoclase | 2.64 |
| Albite | 2.60 |
| Chalcedony | 2.6 |
| Bertrandite | 2.6 |
| Nepheline | 2.6 |
| Anorthoclase | 2.58 |
| Orthoclase | 2.56 |
| Microcline | 2.56 |
| Leucite | 2.5 |
| Haüyne | 2.5 |
| Kaolin | 2.5 |
| Harmotome | 2.5 |
| Cancrinite | 2.45 |
| Hydrargillite | 2.4 |
| Wavellite | 2.4 |
| Brucite | 2.4 |
| Laumontite | 2.4 |
| Apophyllite | 2.35 |
| Sodalite | 2.3 |
| Graphite | 2.3 |
| Tridymite | 2.3 |
| Gypsum | 2.3 |
| Glauconite | 2.3 |
| Scolesite | 2.3 |
| Thomsonite | 2.3 |
| Epistilbite | 2.25 |
| Analcite | 2.2 |
| Hydronephelite | 2.2 |
| Natrolite | 2.2 |
| Opal | 2.2 |
| Heulandite | 2.2 |
| Phillipsite | 2.2 |
| Desmine | 2.15 |
| Hydromagnesite | 2.15 |
| Chabazite | 2.1 |
| Halite | 2.1 |
| Gmelinite | 2.1 |
| Sulphur | 2.0 |
| Meerschaum | 2.0 |
| Coals | < 2.0 |

# INDEX