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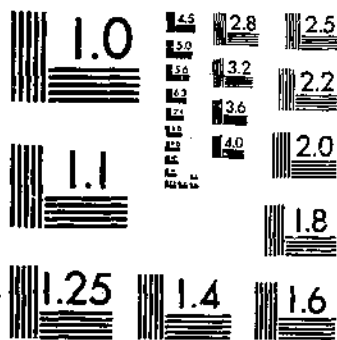
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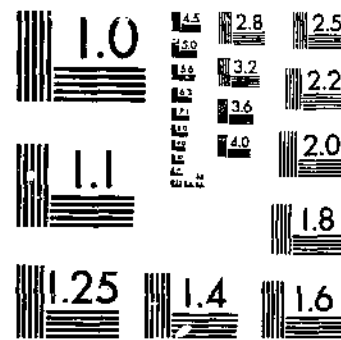
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PETROGRAPHIC METHODS FOR SOIL LABORATORIES
FRY, W. A.

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UNITED STATES DEPARTMENT OF AGRICULTURE
WASHINGTON, D. C.

PETROGRAPHIC METHODS FOR SOIL LABORATORIES

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INTRODUCTION

For many years, almost since the beginning of microscopy, the ordinary microscope has been used for the observation of crystals too small to be otherwise observed. Certain obvious similarities and dissimilarities between different crystalline substances were early noted and were used as confirmatory methods of identification. For example, the cubes of sodium chloride were seen to be identical in appearance with the cubes of potassium chloride, but both were found to be utterly dissimilar to the monoclinic, frequently twinned, crystals of gypsum. Here, then, were two substances which could not be distinguished from each other by simple observation, no matter how perfect the microscope might be as a magnifying instrument, whereas either could be instantly distinguished from the third substance even with a very crude microscope. In process of time such

cases multiplied, and the distinguishing characteristics of the various crystals were studied with greater attention to detail. These studies brought to light a wealth of crystallographic information, some of which extended the lists of definitely identifiable substances, but much of which simply added new members to already large groups of observationally indistinguishable crystals.

Such a result was inevitable. There are only six major crystalline systems, to some one of which each crystal must belong. The subdivisions of these six systems give a somewhat larger number of groups, but at best there is a very large number of crystals falling in each group and therefore having the same general appearance, although they may be completely unlike chemically. Matters are further complicated by the fact that a given substance may, under certain conditions, crystallize in one subdivision of a system, and under other conditions in some other subdivision. For instance, both sodium chloride and potassium alum crystallize in the isometric system, but both may appear as cubes or as octahedrons. It is thus evident that a given crystal not only does not necessarily show definitely diagnostic characteristics on simple observation, but also that it could not be expected to do so.

Common sense supplied a solution to the problem by the simple elimination of all substances except those which could be reasonably expected to crystallize from a given solution. In cases where it was known what could crystallize out of a given solution and where these possible crystals were sufficiently different, identification by appearance could readily be made, if the crystals came down in sufficiently perfect and characteristic form. But they did not always do this. This method is only infrequently applicable, but when it is applicable it is capable of giving very good results if used with judgment.

The methods of qualitative chemical analysis under the microscope have abundantly proved their value but they have severe limitations. (1) The substance to be analyzed under the microscope must be fairly readily soluble without too much preliminary treatment. This practically eliminates most of the silicate minerals. (2) Some of the methods depend on the visual recognition of crystals formed by the substance under analysis and the reagents applied to it. All that has been said as to the uncertainty of crystal determination by ordinary observation applies here with perhaps added force. (3) Microchemical tests on mixed substances leave a degree of uncertainty as regards the composition of any particular crystalline component of the mixture. (4) Microchemical tests do not distinguish between different allotropic forms of the same substance, between different hydrates, or between salts which have qualitatively the same but quantitatively different compositions.

Geologists were early confronted by the problem of identification of crystalline substances in rocks, a problem which combined almost all the difficulties outlined above. The mineral constituents of a granite, for example, usually show no external crystal form whatever and can not therefore be identified even tentatively by their forms. Most microchemical tests are altogether inapplicable. Resort was had, of necessity, to methods based on physical properties which were capable of showing internal crystalline structure regardless of whether or not this internal structure was manifested by external form.

As it happened, the optical properties were particularly well adapted for this purpose. Methods and apparatus were devised and improved, and a vast literature on the microscopic constitution and structure of rocks was rapidly built up. This new field was sufficient to occupy the attention of geologists and mineralogists for many years, and consequently very little attention was paid by them to artificial crystals obtained in the laboratory. Gradually, however, there appeared a small amount of data on the optics of artificial crystals, and finally the exigencies of certain largely chemical problems, notably those of cement, demanded the accumulation and application of definite data in the identification of specific artificial compounds. It was found that artificial crystals were just as susceptible, and perhaps more so, on account of their purity, to optical identification as were the natural crystalline minerals. Methods predominantly suited to rock sections were modified to apply more accurately and conveniently to loose crystals. Thus optical crystallography ceased to be merely a means for rock study and broadened out into its rightful place of a physical method applicable, to some extent at least, in most studies where crystalline material is or may be present.

Aside from the vast field of rock and mineral study, successful application has been made of optical crystallography in the identification of sugars, alkaloids (18),¹ cement constituents, fertilizer materials (5), mixed salts crystallizing from brines and from soil extracts (1), dyes, solid phases obtained in various phase-rule studies, organic substances obtained from the brain, from soils, and from plants (3), silicate melts, and various other miscellaneous materials (8). There has even been some slight progress made in the application of the methods to certain so-called colloidal aggregates (6).

But the success of the methods should not blind one to the fact that optical crystallographical methods, in common with all other methods, have their limitations. Although there are real exceptions, as in the determination of the refraction indices of glasses, and presumably apparent exceptions, as in the study of colloidal aggregates, it may be said in general that optical crystallography applies only to the nonopaque crystals. The opaque crystals have their own special technic, which can be found in any text on metallography (15). Furthermore, the crystals to be identified must be of a size greater than submicroscopic and must have a real crystalline structure and not merely the incipient crystallinity of the so-called "skeleton crystals." These skeleton crystals have a particularly attractive appearance when seen in clusters sticking to the sides of a beaker or test tube, and for this reason have a tendency to tempt one to much futile work which could be successfully and easily accomplished if the crystals were given sufficient time for growth. Skeleton crystals are frequently mistaken for completed forms by workers without considerable crystallographic experience.

The above limitations still leave a vast field of literally hundreds of thousands of compounds open to the study of their optical crystallography. The optics of the naturally occurring minerals have been reasonably well worked out, and the data are readily avail-

¹ Italic numbers in parentheses refer to Literature Cited, p. 95.

able. But the same can be said of only a comparatively small number of the total possible artificial compounds. This lack of data is a continually recurring source of embarrassment, but is becoming less so as more data are being gradually accumulated and compiled.

It is the purpose of this publication to present in very brief form the crystallographic, optical, and manipulative principles absolutely necessary for the petrographic identification of crystals. Only so much is included as seems indispensable. All mathematical treatment has been eliminated so far as possible without loss of clarity. This has been done in spite of the fact that fundamentally both crystallography and optics are almost wholly mathematical sciences. For information beyond the minimum given in this bulletin the reader is referred to the standard texts (2, 4, 7, 13, 16, 20).

CRYSTAL FORM

The primary characteristic of a crystal is its actual or potential geometrical form that determines to which of the six crystallographic systems it belongs. These six systems are based on purely geometrical principles and, in general, but not in detail, it may be said that the optics of a given crystal depend on the system to which it belongs. A complete crystallographic description of the geometrical properties of a given crystal would indicate to the experienced worker whether the crystal was isotropic or anisotropic and, if the latter, whether it was optically uniaxial or biaxial, but it would give no indication as to the refractive indices, the value of the double refraction, the size of the optic axial angle, the dispersion, or the optical character. On the other hand, a complete optical description of a crystal might fail to give any data which would definitely establish its system, for example, it is usually impossible to distinguish between a tetragonal and a hexagonal crystal by optics alone. Furthermore, the optical data never furnish information as to external form. Optically there is no difference between a 6-sided cube, an 8-sided octahedron, and a 12-sided dodecahedron, but the optics would establish the fact that each belonged to the isometric system. Crystallography and optical crystallography are thus mutually related and to a certain extent mutually dependent, but neither is completely expressible in terms of the other. Both should therefore be used to the greatest extent possible.

The six crystallographic systems are the isometric, the tetragonal, the hexagonal, the orthorhombic, the monoclinic, and the triclinic, and they are defined as follows:

The isometric system has three equal axes all at right angles to each other. If each face of the crystal is parallel to two of the axes and at right angles to the third, the form is that of a cube. If each face cuts all three axes at unit distance from the center, the form would be that of an octahedron. There are many other forms, all depending on the relationship between the faces and the axes.

The tetragonal system has two equal axes and a third either longer or shorter than the first two, all at right angles to each other.

The hexagonal system has three equal axes in one plane at 60° from each other and a fourth axis, either longer or shorter and at right angles to the plane of the first three.

The orthorhombic system has three unequal axes all at right angles to each other.

The monoclinic system has three unequal axes, any two of which are at right angles to each other and the third inclined to the plane of the other two.

The triclinic system has three unequal axes all inclined to each other.

In the isometric system, since all the axes are equal, it is a matter of indifference how the axes are denominated. If a cube is set up so that the observer looks squarely into one face, he can readily conceive of three equal axes at right angles intersecting each other in the center of the cube and each one passing through the centers of two opposite faces. That axis pointing toward the observer may be labeled a or \bar{a} , depending on whether he is considering it as directed from the center of the cube toward the front or from the center toward the rear. Similarly, he can label the horizontal axis at right angles to the first as b or \bar{b} , depending on whether its direction is to the right or to the left of the cube center. The vertical axis can be labeled c or \bar{c} , depending on whether its direction is considered as up or down from the center. The front face intersects the a axis at unit distance and is parallel to the other two axes, that is, does not intersect them at all. This face may therefore be labeled (100). The left side face intersects the \bar{b} at unit distance and is parallel to the other two axes. This face may be labeled (0 $\bar{1}$ 0), and so on for all the other faces. An octahedral face intersects all three axes at unit distance and therefore has the symbol (111), ($\bar{1}$ 11), or some other, depending on the location of the particular face.

In the tetragonal system, the unequal axis is always the vertical, that is, the c axis. The unit distance on the c axis is not the same unit as that of the a and b axes, but, with this difference understood, the symbols for the different faces are obtained as in the isometric system.

In the hexagonal system the unequal axis is the c axis, as in the tetragonal system. But since there are four axes altogether, there are four numbers in each face symbol. For example, a basal plane is parallel to all three horizontal axes, but intersects the vertical axis. The symbol is therefore (0001) or (000 $\bar{1}$).

In the orthorhombic system the shorter diagonal axis is denominated a , the longer axis b , and the vertical axis c . The face symbols are derived as in the other systems.

In the monoclinic system b is identified as that axis lying perpendicular to the plane of symmetry of the crystal; a and c lie in the plane of symmetry and are inclined to each other. The face symbols are derived as in the other systems.

In the triclinic system a is usually the shorter diagonal axis and b the longer diagonal axis. There are cases, however, in which this is reversed. c , of course, is the third axis. The face symbols are derived as in the other systems. The angle β is the angle between a and c .

The preceding remarks on crystallography are intended purely as a species of definition of terms. The reader is referred to any good text on crystallography for further information (4, 13, 16).

FUNDAMENTAL PROPERTIES OF LIGHT

For practical purposes light can be defined as radiant energy which affects our organs of vision. We are ignorant of its fundamental character, but its phenomena can be explained sufficiently by either of two theories: (1) That it is a wave motion originating from some luminous source of energy and propagated in an all-pervading ether, or (2) that it is a stream of actual quanta of luminous energy, coming from the source to the observer. The present tendency is to give preference to the second theory, but, so far as applied optical crystallography is concerned, both serve equally well. The wave-motion theory is the one most commonly taught and understood, and, up to the present, all texts of optical crystallography have been written in terms of this theory. For these reasons light will be here considered as simply a transmission of radiant energy by wave motion in an ether, and all questions of quanta will be ignored.

Regardless of theory, there are several fundamental facts concerning the propagation of light which can be verified easily, even by the simplest sort of observation:

(1) Light, in a homogeneous medium, travels in straight lines. Observations on shadows or, better still, observations on images formed by pinhole cameras, as explained in any textbook on physics (17), will give an adequate concept of this fact.

(2) Light traveling in one medium is at least partly reflected back into this medium on striking another medium of optical density different from the first. Mirrors give the best example of this fact.

(3) The path of light, passing from one medium into another medium of different optical density, at any angle other than a right angle, is bent or refracted.

(4) Ordinary so-called white light is made up of various colors which can be separated into a spectrum with red at one extreme and violet at the other. Any transparent prism will demonstrate this fact.

(5) Light will pass through certain substances, which are spoken of as transparent or translucent, and will not pass through certain other substances which are spoken of as opaque. Glass is an example of transparent substances and sheet iron of opaque substances. Between these two extremes there are all gradations. In other words, different substances absorb transmitted light in different degrees; and, usually, with white light, absorb certain colors more or less than other colors.

(6) Under certain conditions light rays can be made to interfere so as to produce darkness.

If a light ray traveling through a homogeneous medium along the line and in the direction as (fig. 1) strikes a medium of different optical density at s at right angles, part of the light enters the second medium and is absorbed or transmitted, as the case may be, but part is reflected back along its original path but in the opposite direction; that is, along sn . Thus, when the angle of incidence, i , is 0° , the path of incidence and the path of reflection are the same, although the directions are opposite. It might be said that the path has been turned through an angle of 180° .

If the ray travels along some line as , making angle i greater than 0° but less than 90° , then the ray, on striking the second medium, is

reflected back into the first medium in such a manner that angle $i = \text{angle } e$. We therefore have the law that, in a homogeneous medium, the angle of incidence is equal to the angle of reflection.

At a certain angle i , which varies with the nature of the two media but which is constant for any two substances at a given temperature, none of the light enters the second medium, but the entire ray is reflected back into the first medium. This angle is known as the critical angle for the two substances. For angles of incidence, therefore, between 0° and the critical angle, only part of the light is reflected, the other part entering the second medium. At angles equal to or greater than the critical angle, but less than 90° , all the light is reflected back into the first medium, none of it entering the second. The maximum of light enters the second medium at 0° incidence, and the amount decreases regularly until it reaches zero at the critical angle.

The light which enters the second medium, is, as has been stated, either absorbed, transmitted, or partly absorbed and partly transmitted. Assuming, for the sake of simplicity, that it has all been transmitted, or that the second medium is perfectly transparent, the following relations hold:

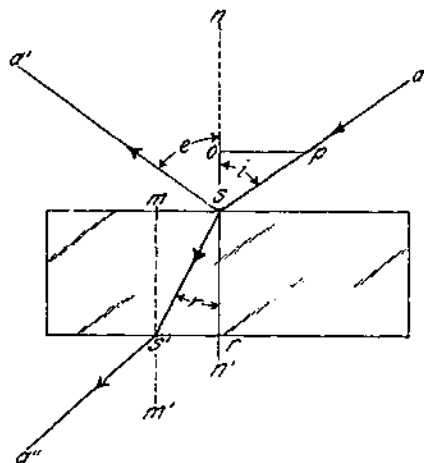


FIGURE 1.—Refraction of light and refractive index relationships

The ray as , on entering the second medium, is bent or refracted from its original direction into some new direction ss' . If nn' is the normal to the surface of the second medium at s , then the angle of incidence, i , has some value other than the angle of refraction, r .

Taking $sp = ss'$

$$\text{then } \sin i = \frac{op}{sp}$$

$$\text{and } \sin r = \frac{s'r}{ss'} = \frac{s'r}{sp}$$

Therefore

$$\frac{\sin i}{\sin r} = \frac{op}{sp} \cdot \frac{sp}{s'r} = \frac{op}{s'r}$$

The value of $\frac{op}{s'r}$ is specific for every known pair of media. Air is usually taken as the first medium and therefore the value $\frac{op}{s'r}$ becomes a constant for any individual substance taken as the second medium.

We may therefore write

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

where the value n denotes refractive index. Hence, in relationship to air as a standard, every known substance has a particular refrac-

tive index, n , which serves to distinguish it from most other substances. Of course there are some substances of which the indices of refraction are so nearly the same as to make their differentiation impracticable by refractive-index measurements alone. But even in such cases, the refractive index differentiates a small group of substances from a vast number of other substances; and the members of the small group can usually be differentiated from each other by further optical tests. At worst, it is much better to be able to determine that a particular substance is one of two or three, or even a dozen, substances than to be totally ignorant of even what it might be.

In the diagram (fig. 1) angle r is shown as less than angle i . This is the condition that obtains when the refractive index of the second medium is greater than the refractive index of the first medium. If the direction of the light ray were reversed, the angle of incidence, i , and the angle of refraction, r , would be interchanged. The ray traveling in the second medium from s' to s would be refracted on passing into the first medium in a direction sa and the angle of incidence would be less than the angle of refraction. All this may be summed up in the statement that, on passing from a medium of lesser into a medium of greater index of refraction, the ray is bent toward the normal; whereas, on passing from a medium of greater into a medium of lesser refractive index, the ray is bent away from the normal.

If the ray passes through the second medium and reenters the first medium again at the point s' , the phenomena are the same as at the point s , except in a reverse direction. Therefore the path $s'a''$ is parallel to the path as . Thus, the aggregate effect is simply a lateral displacement without any change of direction of the ray.

If one looks through a piece of clear, colorless glass, it is quite possible that he will be unconscious of the existence of the glass so long as his view does not include the edges. But the edges themselves stand out in marked contrast to the surrounding air. Assume, for the sake of simplicity, that a bundle of parallel rays are striking the glass at an angle less than the critical angle. Part of the light is reflected back from the surface of the glass and never reaches the observer. But the greater part passes through the glass to the observer without any change of direction. At the edges, however, some of the light is totally reflected back into the glass, some is totally reflected back into the air, some is refracted at varying angles from the glass to the air, and some is refracted at various angles from the air to the glass. Away from the edges, the light suffers no change readily perceptible to the observer. At the edges, it is broken up in a complicated heterogeneous fashion quite perceptible to the observer. Thus, the edges stand out in sharp relief both as compared with the glass and as compared with the surrounding air. But suppose the glass had the same refractive index, the same optical density, as the air. There would be neither reflection nor refraction at the edges, and therefore the edges would be invisible. That is, if the glass and the air were of the same degree of transparency and colorlessness, the glass would not be visible at all. This fact is utilized under the microscope to determine the refractive index of substances. This is discussed on page 33.

POLARIZED LIGHT

As previously mentioned, the phenomena of light are explained by means of the theory that light is simply a series of waves propagated in the ether. An ordinary candle flame owes its luminosity to the myriads of incandescent carbon particles it contains. Each of these particles sends out its own series of waves in all directions. Some of the waves impinge on and are reflected or refracted by various objects in various directions. Thus each reflecting or refracting object becomes a new source of light waves which may be again and again reflected or refracted by other objects, and so on, ad infinitum. In the heterogeneous complex of waves thus formed, certain waves may combine and increase their intensity, and certain other waves may neutralize each other. It is obvious that no satisfactory study of the effect of any ray of light on any particular object can be made under such conditions. An analogy with water waves may serve to make this clear. Think of a very large pond with the surface perfectly smooth. If a marble is dropped into the water a series of waves will spread out, circular fashion, from the place where the marble struck the water. This series of waves has certain definite properties which could be studied by their effects on various objects floating on the water. But suppose that, instead of one marble being dropped, a very large number had been simultaneously dropped. A series of waves would originate and spread out from each point where a marble had struck. But, before any particular wave had proceeded very far, it would meet other waves and become modified or even be destroyed. Objects floating on the water would show the effect, not of any particular series of waves, but of the chance combination of many series of waves, and consequently no study could be made which would directly show the relationship between the objects and a particular series of waves. Going back to the 1-marble series, it is obvious that at some point sufficiently distant from the point of origin the circumference of the circle formed by the waves would become so great that any short arc would be sensibly a straight line, a fact which would further simplify our study. Here the waves could be considered as simply a series of rises and falls of the water surface in one plane, whereas the waves arising from the many marbles would be rises and falls of the water surfaces in many planes at chance angles to each other.

Ordinary light is analogous to the many-marble case. Parallel-plane polarized light is analogous to the 1-marble case. Hence, parallel-plane polarized light can be defined as light whose wave vibrations are all in one plane.

Ordinary light can be polarized in several different ways. Perhaps one of the most universal methods is that of polarization by reflection. Light reflected from almost all polished nonmetallic surfaces is somewhat polarized. But there is a particular angle of incidence for each substance at which the reflected light is more completely polarized than it is at any other angle. This particular angle of maximum polarization is called the polarizing angle. In general it may be said that the polarizing angle is that angle of incidence at which the reflected and the refracted rays are at right angles to each other.

Polarization by reflection, however, is unsatisfactory, because of its incompleteness. The method usually employed in optical crystallography is polarization by a calcite prism, usually known as a Nicol prism. This brings us to the subject of double refraction, or birefringence.

DOUBLE REFRACTION

If a cleavage piece of clear calcite is placed upon a dot on a piece of paper, two dots will in general be seen on looking at the original dot through the calcite. If the calcite is placed upon a very narrow line on the paper, two lines will be seen at certain positions of the calcite. In other words, if a single beam of light is sent through a piece of calcite, two beams will emerge on the other side. Thus calcite has the power to split a beam of light into two beams. This property is possessed to greater or less extent by all crystalline substances which belong to some crystal system other than the isometric. In certain substances it is barely detectable even with the best instrumental equipment, and in other substances, such as calcite, it is easily detectable by the simplest method of observation. Between these two extremes are all gradations. As previously stated, a cleavage piece of calcite possesses the property of splitting a beam of light into two component beams. Each of these beams is plane polarized, and the plane of each is at right angles to that of the other. Consequently, when the beams emerge from the calcite we have plane-polarized light, but we have it polarized in two planes. By suitably cutting the crystal and recementing it, we can get rid of one of the rays by total internal reflection. Thus only one beam emerges and gives us plane-polarized light vibrating in one plane only. A piece of calcite thus cut is usually spoken of as a Nicol prism, or simply as a Nicol.

If two Nicols are so arranged that the polarized beam of light emerging from one, called the polarizer, enters the second, called the analyzer, the resultant phenomena depend on the angular relationship between the polarization planes of the two Nicols.

If the polarization planes of the two Nicols are parallel, the polarized beam passes through the analyzer without double refraction and emerges without any appreciable loss of brightness and without any change in the position of the plane of polarization. If, however, the analyzer be rotated, double refraction takes place, and one of the beams is lost by total reflection in the analyzer. The light, therefore, emerges from the analyzer with decreased brilliance. As the rotation of the analyzer is carried farther and farther, the light lost by internal total reflection becomes greater and greater, and consequently the light emerging becomes less and less. When the two Nicols are at an angle of 45° to each other, the lost light and the emerging light are about equal. When the two Nicols are at an angle of 90° to each other, all the light is lost, and none emerges. There are thus three relative positions of the two Nicols, which have considerable importance in optical crystallography: The parallel position, in which practically all the light emerging from the polarizer is transmitted through the analyzer, the 45° position, in which approximately half the light emerging from the polarizer is transmitted through the analyzer, and the 90° position, usually spoken of as the crossed

position, in which none of the light emerging from the polarizer is transmitted through the analyzer.

It happens that calcite has a very large double refraction. But all crystalline substances, other than those belonging to the isometric system, show double refraction to some extent, usually less than that of calcite.

Suppose a crystal of an isometric substance be placed between two crossed Nicols. Since the crystal has no double refraction, the light emerging from the polarizer is not altered and therefore enters the analyzer just as it would if the crystal were not present. No matter how the crystal is orientated, the effect, or rather, lack of effect on the light is the same. All of it is totally reflected internally by the analyzer, and the observer sees no light at all emerging from the analyzer.

But suppose a doubly refracting crystal be placed between the crossed Nicols. This crystal acts on the light emerging from the polarizer just as the analyzer would. If the plane of vibration of the polarizer and the crystal are parallel, the light emerges from the crystal with practically no diminution in brightness and with its plane of polarization the same as if the crystal were not present. This light is then lost in the analyzer by total internal reflection, again as if the crystal were not present, and the observer sees no light emerging from the analyzer.

If the crystal is rotated somewhat out of its position of parallelism, the light beam coming from the polarizer is doubly refracted anew into two beams with planes of polarization at right angles to each other. There is no arrangement in the crystal to absorb either of these beams as there is in the Nicols. Consequently both beams enter the analyzer. That small part of the light which is vibrating parallel to the plane of the analyzer is transmitted, and the observer sees the crystal faintly. As the crystal is rotated more and more, more and more light is transmitted until the 45° position is reached. At this position the crystal is the brightest. As the rotation becomes greater and greater, less and less light is transmitted, and the crystal appears less and less bright until the 90° position is reached, in which no light is transmitted and the effect to the observer is the same as at the beginning of the rotation.

On the basis of the phenomena shown by crystals when rotated between crossed Nicols, there are two great classes of substances, the singly refracting and the doubly refracting, or, in terms of their effects, those which remain dark during rotation and those which alternately light up and grow dark during rotation. This test is fundamentally one of the most important in optical crystallography. Not only does it give a ready method for distinguishing two major groups of crystals, but it has a very definite bearing on the refractive indices of a given crystal, as will be seen from the following.

It is a well-known fact that a ray of light, passing from a medium of one optical density into a medium of different optical density, is refracted or bent to a definite extent, depending on the difference in the densities of the two media. Suppose, however, that the second medium has different optical densities in different directions. Suppose simply that in certain directions the molecules of the medium are

more closely packed than they are in other directions. In short, suppose the space lattice of the second medium to be parallelopipeds. Then, for the same angle of incidence, the angle of refraction will be different, depending on the direction in which the ray of light enters the second medium. Consequently, the ratio of the angle of incidence to the angle of refraction will be different for different directions in the second medium. Assuming that the first medium is air, the refractive index of the second medium will then depend on the direction in this medium in which the light travels.

The parallelepipedon space lattice gives a crystal in which the packing of molecules is a maximum in a direction corresponding to one dimension of the parallelepipedons, a minimum in a direction corresponding to a second dimension, and intermediate between the other two is a direction corresponding to the third dimension of the parallelepipedons. The packing in any direction other than those corresponding to the three dimensions would then vary, depending on the relation between the direction chosen and the directions of the three dimensions. Correspondingly there would be three definite refractive indices, a maximum, a minimum, and an intermediate. Between the directions corresponding to these three indices there would be a series of varying indices, depending on the direction. All crystals belonging to the orthorhombic, monoclinic, and triclinic systems have these three major refractive indices.

Instead of the packing of molecules being dissimilar in three directions, suppose that in two of these directions the packing becomes the same; say that the packing in the minimum and the intermediate directions becomes identical. Then there are only two directions in the crystals in which the packing differs, a direction of maximum packing and a direction of minimum packing. Between these directions there would then be a series of directions in which the packing varied from the maximum to the minimum. Correspondingly, there would be two major refractive indices, a maximum and a minimum, with a series of varying indices depending on the direction of the light ray in the crystals. Substances belonging to the tetragonal and hexagonal systems have these two major indices.

If the molecular packing is further simplified so that the two directions of the previous paragraph become identical, so that every direction in the crystal has the same packing, there would be only one refractive index for the substance, and this index would be the same regardless of what direction in the crystal the ray of light took. Substances belonging to the isometric (cubic) system have simply one refractive index.

Summing up in reverse order: Isometric crystals have one and only one refractive index, usually denoted by n . Tetragonal and hexagonal substances have two refractive indices each, usually denoted by ϵ and ω . Orthorhombic, monoclinic, and triclinic substances have three refractive indices usually denoted by α , β , and γ .

For the complete study of the refractive indices of any given crystalline substance, one and only one index would have to be determined if the substance is isometric, two indices if the substance is tetragonal or hexagonal, and three indices if the substance is orthorhombic, monoclinic, or triclinic.

BECKE LINES

The critical angle may be further defined as that angle of incidence, of which the sine is equal to the reciprocal of the refractive index. If α denotes the critical angle and n the refractive index, thus,

$$\sin \alpha = \frac{1}{n}$$

Obviously, the greater is n the smaller will $\sin \alpha$ be, and therefore the smaller will the angle α be. Suppose two substances of different refractive indices to be in contact along the line CC' (fig. 2) the normal to which is nn' . Let d' be the critical angle in the substance of higher index and b the critical angle in the substance of lower index. Then d' will be less than b . Then the angle c , the complement of d' , will be greater than angle d , the complement of b . Suppose a ray of light be

directed upward in the figure, with its center striking the contact of the two substances at C' . Then all the light within the angles c and d will be totally reflected and will emerge from the upper surface of the two substances, as shown in Figure 2. Since angle c is larger, it will contain a greater amount of light than d ; and consequently a greater amount will be totally reflected and

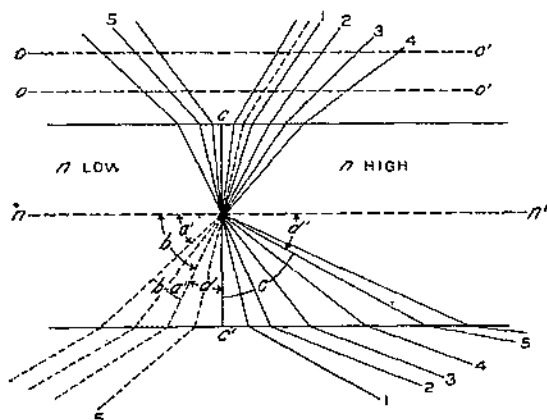


FIGURE 2.—Becke line production and movement

will emerge to the right of the contact than will be the case on the left of the contact. Light within the angle $b-a'$ will be partly reflected and partly refracted, and all light within the angles a' and d' will be partly reflected and partly refracted. But the sum total will be a preponderance of emerging light on the right side of the figure; that is, on the side of the substance of higher index. Therefore, the right side of contact will be brighter than the left side.

If a grain of high index is immersed in an oil of low index, the effect will be a line of light around the edges of the grain. If the plane of observation oo' is raised, it can be seen from the figure that the lines of light will apparently move farther to the right. If the plane is lowered, they will appear to move to the left. The effect on raising the plane is as if the area of the substance of higher index contracted, and on lowering the plane as if it expanded. The band of light is known as the Becke line, named after F. Becke by Salomon (14), and is one of the most commonly used phenomena in refractive-index determinations.

To make the phenomena concrete, suppose a grain of a substance, such as sodium chloride, having a higher index of refraction, be

mounted on a microscope slide in an oil of a lower index of refraction, such as cedar oil, and suppose the microscope be focused on the contact between the grain and the oil. A bright band of light will be seen to surround the grain. Now suppose the focal plane of the microscope be somewhat raised; that is, simply suppose that the tube of the microscope is slightly raised. The band of light will move into the grain. If the focal plane is lowered the band will move outward from the grain. If, on the contrary, the immersion oil had a higher index of refraction than the grain, as for example, cinnamon oil, the phenomena would be reversed. If the focal plane is raised the band of light moves outward from the grain into the oil, and if the focal plane is lowered the band moves inward toward the center of the grain. Put briefly, when the tube of the microscope is raised the band of light moves toward the substance of higher refractive index, and when the tube is lowered the band moves toward the substance of lower refractive index.

If both grain and oil have the same index of refraction, there will be no band of light and consequently no movement either way when the microscope tube is raised or lowered. If, furthermore, the oil and the grain have the same color and the same shade of color, or if both are equally colorless and transparent, the boundary line between the two is invisible, and one does not see the grain at all.

As has been explained previously, the refractive index of a given substance may vary with the direction of the light in the substance, but it is always the same in a given direction in the substance. Therefore, it happens that for a given grain in a given oil, the phenomena of the Becke lines will depend on the orientation, the position of the grain in reference to the incoming light. Methods for determining or altering this orientation will be given later.

If the substance belongs to the isometric system, the direction of the light, and therefore the orientation, is of no consequence. If the substance belongs to any of the other five systems, the direction of the light, and therefore the orientation, is of consequence.

INTERFERENCE OF LIGHT

If one drops a marble in otherwise perfectly still water and observes the effect of the waves thus formed on some small body floating on the water, it will be noticed that the body has simply an up-and-down motion, without any horizontal displacement. If the water moved horizontally, the body would move horizontally with it, and the fact that no such horizontal movement takes place is evidence that the wave motion itself is simply a progressive up-and-down movement of the surface of the water. At the spot where the marble strikes the surface there is at first a depression, and immediately afterwards there is a rise. This vertical movement, up and down, is transmitted to neighboring particles which consequently move up and down, and, in so doing, transmit the movement to still other particles. Thus, the up-and-down movement is propagated farther and farther from the source of the disturbance and is manifested as waves.

If (fig. 3) xx' is the level of an undisturbed surface, and $abcdefg$ is the surface itself during wave motion, then the highest points of the waves, such as b and f , are called crests. The lowest points,

such as d , are called troughs. At the beginning of the wave, particles at the point a are just beginning to rise. Consecutive points continue to rise until the crest b is reached. But, although a and c are on the same level, the direction of movement at a is upward, whereas that at c is downward. The motion continues downward from c until the trough d is reached. Here the direction of motion is reversed, and a rise takes place up to the point e . Points a and c are both on the same level, and both have upward motions. From e the phenomena which started at a is repeated until the next similar point is reached, and so on. The distance ae , or the distance between any two points having the same level and corresponding directions of motion, is called a wave length.

As the motion of the wave progresses from left to right, any particle at a crest, such as b , will move vertically downward until it reaches a point b' the same distance below the level xx' as b is above it. Trough points such as d will move vertically upward to some point d' , making the distance $od' = od$. Intermediate points would have correspondingly intermediate motions; although it should not be forgotten that every point is, at some time, a crest, and at some other time a trough. The distance ob , that is, half the vertical distance from a crest to a trough, is called the amplitude of vibration.

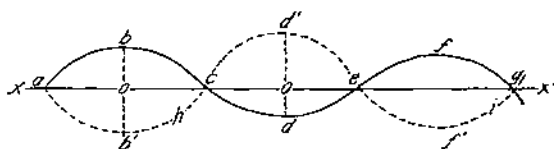


FIGURE 3.—Wave length, amplitude, phase, and interference of light waves

The wave length determines the color of the light. The longest waves which affect our eyes give us the sensation of red, the shortest violet. Other colors have intermediate wave lengths. Ordinary white light is a mixture of all wave lengths from that of violet to that of red.

The amplitude determines the intensity of the light. The intensity varies directly with the square of the amplitude. Any two points, such as a and c , b and f , or h and i , which are at a corresponding position relative to the plane xx' and have a corresponding direction of motion either up or down, are said to be in the same phase.

If two waves of the same wave length are superimposed so that every point in one is in the same phase as every corresponding point in the other, the wave length will remain unchanged. But the forces acting vertically on any point will be increased, and the amplitude of the new wave will be correspondingly increased. The intensity of the light will be increased.

If two waves of the same length are superimposed so that every point in one is in the phase opposite to that of the corresponding point in the other, the vertical forces will neutralize each other, and the amplitude of the new wave will be zero. In other words, there will be no wave at all, and darkness will be the result. Examples are extremely thin films such as soap bubbles when examined in monochromatic light. Here there will be observed a series of alternate bright and dark rings, the latter resulting from the interference of the light. If white light is used in place of monochromatic light,

only certain wave lengths interfere in given positions. These wave lengths are thus removed from the original white light and the residue of light reaching the eye is highly colored. The consequence is, therefore, that instead of dark rings, as with monochromatic light, there is a series of highly colored rings. The same phenomena take place when a cone of light is sent through a doubly refracting substance, as will be seen when interference figures are described (p. 39).

THE PETROGRAPHIC MICROSCOPE AND ACCESSORIES

MECHANICAL PARTS

The petrographic microscope and its optics have been repeatedly described, and adequate accounts of both the mechanical and optical features can be found in numerous texts of microscopy (7). The following description is therefore intended merely as a schematic representation, and for more detailed information the texts cited should be referred to.

Essentially the mechanical parts of a microscope are supports for, and means of adjustment of, the optical parts. They are therefore secondary in importance to the optical parts. Although of only secondary importance, poor supports can render a microscope inconvenient and illy adapted to certain purposes, and poor adjustments can actually make the instrument worthless in certain very necessary functions.

The base, which is usually of a modified horseshoe shape, should be large enough and heavy enough to prevent all tendencies of the microscope to topple when the upper part of the instrument is tilted a reasonable amount from the normal vertical position. On the other hand, it should not be so large as to be in the way of the manipulation or so heavy as to make the instrument unwieldy.

The pillar, in combination with the base should be high enough to allow adequate and convenient working space, between the stage and the base, for the substage equipment and the mirror. Short pillars are particularly annoying when, for example, the insertion of the finger between the substage and the mirror or the tilting of the mirror to obtain oblique illumination, is either impracticable or necessitates other operations.

The joint between the pillar and arm should allow easy tilting of the upper part of the instrument through an angle of 90° and should be provided with a clamp or other mechanism for maintaining any set inclination.

The arm is usually curved or is hollowed concave toward the stage in order to allow more working room on the stage. Other things being equal, that arm which is least in the way is perhaps best.

The fine-adjustment screw is the most important adjustment mechanism of the microscope and is perhaps the most apt to be faulty. This screw should have vernier attachments to allow the reading of complete turns and fractions of turns of the screw, and these readings should be directly convertible into vertical movements, expressed in decimals of millimeters, of the tube of the microscope. The pitch of the screw is not always the same in different parts, and for this reason it is essential that the mechanism be calibrated over

its whole length. This is especially true for instruments which have seen long service. The fine adjustment is not only a means of raising and lowering the tube in order to get a sharp focus on an object, but it is also a measuring device for the amount of raising or lowering. For these reasons the pitch of the screw should be as low and as uniform as practicable.

The coarse adjustment, usually a rack mechanism, should work smoothly and easily but should be tight enough to obviate all spontaneous movement of the tube.

The tube of the microscope usually consists of an inner drawtube and an outer body tube, the former fitting snugly into the latter and movable vertically in reference to the latter, preferably by an independent rack mechanism. The length of the body tube (the distance between the upper ends of the body tube and the shoulder of the objective screw) should be of known standard length, usually 160 mm. The drawtube should be conveniently ruled so that the increase in total tube length can be read when the drawtube is raised. In the tube there should be an iris diaphragm and slots or other arrangements for the reception of an auxiliary lens, a Nicol prism, a Bertrand lens, and other optical accessories. The base of the tube consists of a centering device and a clamp or nose piece for the attachment of the objective lenses.

The stage of the microscope must be of the horizontal revolving type, with the circle graduated in degrees and with appropriate verniers for reading fractions of degrees. While not absolutely necessary, two rectilinear movements of the stage governed by screws at right angles to each other are extremely useful and convenient. The stage should revolve easily and smoothly and should be preferably provided with a set screw for holding it in any given position. The usual clamps for slides must be provided on the table of the stage. These should be readily removable and replaceable. Universal stages, capable of revolving in every direction, are available in many forms and are frequently extremely convenient, especially in connection with the measurement of extinction angles (p. 58).

The substage mechanism must have a vertical movement, controlled by a rack, and also a swing-out movement. The rack should work smoothly and easily but should not be so loose as to slip spontaneously or under the influence of slight jars. The swing-out movement should be easily accomplished, without preliminary operations. Some means of readily removing and replacing the condenser lens, without disturbing the remainder of the substage, adds wonderfully to the satisfaction in using a good microscope. In addition to its optical equipment, the substage should carry an iris diaphragm and a swing-out frame for light filters and other accessories.

The mirror arm and fork must allow the rotation and turning of the mirror to any desired position without the removal of the substage or the lifting of the microscope from the worktable. The mirror fork should slide vertically and be clampable on the mirror arm.

Certain microscopes are equipped with a device for the simultaneous rotation of the two Nicol prisms, one in the tube and the other in the substage. This device consists essentially of two horizontal

arms attached one to each Nicol, the arms themselves being connected by an upright supported by the stage frame. The whole arrangement, including the Nicols, is capable of rotating horizontally through an angle of 90° , the angle being read by verniers attached to the device and moving on the graduated circle of the stage. Theoretically, it makes no difference whether the stage, and therefore objects under examination on it, revolves in reference to the Nicols or whether the Nicols revolve simultaneously in reference to the stage. In either case the final result is the same. There is also doubt as to which is relatively the easiest and more convenient. Some workers prefer the simultaneous rotation of the Nicols, whereas others dislike it. Perhaps, especially in much-used microscopes, the simultaneous rotation of the Nicols gives a steadier movement than would be given by a worn stage on a worn and clogged frame. On the other hand, the upright is occasionally very much in the way and must be detached. Since both can be had on the same microscope at the same time, the preference is to have both and to use either one or the other, depending on the exigencies of the moment or on personal inclination.

The foregoing brief description of the mechanical parts of a petrographic microscope emphasizes the fact that, up to a certain point, the parts are practically the same as those on any ordinary first-class compound microscope. Beyond this point, however, there are radical differences.

(1) The mechanical parts must carry much more optical equipment than the ordinary microscope. The latter usually has only the mirror, the condenser, the objective, and the ocular. The petrographic microscope must carry all of these, and, in addition, provision must be made for two Nicol prisms, auxiliary lenses, the Bertrand lens, quartz wedges, gypsum plates, quarter-undulation plates, and other accessories. (2) The mechanical equipment of the petrographic microscope consists partly of accurate measuring devices; for example, the fine adjustment screw and the graduated revolving stage, together with their verniers. The framework, therefore, becomes not only a carrier for the lens and lighting systems but also an accurately constructed measuring instrument as well. This point should be borne in mind when selecting an instrument for any other than a purely qualitative purpose.

OPTICAL SYSTEM

Although the mechanical equipment of the petrographic microscope has much more rigorous requirements than that of the ordinary microscope, the reverse is true so far as simple magnification is concerned. The prime and often the only requirement of the ordinary microscope is that it should magnify objects to clear visibility. This specialization of purpose has led to the development of lenses and illumination technic which give very great magnifications and very clear images.

As a rule, however, the petrographer and the optical crystallographer have very little interest in the appearance of the objects under examination. The interest is not in what the object looks like, but in the physical effect, frequently measurable, which the object has on light. In fact, the object is not at all visible during certain operations of optical crystallography, for example, the meas-

urement of axial angles. Furthermore, crystals are not generally so small as to require exceedingly high magnification. The result is that petrographic microscopes are not equipped for anything more than very moderate magnification but are equipped with a variety of physical appliances for the production of various optical phenomena which are not used at all in ordinary microscopy.

The mirror is so pivoted on the mirror fork and the mirror arm as to be rotatable any amount in any direction, thus enabling it to be set at any angle and thereby to perform its function of reflecting light from any source directly up into the microscope. One face of the mirror is plane and the other concave. The light reflected from the plane mirror into the microscope is parallel, and that from the concave mirror is convergent. The plane mirror, therefore, gives a weaker illumination than the concave mirror and is used with low-power lenses where a comparatively small amount of light is adequate. The concave mirror, on the other hand, is used with high-power lenses in order to increase the illumination by converging the rays of light. This rule, plane mirror for low magnifications and concave mirror for high magnifications, holds only when the condenser lens is not used. This subject will be discussed again in relation to condensers.

It should be noted here that parallel rays of light coming to the plane mirror from some very distant source, such as the sky, are reflected into the microscope with a slight loss of intensity. On the other hand, light from the same source is reflected into the microscope from the concave mirror with increased intensity, due to the convergence of the rays at the focal point of the mirror. If the light source is brought nearer so that the rays from it to the mirror are no longer parallel, the position of the focal point will change. Adjustment can be made to suit the conditions by sliding the mirror fork up or down the mirror arm, thus changing the distance of the mirror from the object under examination. In general, the nearer the source of light the greater is the focal distance of the mirror.

The condensing lens, as its name implies, is a lens for condensing and thereby increasing the intensity of the light which passes through it. Parallel rays of light passing into the lower surface of the lens are converged on passing out of the upper surface and thus form a cone-shaped bundle of rays meeting at the focal point of the lens. The light is therefore concentrated and the illumination consequently increased. If the light passing into the lower surface is already convergent, as is the case when the concave mirror is used, the convergency of the light leaving the upper surface of the condenser is increased and the focus of the condenser lowered. This lowering may very well bring the focus considerably below the object under examination and lessen, instead of increase, the illumination. For this reason it is generally best to use the plane mirror instead of the concave mirror, in conjunction with the condenser lens.

It is obvious that the best illumination will be obtained when the condenser lens is in focus. To bring it to focus any suitable object is mounted on the stage as usual and focused on with a low-power objective. The image of some fairly distant object, such as the edges of the window, is then projected into the field of the microscope by tilting the plane mirror. The condenser lens is now moved up or

down until the image is quite sharp. The condenser is now in focus. The image can be removed from the field by a slight tilting of the mirror. If the distance of the object from the condenser is changed it is evident that the condenser may need refocusing. Ordinarily this does not occur frequently, but it may occur if microscope slides of greatly different thicknesses are used.

The objective of the microscope is the lens, or usually the system of lenses, which is either screwed into or clamped onto the lower end of the microscope tube directly above the object under examination. It is perhaps the most important single item of the entire microscope equipment, since on it depends not only the magnification but also the clarity and sharpness of the image and consequently of all the other optical phenomena.

Objectives are usually corrected to some extent for spherical and chromatic aberration. Achromatic objectives are corrected for aberration of one color and for primary spherical aberration. Semi-apochromatic objectives are spherically corrected for two and apochromats corrected for three colors.

Oil-immersion objectives are those which are used in contact with a drop of oil, usually cedar oil, placed on the cover glass of the mount. Certain objectives require also a film of oil between the condenser lens and the slide. If the glass of the condenser lens, that of the slide, the cover glass, the objective lens, the immersion oil, and the mounting medium all have the same refractive index, there is a minimum loss of light since there is no refraction of the light when passing from one part of the system to another. Such a system is called homogeneous immersion. The nearer the respective refractive indices are together the less the loss of light. Water in place of cedar oil, for example, would lead to some light loss, and air in place of the water would lead to a still greater loss. It is obvious that only objectives of very short focus can be brought into contact with a drop of oil on a cover glass. Immersion objectives are therefore of high power. Loss of light with low-power objectives is of no practical importance. Dry objectives are those which have only air between the objective and the cover glass. The construction of dry and immersion lenses is different, and there is therefore no advantage gained by using immersion oils with dry objectives. In petrographic work, immersion objectives are practically never used.

Objectives are further described as having such and such angular apertures and numerical apertures, the latter usually being abbreviated to N. A. The angular aperture is the angle whose vertex is the focal point of the objective and whose sides are the light rays coming from the extreme edges of the lens. The greater this angular aperture is the greater will be the amount of light entering the objective from any point of the object and the better will be illumination. If the objective lens is immersed in some oil of a different refractive index, the focal point will change its position and consequently the angular aperture will have a new value. The axis of the lens always passes through the focal point and therefore always bisects the aperture angle, regardless of the position of the focal point.

Let i be the angle formed by the lens axis and the extreme rays passing into the objective, that is, let i be half the angular aperture

when the objective is immersed in air, and let r be the corresponding angle when the objective is immersed in some oil. Let n be the ratio of the sines of these two angles. Then,

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

or,

$$\sin i = n \sin r.$$

Instead of leaving the equation thus expressed in terms of the angle between the lens axis and the extreme rays entering the objective, we can let $2u$ =angular aperture $=2r$.

Wherefore $r=u$.

Substituting, $\sin i = n \sin u$.

Defining $\sin i$ as the numerical aperture of the objective,

$$N. A. = n \sin u,$$

where n is the refractive index of the medium in which the objective is immersed. If the objective is of the dry type, $n=1$, and the formula becomes

$$N. A. = \sin u.$$

For dry objectives, therefore, the numerical aperture varies directly as the sine of half the angular aperture. For immersion objectives, the numerical aperture varies directly as the product of the refractive index of the immersion oil and the sine of half the angular aperture in that oil. The numerical aperture thus increases with the angular aperture. The greater the numerical aperture, the greater will be the amount of light entering the objective and therefore, in general, the better will be the illumination. Most manufacturers designate their objectives by numerical aperture, and it is consequently of importance to have some understanding of the meaning of the term.

The penetration or depth of focus of an objective may be defined as the vertical distance through which the image of an object may be seen sharply when the objective is focused in one position. With low-power objectives, both the bottom and top of fairly large objects may be seen sharply without any change of focus, but with high-power objectives this vertical range of distinct vision becomes considerably less, so that a change of focus becomes necessary in order to see objects in slightly different planes. The depth of focus varies inversely as the numerical aperture. For ordinary observational work a great depth of focus is very desirable, but for measurements of thickness the objective of least depth of focus gives the most accurate results.

Objectives may or may not have flat fields, that is, all points in one horizontal plane may or may not appear equally distinct at the same focus. Frequently, when the objective is focused on a point in the center of the field, the edges of the field appear blurred and require a new focus. This is especially apt to be noticed with high-power objectives and is due to the curvature of the image. Objectives showing this blurring within reason should not be considered as defective, since it is practically impossible to correct entirely for it.

The illuminating power of objectives, all other things being equal, varies as the square of the numerical aperture.

The resolving power of an objective is its capacity to render distinctly and separately visible two points which might otherwise appear as one. In other words, it is the capacity to render visible the finer details of objects. It depends on the correction for chromatic and spherical aberration and on the numerical aperture. Usually, the higher the magnifying power of an objective the greater is the resolving power, but this is not necessarily so. Examination of certain diatoms for finer details of structure is perhaps as good a test of resolving power as any.

The magnifying power of an objective depends on the tube length of the microscope. The greater the tube length the greater the magnification. Actual measurement of the magnification by the objective alone has practically no value, since the objective is always used in conjunction with some ocular. Magnification by a microscope, therefore, means the magnification produced by the objective and the ocular conjointly for a given tube length. Other things being equal, however, the magnification of a microscope depends directly and primarily on the magnification of the objective. Some objectives have their magnification marked directly on them; others are labeled variously.

In general, it may be said that objectives of low magnifying power are short and have a wide expanse of lense surface at their lower extremity. On the other hand, objectives of high magnifying power are long and have very little lens surface at their lower extremity. Objectives of intermediate magnifying power have intermediate appearances. The general subject of magnification will again be discussed in connection with oculars and methods.

The working distance of an objective is the distance of an uncovered object in focus from the front lens. Cover glasses and the brass mounting of the objective decrease this distance.

Dry high-power objectives are corrected for use with cover glasses of certain thicknesses, and a variation of 0.05 mm in this thickness may lower the efficiency of the objective. Usually the correction is for cover glasses from 0.16 to 0.18 mm thick. Water-immersion high-power objectives allow greater variation of cover-glass thickness than do the dry objectives. Low-power and homogeneous-immersion high-power objectives allow any reasonable variation in cover-glass thicknesses.

The ocular, which fits into the upper end of the tube and from which the light directly enters the eye, has for its function the magnification of the image formed by the objective. It is comparatively simple in construction, only two lenses being used in most forms. There are three general types, the Huygens, or negative ocular, the Ramsden, or positive ocular, and compensating oculars. The term "eyepiece" is frequently used as a synonym for ocular. In the Huygens ocular there are two plano-convex lenses with their plane surfaces upward, or toward the eye. The Ramsden ocular likewise consists of two plano-convex lenses, but the convex sides are placed toward each other. Compensating oculars are constructed to partly eliminate differences in focal planes for different colors caused by the objectives.

In addition to these general types, there are various special oculars which are more or less useful for various purposes. For ex-

ample, there are demonstration oculars, carrying pointers for indicating any part of the field; double-demonstration oculars, which enable two persons to view the same field at the same time; and goniometer eyepieces, which revolve horizontally on a graduated circle. A particularly useful form of ocular is one carrying a slot through which various accessories, such as micrometers, may be inserted. Oculars fitted with special optical equipment for the production of particular optical phenomena, such as the Bertrand ocular, will be described in connection with the phenomena.

Up to the present point the description of the optical parts of the microscope has been in general applicable both to the ordinary and to the petrographic microscope. Those appliances peculiarly characteristic of the petrographic microscope will now be described. Perhaps the most fundamental difference between the two types of instrument lies in the fact that the ordinary microscope uses ordinary light, whereas the light used in a petrographic microscope is plane polarized. The polarizer is located in the substage of the microscope and consists of a calcite prism cut and then recemented in a particular way. There are numerous types of Nicols, depending on their method of construction, but all accomplish the same purpose in the same general way.

If the calcite is cut and then recemented at such an angle that one of the rays strikes the planes of division at the critical angle or greater, whereas the other ray strikes the plane at less than the critical angle, the first ray will be totally reflected out of the side of the calcite and can be absorbed. The second ray, polarized in one plane, will pass through the calcite and can be used as a source of illumination for the microscope. The polarizer, therefore, causes a loss of about half the light coming from the mirror. This loss, however, is not serious as very high powers of magnification are not used.

In the tube of the microscope, above the objective, is another Nicol prism so arranged as to slide into and out of the path of light. This Nicol is also capable of rotation through an angle of 90° in order to enable the worker to set it so that its plane of vibration is either parallel to or at right angles to the plane of vibration of the polarizer. This upper Nicol is usually spoken of as the analyzer, and the analyzer and polarizer are said to be parallel or crossed, according to whether their planes of vibration are parallel or at right angles to each other.

Analyzers should not have sloping ends, as they not only cause a slight additional loss of light by reflection (which is not so serious) but displace the image of the object (which is very serious). All analyzers should be tested as to this latter point. Simply observe the positions of a number of small objects on a slide with the analyzer out and then reobserve their positions when the analyzer is inserted. The positions should not have changed to any very noticeable extent.

Certain types of microscopes, notably the "chemical" microscopes, place the analyzer, the so-called cap Nicol, over the ocular instead of in the tube, as is done in the petrographic microscope. This cap Nicol has its uses even in the petrographic microscope, and in the nonpetrographic type of instrument serves its purpose

very well. But for purely petrographic work the petrographic microscope with an analyzer in the tube will prove best.

Both Nicols should be quickly and conveniently removable for cleaning. The upper surfaces, especially of the analyzer, have a tendency to collect dust which interferes with clear vision. If the Nicols are not conveniently removable, cleaning is usually put off far beyond the time when the need arises. In the choice of instruments, the writer would consider the ease with which the Nicols could be cleaned as one of the crucial points affecting his decision.

The Bertrand lens, quartz wedge, gypsum plate, quarter-undulation plate, and micrometers are accessories to, rather than parts of, the petrographic microscope, but they are essential accessories and when used form an integral part of the optical system. Without them certain essential functions of the petrographic microscope could not be accomplished. They are, therefore, described in connection with the microscope, whereas other valuable but not indispensable accessories are described in connection with the particular optical phenomenon they are designed to produce or observe.

The Bertrand lens is inserted in a slot in the tube of the microscope and, together with the ocular, serves as a microscope for the magnification of the interference figure. The axis of the microscope and the center of the inserted lens should exactly coincide or should be easily adjustable to coincidence. This can be tested by observing the interference figure of a section of calcite cut at right angles to the optic axis. The center of the interference cross should lie at the intersection of the cross hairs of the ocular when the Bertrand lens is in place.

The quartz wedge, as its name implies, is, in its simplest form, a wedge-shaped piece of quartz mounted for protection between two plates of glass. This wedge is inserted into the tube of the microscope through a slot provided for the purpose. The increasing thickness of the wedge through which the light must pass, as the wedge is gradually inserted thin end foremost, causes increasing retardation of the light rays. Newton's whole range of colors is given, the colors repeating themselves in successive order as the wedge is inserted. One quartz wedge giving colors of the first, second, and third orders is essential, and another wedge giving colors of the third and higher orders is very desirable. There are various improved forms of quartz wedges which are really improvements; for example, the Wright combination wedge. But for ordinary petrographic work the ordinary wedge is usually sufficient.

The gypsum plate is variously spoken of as the selenite plate, violet of the first-order plate, red of the first-order plate, sensitive plate, and unit-retardation plate. It is insertable in the same slot as the quartz wedge and should have the same elongation as the wedge in order to avoid confusion. A method for testing this elongation will be given under the quarter-undulation plate.

The quarter-undulation mica plate is a sheet of muscovite of such thickness as to give a retardation of one-fourth λ , mounted for protection between glass plates. The quartz wedge, the gypsum plate, and the quarter-undulation plate have various uses which will be given in their places.

The vibration directions in the quarter-undulation plate can be ascertained or confirmed by using the plate as an object and observing the interference figure. The direction of least ease of vibration Z (or γ) is that of the line joining the foci of the two hyperbolæ. The direction of intermediate ease of vibration Y (or β) is at right angles to Z. To ascertain the vibration directions of the gypsum plate, use the plate as an object and observe the interference figure. The direction of the line joining the two yellow quadrants is the Z (or γ) direction. The vibration directions of the quartz wedge can be ascertained by using the wedge as an object and inserting a quarter-undulation plate whose directions are known. This will be explained more fully under the use of the quarter-undulation plate.

At least two micrometers are absolutely essential. One of these should be a standard-stage micrometer with a scale marked off in tenths and hundredths of a millimeter. This micrometer should be used solely for calibrating other micrometers. The other essential micrometer is an eyepiece micrometer and may be of various types. Certain types are circular in shape and are inserted into the ocular. Other and more convenient types are mounted on a rectangular frame which slides into a slot provided for the purpose in the ocular. If only one eyepiece micrometer is to be had, the checkerwork type is the more useful. It is best, however, to have one of this and also one of the linear-scale type. Various screw-micrometer oculars for great refinement of measurement can be had and should be used when extremely accurate results are necessary. For ordinary petrographic purposes the standard-stage micrometer and a suitable checkerwork eyepiece micrometer will be adequate.

Where reflected light is to be used, the vertical illuminator will be found invaluable. It is a device attachable to the lower end of the microscope tube between the tube and the objective. A horizontal beam of light is admitted through an iris diaphragm in the side of the illuminator, is then reflected vertically downward by a semicircular rotatable mirror, passes through the objective onto the object, and thence is reflected back vertically upward through the objective and illuminator to the eye.

CALIBRATION AND MEASUREMENTS

TO DETERMINE THE VIBRATION DIRECTIONS IN NICOL PRISMS

Prepare a section of biotite cut at right angles to its cleavage. Rotate this section, with analyzer out, until it is in its darkest position. The cleavage direction is now parallel to the plane of vibration of the polarizer. If a suitable section of biotite is not available, mount a minute crystal of tourmaline, in which the elongation (the direction of the c axis) can be identified, so that the c axis is horizontal. Rotate the mount, with analyzer out, until the crystal is in its darkest position. The c axis will now be at right angles to the plane of vibration of the polarizer. Another less accurate, but nevertheless fairly satisfactory, method is to detach the polarizer from the microscope, reflect light into the polarizer by means of a preferably horizontal piece of plate glass or other polished surface,

and rotate the polarizer until the glass appears dark. The vibration plane of the Nicol will now be at right angles to the reflecting surface.

The vibration plane of the analyzer can be readily found by comparison with the polarizer. Set the polarizer in some definite position in the microscope and use a good light. Rotate the analyzer until the field is dark. The Nicols are now crossed; that is, their vibration planes are at right angles to each other. The position of the vibration plane of the polarizer being known, that of the analyzer is known also.

The Nicols should be so placed in the microscope that the cross hairs of the ocular are parallel to the vibration planes when the Nicols are crossed.

DETERMINATION OF THE MAGNIFYING POWER OF A LENS SYSTEM

The magnifying power of a lens or system of lenses is not the definite figure it is usually thought to be. The magnification is the number of times the diameter of the object is contained in the diameter of the image; that is, it is the ratio of the diameter of the image to the diameter of the object. But the diameter of the image varies with its distance from the eye, and different eyes see most distinctly at different distances. The magnification is thus a constant, the diameter of the object, divided into a variable, the diameter of the image, this latter being large for far-sighted eyes, smaller for normal eyes, and still smaller for short-sighted eyes. The distance of most distinct vision for normal eyes is somewhere about 10 inches (250 mm). This is usually taken as a standard. It can be shown by elementary geometry that the ratio of the diameter of the image to the diameter of the object is approximately the same as the ratio of the distance of distinct vision to the focal length of the lens. Taking 250 mm as standard, the magnification, N , is then

$$N = \frac{250}{f},$$

where f is the focal length. This is simply a convention and different observers would actually see very differently. For example, a lens of 25 mm focal length would show an apparent magnification of ten times to a normal eye and only five times to an eye which saw most distinctly at a distance of 125 mm (5 inches).

The magnifying power of a microscope may be directly measured by placing a stage micrometer directly on the stage. The microscope is carefully focused on this micrometer. Any suitable scale, for example an ordinary desk rule, but preferably one with units directly convertible into the stage micrometer units, is then placed horizontally beside the microscope at a distance of 250 mm from the exit pupil of the eye. The image of the stage micrometer is observed with one eye and the scale with the other. The scale is moved about horizontally until it coincides with the image of the micrometer. Direct comparison of the two can now be made. If, for instance, the image of a $\frac{1}{10}$ -mm division on the micrometer tallies end to end with a 10-mm division on the scale, the magnifying power of that particular lens combination is 100 diameters.

A better method, perhaps, is to use a camera lucida, if one is available. Place a piece of paper at such a distance from the eye that the actual path of the ray through all its reflections in the camera lucida from the paper to the eye is 250 mm. On the paper mark off the extremities of some convenient division, say a $\frac{1}{16}$ -mm division, of the micrometer image, as seen on the paper through the camera lucida. Measure the distance between the two marks, and find the ratio between this measured diameter of image and the actual size of the micrometer division. If, for instance, the micrometer division is $\frac{1}{16}$ -mm and the distance between the marks is 25 mm, the magnifying power is 250 diameters.

It is not often that one absolutely needs to know the magnifying power of a lens system except as it can be obtained comparatively by simple inspection of the objectives and oculars. It is essential, of course, to know that one objective or ocular will give a higher magnification than another. But to know that one lens combination gives a magnification of exactly 280 diameters, for instance, is usually information of doubtful utility.

HORIZONTAL LINEAR MEASUREMENTS UNDER THE MICROSCOPE

There are several methods for measuring lengths of microscopic objects. The simplest is to use a micrometer stage. This is an arrangement whereby two screws, with vernier attachments, working at right angles to each other, are capable of moving the stage and consequently any object on it. The screws should be calibrated by placing the stage micrometer on the micrometer stage (the distinction should be noted), aligning the screw axis with the stage micrometer and comparing the divisions of the screw vernier with the distances actually passed through by the stage as shown by the cross hairs and the stage micrometer. This calibration should extend through the entire lengths of both screw movements. To measure the length or diameter of any object under the microscope, align the screw axis and the linear direction desired, place one end or side on the cross hair, and turn the screw until the other end or side is on the cross hair. The length or diameter is then given directly by the screw divisions turned through.

A more generally satisfactory method involves the use of the eyepiece micrometer. This micrometer should be calibrated once for all by means of the stage micrometer and for every lens combination. This can be readily done by simple comparison of the images of the two micrometers as seen directly through the microscope. It would seem unnecessary to remark that this comparison does not give directly the magnifying power of the microscope, but experience shows that this is one of the commonest of mistakes. All that is actually done is to compare an image of the stage micrometer magnified by the entire lens combination with an image of the eyepiece micrometer magnified by one or more of the lenses of the ocular only. All that is directly known is that a unit division of the eyepiece micrometer corresponds to so many millimeters, as read on the stage micrometer, and this is all that one needs to know. If the stage micrometer is replaced by an object, the length can be read directly from the eyepiece micrometer. This length expressed as numbers of eyepiece-microme-

ter units multiplied by the value in millimeters of a unit gives the actual length of the object. The checkerwork or net-grating eyepiece micrometers are much more satisfactory than the linear-scale type, as lengths in two directions at right angles to each other can be read without moving the object and diagonal lengths can be immediately calculated by application of the theorem that the square on the hypotenuse is equal to the sum of the squares on the other two sides. Thus any horizontal dimension of an object can be directly read or calculated without altering the position of the object. The objection to the checkerwork micrometer is that the large number of lines engraved on it sometimes interfere with distinct vision. This is unquestionably a valid objection; but the inconvenience of removing and replacing the micrometer, especially if it is of the slide type, is almost inconsequential as compared to the ease and range of measurement available. Generally speaking, however, it is best to have both the linear and checkerwork types of micrometers and, of the latter, one with very small and another with comparatively large unit squares.

There are several types of screw-micrometer oculars available. In principle these are screw-vernier arrangements for moving the micrometer over the image of the object instead of vice versa, as with the micrometer stage. The screw micrometer is capable of giving results of a very high degree of accuracy.

MEASUREMENT OF THICKNESS

The most delicate method of measuring the thickness of a particle is by means of its double refraction. The procedure is exactly the reverse of that given for the determination of the double refraction (which see). This method of thickness measurement, however, is very limited in its application. (1) The substance whose thickness is desired must be doubly refracting, and this requirement eliminates the possibility of applying the method to isotropic substances, including cover glasses and other very common objects. (2) It is necessary to know not merely the maximum double refraction of the substance as listed in the books or as usually determined, but it is essential to know the double refraction of the substance in the particular orientation in which the thickness measurement is to be made. This kind of information is very seldom available. In the rare cases where it is available, however, the method is to be highly recommended both for its accuracy and speed. The procedure is as follows: Rotate the stage until the object is in a position of maximum brilliance between crossed Nicols. Insert the quartz wedge into the tube of the microscope. If the colors of the object mount in the color scale as the wedge is inserted, rotate the object an additional 90°. If they descend in the color scale leave the object as it is and continue the insertion of the wedge until the object, at the point where the thickness is to be measured, becomes black. By removing the object or observing vacant spots in the field of the microscope and counting the number of recurrences of the color as the wedge is withdrawn, the color and its order are identified. Find the double refraction along the upper or right margin of the Michel-Lévy chart. (Fig. 5.) From this point follow the diagonal line to the particular

color of the particular order identified with the wedge. Then follow the horizontal line to the left margin of the chart, where the thickness will be found.

A method of thickness measurement practically universal in its application consists, in principle, in focusing on the plane of the bottom of the object, then refocusing on the plane of the top of the object and reading the difference between the two focal positions, the rise of the tube of the microscope, from the fine-adjustment screw and vernier. This presupposes that the fine adjustment be accurately calibrated. Furthermore, the reading from the fine-adjustment screw will not be the same when the focusing is done through air, as when it is done through the object. There are therefore two cases under this method. The calibration of the fine-adjustment screw presents difficulties, especially to workers of limited experience and equipment, and neither the calibration nor a thickness measurement can be any more accurate than the worker's ability to bring the microscope to a sharp focus and to duplicate this focal reading after raising or lowering the tube of the microscope. It is perhaps true here, more so than in any other phase of microscopic work, that the eye of the observer is as much in need of checking as is the instrument. Fine-adjustment screws undoubtedly do come uncalibrated or occasionally badly calibrated, but it is manifestly unjust to condemn a screw on the basis of results obtained by a person physiologically incapable of obtaining reliable results. There is no desire on the writer's part to stress this point unduly, but it is just as well to face the fact that there are individuals just as much unfitted, physiologically and psychologically, for microscopy as there are other individuals unfitted for music or art.

A fair method of calibrating the fine-adjustment screw is by the use, as object, of a cover glass, the thickness of which has been determined by micrometer calipers. Turn the fine-adjustment screw down as far as practicable, focus on the plane of the lower surface as accurately as possible with the coarse adjustment, complete the focusing with the fine adjustment and read the vernier. Turn the fine adjustment until the focus is on the plane of the upper surface. Again read the vernier. The difference between these two readings divided into the thickness of the cover glass gives the average value for one division of the fine adjustment for the particular screw range used. Leaving the fine adjustment in its last position, lower the tube of the microscope by means of the coarse adjustment to as accurate a focus as possible on the lower plane of the object. Complete the focus with the fine adjustment. This will give a new point of departure which will probably overlap slightly with or leave a slight interval between it and the first range of reading. Raise the tube of the microscope by means of the fine adjustment to a focus on the upper plane of the object. The difference of the readings divided into the cover-glass thickness will give an average value for each division of the fine adjustment over this new screw range. Continue in this way until the upper limit of the screw is reached. Then begin again with the first focus of the fine adjustment adjusted at a different reading from that found at the beginning. This process of calibration can be carried to any desired degree of elaborateness.

If, after a number of complete traverses of the screw have been made, it is found that the averages are all approximately the same, the screw divisions can be considered as calibrated at this average value. If two of the averages are markedly different, the data of the readings will indicate approximately the position in the screw where the trouble is, and this position can be avoided when making future thickness measurements. This process of calibration can be immensely shortened by confining it to one or two complete turns of the screw near the center of the screw range; or, better still, by confining it to the small number of intervals plus a few both above and below the range actually involved in the measurement. This latter procedure has the advantage of providing a check on the screw every time a series of thickness measurements is made, an advantage which becomes more and more important as the microscope becomes older. In making thickness measurements, all focusing with the fine adjustment should be made by movements all in the same direction, either up or down, in order to avoid errors due to lost motion. It should be borne in mind that there are very few fine adjustments which give identical values for each interval over the entire screw length. A certain amount of tolerance is therefore necessary, and occasional rechecking is all the more desirable. An accurate calibration over a small number of uniform intervals is much more satisfactory than an average calibration of the entire screw.

If an object is lying on a microscope slide, the upper surface of the slide can be taken as the plane of the lower surface of the object. By focusing on a scratch or a dust speck on the slide, reading the fine adjustment, then raising the tube by means of the fine adjustment until the upper surface of the object is in focus and again reading the fine adjustment, the difference of the two readings gives a measure of the thickness of the object. But this measure will be different, depending on whether the focusing on the slide surface has been to one side of or through the object. If the point of focus on the slide and that on the upper surface of the object are very close together horizontally, and if the focusing has been done slightly to one side of, and not through, the object, the difference of the fine-adjustment readings, converted into its calibration units, gives directly the thickness of the object. The object of course can be placed at any desired spot on the slide preliminary to the focusing. If the object is flat and has edges sloping outwardly and down, the lower edge can be used as a point of focus instead of the scratch or dust speck.

At times it is necessary to do the focusing through the object. Proceed exactly as above and then multiply the value so obtained by the refractive index of the object. This gives the true thickness. A mounting medium acts in this respect just as does any other object, and therefore thicknesses measured by focusing through the mounting medium must be multiplied by the refractive index of the medium in order to obtain the true thickness. If the lower focus is determined through air, no such multiplication is necessary, since the refractive index of air is unity.

Measurements of slant distances can be made by combining the proper horizontal and vertical measurements. The slant distance

between any two points is the square root of the sum of the squares of the vertical and horizontal distances.

Very fair ideas of the shape of vertical sections of objects with curved surfaces can be obtained by plotting vertical distances as ordinates and horizontal distances as abscissæ and connecting the points by a smooth curve. This is not very often of use and is not very accurate when applied to extremely small objects. A far easier method is to roll the object over and observe its shape directly or with the aid of the eyepiece micrometer when quantitative results are desired. But cases may arise where the rolling is impracticable. The graph method may then serve a good purpose.

MEASUREMENT OF AREAS

Perhaps the most convenient and readily accessible method of measuring areas under the microscope is to use a closely lined check-board micrometer and to count the number of micrometer unit squares covering the image of the object. If the micrometer has been previously calibrated against a stage micrometer, as described above, the area of each unit square is known, and the area of the object is simply this unit area multiplied by the number of units. Since proportional areas rather than absolute areas are usually desired, it is perfectly permissible to state areas directly in terms of micrometer units, regardless of what the calibration of the micrometer may be. For very close work, parts of unit squares on edges of the object's image can be estimated and added to the total. Micrometers so lined as to be directly readable in blocks of units, twenty-fives, and hundreds greatly facilitate the count and relieve eyestrain. At the very best, a worker will occasionally lose sight of the place under count. This may necessitate doing all the counting again, with the possibility of again losing the place, unless some system is used. A fairly satisfactory system is to first count all complete blocks of hundreds, then all complete blocks of twenty-fives not included in the hundreds, then all units not included in either of the preceding, and finally all fractions of units on edges of the image. In case of losing place, it is then necessary to repeat the count only partly instead of completely.

Areal estimations can be made by photographing or drawing with a camera lucida through the microscope, cutting out the areas desired and weighing them, the areal proportion being the same as the weight proportion on the assumption that the paper is perfectly uniform. The paper can be backed with tin foil to give added weight and therefore more accurate results. This method can be used in the absence of a micrometer but is otherwise not recommended.

A statistical method consists in making a number of linear measurements at right angles to each other for numerous particles in a given mount. These measurements, added and averaged, give a rectangle, the area of which can be compared with that of another rectangle similarly obtained. Better results have been obtained with this method and its modifications than would normally be expected; but, owing to the large number of measurements necessary, the method is tedious and long.

MEASUREMENT OF ANGLES

As a preliminary to the measurement of an angle, the stage of the microscope should be very carefully centered. The slide should then be moved until the vertex of the angle is at the intersection of the cross hairs and one side is very near and parallel to one or the other of the cross hairs. A reading is taken from the graduations on the circumference of the stage. The stage is then rotated until the second side of the angle reaches the initial position of the first side. A second reading is taken, and the difference between it and the first reading gives directly the angle desired. Instead of "sides" to the angle one may have cleavage directions or directions of extinction, but the technic is the same. These angular measurements should be repeated, using first one side then the other as the initial side and revolving the stage in opposite directions. Then the stage should be turned 180° from its first position and the measurements repeated in this new position.

A goniometer eyepiece may be used in place of the rotating stage. The only essential difference between the two methods is that with the goniometer eyepiece the object stays still and the cross hairs rotate, whereas with the revolving stage the object rotates and the cross hairs remain still.

Angles can be measured from camera-lucida drawings or from photomicrographs by means of an ordinary protractor. An approximation to an angle can be obtained by use of the checkerwork-eyepiece micrometer and a table of trigonometric functions.

If the angle between two crystal faces is being measured, the methods above give the true angle only when the planes of the faces are parallel to the axis of the microscope, or (which is practically the same) when the intersection of the two faces is vertical. Preliminary examination as to these points should be made before the angle is measured. It should be remembered also that the angle measured is the actual angle between the two faces and not its supplement as read from a reflecting goniometer. Angles between horizontal and vertically slanting faces can sometimes be calculated from data derived from horizontal measurements with the eyepiece micrometer, together with vertical measurements with the fine adjustment. There are various other angles which may be calculated by methods of plane and solid trigonometry, but the need for them is comparatively rare, and reference is therefore made to the standard text (2). The beginner, when dealing with the angular measurements of crystals, should be particularly careful not to be misled by misshaped or unusually oriented crystals. A cube of common salt, for example, shows a beautiful hexagonal outline when it is tilted with a corner uppermost and is examined with an objective of considerable depth of focus. The measurements of these hexagonal angles would be utterly meaningless, and a very casual examination with a lens of less depth of focus would reveal the true form of the crystal. This serves to illustrate one of the essential tests which should never be omitted before making an angular measurement. Both sides of the angle should simultaneously come into focus over their entire length when examined with an objective of minimum depth of focus.

There are apparent exceptions to this rule, but it is safer to follow it than to read angles indiscriminately, at least until one acquires the habit of thinking crystallographically.

OPTICAL METHODS

IMMERSION MEDIA

In all microscopic work immersion media of one kind or another are used in making up the mounts for examination. Their purpose, primarily, is to aid visibility and, secondarily, in conjunction with the cover glass, to protect both the object and the objective lens. The preparation of the mount may become a very complicated matter or may be of the utmost simplicity, depending on the nature of the object and the purpose to be attained. Essentially, however, it consists in embedding an object on a slide in the immersion medium selected and then placing a cover glass over the object. The choice of the immersion medium is a matter of the utmost importance, especially in the determination of the refractive indices of objects. If we mount, say, a broken fragment of glass in some oil of a known refractive index different from that of the glass, the glass is easily visible. If by trial we mount the same glass in oils of refractive index progressively nearer and nearer that of the glass, the glass is invisible. Thus, knowing the refractive index of the oil in which the glass is invisible, we also know the refractive index of the glass.

Ideally, immersion media which are to be used for refractive-index determinations should have the same color and the same intensity of color as the substance to be examined. They should be stable in contact with air and under the influence of light; they should be practically nonvolatile in air, and especially they should not be differentially volatile; and their refractive indices should not vary perceptibly with ordinary changes of temperature. They should have no, or only slight, dispersive effects on light, they should not dissolve the substances to be examined, and they should all be mutually miscible so as to enable the worker to form media of refractive indices intermediate between any two given indices. Needless to say, no such ideal set of media has ever yet been contrived. There are, however, several practicable sets. Larsen (10) gives the refractive indices shown in Table 1.

TABLE 1.—*Refractive indices of immersion media*

	n at 20° C.	$\frac{dn}{dt}$	Dispersion	Remarks
Water.....	1.333		Slight.	Dissolves many of the minerals with low indices.
Acetone.....	1.357		Slight.	
Ethyl alcohol.....	1.362	0.00040	do	Do.
Ethyl butyrate.....	1.381		do	
Methyl butyrate.....	1.386		do	
Ethyl valerate.....	1.393		do	
Amyl alcohol.....	1.409	0.00042	do	Dissolves many minerals with which it is used.

¹ Ordinary kerosene oil may be used, but on mixing with kerosene it forms a milky emulsion, which settles on standing, and then the clear liquid may be decanted off.

TABLE 1.—*Refractive indices of immersion media*—Continued

	n at 20° C.	$\frac{dn}{dt}$	Dispersion	Remarks
Kerosene.....	1.448.....	.00035.....	Slight.....	
Petroleum oil ²				
Russian aboline.....	1.470.....	.0004.....	do.....	
American aboline.....	1.477.....	.0004.....	do.....	
Valvolene ³	1.502.....	.0004.....	do.....	Will not mix with clove oil.
Clove oil ⁴	1.531.....	.00050.....	Moderate.....	Will mix with petroleum oil.
Cinnamon oil ⁵	1.585 to 1.590.....	.0003.....	Strong.....	
Cinnamon oil from Ceylon.....	1.595.....	.0003.....	do.....	
Cinnamic aldehyde.....	1.614 to 1.617.....	.0003.....	do.....	
α -Monobromnaphthalene ⁶	1.658.....	.00048.....	Moderate.....	
Methylene iodide.....	1.737 to 1.741.....	.00070.....	Rather strong.....	Rather expensive. Discolors on exposure to light, but a little copper or tin in the bottle will prevent this change.
Methylene iodide saturated with sulphur.....	1.778.....		do.....	
Methylene iodide, sulphur and iodides.....	1.858.....		do.....	
Piperine and iodides.....	1.68 to 2.10.....			
Sulphur and selenium.....	1.995 ₇ to 2.716 ₈		Very strong.....	
Selenium and arsenic selenide.....	2.72 to 3.17 ₁₁		do.....	

² Any of the medicinal oils may be used, such as Nujol.

³ Any good, clean lubricating oil, such as is used in automobiles, may be used.

⁴ If clove oil does not mix with petroleum oil mix it with rapeseed oil, $n=1.471$.

⁵ The only advantage in using cinnamon oil is that it is less expensive than cinnamic aldehyde.

⁶ Mixtures of clove oil and α -monobromnaphthalene give a set of liquids of lower dispersion than those with cinnamon oil.

⁷ To 100 g. methylene iodide add 35 g. iodoform, 10 g. sulphur, 31 g. SnI₄, 16 g. AsI₃, and 8 g. SbI₃, warm to hasten solution, allow to stand, and filter off undissolved solids. See Merwin (12).

⁸ g is the abbreviation for gram or grams recently adopted by the style manual for United States Government printing.

In making mixtures of two oils to obtain media of intermediate indices, the equation

$$v_1 = n_2 - n$$

$$v_2 = n - n_1$$

where v_1 is the volume of the oil of least index, v_2 the volume of the oil of greater index, n_2 the greater index, n the desired index, and n_1 the lesser index, will be found useful. The refractive index of the mixture prepared in the proportions given by the equation must, however, be measured, as the formula is only approximately correct. The measurement can be made on any refractometer having a sufficiently wide range of readings or can be made somewhat less accurately by a reversal of the process for measuring the refractive index of crystals (which see). Sets of calibrated liquids are on the market.

DETERMINATION OF REFRACTIVE INDEX BY BECKE LINE

Assuming that we are dealing with an isometric substance or with a crystalline nonisometric substance whose orientation can be modified or determined to suit our convenience, we have the following method for determining the refractive index by means of the Becke line.

Mount the substance in any immersion medium of known refractive index. Either the grain and the immersion medium have the same refractive indices or they have different refractive indices. If they have the same refractive indices, the substance will be invisible and will have the same index as that of the medium of

known index. The refractive index of the substance is therefore known.

Almost never, however, would one be able to guess so well or happen to pick the right medium the first time. Practically always the refractive indices of the medium and the substance would be different. In this case focus the microscope on an edge of a grain of the substance. Raise the microscope tube by means of the fine-adjustment screw. If, when the tube is raised, the Becke line moves into the grain, the grain has the higher index; if the Becke line moves outward from the grain, the immersion medium has the higher index. We have thus determined whether the given medium has a higher or lower index than the grain. If its index is lower than that of the grain, obviously we need a medium of higher index. If its index is higher, obviously we need a medium of lower index. Choose another immersion medium on the basis of what has been said in the previous sentence and make another mount. Repeat the observations on the Becke line. In the first mount we found, say, that the index of the grain was the higher:

$$n \text{ (first medium)} < n \text{ (grain)}$$

In the second mount we will find either that

$$n \text{ (first medium)} < n \text{ (second medium)} < n \text{ (grain)}$$

or

$$n \text{ (first medium)} < n \text{ (grain)} < n \text{ (second medium)}$$

In the first case we have found a medium which has a known index nearer that of the grain. That is, we are closer to the true index of the grain than we were in the first mount. In the second case we have established limits between which the index of the grain must lie. By repeating this trial and error method a sufficient number of times we will finally find a medium in which the grain is invisible. The refractive index of the grain is then the same as that of this medium, and since the index of the medium is known that of the grain is also known.

In the use of the Becke line for refractive-index determinations several precautions must be taken as follows:

(1) The grains of the substance to be examined must be dry before they are mounted in any immersion oil. Otherwise, the Becke line is the result, not of the contact between the oil and the grains, but of the contacts between the oil and water and of the water and the grains. The result usually is a heterogeneous mixture of Becke lines practically impossible of interpretation into terms of the refractive indices of the grains and the immersion medium.

(2) The substance under examination should be insoluble, or practically so, in the immersion media used. If the substance is appreciably soluble in the media, the Becke line is the result not of the contact of the substance and the media, but of the contact of the substance and a solution of the substance of unknown concentration and therefore of unknown refractive index.

(3) The surfaces and edges of the grains of the substance to be examined should be clean and free from coatings and adhesions of

foreign substances. If these coatings and adhesions are readily visible, their presence can be recognized and search made for edges which are free from these impurities. But grains coated with thin films of transparent impurities are likely to cause errors. Such coated grains are frequently encountered in substances which have been dried without first having had the coating of mother liquor removed. If such grains are crushed, edges free from the coatings can be readily found.

(4) The line of contact between the grain and the immersion oil should be as nearly vertical as possible. With a transparent thin grain, both the top and bottom edges are visible. If the side contact between the grain and the oil is very much inclined from the vertical, Becke lines may be seen to move both from the bottom and top edges, and confusion may result. Furthermore, the phenomena are complicated by reflection and refraction from the inclined surface.

(5) One should make sure that he is examining an individual crystal and not an aggregate of small crystals. In any given spot in an aggregate, the light effect would be the chance composite of the effects of all the small crystals through which the light had passed and would have no determinable relation to the effects of any given crystal. At different spots on the aggregate the light effects would vary, depending on the uniformity of sizes, orientation, distribution, and degree of packing of the smaller crystals. Especially should one look out for twinned crystals.

(6) One should make sure that he is examining crystals and not skeleton crystals, that is, crystals in an incipient stage of formation. Although the writer has no data on this subject, he is fairly sure that he has noticed several times that skeleton crystals had optical properties quite different from those of the completed crystal.

DETERMINATION OF TWO INDICES OF REFRACTION

The simplest procedure in determining both refractive indices, ω and ϵ , of a uniaxial substance is to find a crystal with a recognizable c axis in the horizontal position. Rotate to extinction between crossed Nicols, with the c axis parallel to the vertical cross hair. Remove the analyzer and by means of Becke line determine whether the crystal in this position has a higher or lower index than that of the embedding oil. Proceed then with the method already described for isotropic substances, except that here all the observations must be made on crystals in the initial orientation, or in that position of extinction which has the c axis parallel to the vertical cross hair. Finally, an oil will be found in which the crystal, in the given orientation, will be invisible. The refractive index of the oil being known, that of the crystal in the given position is also known. Repeat the whole procedure as above except that the crystal is to be in the position of extinction with the c axis at right angles to the vertical cross hair, that is, parallel to the horizontal cross hair. If the given substance is optically positive, the greater of the two indices measured as above is ϵ and the lesser one is ω . If the substance is optically negative, the greater is ω and the lesser ϵ .

If the refractive index is determined as above on grains, so orientated that the optic axis is vertical, that is on grains which give as

interference figure the uniaxial cross with the center in the center of the field, the index is ω .

If refractive indices are determined for two positions of extinction for a number of grains in random orientation, it will be found that one of the two values will be the same in all the grains. This constant index is ω . The other value will vary from grain to grain depending on the orientation. That value which is farthest from ω is nearest ϵ . Since uniaxial grains have a tendency to lie with the c axis horizontal, this value will perhaps be ϵ . Statistically the highest and lowest indices determined on a large number of grains of the same substance in random orientations will be the maximum and minimum indices of the substance and therefore will be ω and ϵ , or ϵ and ω , depending on the optical character of the substance. But selection of grains in proper orientations when possible obviates the necessity for statistical methods.

All the foregoing may be summed up as follows: The refractive index of uniaxial crystals varies with the orientation of the crystal, but for a particular substance in a particular orientation, the index is constant. Therefore, to determine the refractive indices of a particular substance, proceed exactly as with isotropic crystals, except that orientation can not be disregarded as in the case of isotropic substances. Uniaxial substances with the optic axis vertical give ω no matter where the stage is rotated. Uniaxial substances with the optic axis horizontal give ω at one position of extinction and ϵ when rotated 90° to the next extinction. Uniaxial substances with the optic axis neither vertical nor horizontal give ω at one position of extinction and some value between ω and ϵ when rotated 90° to the next position of extinction. Every orientation therefore allows the measurement of ω , but only one orientation allows the measurement of ϵ . Crushed quartz, crystals of sodium nitrate, calcite, and apatite serve very well for demonstrations of the foregoing.

DETERMINATION OF THREE INDICES OF REFRACTION

To determine three refractive indices, α , β , and γ , on biaxial substances, mount material as usual. Find a grain which gives an interference figure with the acute bisectrix in the center of the field. Rotate the stage until the plane of the optic axes, the line joining the foci of the two hyperbolae, is parallel to one or other of the vibration planes of the two Nicols. Test the relative refractive indices of the grain and the embedding oil for this position of the grain. Then proceed exactly as with isotropic substances, except that the grains must all have identical orientations, until an oil is found which has the same index as the grain in this position. With an identical orientation but with the plane of the optic axes 90° from the first position, measure, as above, a second index. One of these two indices, thus measured, will be β and the other may be either α or γ , depending on whether the grain is optically positive or negative. If the grain is positive the lower of the two indices is α and the higher β . If the grain is negative the higher of the two indices is γ and the lower β . In other words, the measurement made normal to the plane of the optic axis is β and the other is either α or γ as above. Two of the indices are thus known, β and α or γ . Working as near as possible on grains lying parallel to the planes of the optic axes, as approximately

determined by interference figures, proceed as above to determine two indices. One of these will be α and the other γ . The one already determined can be ignored, but the two determinations serve as a check. A grain lying normal to the obtuse bisectrix, as determined approximately by interference figures, gives β and either γ or α . This orientation is sometimes more convenient than that of grains lying parallel to the plane of the optic axes.

If the grains do not show any special tendency to lie in any one orientation, the statistical method can be used with some fair degree of certainty. Measure the lowest index shown by any grain in a given mount. This will be α . Then measure the highest shown by any grain. This will be γ .

A variation of this statistical method is to measure the highest and lowest, γ and α , indices of grains showing maximum double refraction. (See determination of amount of double refraction.)

The indices determined on the grains showing the emergence of the acute bisectrix in the center of the field are accurate. Those made on grains lying parallel to the plane of the optic axes and those lying normal to the obtuse bisectrix are subject to error, on account of the indefiniteness of interference figures used in identifying the orientation. Indices determined by the statistical method or its variation are always subject to the doubt as to whether the absolute highest and lowest indices have been found. There are cases, however, where only the statistical method is applicable. Any of the methods usually give results sufficiently accurate for ordinary determinative work. In fact, sometimes simply the mean refraction index, not necessarily β , is sufficient. But for work of high accuracy the measurements should be checked and rechecked, and the results tested by substitution in the formula

$$\tan^2 V = \frac{\alpha^2(\gamma^2 - \beta^2)}{\gamma^2(\beta^2 - \alpha^2)}$$

when V is half the optic axial angle and β , γ , and α are the measured indices. The calculation of V itself depends on the accurate measurement of β (see measurement of axial angle), but fortunately this measurement is of a comparatively high order of accuracy and the formula serves to check either α or γ of a much lower order of accuracy.

Occasionally, as has been said, the mean index of refraction is sufficient for ordinary determinative purposes. But, for purposes of record, the measured indices should always be definitely ϵ , ω , α , β , or γ , as the case may be, except of course in isotropic substances, where there is only one index. Indices measured without regard to orientation are usually worthless. There are cases, however, where it is practically impossible to obtain the proper orientation for the measurement of specific indices, such as are presented occasionally by rare substances fixed in one unsuitable orientation in a permanent mount. There are other cases where the worker has not the time to measure the specific indices, and there are still other cases where, for the purpose in hand, it is not essential that the particular worker should have the specific indices. In all such cases, indices should be given with some reference to the orientation in which the measurement was actually made; for example, index parallel or normal to

elongation of crystal, index parallel to plane of optic axes with acute bisectrix so many degrees from center of field, index parallel to c axis, index parallel to (111), index with optic axis (or acute bisectrix) emerging just out of field so many degrees to left of vertical cross hair, etc. Such data can scarcely be considered as publishable per se and are not always unambiguous, but they do have a value to the worker himself especially when working with substances which show a strong inclination to lie in particular positions.

Suitable substances for the demonstration of the foregoing are muscovite, potassium nitrate, ammonium nitrate, and aragonite.

Cases occur, especially with platy minerals, in which the grains persistently lie in one orientation. Sometimes, as with the micas, the acute bisectrix emerges nearly normal to the plate, and approximate values of β or γ can be measured directly. But another orientation is necessary for the measurement of the third index. It is possible, with patience and practice, to tilt even plates on their edges by judicious movements of the cover glass. This is naturally more easily done in viscous mounts. In order to give room for the grain to turn over, crushed glass may be mixed with the preparation. The glass particles, if not too small, support the cover glass, thus leaving the plates free to move. If the plate will not remain edge up, it is possible by quick observation to compare its index with that of oil as the plate passes through the vertical position.

Rod-shaped crystals present similar difficulties of orientation. The orientation can be altered by simply rolling the rods. Crushing frequently enables one to find fragments end up. But changing the orientation of any particles which have decidedly different dimensions is likely at any time to tax one's patience and ingenuity.

The refractive indices as measured must be consistent with the other optical properties. If a uniaxial substance is optically positive with the quartz wedge, gypsum plate, or quarter-undulation plate, ϵ must be greater than ω . If the substance is optically negative, ω is the greater. If a biaxial substance is optically positive, $\gamma - \beta$ must be greater than $\beta - \alpha$. If the substance is negative, $\beta - \alpha$ must be greater. If the substance shows strong double refraction, two at least of the indices must be considerably different. Furthermore, in all cases the double refraction, as actually measured, must check with the numerical difference of the indices involved. If the optic angle is small, two of the indices must be very close together and both quite different from the third index.

INTERFERENCE FIGURES

CONVERGENT LIGHT IN CRYSTALS

Convergent light when transmitted through crystals under certain conditions, which will be discussed below, is modified by interference phenomena (p. 14) and as a result shows very beautiful figures, usually called interference figures. These figures are of fundamental importance. Under suitable conditions they are produced by all crystals other than those belonging to the isometric system. Their absence therefore is an indication that the given crystal belongs to the isometric system. One type of figure is characteristic of the tetragonal and hexagonal systems, the uniaxial group, and

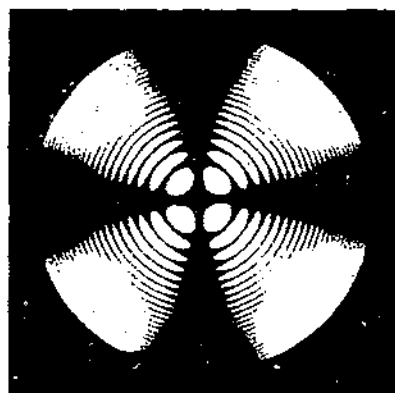
another type of figure is characteristic of the remaining systems, the biaxial group. Thus, direct observation of the absence of, or of the type of figure enables one to throw a given substance into one of three major groups, thus eliminating all substances in the other two groups. Determination of the optical character (p. 45) on the interference figure divides the uniaxial and biaxial groups each into two subgroups. Measurements on biaxial figures give the optic axial angles, and observations on the color distributions establish the character of the dispersion. Furthermore, the interference figure is the best and sometimes the only means of determining the orientation of a given crystal and therefore has a direct bearing on the measurement of refractive indices.

If a cone of light is passed through any given crystal, the effect of the crystal on the light depends on the crystal system to which the substance belongs, in other words, it depends on the character of the molecular packing in the crystal. Since the packing in isometric crystals is the same in every direction, substances belonging to this system show no special effect on the cone of light any more than that shown by a piece of glass or other amorphous substance. Quite distinct effects are shown, however, by substances in which the packing varies with the direction.

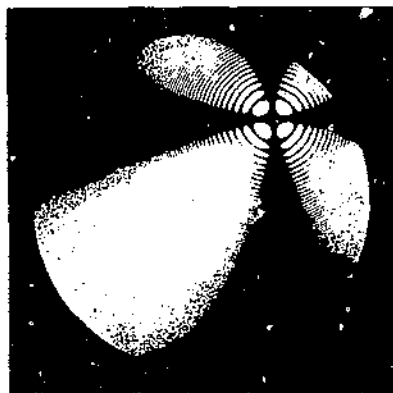
As previously explained, crystals may be divided into two groups, in addition to the isometric, according to the character of the space lattice. In the first group the packing is uniform in one direction, called the direction of the optic axis, and uniformly different from that of the optic axis in any direction at right angles to that axis. The optics of this group may be visualized roughly as a right circular cylinder, or accurately as an ellipsoid of revolution. In the ellipsoid of revolution the major axis represents the optic axis. All lines at right angles to this axis have the same length and the same optics. Substances belonging to the tetragonal and hexagonal systems have this structure. In the second group there are three directions in which the packing differs. The optics of this group may be visualized best by an oblate ellipsoid. Here there are two major axes and a third intermediate axis. Substances belonging to the orthorhombic, monoclinic, and triclinic systems have this structure.

The first group having only one major axis is called the uniaxial group. The second group, having two major axes, is called the biaxial group. The distinction between these two groups is of fundamental importance. In practice, the distinction is made by observing the interference figures shown by the given substances. (Fig. 4.)

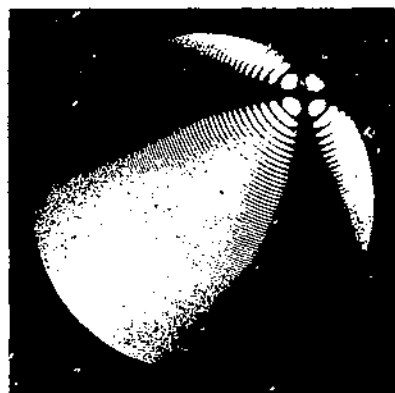
If a cone of light is passed through a uniaxial substance in a direction parallel to the optic axis of the substance, the rays at the center of the cone will strike the substance at right angles and will pass through without double refraction. All other rays, however, will be doubly refracted more and more as their angular distance from the axis of the cone is greater and greater. At any given distance from the axis the difference of path due to the double refraction will be the same, and the visible result, in the ideal case, will be a series of concentric circles showing a succession of colors in the Newton rings. The crossed Nicols cut out all light vibrations parallel to their planes, and consequently the series of concentric



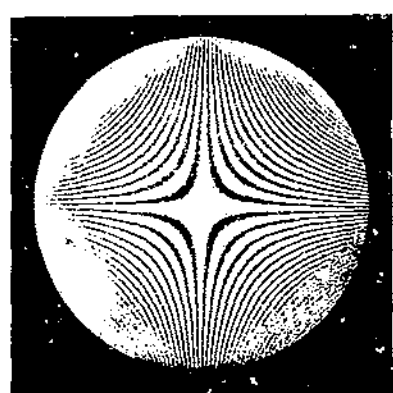
A



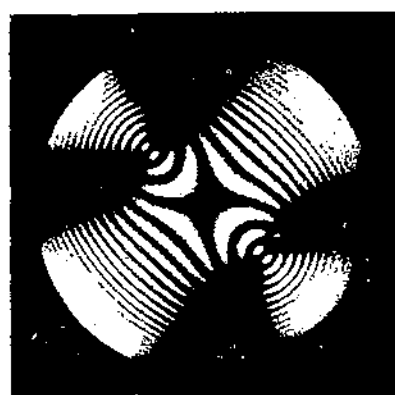
B



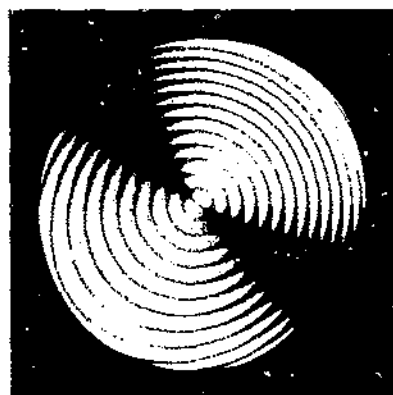
C



D



E



F

FIGURE 4.—A, Interference figure of uniaxial crystal (calcite), with optic axis vertical; B, same, with optic axis tilted from vertical; C, same, with optic axis tilted almost to edge of microscope field; D, same, with optic axis horizontal; E, interference figure of biaxial crystal (aragonite), with acute bisectrix vertical; F, interference figure of biaxial crystal (aragonite), with optic axis vertical.

From JOHANNESSEN'S *Manual of Petrographic Methods*, New York, 1918. Courtesy of McGraw-Hill Book Co. (Inc.).

circles is broken by a black cross. (Fig. 4, A.) The center of the cross is coincident with the center of the rings and is on the optic axis. If the axis of the cone of light and the optic axis are parallel, the center of the cross is in the center of the field of the microscope. As the stage of the microscope is revolved, no change whatever takes place. If the optic axis and the axis of the cone are slightly inclined to each other, the center of the cross will be slightly outside the center of the microscope field (fig. 4, B and C) and will describe a circle around the center of the field as the stage is rotated. As the mutual inclination of the optic axis and the cone axis becomes greater and greater, the center of the cross is farther and farther from the center of the field and describes a greater and greater circle as the stage is rotated. When the mutual inclination is sufficiently great, the center of the cross is no longer within the field, and only the straight bars of the cross are visible. These pass successively across the field of the microscope at right angles to each other as the stage is rotated.

The limiting case is that in which the optic axis of the substance is at right angles to the axis of the cone. (Fig. 4, D.) Not only the center of the cross but the bars also are no longer visible. The whole figure is rather indistinct.

As the stage carrying the mineral is rotated, there are certain positions in which two hyperbolæ will flash into the field from opposite quadrants, arrange themselves cruciform, and then quickly disappear in adjacent quadrants. As the rotation of the stage is continued, presently the phenomena of the hyperbolæ are repeated in the next quadrant. In a rotation of the stage through 360° , these phenomena occur four times, with a duration in each quadrant amounting to about 10° rotation (II, p. 36).

The optic axis is in the direction of the line separating the entering and departing hyperbolæ.

If a cone of light is passed through a biaxial crystal, the phenomena are much more complicated. There are four important directions in biaxial crystals which it is perhaps well to consider separately. The first is the direction of the acute bisectrix, that is, the direction of the line bisecting the acute angle formed by the two optic axes of the crystal. The second is the direction of the obtuse bisectrix; that is, the direction of the line bisecting the obtuse angle formed by the two hyperbolæ. The third direction is that of the optic normal; that is, the direction of a line perpendicular to the plane formed by the two optic axes. The fourth direction is that of an optic axis.

If a given biaxial crystal has an optic angle (acute angle between the two optic axes) not too large to be included in the field of the microscope, and if a cone of light be passed through the crystal parallel to the acute bisectrix, the crystal being rotated until its axial plane is parallel to the plane of vibration of one or other of the two Nicols, a dark cross will be seen, as in the case of a uniaxial crystal. But instead of the colored circular rings around the center of the cross, there will be two sets of roughly elliptical rings with their centers on the same bar but on opposite sides of the center of the cross. Toward the cross center these two sets of rings have a tendency to merge and together form a shape suggestive of a dumb-bell. If the crystal is so thin or so slightly doubly refracting that the colored rings do not appear, the figure is the same as that of a uniaxial crystal, so long as the position of the grain remains un-

changed. But if the stage is rotated the resemblance immediately ceases. The cross breaks up into two hyperbolæ, their foci being the two centers, "eyes," of the colored rings. These hyperbolæ reach their maximum distance apart when the rotation has reached 45° . (Fig. 4, E.) As the rotation is continued they gradually approach each other and again form a cross at 90° rotation. The distance of the two foci from each other is a measure of the optic axial angle, as will be explained later. Certain substances have such large axial angles that both foci can not be seen in the field at the same time.

If the cone of light passes through the crystal parallel to the obtuse bisectrix, the phenomena are much the same in principle as when the light is transmitted parallel to the acute bisectrix. But the obtuse angle is too great to allow the foci to enter the field. On rotation of the stage the two hyperbolæ enter the field, form a cross, then open and depart from the field. The hyperbolæ formed when the light is transmitted parallel to the obtuse bisectrix are vague and undefined in comparison with those formed when the light is transmitted parallel to the acute bisectrix.

If the cone of light passes through the crystal parallel to the optic normal, the interference figure obtained is similar to that given by a uniaxial crystal when the light is transmitted perpendicularly to the optic axis.

If the cone of light passes through the crystal parallel to an optic axis, the interference figure is the same as that which would be obtained if the light were transmitted parallel to the acute bisectrix, except that one of the foci of the hyperbolæ, instead of the center of the cross, is in the center of the field of the microscope. (Fig. 4, F.) If the axial angle is sufficiently large, the other focus will be outside the field. The hyperbola whose focus is in the center of the field becomes a straight line when the stage is rotated to a position in which the axial plane of the crystal is parallel to the vibration plane of one or the other of the Nicols. A 45° rotation of the stage brings the hyperbola to its maximum curvature, and in this position its convex side is toward the acute bisectrix. The greater the optic axial angle, the less is the curvature of the hyperbola. Crystals are sometimes found in which the axial angle is so great that the curvature of the hyperbola is no longer perceptible in any position. So far as can be detected by the eye, the hyperbola is simply a straight line revolving around its center in a direction opposite to the direction of rotation of the stage. Since no curvature can be detected, it is impossible to ascertain from the figure the direction in which the acute bisectrix lies.

Generally speaking, one does not often find crystals of either uniaxial or biaxial substance, which lie on the microscope slide in exactly one of the positions described above. Usually the position of the grain is somewhere intermediate between some pair of the positions described, and the interference figure shows itself naturally as a combination of the phenomena given by the two positions. It is well to conceive of the whole phenomena of interference figures as simply a gradual change of appearance as the observed crystal is tilted or rotated from one position to another, and it is absolutely indispensable to realize that the phenomena are three dimensional and not two dimensional. When working with uniaxial crystals or

with biaxial crystals of very small axial angle, it is well to consider the uniaxial figure as simply the limiting case of a biaxial figure as the axial angle approaches zero. There are biaxial crystals, for example, biotite, in which the axial angle is so small that the interference figure is indistinguishable from the uniaxial cross.

The colored curves of both the uniaxial and biaxial figures depend both on the thickness of the crystal examined and on its degree of double refraction. Very thin grains of only slightly doubly refracting crystals do not show the colored curves. This lack, however, is not usually particularly important, since the black cross and the hyperbolæ are the essential phenomena to be observed.

To obtain an interference figure, use a high-power objective, about 4 mm., center the objective carefully, move the microscope slide until the crystal to be examined is at the intersection of the cross hairs, that is, in the center of the field, focus on the crystal, cross the Nicols, raise the condenser as high as possible, and remove the ocular. The figure should then be visible. A pinhole cap for the tube of the microscope aids visibility by cutting out side light. Another method is to leave the ocular in and to insert a Bertrand lens in the tube of the microscope in the slot provided for it. The figure thus obtained is much larger than that obtained when the ocular is removed, but it is also blurred. Which method to use is perhaps a question of personal preference, depending on whether one prefers to observe a clear small figure or a large hazy one. It is a fact, however, that figures difficult to obtain are more apt to be visible when the ocular is removed.

There is usually no difficulty in interpreting an interference figure if the emergence of an optic axis (the foci of the hyperbolæ or the center of the uniaxial cross) or the emergence of the acute bisectrix is within the field of the microscope. If the interference figure is a cross which remains a cross with no separation into hyperbolæ during a complete rotation of the stage, then the crystal is in all probability uniaxial. It should be borne in mind, however, that there is a possibility that the crystal is biaxial with an imperceptible axial angle. If the interference figure alternately forms a cross and breaks up into hyperbolæ as the stage is revolved, there is no doubt that the crystal is biaxial. If two apparently straight bars cross the field alternately and at right angles to each other, the crystal is probably uniaxial, but may be biaxial with a very perceptible axial angle, as could be seen if the emergence of the acute bisectrix were visible. If two dark curves alternately cross the field as the stage is rotated, the crystal is probably biaxial but may be uniaxial with the emergence of the optic axis tilted considerably out of the field.

Practically all these doubts may be settled by changing the position of the crystal on the slide. To do this requires considerable skill and patience and presupposes a mount in which the individual crystals do not adhere to the slide, to the cover glass, or to each other. Tapping and jiggling the cover glass with the point of a pencil are remarkably effective. In order to allow room for a crystal to turn over, it is sometimes helpful to mix crushed glass with the substance to be examined. If the glass particles are considerably larger than the crystals, they support the cover glass and allow

ample room for the tilting and turning of individual crystal particles. Most of the time, however, it is perhaps easier and quicker to search for another crystal lying in a more suitable position.

This search need not necessarily be a blind series of trials. If the Nicols are crossed, any given particle which remains perfectly dark during a complete rotation of the stage is either isotropic or will give a practicable figure. Likewise, any given particle which remains bright during a complete rotation of the stage between crossed Nicols will probably give a practicable figure. On the other hand, particles which alternately and distinctly change from perfect darkness to brilliancy as the stage is rotated between crossed Nichols will probably not give practicable figures, and, if necessary, should have their positions changed.

Rounded grains of quartz furnish examples of almost all forms of uniaxial figures and can be readily tilted or rolled from one orientation to another. Mica is one of the most difficult substances to tilt and should be used for practice.

OPTICAL CHARACTER

After having ascertained the uniaxiality or biaxiality of a given particle by observation of its interference figure, it is convenient to use the same figure for the determination of the positive or negative character of the crystal, and thus subdivide each of the two major groups into two subgroups.

If, in uniaxial crystals, the extraordinary ray is the faster ray, that is, if $\epsilon < \omega$, the crystal is defined as optically negative. If the ordinary ray is the faster, that is, if $\epsilon > \omega$, the crystal is defined as optically positive.

If, in biaxial crystals, the direction of vibration of the slow ray is the acute bisectrix, the crystal is defined as optically positive. If the direction of vibration of the fast ray is the acute bisectrix, then the crystal is defined as optically negative. In general, it may be stated as a close approximation that the crystal is positive if $\gamma - \beta > \beta - \alpha$, and negative if $\gamma - \beta < \beta - \alpha$. This relationship of the refractive indices should be used merely as a check and not as an actual determination except when no other means are readily available. It should be borne in mind that it is perfectly possible for a given crystal to be positive with one wave length of light and negative with some other wave lengths.

There are three convenient methods for the determination of the optical character of a crystal; the quarter-undulation mica-plate method, the quartz-wedge method, and the selenite-plate method.

To use the quarter-undulation mica plate, find or place the crystal in such a position that the optic axis emerges in the field somewhere near the center. In other words, obtain an interference figure showing the center of the cross nearly in the center of the field. Insert the quarter-undulation mica plate in the tube of the microscope in the slot provided for the purpose. The dark cross of the interference figure will disappear, and a dim white cross will take its place. Two dark spots appear in opposite quadrants. With negative interference figures the two dark spots lie along the direction of the slow ray of the quarter-undulation mica plate. With positive crystals the two dark spots lie along the direction of the fastest

ray of the mica plate. If colored rings are present in the interference figure, they are disjoined into four quadrants, those in the two opposite quadrants appearing to be removed outward from the center of the figure and those in the two other opposite quadrants appearing to be removed toward the center. The pairs of opposite quadrants in which both the ring phenomena and the dark spots appear may be reversed with different plates or in different microscopes, depending on the way in which the mica plate is mounted and on the direction of the slot in the tube of the microscope. Each microscope and mica plate should be calibrated once for all by observing the phenomena given by the particular microscope with the particular plate on an interference figure of a crystal of known optical character. Muscovite is optically negative, and its acute bisectrix lies almost perpendicular to the cleavage plane. Since a flake of this mineral lies flat on its cleavage plane on the microscope slide, it gives a good interference figure with a minimum of manipulation. It is not even necessary to prepare a slide. The cleavage piece may be placed directly on the stage of the microscope with equally good results. For these reasons a flake of muscovite serves as an excellent test piece for the calibration.

The quartz wedge (p. 24) is especially useful on highly colored interference figures. Ideally, one should use the wedge on crystal mounts which show the emergence of the optic axis of uniaxial crystals or of the acute bisectrix of biaxial crystals. Obtain the cross of the uniaxial figure, or, if the crystal is biaxial, rotate the stage until the hyperbolæ coalesce to form a cross. Insert the quartz wedge, thin end foremost, in the slot of the tube of the microscope. As the quartz wedge advances, the colored curves in two opposite quadrants of the figure will move in toward the center, and the curves in the two other opposite quadrants will move outward from the center. The appearance is as if the colors were pouring into the center of the figure from two opposite directions and were pouring out of the center in two opposite directions at right angles to the first two directions. As the wedge is withdrawn the phenomena are reversed. Since the colors reach higher and higher orders of Newton's color scale as thicker and thicker portions of the wedge pass over the field, it is well to insert the wedge always thin edge foremost and to confine one's attention to the color movements during the insertion. Furthermore, one thus avoids the possibility of errors due to misinterpretation of the color movements. With the same wedge and the same microscope the colors will always move inward in the same pair of opposite quadrants and outward in the other pair for positive crystals and the reverse for negative crystals. It is therefore sufficient to note the color movements produced in a particular microscope by a particular wedge on an interference figure of known optical character in order to have that combination of instruments calibrated for all time. Here, again, a cleavage flake of muscovite serves as an excellent test piece. The flake should be comparatively thick. Otherwise, the colored rings will not show up very well.

The essence of the phenomena produced by the quartz wedge on an interference figure is that in any particular quadrant of the figure the color movement is always the same for crystals of given optical character. Therefore it is not necessary that the crystal be accu-

rately orientated. Uniaxial figures with the center of the cross entirely out of the field of the microscope still show by the direction of bars the general position of the emergence of the optic axis. If this position is conceived as the center of the figure, the positions of the bars determine whether one is observing the upper right, upper left, lower right, or lower left quadrant. If the quartz wedge is inserted and the movement of the colors in the quadrant noted, the optical character is determined. The same holds for biaxial crystals, except that the acute bisectrix, although perhaps entirely out of the field, must be conceived of as the center of the figure. The hyperbolæ are convex toward the acute bisectrix. This fact locates the direction of the acute bisectrix and therefore determines the quadrant under observation.

Very thin particles and particles with very low double refraction do not show interference figures with colored curves, and therefore the quartz wedge is not usually satisfactory with this type of material. The selenite plate, on the other hand, although not well adapted to particles which show interference figures with colored curves, is particularly suitable for interference figures without colored curves.

The selenite plate, sometimes called the sensitive-tint plate, the red or violet of the first-order plate, or the unit-retardation plate, is a plate of gypsum so cut as to give a red or violet interference color of the first order. If such a plate is placed over an interference figure showing the dark cross, two opposite quadrants of the figure will become blue and the other pair of opposite quadrants will become yellow. This phenomenon is best seen in a uniaxial interference figure, showing the emergence of the optic axis, or in a biaxial figure, with the crystal rotated to the position where the hyperbolæ form a cross and the acute bisectrix emerges in the field of view. But, as in the case of the quartz wedge, it is not necessary that the optic axis or the acute bisectrix emerge within the field. The coloration of the different quadrants is the essential part of the phenomenon. As has been previously explained, the quadrants can be identified in the case of a uniaxial figure by the relative positions taken by the dark bars as the stage is rotated and, in the case of biaxial figures, by the direction of convexity of the hyperbolæ. Knowing the particular quadrant under examination, one has simply to note the color given to this quadrant by the selenite plate. The opposite quadrant, whether it is invisible or not, will be similarly colored, and the other pair of quadrants will be colored differently from this first pair.

To use the selenite plate, first obtain an interference figure, preferably showing the emergence of an optic axis or of an acute bisectrix. If the figure is biaxial, rotate the stage until the hyperbolæ form a cross. If it is not convenient to obtain figures showing the emergence of the optic axis or of the acute bisectrix, identify the quadrant under observation. Insert the selenite plate in the tube of the microscope in the slot provided for the purpose, and note the color given.

It is not absolutely necessary to rotate the biaxial figure until the cross is formed. If, for example, the figure is in the 45° position, in which the hyperbolæ are at their maximum separation, the con-

cave sides of the hyperbolae will become similarly colored and the convex sides will show the other color. The quadrant principle, however, still holds and is perhaps the easiest way to remember the color relationships.

Which of the two colors, blue or yellow, will appear in a given pair of quadrants depends on the mounting of the plate and on the direction of the slot in which the plate is inserted. As is the case with both the mica plate and the quartz wedge, it is necessary to calibrate each selenite plate with each microscope. Here again a cleavage flake of muscovite (optically negative) is almost an ideal test piece. Since interference figures showing colored curves are not desired, the flake should be comparatively thin.

Certain microscopes have a selenite plate attached to the substage mechanism between the polarizer and the condenser. The effect is the same as if the plate were inserted in the microscope tube in the same direction. These microscopes also usually have a slot in the tube for the insertion of another selenite plate. One can choose which he desires to use. It should be remembered, however, that if the plates are mounted similarly, the color effects will be reversed if the insertion directions are at right angles and that if the plates are mounted dissimilarly the color effects will be the same if the insertion directions are at right angles; that similarly mounted plates will give the same color effects when inserted in the same direction; and that dissimilarly mounted plates will give opposite color effects when inserted similarly. It is usually easier on the memory and much more convenient practically to use one plate in one direction exclusively. Any doubt that may arise as to the interpretation of the colors can be immediately settled by test on any substance of known optical character, muscovite being about the most convenient.

Optical character can be studied on any crystal giving a good interference figure. Those crystals suggested for interference figure observations serve admirably for optical character determinations.

OPTIC-AXIAL ANGLE

Optic-axial angles, although sometimes variable, frequently serve as a ready means of distinguishing between two or more substances of the same group or subgroup. This is especially true when the angles are widely different. The optic-axial angle is the acute angle formed by the two optic axes. The apparent angle when measured in air is denoted by $2E$. The true angle is denoted by $2V$. When measured in oil or water the apparent angle is denoted by $2H$.

The true axial angle, $2V$, can be calculated from the values of the three refractive indices, provided these latter are known with sufficient accuracy.

If the crystal is optically negative,

$$\tan^2 V = \frac{\alpha^2(\gamma^2 - \beta^2)}{\gamma^2(\beta^2 - \alpha^2)}.$$

If the crystal is optically positive,

$$\tan^2 V = \frac{\gamma^2(\beta^2 - \alpha^2)}{\alpha^2(\gamma^2 - \beta^2)}.$$

It should be noted that, since the acute optic angle is $2V$, both the formulas give angles which must be doubled in order to obtain the true axial angle. Refractive indices are measured under the microscope to only about the third decimal. For a large number (perhaps most) of crystals this is not a sufficient degree of accuracy to enable the axial angle to be calculated other than approximately. The formulas should therefore be used for the calculation of the axial angle only as a check or when no other means of obtaining the angle are available. As a matter of fact, the formulas are more likely to be of use as a check on the index measurements than as a check on the angle measurements.

The curvature of the hyperbolæ gives a rough indication of the size of the optic-axial angle. If the interference figure shows the focus of one of the hyperbolæ nearly in the center of the field, and if the hyperbola itself is apparently a straight line when the figure is turned to the 45° position, the axial angle is nearly 90° . As the axial angle becomes smaller the curvature of the hyperbola becomes greater. A relatively small amount of experience will enable one to make a rough estimate of the axial angle from the hyperbola curvature, which in certain cases will be sufficiently accurate. For example, certain minerals have very variable axial angles, and an approximation within the limits of variation is sufficient for ordinary determinative purposes, provided the other optical constants can be determined satisfactorily.

Perhaps the most generally used method for the actual measurement of the optic-axial angle resolves itself simply into a measurement of the distance between the two foci of the hyperbolæ. For this purpose interference figures should be obtained which show the emergence of the acute bisectrix at, or very nearly at, the center of the field. If the emergence of the acute bisectrix is much out of the center, the distance measured between the two foci will not be the true distance, and consequently the true axial angle will not be obtained. Furthermore, it is essential that both foci of the hyperbolæ appear in the field. After a suitable figure has been obtained, it is rotated to the 45° position, where the separation of the hyperbolæ is at a maximum, and the distance between the two foci is measured with an ocular cross-grating micrometer.

If a series of such measurements are made on crystals of different known optic-axial angles, a chart can be constructed by plotting distances against angles. By interpolation on this chart any distance measured between the foci can be converted to terms of optic-axial angles. There are many refinements of this method, but the essentials are as given above. It should be borne in mind that the chart so constructed holds only for the particular combination of lenses and micrometers used in its construction. Furthermore, one should not confuse $2E$ and $2H$.

The relationship between $2E$ and $2V$ is given by the formula

$$\sin E = \beta \sin \gamma,$$

that is, the sine of the apparent optic-axial angle measured in air is equal to the intermediate index of refraction multiplied into the

sine of the true axial angle. It is perhaps more convenient to state the formula as

$$\sin V = \frac{\sin E}{\beta}$$

this is, the sine of the true optic-axial angle is equal to the sine of the apparent axial angle divided by the intermediate index of refraction. Thus, if the apparent axial angle in air is measured and the β index is known, the true axial angle can be calculated.

A very good method for measuring the apparent optic-axial angle by measuring the distance between the two foci of the hyperbolæ is symbolized by the formula:

$$\sin E = \frac{D}{K}$$

in which D is half the distance between the points of emergence of the optic axes and K is a constant which must be determined once for all for any lens combination. To determine this constant it is best to use a number of crystals of known and differing axial angles and to take the mean as the most nearly correct value for K . With this constant once determined, one has only to divide it into a particular distance reading in order to obtain the sine of half the apparent axial angle. This is one of the most satisfactory methods known.

The optic-axial angle varies for different wave lengths of light. Consequently, for very accurate measurements, light of known wave length should be used. Most of the angles given in the literature, however, are for white light, and for ordinary purposes this is sufficient. Even if the angles should be measured in monochromatic light, their values for white light should be given also, as in ordinary determinative work it is not always convenient to use monochromatic light.

The micas, potassium nitrate, aragonite, and calcium nitrate are suggested as objects for axial angle measurements.

DISPERSION OF OPTIC AXES

Ordinarily, isotropic substances—a glass prism, for example—deflect light rays according to their wave length. The red, with the greater wave length, will appear at one end of the spectrum, and the blue, with the lesser wave length, will appear at the other end. The red will be less deflected from the original direction of the light rays than will the blue. The actual amount of deflection for either the red or the blue, or for any other color, will depend on the relative refractive indices of the deflecting body and its surrounding medium. The greater the difference of the refractive indices of the deflecting body and its surrounding medium the greater will be the deflection. Since a beam of light consisting of different wave lengths, each of which is differently deflected, can be spread over a screen as a spectrum, we speak of the light having been dispersed. From what has just been said above, it is obvious that in isotropic bodies which include isometric crystals, the dispersion will always be less for the red than for the blue. The fact of dispersion is therefore of no special determinative importance in ordinary work on isometric crystals.

With doubly refracting crystals the case is different. Any double-refracting crystal is a dispersive body with a refractive index which varies, often considerably, with different directions in the crystal.

In any given mounting medium the dispersion for any given wave length of light will therefore vary with the direction in the crystal in which the light is propagated. Consequently, it happens in certain uniaxial crystals, tetragonal or hexagonal, which have their ordinary and extraordinary refractive indices very close together, that the extraordinary-ray direction is the vibration direction of the slow ray for light of one wave length and is the vibration direction of the fast ray for light of another wave length, or vice versa. Thus the crystal may be optically positive for light of one wave length and optically negative for light of another wave length. Ordinarily, the dispersion of uniaxial crystals is of no special determinative importance, but it is essential to realize that the basically important determination of positive or negative optical character may be reversed by a change in the color of the light used.

Biaxial crystals, that is, crystals belonging to the orthorhombic, monoclinic, or triclinic systems, have dispersions which are characteristically different for each of the three systems. Observation is made on an interference figure which shows the emergences of the optic axes and also the colored rings surrounding the points of emergence. The distribution of the colors is spoken of as resulting from the dispersion of the optic axes. The relative positions of the red and violet rays are to be noted, all other colors being neglected. Sometimes the red is dispersed more and sometimes less than the violet. This is customarily expressed as $\rho > v$ or $\rho < v$, as the case may be; that is, the dispersion of red is greater or less than that of the violet.

Interference figures given by crystals of the orthorhombic system are symmetrical to two planes at right angles to each other. One of the planes is the plane of the optic axes which, of course, contains both optic axes and the acute bisectrix. The other plane passes through the acute bisectrix and is at right angles to the first plane. Put more simply, perhaps, the figures given by orthorhombic crystals are symmetrical to the line joining the foci of the two hyperbolæ and also symmetrical to a line at right angles to this line and passing through the acute bisectrix. The dispersion of any particular crystal is always least for that color which lies immediately adjacent to the concave sides of the hyperbolæ, and greatest for that color which borders the convex sides of the hyperbolæ. It is best to rotate the figures to the 45° position when observing the positions of these colors. In some few cases a change in the wave length of the light used may change the position of the plane of the optic axes to a new position at right angles to the first. This is called crossed axial plane dispersion. In such cases the crystal will be uniaxial with light of some intermediate wave length. Crystals showing crossed axial plane dispersion give very complicated figures with white light, owing to the fact that the figures are the resultants of all the superposed figures formed by the various color components of the white light.

Monoclinic crystals present interference figures which have only one plane of symmetry, instead of two, as in the orthorhombic sys-

tem. There are three possible cases: (1) Inclined dispersion of both bisectrices; (2) horizontal dispersion of the acute bisectrix, and (3) crossed dispersion of the obtuse bisectrix.

Inclined dispersion of both bisectrices simply means that the bisectrices of both the acute and obtuse optical angles differ in direction by some angle for different wave lengths of light. It is always accompanied by a dispersion of the optic axes. The interference figure is symmetrical to the plane of the optic axes. That is, it is symmetrical to a line joining the foci of the two hyperbolæ. But it is not symmetrical to a plane at right angles to the plane of the optic axes, as is the case in the orthorhombic system. Crystals, therefore, belonging to the orthorhombic system can be distinguished from crystals belonging to the monoclinic system and showing inclined dispersion of the bisectrices by simple inspection of the interference figures. The crystal is orthorhombic if the interference figure has two planes of symmetry and monoclinic if it has only one plane of symmetry. In monoclinic-interference figures showing inclined dispersion of the bisectrices, the colored curves around the foci of the hyperbolæ will differ in size and somewhat in shape at the two foci. There is a tendency for the curves to be more elongated near one focus than near the other. Also, the colors around one focus will be more intense than those around the other, and in a different sequence. Usually the relative dispersion of red and violet is shown as with orthorhombic crystals, but if the dispersion of the bisectrices and the optic axes is very great, the relative positions of the red and violet in relation to the hyperbolæ may be reversed at the two foci. Red may lie on the concave side of one hyperbola at the focus and violet on the concave side of the other hyperbola at its focus. Fortunately, the high dispersion which brings about this condition is not common.

Horizontal dispersion of the acute bisectrix means that, with a change in the wave length of the light used, the position of the interference figure will change into a new position parallel to the first. In other words, the plane of the optic axes will appear, in the interference figure, to be shifted in a direction at right angles to itself. Thus, the use of the spectrum colors in order will shift the interference farther and farther from its initial position. This change in position can not, of course, be seen when white light is used exclusively. Color screens can be used in the substage of the microscope. If white light is used, the stage should be rotated until the principal sections of the interference figure are parallel to those of the Nicols, or until the cross is formed. It will then be noticed that the dark bar passing through the two foci, both at the top and at the bottom, will be bordered by different colors. Here again there is only one plane of symmetry.

Crossed dispersion of the obtuse bisectrix means that if successively greater and greater or less and less wave lengths of light are used, the interference figure will appear to rotate about its center.

In white light the distribution of colors in the two melatopes (foci of the hyperbolæ) differs from right to left and from top to bottom. The colors occur in inverse order, so that if the figure is rotated through 180° about the acute bisectrix, each melatope will occupy the position previously held by the other, and the color distribution will be exactly the same as before. When the inter-

ference figure is in parallel position so that its bars coincide with the principal planes of the Nicols, the black cross is unsymmetrically bordered by colored bands. That is, the upper left and lower right sides are bordered by one color, and the upper right and lower left by another (?).

Triclinic crystals give interference figures which are entirely unsymmetrical. This can best be seen when the emergence of the acute bisectrix is in the center of the field.

MEASUREMENT OF DOUBLE REFRACTION (BIREFRINGENCE)

Double refraction is, of course, confined to crystals which have different degrees of ease of vibration (different refractive indices) in different directions. Isometric crystals normally have no double refraction, or it may be said that their double refraction is zero. Certain crystals have such low double refraction that it can barely be detected. There are still other crystals which have extremely high double refractions, so much so that the difference in refractive indices in different directions in a given crystal is often much greater than the difference between the refractive indices of some chemically entirely distinct crystals. Between the barely perceptible and the extremely high double refractions there is a whole series of intermediate double refractions. The measurement of double-refraction values is, therefore, very useful as a means of identification of crystalline substances.

The maximum double refraction of any given crystal is expressed simply as the arithmetical difference between the highest and lowest refractive index of the crystal. Thus the maximum double refraction of a uniaxial crystal is $\epsilon - \omega$ or $\omega - \epsilon$, according to whether ϵ or ω is the greater. Likewise, the maximum double refraction of a biaxial crystal is $\gamma - \alpha$. Since biaxial crystals have three indices of refraction, there is also the double refraction denoted by $\gamma - \beta$ and $\beta - \alpha$, both of which are always less than the maximum for a given crystal. It follows, therefore, that if the refractive indices of a particular crystal are known with sufficient accuracy, the double refraction can be obtained by simple subtraction. It is almost always best, however, to obtain the double refraction by direct measurement, as the value so obtained serves as a mutual check on the refractive-index determinations.

Crystals of the same substance lying in random relationship to the direction of the light may show any degree of double refraction, ranging from zero to the maximum for that substance. The first essential, therefore, is to orientate the crystal so that it shows the particular double refraction desired, either the maximum of the $\gamma - \beta$ or of the $\beta - \alpha$.

Uniaxial crystals show their maximum double refractions when the crystals are so orientated that the optic axis lies parallel to the plane of the microscope slide. Stated conversely, they show their maximum double refraction when the optic axis is at right angles to the direction of light propagation. This orientation can be recognized as explained under uniaxial-interference figures. It is essential to search the mount for a particle already in this orientation or else turn a particle into it. Because of the fact that the optic axis of uniaxial crystals is usually parallel to the length of the crystal, it happens that a great many uniaxial substances show a natural

tendency to lie in the proper orientation for double-refraction measurements. So far as double refraction is concerned, this is a great convenience which, nevertheless, does not prevent the orientation from being the worst possible when interference figures showing the emergence of an optic axis are desired.

After a particle with the proper orientation has been found, it is rotated to extinction between crossed Nicols. It is then further rotated 45° either clockwise or anticlockwise. This brings it to a state of maximum illumination. A quartz wedge is then inserted, also in a 45° direction. As the quartz wedge advances, either one of two phenomena may take place. If the vibration directions of the fast ray of both the particle and the wedge coincide, then, as the wedge advances the interference colors will rise in the order in Newton's scale. Each new color will start in the interior of the particle and progress toward the edge. The reverse, of course, takes place as the wedge is withdrawn. On the other hand, if the fast-vibration direction of the quartz wedge coincides with the slow-vibration direction of the particle, or vice versa, the interference colors fall in the order in Newton's scale, each new color progressing from the edge of the particle toward its interior. If the first set of phenomena takes place, the particle should be rerotated back to extinction between crossed Nicols and then further rotated to a new 45° position at right angles to the first 45° position. It is not absolutely essential that the rotation be just as stated. It is essential, however, that the two 45° positions be approximately 90° apart. In this new 45° position the second set of phenomena will be observed as the quartz wedge advances. If the particle is of uniform thickness, the colors will fall in order until gray or black is reached. If the particle is not of uniform thickness the gray or black must be watched for in some particular predetermined spot of the particle, preferably its center. When the gray or black color is reached, the advance of the wedge should be stopped. The interference color given by the quartz wedge alone at this point should be noted. If there are vacant spots in the field, this interference color may be noted at these spots; otherwise it is necessary to remove the particle, possibly the whole slide. The wedge is then slowly withdrawn, and the order of the interference color noted by counting the number of times the color has appeared during withdrawal. The color and the order of the color are then known. The thickness of the particle is the only other essential. In the case of nonuniform thickness it is necessary to know the thickness at the point where the black appeared.

The interference color, the order of the color, and the thickness of the particle being known, reference should be made to the chart of double refraction of Michel-Lévy. (Fig. 5.) This chart is included in most textbooks of petrographic methods. In it the ordinates represent thickness and the abscissæ double refraction. To use it, simply follow the thickness line toward the right until the observed color of the ascertained order is reached. From this point follow the diagonal line upward and to the right to the edge of the chart. Here the double refraction will be found. It is of course obvious that the chart can be used backwards to determine the thickness if the double refraction is previously known.

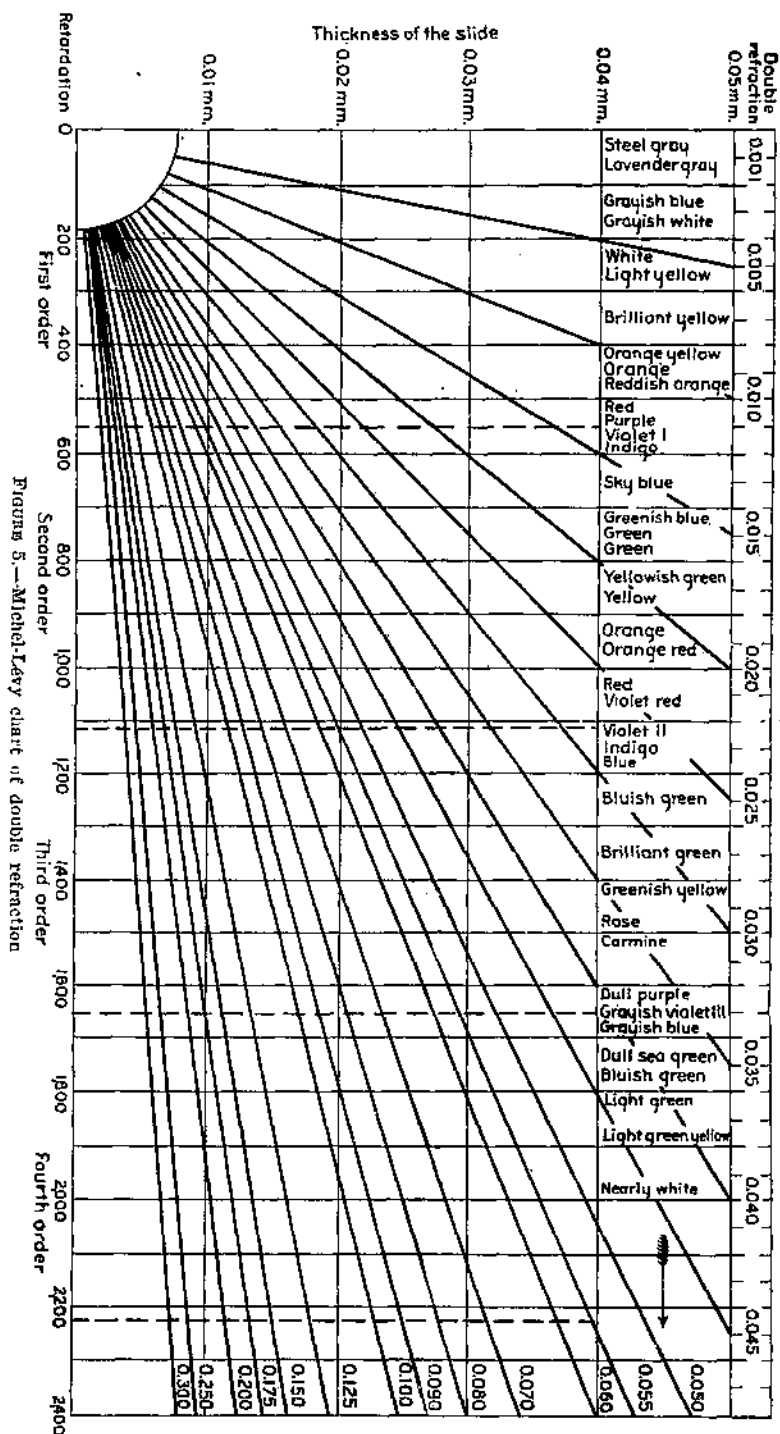


FIGURE 5.—Michel-Lévy chart of double refraction

The double refraction of a particle of a biaxial crystal in any orientation can be calculated from the formula:

$$\gamma' - \alpha' = (\gamma - \alpha) \sin \theta \sin \theta'$$

in which $\gamma' - \alpha'$ is the double refraction for the particular orientation in question, γ is the maximum refractive index of the crystal, α the minimum refractive index of the crystal, and θ and θ' are the angles, respectively, between the two optic axes and the perpendicular to the section of the crystal under examination. The values obtained by the use of this formula will vary, however, from the maximum double refraction of the crystal down to the minimum, depending on the orientation.

Crystals lying on the slide so that the plane of the optic axes is parallel to the plane of the slide, or, in other words, lying so that the light is transmitted normally to the plane of the optic axes, give the maximum double refraction of the crystal, $\gamma - \alpha$. This orientation can be identified by the interference figure as previously explained. After a properly orientated particle has been located, the procedure for the determination of the double refraction by means of the quartz wedge and the Michel-Lévy chart is exactly as already described for uniaxial crystals. Crystals so orientated as to show the emergence of a bisectrix in the center of the field give, under the same procedure, the double refraction corresponding to $\gamma - \beta$ or $\beta - \alpha$. Incidentally, these last two determinations can be checked qualitatively if the optical character of the crystal has been already determined. If the crystal is positive $\gamma - \beta > \beta - \alpha$; and if negative, $\gamma - \beta < \beta - \alpha$. This test does not hold, however, when the true optical angle, $2V$, is near 90° .

It is not always convenient to place a crystal particle in exactly the orientation desired, and consequently it is of interest to know something about the probable error in measurements made on imperfectly orientated particles. The error of course, varies with the degree of double refraction, and therefore differs for different substances. According to Wright (20), however:

It may be assumed in general that the birefringence of a plate inclined at an angle of 5° to 10° with the true direction (optic normal or bisectrix) will be in error about 2 per cent of the true value for $(\gamma - \alpha)$, $(\gamma - \beta)$, or $(\beta - \alpha)$; an inclination of 10° to 15° , about 5 per cent, while for 15° to 20° inclination the error may be as much as 10 per cent of the correct value desired. . . . The actual error of such a determination should not exceed 10 per cent of the correct value of the birefringence of the section. The probability of finding a section making an angle within 10° of a particular direction is about 1 in 66; and a section within 20° about 1 in 16.

Whether the double refraction of a given crystal is high or low can be ascertained immediately by crossing the Nicols and observing the interference colors. The higher the order of the colors in Newton's scale the higher is the double refraction, and we should accustom our eyes to distinguish between, at least, high and low order colors. The very low order colors are usually dull grays, perhaps grading off into other dull colors. The very high order colors, on the other hand, are brilliant, sometimes so much so as to appear almost white. A microscopic slide made up of mixed quartz and calcite brings out the contrast between the high and low order colors very well and illustrates the ease with which highly doubly refract-

ing substances can be "spotted," even when occurring as very minute quantities admixed with substances of low double refraction. Unfortunately, the converse does not hold. Hunting for traces of a substance with a low double refraction when it is admixed with substances of high double refraction is apt to be a long and perhaps a fairly hopeless quest. This is owing partly to the fact that the brilliance of the high-order interference colors has a tendency to blind one to the low-order colors, but the relative hardness and solubility of the two substances also have their effects under certain conditions. If, for example, quartz and calcite are ground together, the calcite being the softer, has a tendency to adhere to and mask the quartz grains. Likewise, if sodium nitrate, NaNO_3 , and gypsum, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, are crystallized together, there is a tendency for the very soluble and highly doubly refracting sodium nitrate to coat and thereby mask the less soluble and low doubly refracting gypsum. Exceptions could undoubtedly be found, but it seems to be a general rule that substances of high double refraction are more apt to mask substances of low double refraction than vice versa.

Another method for judging the relative degree of double refraction of a substance depends on the change in relief, that is, the change in visibility if any, of the particles as the stage is rotated. If calcite, for example, is mounted in an oil which has a refractive index very close to, but not exactly either the maximum or minimum index of the calcite, particles so orientated that they show the maximum double refraction (particles so orientated that the light is transmitted perpendicularly to the optic axis) will be barely visible in one position and will be more and more distinctly visible as the stage is rotated. Maximum relief will occur at 90° from the position of minimum relief, after which the relief will become less and less, as the stage is further rotated until another position of minimum relief is reached at 180° from the first position. If the stage is further rotated the relief will become greater up to 270° , and from thence will become less until the initial position is reached. In the case of a highly doubly refracting substance like calcite, mounted as stated, the change of relief on rotation of the stage is very great. At the positions of maximum relief the particles appear to stand out of the oil and to have dark shadows on their sides. The surfaces of the particles are distinctly visible, and most of the inclusions in the interior of the particles are invisible. In the position of minimum relief the exact opposite is true. The surfaces of the particles are not visible at all, only the horizontal outline being seen, and the inclusions stand out prominently. Intermediate positions between those of maximum and minimum relief give intermediate phenomena.

It should be borne in mind that particles so orientated that the light is transmitted parallel to the optic axis will show no change in relief as the stage is rotated, no matter how great the double refraction may be. As the particle is tilted out of this orientation the change in relief becomes more and more pronounced until the maximum is reached when the light is transmitted perpendicularly to the optic axis. If quartz is mounted in a similar way and the stage is rotated, it will be noticed that none of the particles shows a very great change of relief. At the most, the outline of certain

particles will be more distinct in certain positions as the stage is rotated. Thus, properly orientated particles of highly double refracting substances show a very great change of relief on rotation, and particles of substances with very low double refraction show very little change of relief. The change of relief on rotation is, therefore, a rough indication of the amount of double refraction. The phenomena will take place only in polarized light. The polarizer should, therefore, be in, but the analyzer should be removed.

The orientation of the particles can be ascertained by means of interference figures, as previously explained. It is, of course, obvious that if one is seeking for particles showing particular types of interference figures, the change of relief on rotation would be a fair guide. For example, in the case of calcite just described, those particles which showed great change of relief would not show an interference figure with the optic axis emerging in the center of the field, whereas particles showing no change of relief would probably give such a figure.

Suitable substances for the study of double refraction are calcite, quartz, sodium sulphate, and potassium sulphate.

EXTINCTION ANGLES

It has been previously explained that if an isotropic (amorphous or isometric) substance is placed between crossed Nicols and the stage rotated, the particles of the substance remain dark during the complete rotation of the stage, no matter what relationship the position of the particles may have in reference to the direction of the transmitted light. Except abnormally, such particles never light up between crossed Nicols, and therefore can not be said to extinguish. It may be said that every possible position of the particle is a position of extinction. For this reason no particular position has any especial significance. The fact that a given substance remains dark, in any orientation, during a complete rotation of the stage between crossed Nicols, simply indicates that the substance is amorphous, or isotropic, and nothing more. It is essential to remember, however, that crystals of some of the other systems in one orientation, that in which the light is transmitted parallel to the optic axis, behave as do isotropic substances. If this is suspected, the orientation of the particle under examination should be changed. If it still remains dark during a complete rotation of the stage it is certainly amorphous or isometric.

Except in the one case just noted, crystals of all the other five systems behave very differently when rotated between crossed Nicols. During a complete rotation they light up and then become dark (extinguish) four times. That is, during a complete rotation of the stage, there are four positions of maximum brightness and four positions of maximum darkness. As the stage is rotated from a position of maximum brightness, the brightness gradually fades until in the position of maximum darkness there is usually no light whatever visible through the crystal. These positions of maximum darkness are called the positions of extinction and have a very definite relationship to the structure of the crystal.

It will be recalled that in the tetragonal, hexagonal, and orthorhombic systems all the principal vibration directions of light are

parallel to the crystallographic axes. In the monoclinic system only one vibration direction coincides with a crystallographic axis, namely, the crystallographic axis *b*. The other two vibration directions may be anywhere in the plane determined by the crystallographic axes *a* and *c*. As a rule, neither of these two vibration directions is parallel to either of the two axes *a* or *c*. It is possible, however, for one of the vibration directions to be parallel to one of the axes, but since the angle between *a* and *c* is not a right angle in the monoclinic system and the angle between the two vibration directions is a right angle, it is impossible for both vibration directions to be respectively parallel to *a* and *c* in the same crystal. Stated briefly, in the monoclinic system, one of the vibration directions will be parallel to a crystallographic axis, another vibration direction will be inclined to the crystallographic axes, and the third direction may be either parallel or inclined, probably inclined, to the crystallographic axes. In the triclinic system it is possible for one and only one vibration direction to be parallel to a crystallographic axis, but usually all the vibration directions are inclined to all the axes.

The foregoing may be summed up in the statement that in the tetragonal, hexagonal, and orthorhombic systems every vibration direction is parallel to some crystallographic axis; in the monoclinic system two vibration directions, but probably only one, may be parallel to crystallographic axes, and in the triclinic system one vibration direction, but probably none, may be parallel to a crystallographic axis.

The vibration directions are shown by the positions of extinction of the crystal between crossed Nicols. The directions of the crystallographic axes may be determined by crystal edges when present or by cleavage lines. The extinction angle is simply the angle between the extinction direction and a crystallographic axis. Different orientations of the crystal, however, may give different extinction angles, and it is therefore necessary to find the orientation in which the angle between a given vibration direction and a given crystallographic axis is the maximum. Interference figures and double refraction observations should here be used as well as all the crystallographic information that can be obtained.

The procedure is comparatively simple. Be sure that the two Nicols are accurately crossed, that the cross hairs are parallel to the vibration directions of the Nicols, and that the objective of the microscope is accurately centered. Place the crystal so that a crystal edge, or a cleavage line, is parallel to one of the cross hairs. Read this position on the stage vernier. Rotate the stage until the crystal extinguishes. Then read the vernier again. The angle given by the difference of the two readings is the extinction angle. It is well to make a number of measurements in this way, then rotate the stage 180° and make a similar number of corresponding measurements. The average of all these measurements should then be taken.

In the measurements of extinction angles, and, in fact, in any work where a change in the orientation of a crystal is necessary or desirable, a universal stage will be found a very convenient accessory. It is not recommended; nevertheless, if a good universal stage is not available, a passable substitute may be contrived by grinding down the round knob of a broken bell jar or of a desiccator to hem-

ispherical shape. If this is set on its round side in the central opening of the ordinary microscope stage, and a crystal is stuck to its flat side by a drop of cedar oil, a considerable amount of tilting can be done with fair convenience. There are, of course, no means of reading angles except that furnished by the microscope stage for horizontal angles, but the contrivance is capable of yielding a considerable amount of qualitative information.

Probably the greatest source of error in the measurement of extinction angles lies in the difficulty of accurately determining the position of extinction. As has been said before, this position is simply the position of maximum darkness, and on both sides lie series of positions of only slightly less darkness. This is especially true in crystals of very low double refraction. In such crystals the position of maximum brightness yields merely grays of a very low order, and these grays fade out gradually into darkness as the stage is rotated toward a position of maximum darkness. It frequently happens in such cases that the stage may be rotated several degrees either way about the position of extinction without any easily perceptible change of illumination being noted. Furthermore, human eyes differ in their ability to detect slight differences in degree of darkness. A given eye may be more sensitive to a color change than to a change in degree of illumination.

If a colorless crystal, mounted in a colorless oil, is at the position of extinction between crossed Nicols, and a selenite plate is inserted in the tube of the microscope, both the crystal and the surrounding empty field will have exactly the same shade of color and, so far as color is concerned, will be indistinguishable. If now the microscope stage is slightly rotated so as to move the crystal slightly out of the position of extinction, the color of the crystal will change distinctly, and the empty field will remain of the same color as before the rotation. The crystal and the field will then stand out in strong contrast. As the stage is further rotated the contrast will increase until the position of maximum brightness is reached, and will then decrease until the colors of the crystal and the field again become identical at the next position of extinction, and so on, for a complete rotation. The quartz wedge can be used exactly in the same manner instead of the selenite plate and will give the same phenomena. One should be careful, however, in his choice of colors out of the whole series of colors given by the quartz wedge, since all colors are not equally sensitive. Violet, sometimes called the sensitive tint, or red of the first order, is the best color to use. This color is given by the selenite plate. Numerous adjuncts have been devised to render more accurate the determination of the position of extinction. Perhaps the best of these is the Wright biquartz wedge plate. This plate is placed in the focal plane of the ocular. Each half of the field is equally illuminated when the crystal is in the position of extinction. A very slight rotation of the crystal out of the position of extinction produces a marked difference in the illumination of the two halves of the field.

No single best method for determining the position of extinction can be prescribed. Natural color in a crystal, for example, may very well render any of the color methods inapplicable and force one to use some method involving degrees of illumination. Personal pecu-

liarities of vision may make one method more advisable for one individual than for another. Such decisions, of course, must be made by the individual worker.

The plagioclases, gypsum, hornblende, and asbestos serve very well for a study of extinction angles.

SIGN OF ELONGATION

Under the same conditions and when free to grow unimpeded, crystals of any given substance have an exceedingly strong tendency to take on characteristic forms. Thus mica is flattened parallel to a basal plane of the crystal, and apatite is elongated parallel to the prism edges, that is, parallel to the *c* axis of the crystal. The relationship between the direction of elongation of a crystal and the vibration directions in the crystal is sometimes of determinative value. This relationship is expressed as either positive or negative, and the elongation of the crystal is spoken of as positive or negative. If the elongation of the crystal is parallel to the fast ray, the elongation is negative. If the elongation is parallel to the slow ray, the elongation is positive. The direction of elongation can be observed directly, either on the crystal edges themselves or on cleavage lines. The directions of the fast and slow rays can be determined by means of the quartz wedge, as already explained, in reference to optical character.

Uniaxial minerals are usually elongated parallel to the vertical crystallographic axis *c*, and for this reason the sign of the optical character is usually the same as the sign of the elongation. But there are exceptions: for example, some apophyllites. In biaxial crystals the elongation direction may not be parallel to any axis of vibration, and the sign of elongation is determined by the axis nearest the direction of elongation.

COLOR OF CRYSTALS

The color of small crystals or fragments, when observed under the microscope in transmitted light, is always much paler than the color shown microscopically, in ordinary light. Very faintly colored substances, such as some amethysts, may appear absolutely colorless. Substances opaque and black to the naked eye, such as some of the ferromagnesian minerals, may be transparent, although deeply colored, when observed in their fragments under the microscope. In transmitted light under the microscope all opaque substances appear black, regardless of their color. It is consequently unsafe to draw too liberal conclusions as to colors on the basis of microscopic appearance.

With due reservations it may be said that the color shown under the microscope by substances known to be chemically pure is of some determinative value. But substances deeply enough tinted to show color in transmitted light under the microscope are comparatively scarce. When such substances are examined, however, the color should be noted.

In general, it may be said that the color of natural minerals is an ambiguous and frequently undependable guide. But here again color should be noted when present and used determinatively when conditions warrant such use. It is perhaps never safe, however, to take color alone as a determinative characteristic.

PLEOCHROISM

If white light is transmitted through any substance it will be found that somewhat less light emerges than entered. In other words, it will be found that the substance absorbed part of the light. If the amount of light absorbed is very minute, the substance is said to be transparent. If all the light is absorbed, the substance is opaque. Certain substances not only absorb some of the light, but they absorb it differentially: that is, they absorb certain wave lengths of light (certain colors) to a greater extent than other wave lengths. White light transmitted through such a substance therefore emerges with a different proportion, or even constitution of color constituents, and the substance appears to be colored. In isotropic substances the optical properties, including the absorption, are the same in every direction. Consequently, an isotropic substance is colorless, opaque, or of the same shade of the same color, no matter in what direction the light passes through it. On the other hand, doubly refracting substances have different optical properties in different directions. This may include the absorption, and if the absorption is sufficiently different in the different directions, the substance may be differently colored, depending on the direction in which the light is transmitted. Absorption of course depends partly on the thickness of the absorbing substance, and this fact should be taken into consideration when comparisons between colors are made. The phenomenon of changed colors with changed directions of transmitted light is called pleochroism, occasionally dichroism, when two colors are manifested, and trichroism when three are manifested. This property is possessed to a greater or lesser extent by a large number of doubly refracting substances, and when present has considerable determinative value.

Neither uniaxial nor biaxial crystals show pleochroism when the light is transmitted parallel to an optic axis and the microscope stage is rotated. In uniaxial crystals the maximum pleochroism is shown when the light is transmitted at right angles to the optic axis. In biaxial crystals the maximum pleochroism may lie either in the plane of the optic axes or at right angles to it. It is, therefore, necessary to know the orientation of the crystal under examination, and this can be determined as usual by means of interference figures.

The procedure is simple. Find a properly orientated particle on the microscope slide. Rotate the stage until the particle extinguishes between crossed Nicols. Remove the analyzer and observe the color. Rotate the stage 90° without replacing the analyzer and observe the color in this new position. This procedure is not, of course, obligatory. The essential elements are that the orientation be so chosen as to give maximum pleochroism and that the absorption directions be stated in relationship to the optical directions of the crystal. Pleochroism in uniaxial substances may be expressed as absorption $E > O$, as the case may be, O being the direction of vibration of the ordinary ray and E that of the extraordinary ray. Pleochroism in biaxial crystals may be expressed as, for example, absorption $(Z=Y) > X$, or X violet red, Y wine yellow, Z yellowish rose; X , Y , Z being the directions of greatest, intermediate, and least ease of

vibration, respectively. The German letters *a*, *b* and *c* may be substituted for *X*, *Y*, and *Z*, respectively.

Great refinement is not usually necessary in observation on pleochroism. Frequently the knowledge that the substance is pleochroic is sufficient, together with other data, for all practical determinative purposes. There are, however, special accessories for observing very faint pleochroism if this should be considered desirable. For such, reference should be made to the trade catalogues and to the detailed texts of petrographic methods.

For the beginner, tourmaline is perhaps one of the best substances for practice observations on pleochroic phenomena.

ORIENTATION

The term "orientation" is a general expression which includes all the relations between the optical and crystallographic directions in crystals. In a more restricted sense it refers particularly to the position of a crystal under the microscope in relation to the axis of the microscope. Angles between the principal vibration directions and the crystallographic axes are preeminently orientation data, although they also serve for extinction data. In fact, extinction angles are themselves orientation data, in that they show the angular relationships between the plane of the optic axes and some crystallographic axis or face. Complete orientation data should show the angles between every vibration direction and every crystallographic axis.

APPLICATION OF METHODS

No one of the methods previously described is in itself sufficient to identify a given substance except in rare and special circumstances. While different substances differ in individual properties, it is very frequently possible to find two distinct substances which have some particular one or more optical properties in common. For example, it can not be said that two substances having the same refractive indices are identical. There are whole series of glasses from which individual specimens can be selected having the same indices as most of the common soil minerals. Sodium nitrate and calcite are both uniaxial and negative and their interference figures closely resemble each other, but their refractive indices are markedly different. Potassium chloride, sodium chloride, and ammonium chloride are all isotropic, but they differ radically in their indices.

Different substances may thus have some particular properties in common, but still differ widely from each other in their ensemble of properties. Certain properties may be considered as general or group properties and other properties may be considered as specific. A classification is therefore possible. The following sketch of the procedure for the identification of a pure substance will illustrate the application of the methods when used in conjunction with the classificatory system generally adopted.

PURE SUBSTANCES

Mount the substance in any medium which does not dissolve or react with it and which has a known, preferably intermediate, index

of refraction. If the grains stand out very prominently under the microscope, so as to show black borders, it is best to determine by Becke lines whether the index of the grains is higher or lower than that of the oil and then to make a new mount with some other oil, with an index nearer that of the substance.

Cross the Nicols and rotate the stage of the microscope. Either the crystal under observation will remain dark during a complete rotation, or it will not. If it remains dark, raise the condenser, remove the ocular, and observe whether or not an interference figure is present. If no interference figure is visible the crystal is isometric, and one should proceed at once to the determination of the refractive index (p. 34). In Table 2 isotropic substances will be found arranged according to increasing index of refraction. If, on the other hand, the crystal alternately lights up and extinguishes during rotation, between crossed Nicols, if it remains light during rotation, or if it remains dark during rotation but gives an interference figure, it is anisotropic and belongs to some crystal system other than the isometric.

If it has not already been done, obtain an interference figure and observe whether it is a uniaxial cross or a biaxial system of hyperbolæ. If the particular crystal grain under observation does not give a suitable figure, tilt it to a new position, if practicable, or find another grain which is already properly orientated. If the figure is uniaxial, the crystal belongs to either the tetragonal or hexagonal system. If it is biaxial, the crystal is orthorhombic, monoclinic, or triclinic. Whichever the figure may be, uniaxial or biaxial, determine the optical character by means of the quartz wedge or selenite plate. This classifies the substance as uniaxial positive, uniaxial negative, biaxial positive, or biaxial negative. If the substance is uniaxial determine the ω index; if biaxial, determine the β index. Uniaxial positive substances are listed in Table 3 according to increasing value of ω . Uniaxial negative substances are listed in Table 4, likewise according to increasing value of ω . Biaxial positive substances are listed in Table 5 according to increasing value of β . Biaxial negative substances also are listed in Table 6, according to increasing value of β . Refer to the appropriate table and find the ω or β index, as the case may be, which has been determined on the given substance. If the given substance is included in the table, its name and composition will be found in the same row with the refractive index. Determine the other properties of the substance listed in the table as a confirmation of the identification. If, as may very well happen, more than one substance has about the same ω or β index in a given table, the determination of the other constants serves to distinguish these substances from each other.

IDENTIFICATION OF MINERALS IN SOILS

It is a truism, of course, that soils are the residue from the disintegration and decomposition of rocks plus organic matter. Ignoring the organic matter, a soil can therefore be expected to consist essentially of the common rock-forming minerals and their decomposition products. The mineral particles vary widely in size and are frequently much diluted and sometimes masked by the colloidal and

petrographically indeterminable decomposition products. A preliminary removal of the colloids is therefore always advisable and sometimes necessary. For quantitative work (p. 71) it is almost necessary to size the soil minerals. Both the removal of the colloids and the sizing of the minerals can be accomplished by various methods of mechanical analysis. Perhaps the simplest method is ordinary sieving. Various other methods will readily suggest themselves, for example, elutriation and centrifuging. In soil laboratories it is customary to use the equipment and methods of the current system of mechanical analysis.

Quartz is present in practically all soils and usually constitutes the major mass of the sand fractions. Its large quantity makes it a diluent for the other soil minerals. It therefore tends to distract the attention from, and increase the time of search for, other minerals occurring in comparatively small quantities, unless some means is taken to remove it, at least partly, from the range of vision. Preliminary mechanical separation of quartz from the sample is not always practicable and is seldom convenient, but it happens, as a very little experience will demonstrate, that the refractive index of quartz is exceptionally well located for soil work. If the sample is mounted in an oil with an index of refraction the same as that of the ordinary ray of quartz, 1.544, every one of the quartz grains will disappear in some one or other position of the stage, depending on the orientation of the grains. No quartz grain, regardless of the position of the stage, will stand out prominently. In this mount all the quartz is either invisible or only vaguely visible, whereas most of the other soil components stand out with a considerable degree of prominence and can therefore be readily found. Furthermore, one of the indices of refraction of the quartz has been determined by comparison with the oil. Examine some of these vaguely seen or invisible grains for interference figures and optical character. Quartz is uniaxial and positive. Complete the quartz identification either by a measurement of maximum double refraction, 0.009, which should be added to 1.544 to give the value of the undetermined index of refraction, 1.553; or make another mount in an oil of this latter index and determine the index of precisely similar particles by direct comparison. It is not necessary, but another maximum double refraction measurement on a grain of this second mount will serve as a check and will add considerably to the beginner's confidence that he is observing the same component in both the mounts if he is unfamiliar with the microscopic appearance of the soil minerals.

The first mount should now be very carefully examined for grains which have a similar vague appearance but are otherwise different from the quartz grains already determined. This examination should include the search for grains with refractive indices slightly different from those of quartz, grains which give biaxial instead of uniaxial interference figures, grains optically negative instead of positive, and grains which are isotropic instead of doubly refracting. In this examination a familiarity with the relief appearances of different probable components and with the appearance of the different orders of colors in Newton's scale, together with the lavish use of Becke-line movements, will be found invaluable.

If in this mount a grain is found which does not practically disappear in some position of the stage it is, barring the effects of surface coatings, almost certainly not quartz. A biaxial grain may rarely be quartz, but the chances are overwhelmingly against it. An optically negative grain or an isotropic grain is certainly not quartz.

It is probable that one or more vaguely visible components, differing from quartz, as indicated in the preceding paragraph, will be found. If so, determine every property which it is possible to determine in this mount. This will usually include all determinable properties except refractive indices. Estimate these by relief and Becke-line movements and determine them accurately in other mounts on grains having exactly the same composite of properties. Reference should then be made to the tables of the optical properties of minerals and the component identified by finding that mineral there listed whose properties agree with those determined.

When the region of refractive indices near that of quartz has been exhausted, find grains farther and farther removed from quartz in refractive index and proceed on each one of them as above. This procedure will lead to the identification of all determinable components found in the sample. Every mount made should be carefully scanned for components not hitherto noticed. As several mounts will probably be made during the course of the work, each one containing perhaps several hundred grains, the list of components identified can be considered as practically complete.

As an illustration of the identification of a mineral by the above procedure combined with a rigorous application of the tables, suppose that in the first mount a mineral is found with the following properties: Biaxial, optically negative, optic axial angle about 40° , cleavage microscopic and very perfect in one direction and therefore giving rise to a platy, tabletlike appearance, colorless, perceptible dispersion with $\rho > \nu$, the acute bisectrix emerging practically normal to the cleavage plates, double refraction on plates lying less flat than that of quartz, about 0.004, double refraction on tilted edges much greater, all indices of refraction higher than those of quartz, but, judging by relief, not much, if any higher than 1.620. This gives a composite of several properties, each of which varies from mineral to mineral. That there should be another mineral with an identical composite is of course possible, but the probability is almost vanishingly small.

Other mounts are made and two indices of refraction are measured on flat-lying plates. A third index is measured on tilted plates. Check examinations should be made of each plate on which an index is measured in order to assure one's self that it has the same identical composite of properties as determined in the first mount. Suppose the three indices measured are ± 1.594 , ± 1.590 , and ± 1.561 . The second one, ± 1.590 is obviously β both on account of its numerical relation to the other two and from the particular orientation in which it was measured. Add ± 0.005 to this index to allow for errors of observation. This gives a minimum of 1.585 and 1.595.

In the tables, for example, those of Larsen (10), turn to the biaxial negative group. In the β column mark off all minerals having a β index between 1.585 and 1.595. There are some 19 of these min-

erals (10, p. 251-253). Six of these are immediately eliminated by the possession of distinctive characteristic colors entirely foreign to the colorlessness of the mineral under examination. One more is eliminated by lack of cleavage. Two more are eliminated by the possession of very large optic axial angles. Another is eliminated by strong dispersion of a character contrary to that of the mineral under identification. Six more are eliminated because of too low α values. This leaves three. Two of these can be eliminated by double refraction, by orientation when possible, and by the possession of two instead of one direction of cleavage. The properties of the remaining mineral, muscovite, check with those determined on the unknown, and the unknown is therefore identified.

The foregoing illustration presents an especially difficult example, both as to technic and as to the complexity of the data to be interpreted, but there are still other complications which have not been taken into consideration. One of these, and perhaps the most serious, is the natural variation of muscovite. Another is the variation of properties due to weathering. But, except in extreme cases, it is doubtful if any petrographer would experience any difficulty whatever in the identification. This is due to the fact that the properties, as written down, appear to have equal determinative value. They do not have such equal values. The highly developed cleavage, the biaxial negative character, and the emergence of the acute bisectrix almost normal to the cleavage plane are, when coupled with the relief appearance of the plates, practically enough to convince anyone familiar with minerals of the identity of this one. The observation and measurements of the other properties would be essentially confirmatory rather than determinative.

As a simpler example, suppose a mineral found with the following properties: Uniaxial, optically negative, extremely high double refraction (0.172), $\omega = 1.658$, and occurring as rhomblike forms. Adding ± 0.005 as a safety factor to the known index gives 1.653 and 1.663. Reference to the uniaxial negative group of tables shows only four minerals with an ordinary ray index between these limits. Three of these have double refractions entirely too low. The remaining one, calcite, has properties which check with those determined.

After each identification the worker should, at least until he is intimately familiar with the appearance of the common minerals, make up a mount from a known sample and compare it in more or less detail with the just identified "unknown." It will be found that most minerals have outstanding characteristics which materially reduce the labor and add to the certainty of identification. Among these characteristics are the twinning of the feldspars, the high double refraction of the calcite-dolomite-siderite series, the cleavage of the micas, the high refraction of rutile, the low refraction of fluorite, and the color, within limits, of ferromagnesian silicates such as augite and hornblende. It is true that the tables contain all these facts, but they do not, and probably can not, give them proper emphasis without opening up possibilities of misinterpretation. To those familiar with the minerals there is no need of any such emphasis, and no one unfamiliar with them should attempt their identification in soils or rocks.

The procedure for the identification of minerals in soils as written above is in no sense obligatory. It is intended primarily as a guide, reliable though possibly cumbersome, for beginners. It, therefore, very probably goes into details altogether unnecessary for those previously experienced in some other application of petrographic methods. For the encouragement of beginners it should be stated that, with the development of manipulative skill and barring the necessity for time-consuming search, any ordinary mineral should be identified in a soil or elsewhere in a maximum of not more than 15 minutes, probably much less. The beginner should be advised against a too-rigorous application and slavish following of the tables. At the best the tables are guides, and in no sense are they systems of ultimate pigeonholes, in which every substance fits snugly in its ordered place without possibility of erratic arrangement. In the main, minerals, in common with most other natural objects, are variables, and there is perhaps no substitute for an intimate first-hand knowledge of them.

There are special problems of identification of soil minerals for which no definite procedure can be outlined beforehand. The identification of weathered and decomposed minerals gives rise to perhaps the larger group of these problems. A decomposed mineral is, from the very fact that it is decomposed, different from what it was before decomposition. The determination of its original nature therefore literally means the determination of what it was before it was changed into what it is. If decomposition has gone too far the problem is of course insoluble. For example, there are no means known at present by which the parent species of the clay minerals of soils can be determined. One can conjecture, and in certain cases there might be a basis in fact and in reason for the conjectures. For instance, if the parent rock is a mica schist consisting essentially of quartz and micas, and if there is no probability of the clay having been brought in from outside sources, it is reasonable to believe that the clay minerals are the decomposition products of the micas. This reasoning, however, is in no sense a determination. Such absurdly extreme examples could be multiplied.

The usual type of cases is that in which the original mineral has been partly but not wholly altered and has certain of its primal characteristics remaining. Biotite furnishes a fair example. Under the influence of the weathering agencies its iron is oxidized, and there is a tendency toward the extraction of the bases. Optically the color changes, the interference figure becomes blurred, and its refractive indices may change slightly. On the other hand, its highly characteristic cleavage and optical character remain. In the early stages of decomposition the changes are so slight as to be negligible, but they become progressively greater and greater. Suppose they have progressed to the point where the observable and measurable properties do not yield sufficient data for identification and where the general appearance is decidedly that of decomposed material. How is one to know that this is decomposed biotite? Speaking in terms of definitive, unquestionable knowledge, the answer is, of course, that one can not know. But for practical purposes and within the limitations of reasoning implied by such purposes, the means of knowing are comparatively simple. In the first place, the substance has

some of the properties and characteristics of biotite. These are indicative. If, in the second place, the observer's experience has included the examination of biotites in various and numerous stages of decomposition, he will recognize that the material under examination shows not only the residual properties of decomposed biotite but also the very changes and alterations common to weathered biotite. He will, therefore, be able to approximately classify his material at some place in a known series. This is not absolute identification, but it has a high degree of probability.

In any work of this kind the question is likely to arise as to just how far a given mineral can be altered and still be called by its original name. Since alteration is a fairly continuous process, at least over a considerable part of its range, any such line of demarcation between, say, biotite and nonbiotite, would have to be arbitrary and would present almost insuperable difficulties in its location. The solution of the question in any given case must, for the time being, be left to the common sense of the individual worker.

Another type of identification is that presented by inclusions of one substance in grains of another. These inclusions may be gaseous, liquid, or solid. Quartz and volcanic materials are especially apt to carry them, although they may very well occur in other soil minerals. Gaseous and liquid inclusions can be readily distinguished from each other and from solid inclusions by the comparative width of their dark borders. These dark borders are total-reflection phenomena depending on the relative refractive indices of the inclusion and the including material. As the refractive indices of gases and liquids are usually quite different both from each other and from solids, the dark borders are wide and prominent in the case of gases in solids, present to some extent but not so pronounced in the case of liquids in solids, and absent or imperceptible in the case of solids in solids. Occasionally liquid inclusions carrying a bubble of gas are found.

Generally speaking, residual material is much more apt to carry inclusions than is distantly transported material. The reason for this is apparently that the inclusions cause strain in their carriers and, therefore, render them more subject to comminative forces than are the grains free from inclusions. The result, of course, is that, in the main, distantly transported material is relatively free of inclusions.

The solid inclusions are commonly rutile, apatite, calcite, and limonite. The difficulty in identifying the inclusions is sometimes due mainly to their small size. But the more usual difficulty is due to the impracticability of obtaining complete optical data. The inclusions are in contact with their containing minerals and not with the mounting medium. Refractive indices must, therefore, be estimated by relief and are consequently subject to all the errors of this method. The other optical properties are equally difficult to determine. On the other hand the inclusions, when crystalline, usually occur in well-developed characteristic forms. Rutile, for instance, occurs as long slender needles which can scarcely be mistaken for any other mineral. The procedure, then, is to mount the containing minerals in an oil in which they disappear, thus revealing the inclusions. Obtain all the optical data possible on the inclusions, and pay particular attention to the crystallographic form and habit. The

combined optical and crystallographic data are frequently sufficient to lead to a reasonable, though not always conclusive, identification. Fortunately, the identification of inclusions becomes of importance only in reference to very special problems.

Occasionally it is necessary or desirable to know something of the origin of the soil quartz. Primary quartz, that is quartz which originated by crystallization from a magma, may carry inclusions of those minerals which themselves crystallized from the magma. Rutile needles are the commonest and perhaps the most characteristic of this type of inclusion. On the other hand, secondary quartz, that is, quartz which originated by crystallization from water solutions, may carry inclusions of those minerals which are themselves of a secondary character. Limonite and calcite are characteristic of this type of inclusions. It is possible, of course, for secondary quartz to carry inclusions of primary minerals, but it is scarcely thinkable that primary quartz should carry inclusions of secondary minerals. This, of course, is on the assumption that one has made careful observations to convince himself that the inclusions are actually such and are not infiltrations through cracks and crevices. It follows, of course, that quartz containing secondary minerals as inclusions is itself of secondary origin; quartz containing no inclusions may be, so far as we can tell, of either primary or secondary origin, and quartz containing primary minerals as inclusions is probably itself of primary origin. In certain characteristic cases this probability becomes perhaps more than a practical certainty. A quantitative estimation of the percentage of quartz-carrying secondary inclusions will give a minimum value for the quantity of secondary quartz in the sample.

By way of summarization it may be said that with clean sand fractions of such youthful soils as the Durham and such naturally sorted materials as some of the coastal-plain soils, the petrographic identification of the constituent minerals attains a degree of certainty somewhat greater than that reached in the identification of constituents of rock sections. The reason for this is that, with the sands, as many mounts as needed may be made and the orientation of individual grains may be altered, thus making possible the actual measurement of the optical properties, notably the refractive indices, instead of approximately estimating them, as is frequently necessary with rock sections. The degree of certainty is perhaps as great as is attainable by petrographic methods alone, and when these methods are used in conjunction with chemical analysis the identifications can be considered as practically absolute. The identification of minerals in the silt fractions of soils, although still comparing favorably with identifications of similar-sized materials in rock sections, does not always give as clear-cut and comprehensive results as are obtained on the larger-sized sand particles. Ordinarily there is no reason whatever for doubting an identification of a silt particle, but the petrographer has a tendency to feel that he could get better and clearer results if the particles were larger. Particles of the clay fractions of soils can not, of course, be identified at all petrographically, and recourse must be had to X-ray methods. In the sands and silts the identity of decomposed minerals can be established with varying degrees of assurance ranging

from practical certainty to no certainty at all, depending on the extent of decomposition. The petrographer has to exercise his common sense in deciding just how far he can carry the identification.

PERCENTAGE ESTIMATION OF CONSTITUENTS IN A MIXTURE (MECHANICAL ANALYSIS)

In addition to determining the minerals present in soils, it is frequently of great importance to determine their relative quantities. In such instances there are in general three types of preparation, the constituents of which the microscopist may be called on to estimate. In soils laboratories these mixtures may be either firmly consolidated as rocks, or, on the other hand, may be in the form of loose materials. Of these, the simplest to estimate is the rock-section type of mount, in which all the particles can be assumed to have the same thickness and are usually in contact with each other without vacant spaces over the whole field of the microscope. A second, more difficult type of preparation, is that presented by ordinary mounts of previously sized materials, such as separates from mechanical soil analyses. Here the thickness of the particles can not always be assumed as uniform, and the amount of vacant space in any given field of view is frequently large. The third type of preparation and the most difficult of all is that in which there is no preliminary sizing whatever and in which the amount of vacant spaces is large. This type is presented by mounts of untreated soils, crushed crystal mixtures, crystal mixtures obtained by direct evaporation on the slide, and a multitude of similar materials from various sources. All the types are further slightly complicated by occasional overlapping of particles and by the presence of inclusions of one substance in another. The second and third types are sometimes seriously complicated by coatings of one or more substances on grains. The third type is frequently complicated by aggregates, the character of which is indeterminate.

No matter which type of preparation one is working on, the first task is to identify, so far as possible, every substance occurring in the mixture. With coarse-grained rocks and clean sands this identification is usually complete and easy. With other mixtures, the identification of certain of the constituents is frequently difficult, and, in the case of aggregates, deeply coated grains, substances whose optics are unknown, substances with abnormal optics, and extremely fine-grained substances, the identification may be impossible or practically so. With such mixtures there are thus three classes of constituents: (1) known constituents to be estimated individually; (2) a class of doubtful substances to be subgrouped and estimated as probably so-and-so, or as having such-and-such properties; and (3) a class of unknowns to be lumped together and estimated as such. Aggregates can sometimes be broken up into their constituents by simple crushing or by treatment with acids to remove cementing material. Coated grains can frequently be cleaned by treatment with hydrochloric or oxalic acids, and extremely fine-grained materials can often be improved by allowing the crystals an opportunity to grow.

By these and similar means which will readily suggest themselves to a chemist, doubtful and unknown substances may be rendered

identifiable. The qualitative identification of the constituents of the mixture, which are usually comparatively few, almost always brings to the attention some characteristics of the different constituents which serve to distinguish any one of them, practically at a glance, from all the other constituents present. For example, one of the constituents may be colored, whereas the other constituents are colorless or differently colored, as is the case of hornblende admixed with quartz, orthoclase, or perhaps micas. One of the constituents may have a very high double refraction, whereas all the other constituents have comparatively low double refractions, as would be the case of calcite or dolomite in the mixture just cited. If this same mixture were mounted in an oil with an index of refraction very near that of quartz, the orthoclase and colorless mica could be immediately distinguished from the quartz by their reliefs and from each other by the opposite movements of the Becke lines on slightly raising the tube of the microscope. If a mixture of sodium and potassium chloride is mounted in an oil with a refractive index between the indices of the two substances, the movement of the Becke lines would again immediately distinguish one from the other. If ammonium chloride is added to the mixture its relief in the same mount as above would serve to identify it in this mixture.

Thus, knowing what substances are present and having a means for the immediate recognition of each of them, the worker can proceed with his quantitative work unhampered and uninterrupted by the necessity of a long process of qualitative identification. Furthermore, the preliminary qualitative identification gives one a very definite idea of the best mount for the quantitative work; for instance, it shows the one best oil in which to mount the sodium and potassium chloride mixture mentioned above, that is, an oil with a refractive index between those of the two constituents. It occasionally happens, rarely, however, that two constituents of a mixture have properties so nearly alike that immediate distinction during the quantitative process is difficult. What to do in such a case depends not only on the characteristics of the two similar substances but also on the characteristics of the other substances in the mixture. It may even become necessary to determine the combined quantity of the two substances in one type of mount and then determine their mutual ratio in an entirely different type of mount.

To determine the percentage composition of a rock section, calculate the total area of the microscope field for the particular lens combination used by means of the formula

$$A = \pi r^2$$

where A is the area, π is 3.1416, and r is the radius of the field expressed as linear checkerwork eyepiece micrometer divisions. If any vacant places are present, determine their total area by micrometer count and subtract the result from the field area just calculated. This gives the net area covered by the substances to be estimated. Determine by micrometer count the areas of each substance in the field. As a check on the counting, the sum of the areas of the substances plus the areas of the vacant spaces, if any, should equal, or nearly equal, the total calculated area of the field. Any large discrepancy indicates an error in counting, and the work should be

repeated. Some systematic procedure in counting, for instance, by quadrants and left to right by rows or columns on the micrometer, is practically a necessity. It relieves eyestrain, lessens the tax on the attention, and often avoids the total loss of count due to interruption.

Since the thickness of the rock section can be assumed as uniform, the volumes of the constituents vary with their areas. The area of any one substance, therefore, divided by the net area of the field and multiplied by 100 gives the percentage by volume of that substance; that is,

$$\text{Per cent by volume} = \frac{\text{Area of substance}}{\text{Net area of field}} \times 100.$$

In this way the percentage by volume of each constituent can be determined, and the total should, of course, equal nearly 100. But it is not often that the percentage by volume is wanted, as practically always the percentage by weight is desired. This can be obtained from the volume percentage by multiplying the volume percentage of each constituent by the specific gravity of the constituent, summing up the figures so obtained, and taking the ratio between the figure for the individual constituent and that of the sum. A more direct method is to multiply the area of each constituent by the specific gravity of the constituent, sum up the figures so obtained, use the figure for an individual constituent as the numerator, the sum as the denominator, reduce this fraction to a decimal, and multiply by 100. This gives the percentage by weight of the constituent considered.

The sources of error are variations in the thickness of the section, inaccuracies from whatever cause in the counting, the presence of unestimated or only approximately estimated inclusions of other substances, and inaccuracies in the figures taken for the specific gravities. These latter vary considerably in certain minerals, and usually there is no practicable way of knowing precisely what figure to select.

In spite of these sources of error, however, the method is remarkably exact when applied to a single field of the microscope. But to make it applicable to the entire work it is necessary to resort to statistical methods. A number of fields should be counted and the results averaged. If the rock is very uniform, a very few fields are sufficient. If, on the other hand, the rock is very variable, it is necessary to increase the number of fields. Right here there is room for the exercise of a considerable amount of judgment. Theoretically a number of fields should be taken so that the addition of any other probable field will not seriously alter the average figures already obtained. Throughout all the work the areas themselves need not be determined by actual count. Any method, for instance the statistical linear method given in the discussion of area measurements may be used.

The procedure for the percentage determination of loose but sized material may be substantially the same as that given for rock sections. Usually, however, the vacant area on the slide exceeds that of the constituents. For this reason it is better to obtain the total area covered by the constituents, either by actual count or by

summation of the counts of the individual constituents, rather than by counting the areas of the vacant spaces and subtracting the total from the field area. The final results, however, are not of the same order of accuracy as those obtained for rock sections. All the sources of error in rock sections are still present and that one due to variations in thickness is vastly increased. For example, rounded quartz grains and flat flakes of mica of the same minor diameter would be held by the same screen in the sizing operation. But their thickness on the slide would be vastly different, and consequently the calculation of volumes or weights on the assumption of uniform thickness might be very seriously in error. Such error can be partly eliminated by measuring the thickness of each grain and calculating the volume by multiplying this thickness by the area of the grain. This procedure does not entirely remove the inaccuracy, since the grains are almost always rounded instead of rectangular, but it yields results sufficiently approximative for most purposes. If none of the constituents shows a thickness of uniformly extreme variation from the average thickness of all the particles present, it is safe to assume that the volumes vary approximately the same as the areas. The determination of both the area and thickness of each individual particle is likely to be a long and tedious job. It can frequently be shortened by multiplying the total area of the thin substance by a factor whose value can be determined from the relationship between the average thickness of the thin substance and that of the other substances in the mixture. In most cases of carefully sized materials, such a factor can usually be determined from a comparatively few thickness measurements.

It is seldom that all the detailed work indicated in the preceding paragraph is justified by the requirements of the problem; in fact, it is very doubtful whether the additional degree of accuracy obtained is ever sufficient to justify the time and labor expended. This can be realized readily when it is recalled that the percentage composition of a single field bears only a statistical relation to the true composition of the sample. The preceding paragraph has been written more with the idea of bringing out the principles involved than with any idea as to the actual application of the details except in extremely rare and unusual circumstances.

The method usually employed for the analysis of carefully sized materials is simply the direct count of the number of particles of each constituent. The composition by volume then is

$$\text{Per cent by volume} = \frac{\text{Number of particles of one constituent}}{\text{Total number particles counted}} \times 100.$$

The percentage by weight can be readily calculated as given in the discussion of rock sections. This method is based on the assumption, usually well founded, that each substance in the mixture has the same average particle volume. Mica is the most common exception. The number of mica or similar particles should be multiplied by a factor which can be determined by a comparison of the volume figures obtained by area and thickness measurements for a few of the mica and nonmica particles. If the number of mica particles is insignificant, as is the case in certain soils, it is scarcely worth while to make this correction. On the other hand, highly micaceous soils will yield

results wide of the truth if the factor is not applied. It should be remembered that a comparatively small quantity by weight of thin mica flakes can make an altogether disproportionate showing when scattered throughout a soil.

If the material is unsized and if the particle sizes vary widely, results of even a fair degree of accuracy are probably not attainable by any method other than that involving the volume determination of each individual particle by means of areal and thickness measurements. If colloidal material is present in quantity too great to be neglected, as in most soils, the quantitative determination of the percentage composition is practically a microscopic impossibility unless the colloids can be estimated by some other than microscopic means and allowed for in the calculations of the noncolloidal constituents. It may be said, in general, that the quantitative microscopic analysis of such materials as those under discussion should be undertaken only under the most exceptional circumstances.

Nevertheless, the microscopist is continually being called on to give some sort of estimate of the quantity of one or more constituents in just such materials. Rough approximations can be arrived at as follows: Determine the percentage of the constituent by rapid areal measurements. Determine by inspection, supplemented if necessary by a few thickness measurements, whether the average particle thickness of the constituent is near, less than, or greater than the average particle thickness of the mixture. If near, the percentage can be reported as about so-and-so; if less than, it can be reported as not greater than so-and-so; and if greater than, it can be reported as not less than so-and-so. Ordinarily, this rough sort of approximation is sufficient for the purpose. It at least gives a fairly reliable idea of the maximum or minimum quantity probably present.

It scarcely need be said that in all quantitative work on loose materials the grains should be as free as possible from coatings and adhesions of foreign substances, as it is practically impossible to make any estimation of the total volume of such substances. Coatings of opaque materials, such as iron hydroxide, may lead to an entirely wrong identification of the grain. Calcium carbonate is a particularly bothersome coating. Its high double refraction and relief in ordinary mounts, even when occurring only as a thin veneer on other substances, may lead to a very large overestimate of the quantity present. Alkali salts have a strong tendency to occur as coatings on the other soil grains. In general it is best, where practicable, to determine the quantity of colloids, including organic matter, calcium carbonate, and water-soluble salts by chemical means and to determine the other constituents microscopically in the residues.

Mineralogical analyses of soils (11) show that the following minerals may ordinarily be expected to occur in soils, though not all of them in any one soil: Quartz and other forms of silica such as chalcedony as the major component; most of the feldspars as orthoclase, microcline, albite, oligoclase, andesine, and labradorite; muscovite and biotite; chlorite; glauconite; epidote; hornblende and glaucophane; pyroxene, especially augite; magnetite, hematite, and limonite; apatite; and calcite and dolomite. Almost any other mineral may occur occasionally under special circumstances.

DIFFERENTIATION OF SOIL COLLOIDS FROM SOIL CRYSTALLINE MATERIAL

It is well recognized that in addition to the definite crystalline material in soils there are always present quantities of material varying from a small percentage up to sometimes as high as 80 per cent of material which can not be identified by petrographic methods. This material is of two general types—inorganic material, presumably formed by the decomposition of minerals, and organic matter, which comprises, for the most part, the residual products derived from animals and plants. Most of this material is extremely finely divided. Soil scientists are accustomed to describe it in terms of particle size after dispersion in water alone or in water with the addition of dispersing agents. After dispersion this material consists of very small particles ranging from 5μ downward. Soil scientists usually designate this extremely fine material as clay, regardless of its chemical composition. It follows, therefore, that the soil clay is not necessarily chemically identical with the amorphous mineral known as kaolin. Many soil scientists divide this portion of the soil into two parts, one of which is known as soil colloid because it possesses, to a great degree, those properties which characterize the group of substances of diverse origin which are so known and which possess the properties of moisture absorption, swelling with water or other liquids, and the ability to adsorb ions of various sorts. Where the dividing line should be drawn between the coarser noncrystalline material and the supposedly truly colloidal part of the soil has not found general agreement. To some scientists, any material which, in the dispersed condition has a maximum apparent diameter of 2μ or less is colloidal; others wish to make the upper limit 1μ , and some continue to regard as colloid only that material having a maximum apparent diameter of 0.1μ .

It is not the present purpose to attempt a discussion of this problem for the reason that, to the soil petrographer, the only differentiation that is possible is between those particles of the soil which have definite mineralogical and petrographical characteristics and those which have not these characteristics. To him, then, all which is not definitely crystalline under the microscope is more or less definitely colloidal in character. This distinction may be kept in mind in spite of the fact that X-ray studies (6, 9) have shown that many substances with marked colloidal properties gave definite diffraction patterns and are therefore crystalline, and in spite of the fact that even the typical colloid from which the group name is derived, gelatine, in the dry condition, gives a perfectly defined interference figure in polarized light. Glass also, which is generally considered as a true colloid, often shows the phenomenon of double refraction. It would appear, therefore, to the student of petrography of soils that his province is limited to differentiating between identifiable materials on the one hand and those not definitely determinable on the other; and, further, to gaining such information as may be useful concerning the unidentifiable fraction. It may be remarked that the lack of agreement above mentioned concerning even the size limits of those particles which shall be called colloidal accounts for the divergence between the quantities of colloid as ascertained by microscopic examination and those obtained for the same soils by other methods. It is suggested, therefore, when studies are made of this

unidentifiable or incompletely identifiable fraction of the soil that the results should be ascribed to unknown substances having such-and-such properties and characteristics, probably (or possibly) so-and-so. Or, when the data obtainable do not justify even a guess as to their nature, simply as unknown substances having such-and-such properties and characteristics.

This manner of reporting results automatically limits the term colloid to that portion of the sample consisting of particles of unknown substances which are within or near generally accepted colloidal dimensions. It will be seen that in such case the term will apply equally to organic and inorganic material. Nevertheless, information of considerable importance concerning this fine material present in the soil may be obtained by the use of the petrographic microscope.

In dry soils, such as are used for ordinary or petrographic study, the colloids occur as aggregate masses, either free or as coatings on other soil materials. The one characteristic that all seem to have in common is the aggregated structure. This can frequently be recognized by ordinary transmitted light. The masses are seen to be not uniform continuous material but conglomerations of multitudinous and extremely fine particles. This is particularly noticeable around the edges of the mass. The fracture is not along cleavage lines as in certain minerals. To the naked eye it generally appears conchoidal, but under the microscope the conchoidal surfaces are seen to be totally lacking in the smoothness and mirrorlike qualities of the fracture surfaces of such materials as glass or quartz. On the contrary, the fracture surface of the colloid aggregate is usually an especially favorable place to observe the very fine particles. Examination in reflected light shows the same thing and sometimes to better advantage in the case of subtranslucent to opaque aggregates. Reflected light from a vertical illuminator (pp. 25, 82) occasionally brings out an aggregate structure which would not be easily visible with ordinary reflected daylight. Best of all, examination with a dark-field illumination practically always renders the structure distinct and unmistakable. During the course of the microscopic examination with ordinary light the color of the aggregates, both in transmitted and reflected light, should be noted as well as their degree of transparency or opacity.

Under the petrographic microscope, between crossed Nicols, the aggregates of soil colloids may or may not be doubly refracting. Those showing some degree of double refraction are perhaps more common than those showing none. Absence of double refraction, isotropy, seems usually associated with high iron content.

The appearance of the doubly refracting aggregates between crossed Nicols is variable. Sometimes it is that usually spoken of as aggregate polarization—that is, the aggregate appears speckled with small light and dark areas which alternately extinguish and light up as the stage is rotated. More often, however, the polarization is wavy—that is, the aggregate does not extinguish all over at the same time, but progressively from part to part as the stage is rotated, the band of extinction being usually vague as to borders, comparatively narrow, and always followed by a band of light. Occasionally the appearance simulates that of ordinary normal crystals.

Interference figures are usually easily obtained from the doubly refracting aggregates, but they are not universally obtainable. These figures at best are fairly clear and distinct, but never nearly so good as those given by clean well-crystallized calcite or quartz, for example. At the worst, the figures are barely discernible. Usually they are considerably blurred and unsatisfactory. The optic angle, as estimated from the interference figures, varies from sensibly zero up to values where the foci of the hyperbolae are outside the field of the microscope. There are therefore aggregates which could be classed as uniaxial or biaxial, as the case may be. In any one sample the optic angles of various aggregates may vary considerably. The gypsum plate shows that certain aggregates are optically positive and others optically negative. No correlation between any of these properties and chemical composition is known.

The refractive indices of aggregates of soil colloids usually vary from about 1.56 to 1.62. There are aggregates, however, especially in lateritic soils, with very much higher indices. The refractive indices seem to vary with the iron content.

The preceding description of aggregates of soil colloids brings out the fact that they possess numerous properties in common with crystalline material. Their one outstanding and distinctive characteristic is the aggregate structure. Fortunately, however, there is only one common soil constituent with which they may be confused. This is highly decomposed mica, and there are real grounds for the tentative belief that highly decomposed mica should be classified as a colloid. But, aside from this possibility of misidentification, a very little experience should enable one to readily differentiate soil colloidal aggregates from any other substance likely to be found in soils. The general problem of determining by microscopic means alone whether any given substance is colloidal or crystalline is perhaps insoluble with our present knowledge. X-ray methods offer perhaps the best solution of the problem (6, 9).

SOIL ORGANIC MATTER AND RESIDUE OF ORGANISMS

The organic matter of soils consists predominantly of plant residues in various stages of decay. There is also present, of course, organic matter from animal and other sources, but the quantity is comparatively small, and the identity of the material is seldom determinable. Bacteria, nematodes, earthworms, fertilizer applications, etc., furnish their quotas. No matter what the source, however, soils are devoid of crystalline organic matter, detectable microscopically, without a considerable amount of preliminary extraction and purification. Petrographic methods are, therefore, inapplicable to the organic matter of untreated soils. But something can be done by direct microscopic observation. Cell structure is a characteristic of practically all vegetable and animal tissues and is not found elsewhere in nature except in such rare and unusual substances as petrified wood. The existence in a soil, therefore, of material showing cell structure is practically always sufficient evidence of its organic nature. Detailed identifications as to genus and species are problems for those specializing in the subjects concerned, for instance botanists and bacteriologists.

Charcoal, bituminous coal, and anthracite present slightly different problems. All three are opaque and have no optical properties of determinative value. Their streaks, obtained by rubbing the materials on white paper, are indicative but not conclusively so. Occasionally it is possible to observe cell structure in charcoal by reflected light. If particles sufficiently large can be isolated from the soil, their combustibility can be tested and their odor and behavior on burning ascertained. Aside from the application of such miscellaneous tests as these, there is no way of identifying any of these three substances.

Investigations on the organic matter of soils, involving extensive extraction and purification operations, frequently yield organic products of a crystalline nature. There is usually a considerable amount of chemical information available, and the petrographer is called in largely in a confirmatory capacity. The procedure is simply a comparison of the optics and other characteristics of the given substance with those of the substance or substances which the chemical information indicates as probable or possible. On account of the meagerness of the published data on the optics of organic compounds, it is commonly necessary, and always safer and more satisfying, to make this comparison by a direct examination of all the substances involved.

There are certain inorganic residues of organisms, which sometimes assume importance in soils. These may be generally comprised under the denominations of shell fragments, diatoms, and sponge spicules. Shell fragments are important mainly because of the calcium carbonate of which they are composed and to a less extent because of the light their presence sometimes throws on the previous history of the soil. They can be immediately identified by their general appearance and can be readily located in mounts by their extremely high double refraction between crossed Nicols. The presence of diatoms throws light on a soil's previous history. They can be identified as diatoms by general appearance, but specific identification as species is beyond the field of petrography. Sponge spicules not only give information as to the history of the soils in which they occur but, in at least one case, have assumed practical importance on account of the irritating effect they had on the feet of mules used in plowing the fields. They are readily identified by their long, narrow, slightly curved, hollow, sometimes spined, and sharply pointed forms. Specialists easily distinguish between fresh-water and salt-water species and thus add to the known history of the soil.

SHAPE OF PARTICLES

The examination of soil particles as to shape sometimes assumes importance, especially in reference to the degree of rounding and the conclusions as to weathering and transport which can be drawn therefrom. In this sort of examination it is essential that the outside and not the inside of the particles be clearly visible. For identification purposes, as has been seen, the better the mount the nearer are the refractive indices of the particle and the oil. This greatly accentuates visibility of the interior and subordinates that of the exterior of the particle. In the perfect case the outlines of the

particle are invisible. Obviously, a directly contrary effect is desired when the exterior characteristics are to be observed. This is readily obtained by mounting the particles in a medium, the refractive index of which is markedly different from those of the particles. This type of mount subordinates the interior and accentuates the exterior characteristics of the particles. For soil particles, water or air, preferably the former, is a fairly satisfactory mounting medium. The water, however, when used alone, evaporates rather rapidly and in so doing pulls the particles so close together as to hide many of the individual edges. The addition of more water does not necessarily correct this packing, and seriously alters the positions of the grains. These inconveniences can be largely eliminated by using a minimum amount of water and carefully forming a rim of oil around and slightly under the edges of the cover glass. This type of mount is by no means permanent, but if properly made will delay evaporation sufficiently to give ample time for the examination. The examination itself is simply direct observation as to whether the particles are in general smoothly rounded, smoothly elliptical, or sharply angular with rounded edges. A quantitative expression of the degree of rounding can be obtained by statistical calculations from a number of measurements of maximum and minimum horizontal diameters and, if desirable, vertical diameters.

A certain amount of judgment is necessary both in obtaining and in interpreting the data. Extremely resistant minerals, such as zircon, are apt to retain beautifully distinct crystallographic forms long after the other minerals of the soil have become round. In fact, sharply angular crystals of zircon are common components of certain beach sands. The outline form of mica plates is particularly difficult to interpret, owing to the unusual properties of this mineral, its softness, capacity to bend, elasticity, cleavage, and ease of flotation. Fibrous and needle-shaped minerals often retain these forms to some extent, at least, regardless of the amount of transport and weathering. Feldspars, on account of their cleavage and twinning, are liable to show an angularity greater than would normally be expected in certain distantly transported soil. On the other hand, they seem to show more rounding than would normally be expected in highly weathered sedentary soils. This is probably explained by their susceptibility to chemical weathering and the absence of breakage in such soils. Quartz particles have no properties which would throw serious doubts on the interpretation of their angularity or roundness, as the case may be, and are usually the most abundant components above silt size. For these reasons quartz is perhaps the safest of all soil minerals on which to base conclusions.

As the preceding paragraph shows, the comparison of the two soils as to particle shape is susceptible to various complications which can not always be easily solved. But in spite of this, it is a fact that there are soils in which the particles are in general distinctly rounded, others in which they are just as distinctly angular, and still others in which they are of a shape intermediate between the two extremes. These three groups are easily distinguishable from one another. But close distinctions between members of the same group, especially of the group consisting of intermediately shaped particles, are apt to be uncertain and unsatisfactory.

RESIDUES FROM THE EVAPORATION OF SOIL SOLUTIONS

In the main, residues left on the evaporation of soil solutions are fairly well crystallized. They consist essentially of the chlorides, sulphates, carbonates, and sometimes nitrates of the alkali and alkaline-earth metals. Other substances may, of course, be present and sometimes in important quantities, for instance, borax. Soils from humid areas yield small total quantities of residues, whereas soils from arid alkali areas may yield excessively large total quantities. In general, it may be said that gypsum and calcite are the commonest constituents in residues from humid soils, and that these, plus a whole assortment of the chlorides, sulphates, and carbonates, are common in the residues from alkali soils (1).

There are only two sources of difficulty in the identification of these salts. If the evaporation has been too rapid, the crystals are apt to be extremely small and closely interwoven or mutually enmeshed. The result is a heterogeneous mass of small, closely aggregated crystals, the individual components of which are practically indeterminable. Evaporation at room temperature, although slow, yields a much more manageable product than does more rapid evaporation at higher temperatures, and it probably saves time in the long run. Cases have arisen in which partial resolution and recrystallization were necessary.

A second source of difficulty in identification arises from the presence of colloidal coatings, inorganic, organic, or both, on the crystals. Filtration of the original solution through Pasteur-Chamberland filter tubes does much to prevent these coatings. If the filtered solution is boiled to coagulate the colloids, but not sufficiently to reduce the volume to the point where crystallization begins, and then refiltered through Pasteur-Chamberland filters, an additional quantity of colloid is removed and the chances of coatings still further reduced. This is usually sufficiently efficacious so far as inorganic colloids are concerned. But sometimes the solution contains organic materials which persist in spite of the treatment and which, if not removed, form the most bothersome sort of coatings. Evaporation, treatment with absolute alcohol or ether, resolution, and recrystallization will usually remove the organic matter and yields salts sufficiently clean for identification. If the volumes are small the cleaning process outlined above is not onerous, but large volumes mean a long and tedious task.

The procedure for the petrographic identification of the salts, once they are obtained in an identifiable condition, is exactly similar to that for the identification of soil minerals. As with certain fertilizer materials, however, there is the possibility of the presence of numerous double salts, and care is necessary in order to avoid missing some of them.

Where complete data are not desired, far less elaborate procedures can be devised. About the simplest procedure is to evaporate a few drops of the solution, concentrated somewhat if necessary, directly on a microscope slide, and to examine the crystals either as they form or after drying. Gypsum, on account of its low solubility as compared to the alkali salts, is usually one of the first substances to crystallize and appears in well-formed characteristically shaped crys-

tals, which are readily recognizable. Carbonates and nitrates can be recognized by their high double refraction and can be further identified by other optical determinations. Refractive-index measurements are necessary to distinguish between sodium and potassium chlorides. Sulphates other than gypsum usually require fairly complete data for certain identification.

VERTICAL ILLUMINATION

The vertical illuminator is almost universally used in the examination of metals and ore minerals (15). In a soils laboratory it can be used to advantage in the examination of opaque materials and of surfaces; in fact, wherever reflected light is normally used. It improves the illumination, enables the worker to see into holes and cavities where slanting side light would not reach, and, in conjunction with Nicol prisms, furnishes a means for determining the isotropy or anisotropy of opaque substances, the latter being something which can not be done at all with the ordinary petrographic equipment. For this purpose, a Nicol is placed in the path of the horizontal beam of light and the analyzer Nicol is inserted in the tube of the microscope. The first Nicol is rotated until it is in the crossed position with reference to the second Nicol. Under these conditions an isotropic substance will remain dark during a complete rotation of the stage, whereas an anisotropic substance will alternately darken and lighten as the stage is revolved. Substances which remain dark are either amorphous or isometric, and substances which alternately lighten and darken are crystalline and belong to one of the systems of crystallization other than the isometric. In determinative work this information enables one to eliminate a large group of substances.

PARTICLE SURFACES

The mounting for the examination of the surfaces of soil particles is the same as that for the observation of particle shape. Highly weathered surfaces, especially of the feldspars, usually have a pitted and corroded appearance. Fresh crystal faces and cleavage surfaces, on the contrary, are smooth and sometimes mirrorlike. Fracture surfaces are jagged or conchoidal, according to the nature of the substance. Fused surfaces can usually be recognized by their smooth globular form. Any surface may carry coatings or adhesions of foreign materials, especially of colloids such as iron hydroxide, clay materials, and organic matter.

Whether transmitted or reflected light should be used depends on a number of circumstances, such as the nature and thickness of coatings, size of particles, and their opacity or transparency. In general, it is best to try both. It is even sometimes advisable to change entirely the system of mounting and to search for impurities in the same mounts that are used for identification purposes. Whether these impurities are inclusions, surface adhesions, or both can then be determined by examination of the surfaces themselves.

Ordinarily the detailed examination of the surfaces of soil particles does not furnish any particularly important information which could not be obtained as well and sometimes perhaps better otherwise. Special occasions arise, however, where a large part of the interest

centers in the surfaces. For example, in the study of methods for the dispersion of colloids, it is essential to know something as to the extent to which colloidal coatings have been removed from the soil particles.

Mixed crystals obtained from various sources, the evaporation of soil and similar solutions, and phase-rule studies, frequently show crystals of one substance carrying partial coatings of crystals of the second substance. If an examination of the materials shows no instance of a contrary relation between the two substances it is reasonable to assume that the second substance crystallized subsequent to the first. An indication is thereby obtained as to the relative solubilities of the two substances in the given solution.

SOIL STRUCTURE

Microscopic observations on the structure of soils is practically impossible in the case of loose materials, such as sands, silts, and wet clays. Something can be done, however, with partly consolidated materials, such as dry clays, with their contained sand and silt, highly decomposed but not entirely disintegrated rocks, soil cakes from pressure, packing and heating experiments, concretions, and the like. The technic varies radically with the degree of consolidation. Concretions are frequently as hard and firmly consolidated as are many rocks and can be sectioned and mounted for microscopic study just as are rocks. It is otherwise, however, with the less consolidated types of materials, which are too fragile to stand the grinding and polishing operations incident to the making of sections unless they are strengthened by some artificial means. The means usually employed is impregnation of the material by some cementing or binding substance. Numerous substances have been used for this purpose, such as Canada balsam, paraffin, copal gum, shellac, and various commercial cements. None of them has proved perfectly satisfactory, and apparently there is no way to predict which will be best in a given case. Experience is the only guide. The writer's general preference is toward paraffin, partly because of its cheapness and availability and partly because of the ease of working the paraffin-impregnated material.

The technic of impregnating the material is simple. Drop a lump of the air-dry hardened material into a dish of melted paraffin and let it remain until no more gas bubbles are given off. This may require upward of two hours or more for a lump less than an inch in diameter. Care should be taken to keep the temperature between the melting and smoking points of the paraffin. When no more bubbles are given off the lump is removed and thoroughly cooled. It is now ready for sectioning. This can be done by carefully grinding one side to a flat and fairly smooth surface, cementing this surface to a slide by means of Canada balsam, and then grinding the opposite side until the desired thinness is reached. A cover glass cemented over the section by Canada balsam completes the operation. In the absence of grinding apparatus the same results can be attained by cutting and scraping with a pocket knife and rubbing on any sufficiently hard and smooth surface. If Canada balsam is used in place of the paraffin, greater hardness and solidity are attained.

Sand grains admixed with the material are almost certain to tear or pull out during the grinding. If they are present in large quantity they may seriously impair the quality of the section. Silts and clays, on the other hand, usually yield very fair sections.

Sections made as already described are not well adapted to the identification of the component minerals. They do, however, make it possible to observe microscopic structural features which might otherwise be unnoticed. In this respect they have the advantage of allowing the use of both transmitted and reflected light.

If for any reason whatever it is found to be impracticable to make thin, transparent sections, some information can usually be obtained by direct examination of a surface of the material in reflected light. Stratification, shrinkage cracks, pores, and the like are frequently seen with great distinctness, provided the proper magnification is used. Too high a magnification, by limiting the field of view and accentuating inconsequential details, just as frequently as not hides more than it reveals. In examinations of this kind are found some of the best illustrations of the wisdom of starting with the lowest power lenses and working up to the higher ones as the need arises.

Visibility of fine structures in reflected light is sometimes very greatly improved by varnishing the surface under examination. The surface should be as smooth and flat as the nature of the materials will allow. Ordinary shellac makes a very good varnish. The visibility can sometimes be even further improved by cementing a cover glass over the varnished surface.

Soil materials do not lend themselves to the making of sections and polished surfaces nearly so well as do rocks. The sections and surfaces that can be prepared are usually of inferior quality. Although their examination yields a certain amount of data in special cases, their usefulness is not sufficiently established to suggest any more than incidental and occasional preparations. On the other hand, the structure of soils offers a wide field for research, and if methods could be devised for collecting soils and preparing thin sections of them, comparable in quality to those of rocks, without altering or destroying the field structure, the results might be of considerable value, both from a theoretical and a practical standpoint.

ULTRAMICROSCOPES

Ultramicroscopes in general are various modifications of the dark-field illumination principle. The dark-field illuminator is simply a condenser with a blackened circle in the center of the field. This circle cuts out all direct light. The light passing the edges of the circle is reflected slantwise from the sides of the condenser to the objects. From thence it is again reflected to the eye. The effect is that of a very luminous object, a reflecting mirror, for example, on a dark background. Particles invisible in ordinary transmitted or reflected light are thus rendered brilliantly visible. For certain purposes the dark-field illuminator is dispensed with, a strong beam of light being passed through a colloidal solution in such a direction, usually at right angles, as not to enter the objective. The microscope is focused on a plane within the beam. Reflections from the suspended particles may then enter the objective and thus render the

particles visible. The effect is somewhat like that of dust motes seen in a beam of sunlight in a darkened room. The visibility is usually not quite so good as when the dark-field illuminator is used. The difference is essentially, though not entirely, a difference in degree of darkness of the background.

A certain amount of care is necessary in making mounts for ultra-microscopic observations. If the suspension is too concentrated, there will be a large amount of light scattered in various directions from the particles. Part of this light will be again and again reflected from the slide and from other particles and will reach the observer as a general illumination of the whole field of view, thus tending to nullify the advantages of the dark field. Dirty or scratched slides and cover glasses have the same effect. Colloid particles with the same refractive index as that of the mounting medium do not reflect light and are therefore invisible. Silica gel in water is an example approximative of this condition. Owing to the increased number of particles within the field, thick mounts are inclined to give the same effects as mounts of too concentrated materials, although thinner mounts might be perfectly satisfactory.

In one way or another, the ultramicroscope has an extremely wide application. In soils work it is used consistently for approximate measurements of size of soil colloidal particles and for the determination of the rates of movements of these particles in cataphoresis experiments.

FERTILIZER MATERIALS

The methods for the identification of fertilizer materials vary considerably, according to the character of the materials. The crystalline components can best be identified by a procedure exactly like that used for soil minerals. Organic components must be identified by cell structure, just as with the organic matter of soils. Amorphous and submicroscopically crystalline components, such as are frequently found both in phosphate rock and superphosphate, are often microscopically unidentifiable, and resort must be had to chemical methods. The greatest difficulty that is apt to arise in the identification of the crystalline components, especially with mixed fertilizers, is the dirtiness of the crystal surfaces. Crushing the materials has a tendency to expose new and cleaner surfaces, but too much crushing tends to dirty the surfaces thus exposed. Another difficulty arises from the large number of double salts that may be found in materials from such deposits as those of Stassfurt. The identification of these may inordinately prolong the examination without adding anything of vital importance to the information obtained. Chemical analyses of the particular fertilizer under examination are usually available to the microscopist, and he can save time by using these as general guides as to what he may reasonably expect to find. It is futile, for instance, to spend time hunting for salts of nitric acid in a mixture where all the nitrogen is in the form of ammonia. On the other hand, for example, it is sometimes desirable to know whether the potash of a given fertilizer is present as the chloride or the sulphate. If both chlorides and sulphates are present, chemistry can not well answer the question, and the petrographer is called on to identify the compounds of potash present.

MISCELLANEOUS MATERIALS

An appreciable part of the work of a petrographer in a general laboratory is apt to be the examination of miscellaneous samples originating both in the laboratory itself and from outside sources. These samples are usually of a most diverse and heterogeneous character and are submitted in almost every conceivable condition. Many of them are important. The vast majority of them, whether important or not, represent a very real desire for information on the part of the sender. Some few, of course, are inconsequential and probably represent nothing more than puerile curiosity. In any case, the petrographer's task is to take the sample as it comes and make the most of it.

The miscellaneous character of the materials precludes the possibility of any fixed procedure. Soils, rocks, glass in foods, waste products from all sorts of manufactories, fertilizers, natural deposits unfamiliar to the sender, spots on plants, crystals developed in sometimes unknown solutions, ashes of both wood and coal, electric-furnace products, crystals in plant tissue, ores and gems, boiler scale, various cements, deep-sea deposits, fibers, both natural and artificial, crystalline material extracted from soils and plants, enamel from teeth, scouring soaps, and an almost indefinite number of other substances comprise a list of materials to which no one set procedure can be applicable.

There are a few general principles, however. (1) Get all the information available concerning the sample. Usually this is apt to be meager enough, but what there is of it is sometimes of very great help. The mere knowledge of the State from which a natural sample comes, for instance, may suggest that it be tested for phosphates. (2) Find out as near as may be what information the sender wants. A vast amount of purposeless work can be done on any sample, and it is manifestly best for all concerned for the petrographer to confine his attention, within reason, to the subject at hand. (3) Do not hesitate to use chemical, physical, biological, rule of thumb, or any other methods which seem to offer a solution of the problem. The methods of petrography have an extremely wide application, but they are not all sufficient. (4) Know experts to whom the sample can be transferred when the preliminary information or tests show conclusively that the problems involved are essentially theirs.

INSPECTION OF SAMPLES FOR PURITY

Precipitates, commercial products, fractional-crystallization products, various laboratory preparations, and the like offer numerous occasions where an inspection, both rapid and economical of material, is desirable. Petrographic methods are especially suitable for such purposes. If a substance is mounted in an oil of approximately its own refractive index it becomes invisible, or nearly so, at least in some of its orientations. Other substances which may be present are not apt to have the same refractive indices and, therefore, are easily visible and readily detected. If it happens that the refractive indices are not sufficiently different to afford a ready means of differentiation, some one or more of the other optical properties

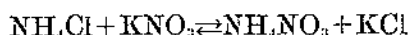
can be utilized. For example, suppose potassium chloride is to be examined. If the sample is mounted in an oil of refractive index 1.490, the potassium chloride can not be seen, whereas other substances, such as sodium chloride, will stand out prominently and can be almost immediately found. Potassium nitrate with small quantities of sodium nitrate affords a more complicated example. The maximum and minimum refractive indices of potassium nitrate are 1.335 and 1.506. Those of sodium nitrate are 1.336 and 1.587. If the sample is mounted in an oil of about 1.510, any particle in any orientation showing an index higher than this is certainly not potassium nitrate. Particles showing lower indices, however, may or may not be potassium nitrate. Changing the orientation of the particles and retesting the refractive index may give the desired differentiation. If not, the interference figures probably will.

Both inclusions of mother liquor and surface coatings stand out just as prominently as crystals of other substances, as has been previously explained. They can, therefore, be readily found and some rough idea formed as to their quantity.

It is believed that this application of petrographic methods for inspection purposes has a much wider field of usefulness than has been so far accorded it, especially in the control of commercial processes. Although the methods can not entirely replace chemical analysis, they frequently can materially reduce the number and elaborateness of the analyses. This partial substitution of rapid and inexpensive methods for slow and sometimes expensive ones is deserving of more attention than it has received.

PHASE-RULE PROBLEMS

Mixed solid components obtained at various stages in phase-rule studies frequently present almost insuperable difficulties in identification by purely chemical means. If the components are crystalline, however, petrographic methods are usually capable of solving the problem extremely rapidly and comparatively easily. In such studies the total number of possible components is strictly limited, their chemical character can be predicted, and the number possible in the solid state is known. The problem therefore simplifies itself into the question as to which components, out of a small number of possibilities, actually occur in a given mixture. Obviously, other things being equal, it is easier to answer such a question than it is to answer the more common question as to what, out of an unlimited number of possibilities, is the composition of a given mixture. As an illustration, take an actual case. A saturated solution was made of mixed NH_4Cl and KNO_3 and an excess of the salts added. These salts would react reversibly until equilibrium was reached, as represented in the following equation:



Ignoring double salts, the identification of which was not essential in the given problem, there were thus four possible compounds. One of these would be in solution, and only three could exist simultaneously in the solid phase. The question then was simply which three of the four were present in the sample under examination.

NH_4Cl and KCl are isotropic and KNO_3 and NH_4NO_3 are both strongly doubly refracting. Any isotropic substance found in the mixture was probably, therefore, either NH_4Cl or KCl , and any doubly refracting substance was probably either KNO_3 or NH_4NO_3 . The refractive index of NH_4Cl is comparatively high, about 1.64, and that of KCl is comparatively low, about 1.49. These two salts could, therefore, be readily distinguished from the nitrates by their isotropy and from each other by their refractive indices. The optic axial angle of KNO_3 is extremely small, and that of NH_4NO_3 is comparatively large. These two could, therefore, be distinguished from the chlorides by their double refraction and from each other by their optic axial angles. The actual procedure was to mount the material in an oil of refractive index about 1.54. Isotropic substances having a lower index than this were, therefore, tentatively identified as KCl , and those having a higher index were identified as NH_4Cl . Doubly refracting substances with very small optic axial angles were tentatively identified as KNO_3 , and those having comparatively large angles were likewise identified as NH_4NO_3 . Familiarity with the properties of these salts and of the possible double salts made it feasible to observe variant properties, when present, and thus to obtain data indicative of the presence or absence of the double salts. Finally, the identifications were established definitely by such additional observations and measurements as were necessary.

The above case is comparatively simple and free from complications. The presence of double salts increases the amount of detailed work necessary before satisfactory identifications are reached, but in no wise alters the general character of the procedure which is, briefly, to make the minimum number of observations and measurements necessary to distinguish between the components possibly present. The amount of work increases as does the number of components and also as the properties of two or more components tend toward identity. Special care has to be exercised in the mounting of strongly hygroscopic salts in order to avoid the taking up of water. If the saturated solution of the salts is used as a mounting medium, a rim of oil around the edges of the cover glass acts as an effective guard against the dilution of the solution by moisture from the atmosphere.

APPENDIX

Tables 2, 3, 4, 5, and 6 were compiled solely with the idea of giving an illustration of the optical classification of crystals and of affording a limited and uncomplicated collection of data for practice on the application of the methods. For any except the very simplest determinative work, the tables of Larson (10) and Winchell (19) are practically indispensable.

 TABLE 2.—Isotropic substances ¹

Formula	Mineral name	System and habit	Cleavage	Color	n
NaF		Isometric	(100)	Colorless	1.336
CaF ₂	Fluorite	Cubes	(111) perfect	Variable	1.434
NaAl(SO ₄) ₂ ·12H ₂ O		do.		do.	1.438
KAl(SO ₄) ₂ ·12H ₂ O	Alum	Octahedral	None	Colorless	1.4562
(NH ₄)Al(SO ₄) ₂ ·12H ₂ O		Isometric		do.	1.4594
SiO ₂	Cristobalite	Pseudo-isometric or octahedral (211)		White	1.486
Na ₂ O·Al ₂ O ₃ ·4SiO ₂ ·2H ₂ O	Analcite	Isometric	(100) trace	Colorless	1.487
KCl	Sylvite	Plagioclinal	Cubic, perfect	do.	1.490
K ₂ O·Al ₂ O ₃ ·4SiO ₂	Leucite	Pseudo-isometric (211)	Imperfect	do.	1.509
K ₂ Mg ₂ (SO ₄) ₃	Langbeinite	Highly modified tetrahedral		do.	1.535
NaCl	Halite	Cubes	Cubic, perfect	do.	1.544
KBr		Isometric		do.	1.559
Sr(NO ₃) ₂		do.		do.	1.567
Ba(NO ₃) ₂	Nitrobarite	Isometric or octahedral		do.	1.571
NH ₄ Cl		Isometric	(111) imperfect	do.	1.642
KI		do.		do.	1.677
Mg ₃ Al ₂ (SiO ₄) ₃	Pyrope-garnet	(110), (211)	None	Red	1.705-1.742
MgAl ₂ O ₄	Spinel	Octahedral	(111) imperfect	Red and variable	1.723-1.75
Ca ₃ Al ₂ (SiO ₄) ₃	Grossularite-garnet	(110), (211)	None	Variable	1.735
MgO	Periclase	Cubes	(100) perfect, (111) poor	Colorless	1.736
As ₂ O ₃	Arsenolite	Octahedral		White	1.755
(Mg, Fe)Al ₂ O ₄	Pleonaste	(111), rarely (100)	None	Black	1.77
Fe ₃ Al ₂ (SiO ₄) ₃	Almandite-garnet	(110), (211)		Dark red	1.778-1.83
Pb(NO ₃) ₂		Isometric		Colorless	1.7838
(Mn, Fe) ₃ Al ₂ (SiO ₄) ₃	Spessartite-garnet	(110), (211)	None	Reddish	1.811
CaO	Cubes	(100) perfect		Colorless	1.83
Ca ₃ Fe ₂ (SiO ₄) ₃	Andradite-garnet	(110), (211)	Conchoidal	Variable	1.895
ZnS	Sphalerite	Tetrahedral	(110) perfect	Colorless and variable	2.37

¹ Remain dark on rotation between crossed Nicols and do not give an interference figure.

TABLE 3.—Uniaxial positive substances¹

Composition	Mineral name	System and habit	Cleavage	Color	ϵ_D	ω_D	$\epsilon-\omega$
$\text{Na}_3\text{PO}_4 \cdot 12\text{H}_2\text{O}$	Chabazite-zeolite	Trigonal			1.4324	1.4458	0.0006
$(\text{Ca}, \text{Na})\text{Al}_2(\text{SiO}_3)_4 \cdot 6\text{H}_2\text{O}$	Chabazite-zeolite	Pseudo-trigonal, cubic	(10 $\bar{1}$ 1) distinct	White	1.482	1.480	.002
$\text{NaK}_3(\text{SO}_4)_2$	Aphthitalite	Trigonal			1.4996	1.4901	.0095
$(\text{K}, \text{Na})_2\text{SO}_4$	Aphthitalite	Trigonal, tabular, rhombic	(10 $\bar{1}$ 0) rather distinct (0001) imperfect	White	1.499	1.491	.008
$\text{K}_2\text{Al}_2(\text{SiO}_3)_4$	Leucite	Pseudo-isometric (211)	(110) poor	Colorless	1.509	1.508	.001
SiO_2	Quartz	Trigonal, hexagonal, prisms and pyramids	None	do	1.553	1.544	.009
$\text{Fe}_2(\text{SO}_4)_3 \cdot 9\text{H}_2\text{O}$	Coquimbite	Trigonal	(10 $\bar{1}$ 0), (10 $\bar{1}$ 1), (01 $\bar{1}$ 1) imperfect	White, yellow, violet	1.556	1.550	.006
$\text{K}(\text{AlO}_2\text{H}_2)_3(\text{SO}_4)_2$	Alunite	Trigonal tabular (0001), or cubic	(0001) distinct	White	1.592	1.572	.020
Zn_2SiO_4	Willemite	Trigonal	(0001) variable (1120) variable	White, green, red, brown, and variable	1.723	1.694	.329
CaWO_4	Scheelite	Tetragonal, octahedral, or tabular	(111) distinct	White, yellow, brown, gray	1.934	1.918	.016
ZrSiO_4	Zircon	Tetragonal, short prisms and pyramids	(110) rare	Colorless, yellow, brown, gray, pink, and variable	1.968-2.015	1.923-1.960	0.045-.055
Hg_2Cl_2	Calomel	Tetragonal	(100), (111) rather distinct	Colorless	2.656	1.973	.683
SnO_2	Cassiterite	Tetragonal	(100), (111) imperfect	Brown, black, gray, white	2.993	1.997	.996
ZnS	Wurtzite	Hexagonal, short prisms, lamellar (0001)	(1120) easy, (0001) difficult	Variable	2.378	2.350	.022
TiO_2	Rutile	Tetragonal prismatic	(100), (110) distinct	Yellow, red, brown, and variable	2.903	2.610	.287
CSi^2	Moissanite	Hexagonal plates (0001)		Green to black	2.697	2.654	.043
HgS	Cinnabar	Hexagonal	(10 $\bar{1}$ 0) perfect	Cochineal red	3.201	2.854	.347

¹ Give a uniaxial cross and are optically positive with the gypsum plate or quartz wedge.² Pleochroism (p. 62) ω =light blue, ϵ =deep indigo blue.

TABLE 4.—Uniaxial negative substances ¹

Composition	Mineral name	System and habit	Cleavage	Color	ω_n	ϵ_n	$\omega - \epsilon$
(Na ₂ , Ca) Al ₂ (SiO ₃) ₄ · 6H ₂ O	Gmelinite-zeolite	Trigonal	(10 $\bar{1}$ 0) easy	Colorless	1.465	1.464	0.001
Do	Chabazite	Trigonal cubic habit	(10 $\bar{1}$ 1) distinct	White	1.480	1.478	.002
SiO ₂	Cristobalite	Tetragonal and pseudo-isometric, octagonal		Colorless	1.487	1.484	.003
Na ₂ Al ₂ (SiO ₃) ₄ · 2H ₂ O	Analcite	Pseudo-isometric (211)	Cubic, trace	do	1.487	1.486	.001
MgNa ₂ (SO ₄) ₂ · 2½H ₂ O	Loewite	Trigonal	(0001) distinct	White	1.490	1.471	.019
KH ₂ PO ₄		Tetragonal			1.5095	1.4684	.0411
NaSO ₄ · 6H ₂ O		do		Green	1.5109	1.4873	.0236
NH ₄ H ₂ PO ₄		do			1.5246	1.4702	.0544
Na ₂ Al ₂ (SiO ₃) ₄	Nephelite	Hexagonal	(10 $\bar{1}$ 0), (0001) imperfect	Colorless	1.542	1.538	.004
Be ₃ Al ₂ (SiO ₃) ₆	Beryl	Hexagonal prisms	(0001) imperfect	Colorless, green, blue, yellow, and variable.	1.568-1.598	1.504-1.590	.004-.008
NaNO ₃	Soda niter	Trigonal	(10 $\bar{1}$ 1) perfect	White	1.587	1.336	.251
K ₂ O · 4(Mg, Fe)O	Biotite	Monoclinic, hexagonal plates	(001) microscopic	Brown, black, and green	1.600		Strong.
2(Al, Fe)O ₃ · 6SiO ₂ · H ₂ O			(0001) imperfect	Colorless and variable	1.634	1.631	.003
Ca ₂ (PO ₄) ₂ · Ca(F, Cl) ₂	Apatite	Hexagonal prisms	(001) microscopic	Black	1.64		.050
Iron-rich biotite	Lepidomelane	Monoclinic scales	(10 $\bar{1}$ 1) perfect	Colorless and variable	1.658	1.486	.172
CaCO ₃	Calcite	Trigonal	(1101) perfect	White	1.681	1.500	.181
CaMg(CO ₃) ₂	Dolomite	Trigonal rhombic					
Na ₂ O · (Fe, Mg, Cr)O · Al ₂ O ₃	Tourmaline ²	Hexagonal prisms	None	Black and variable	1.687	1.641	.046
SiO ₂ · B ₂ O ₃ · H ₂ O							
Ca(Mg, Fe)(CO ₃) ₂	Dolomite	Trigonal rhombic	(10 $\bar{1}$ 1) perfect	White	1.695	1.510	.185
MgCO ₃	Magnesite	Trigonal massive	do	Colorless, white, and variable	1.700	1.569	.131
(Mg, Fe)CO ₃		Trigonal rhombic	do	White	1.726	1.526	.199
Al ₂ O ₃	Corundum	Trigonal	(0001) perfect parting	Red, blue, and variable	1.768	1.760	.008
ZnCO ₃	Smithsonite	do	(10 $\bar{1}$ 1) perfect	Colorless and variable	1.818	1.618	.200
MnCO ₃	Rhodochrosite	do	(10 $\bar{1}$ 0) perfect	Pink	1.817	1.597	.220
(Mn, Fe)CO ₃		Trigonal rhombic	(10 $\bar{1}$ 1) perfect	do	1.826	1.605	.221
(Fe, Mg)CO ₃	Siderite	Trigonal	do	Colorless to brown	1.830	1.596	.234
(Fe, Mn)CO ₃		do	do	Colorless and variable	1.849	1.615	.234
FeCO ₃		do	do	do	1.855-1.875	1.613-1.633	.242
PbO ₂	Plattnerite	Tetragonal		Black	2.341		
TiO ₂	Anatase	Tetragonal octahedral	(001), (111) perfect	Brown and variable	2.554	2.493	.061
PbO	Litharge	Tetragonal tabular (001)	(110) perfect	Red and variable	2.665 _L	2.535 _L	.130

¹ Give a uniaxial cross and are optically negative with the gypsum plate or quartz wedge.

² Pleochroism strong, ω =green to bluish green, ϵ =yellow.

TABLE 5.—*Biaxial positive substances*¹

Substance	System	α	β	γ	Color pleochroism	2V	Dispersion	Orientation
Na_3AlF_6 (cryolite).....	Monoclinic.....	1.364			Color variable.....	43	$\rho < v$	AXial plane \perp (010). $Z \wedge c = 43^\circ 54'$ in acute $\angle \beta$.
$\text{Na}_2\text{HPO}_4 \cdot 7\text{H}_2\text{O}$	do.....	1.441	1.442	1.463		38 50	Not perceptible.....	AXial plane \perp b (010). $Z \wedge c = 72^\circ$ in acute $\angle \beta$.
$\text{K}_2\text{Mg}(\text{SO}_4)_2 \cdot 6\text{H}_2\text{O}$ (picromerite).....	do.....	1.461	1.463	1.476	White.....	48		AXial plane b (010). $Z \wedge c = 103^\circ 38'$.
$(\text{NH}_4)_2\text{Mg}(\text{F O}_4)_2 \cdot 6\text{H}_2\text{O}$	do.....	1.472	1.473	1.479		51 11		$Z \wedge a = 1^\circ 10'$. $X \wedge c = -1^\circ$.
Na_2SO_4 (thenardite).....	Orthorhombic.....	1.464	1.474	1.485	White and variable.....	84	$\rho > v$, weak.....	AXial plane b (010). $Z \wedge c = 94^\circ 58'$.
$\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ (melanterite).....	Monoclinic.....	1.471	1.478	1.486	Green, yellow.....	86	do.....	$Z \wedge a = 12^\circ 8'$.
$\text{K}_2\text{Fe}(\text{SO}_4)_2 \cdot 6\text{H}_2\text{O}$	do.....	1.476	1.482	1.497		67 7		$X = b$. $Y = c$.
K_2SO_4 (arcanite).....	Orthorhombic.....	1.494	1.495	1.497		67	$\rho > v$, moderate.....	$Y = b$. $Z \wedge c = -61^\circ$.
$\text{NH}_4\text{MgPO}_4 \cdot 6\text{H}_2\text{O}$ (struvite).....	do.....	1.495	1.496	1.504	Colorless and variable.....	37	$\rho > v$, strong.....	AXial plane b (010). $Z \wedge c = 101^\circ 57'$.
$\text{KAl}(\text{SiO}_3)_2$ (leucite).....	Triclinic.....	1.515	1.518	1.523	do.....	(?)		$Z \wedge a = 2^\circ 35'$.
$\text{Ca}_2\text{H}_2(\text{PO}_4)_2$ (monetite).....	do.....	1.508			do.....	(?)		$X = b$. $Z = a$.
$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ (gypsum).....	Monoclinic.....	1.520	1.523	1.530	White.....	58	$\rho > v$, perceptible.....	X emerges from (100). $Y = b$.
$(\text{NH}_4)_2\text{SO}_4$ (muscagnite).....	Orthorhombic.....	1.521	1.523	1.533	Colorless and variable.....	52	$\rho > v$, feeble.....	$X \wedge c = 37 \frac{1}{2}^\circ$. $Z = a$.
$\text{NaAlSi}_3\text{O}_8$ (albite).....	Triclinic.....	1.525	1.529	1.536	Colorless.....	74	$\rho < v$, weak.....	$X = c$. On (010) $X \wedge (001) = 24^\circ$.
$\text{MgSO}_4 \cdot \text{H}_2\text{O}$ (kieserite).....	Monoclinic.....	1.523	1.535	1.586	White.....	57	$\rho > v$, moderate.....	On (010) $X \wedge (010) = 31 \frac{1}{2}^\circ$. $Y = b$.
$\text{Ca}_2\text{H}_2(\text{PO}_4)_2 \cdot 4\text{H}_2\text{O}$ (brushite).....	do.....	1.539	1.545	1.551	do.....	86		$X \wedge c = 76 \frac{1}{2}^\circ$. $Z = b$.
Na, Ca feldspar (andesine).....	Triclinic.....	1.550	1.553	1.557	Colorless and variable.....	88		On (010) $X \wedge (001) = 3^\circ$. On (010) $X \wedge (010) = 2^\circ$.
$\text{CaC}_2\text{O}_4 \cdot \text{H}_2\text{O}$ (whewellite).....	Monoclinic.....	1.491	1.555	1.650	Colorless.....	84	$\rho < v$, weak.....	$X = b$. $Z \wedge c = -11^\circ$.
Ca, Na feldspar (labradorite).....	Triclinic.....	1.559	1.563	1.568	do.....	79		On (010) $X \wedge (001) = 21^\circ$. On (001) $X \wedge (010) = 9^\circ$.
CaSO_4 (anhydrite).....	Orthorhombic.....	1.571	1.576	1.614	do.....	42	$\rho < v$	$X = c$. $Z = a$.
Fe, Mg, Al silicate, hydrated, prochlorite).....	Monoclinic.....	1.606	1.606	1.610	Green.....	(4)	$\rho < v$, perceptible.....	Z near c .
BaSO_4 (barite).....	Orthorhombic.....	1.636	1.637	1.648	White.....	37 $\frac{1}{2}$	$\rho < v$, weak.....	$X = c$. $Z = a$.

BaCl ₂ ·2H ₂ O.....	Monoclinic.....	1.635	1.646	1.660	.....	53	46	{ Axial plane (010). ZΛc=8° in obtuse Λβ.
Al ₂ SiO ₅ (sillimanite).....	Orthorhombic.....	1.638	1.642	1.653	Colorless, gray.....	20	p>v, strong.....	{ X=b. Z=c.
(Mg, Fe) ₂ SiO ₄ (olivine).....	.....do.....	1.662	1.680	1.699	Green, brown, and variable.....	(3)	p<v.....	{ X=b. Z=a.
Ca(Mg, Fe) ₂ (Al, Fe) ₂ (SiO ₄) ₂ (augite).....	Monoclinic.....	1.698	1.704	1.723	Green and variable.....	60	.....do.....	{ Y=b. ZΛc=38° to 54°.
(Ce, La, Di) ₂ (PO ₄) ₂ (monazite).....	.....do.....	1.786	1.788	1.837	Red, brown, and variable.....	14	p<v, weak.....	{ X=b. ZΛc=2°.
S (sulphur).....	Orthorhombic.....	1.950	2.043	2.240	Yellow.....	69	p<v.....	{ X=a. Z=c.

¹ Give hyperbolæ as interference figure, and are optically positive with gypsum plate or quartz wedge.

² Small.

³ Large.

⁴ Very small.

TABLE 6.—*Biaxial negative substances*¹

Substance	System	α	β	γ	Color pleochroism	2V	Dispersion	Orientation
Na ₂ SO ₄ ·10H ₂ O (mirabilite).....	Monoclinic.....	1.394	1.396	1.398	White.....	76	p<v.....	{ X=b or Y=b. ZΛc=30°.
Na ₂ HPO ₄ ·12H ₂ O.....	.....do.....	1.432	1.433	1.437	.....	56	43	{ Distinct, inclined..... Axial plane b (010). XΛc=31° in acute Λβ.
Na ₂ CO ₃ ·10H ₂ O (natron) ¹.....	.....do.....	1.405	1.425	1.440	White.....	71	p>v, perceptible.....	{ X=b. Z=a.
MgSO ₄ ·7H ₂ O (epsomite).....	Orthorhombic.....	1.433	1.455	1.461	.....do.....	52	p<v, weak.....	{ Z=b. X||c.
NaH ₂ PO ₄ ·2H ₂ O.....	.....do.....	1.440	1.463	1.482	.....do.....	82	50	{ Axial plane b (010). X||c.
Na ₂ B ₄ O ₇ ·10H ₂ O (borax).....	Monoclinic.....	1.447	1.470	1.472	.....do.....	39	p>v, strong.....	{ Y=b. ZΛc=56.0°.
NaH ₂ PO ₄ ·H ₂ O.....	Orthorhombic.....	1.456	1.485	1.487	.....	29	22	{ Axial plane b (010). X||a.
K ₂ Mg(SO ₄) ₂ ·4H ₂ O (leonite).....	Monoclinic.....	1.483	1.487	1.490	Colorless.....	86	p<v.....	{ Y=b. ZΛc=small.
Na ₂ Mg(SO ₄) ₂ ·4H ₂ O (bloodite).....	.....do.....	1.486	1.488	1.489	.....do.....	71	p<v, strong.....	{ Y=b. XΛc=41.1°.
KNO ₃ (niter).....	Orthorhombic.....	1.334	1.505	1.506	.....do.....	7	.....do.....	{ X=c. Z=b.
MgSO ₄ ·KCl·3H ₂ O (kainite).....	Monoclinic.....	1.494	1.505	1.516	.....do.....	85	p>v, small.....	{ Y=b. XΛc=-8°.
Na ₂ CO ₃ ·H ₂ O (thermonatrite).....	Orthorhombic.....	1.420	1.506	1.524	White.....	45	p<v, weak.....	{ Z=b.
K ₂ Ca(SO ₄) ₂ ·H ₂ O (syngenite).....	Monoclinic.....	1.500	1.517	1.518	.....do.....	27	p<v, very strong.....	{ YΛc=-2.3°.

¹ Give hyperbolæ as interference figure and are optically negative with gypsum plate or quartz wedge.

TABLE 6.—*Biaxial negative substances*—Continued

Substance	System	α	β	γ	Color pleochroism	2V	Dispersion	Orientation
KAlSi ₃ O ₈ (orthoclase).....	Monoclinic.....	1.518	1.524	1.526	{White, colorless pink, and variable.	0-70	Weak.....	{Y or Z=b, X∧a=5°.
KAlSi ₃ O ₈ (microcline).....	Triclinic.....	1.522	1.526	1.530	do.....	83	$\rho > v$, weak.....	{Extinction on (001)=15°. Extinction on (010)=5°-6°.
(Na, K)AlSi ₃ O ₈ (anorthoclase).....	do.....	1.523	1.529	1.531	do.....	32-54	do.....	{Extinction on (001)=1°-6°. Extinction on (010)=0°-10°.
Na ₂ Ca(SO ₄) ₂ (glauconite).....	Monoclinic.....	1.515	1.532	1.536	Colorless.....	7	$\rho > v$, strong.....	{Z=b, Y∧c=14.2°.
CuSO ₄ ·5H ₂ O (chalcantite).....	Triclinic.....	1.516	1.530	1.546	Blue.....	56	$\rho < v$, perceptible.....	
Na, Ca, feldspar (oligoclase).....	do.....	1.539	1.543	1.547	Colorless.....	86	$\rho < v$, weak.....	{On (010) X∧(001)=0°. On (001) X∧(010)=1°.
(NH ₄) ₂ C ₂ O ₄ ·H ₂ O (oxammite).....	Orthorhombic.....	1.439	1.547	1.595	White.....	60	$\rho < v$	{X=c, Y=a.
2CaSO ₄ ·MgSO ₄ ·K ₂ SO ₄ ·2H ₂ O (polyhalite).....	Triclinic.....	1.548	1.562	1.567	Flesh red, yellow, and variable	70		
Mg ₃ Si ₂ O ₇ ·2H ₂ O (serpentine).....	Orthorhombic.....	1.560	1.570	1.571	Green.....	20-90		{X=b, Z=c.
K, Mg, Fe, Al (silicate, hydrated, biotite).....	Monoclinic.....	1.541	1.574	1.574	Black and variable.....	0-50	$\rho < v$, perceptible.....	{Y=b, X∧c=3°.
CaAl ₂ Si ₂ O ₈ (anorthite).....	Triclinic.....	1.576	1.584	1.588	White.....	77	$\rho < v$	{On (010) X∧(001)=-37°. On (001) X∧(010)=-40°.
K ₂ Al ₂ Si ₆ O ₂₂ ·2H ₂ O (muscovite).....	Monoclinic.....	1.561	1.590	1.594	Colorless.....	40	$\rho > v$, perceptible.....	{Z=b, X∧c=0°.
Al, Fe, Mg, Ca, Na (silicate, hornblende).....	do.....	1.629	1.642	1.653	Green, black, brown, and variable.	84	$\rho < v$	{Y=b, Z∧c=15°-25°.
CaCO ₃ (aragonite).....	Orthorhombic.....	1.531	1.682	1.686	Colorless.....	19	$\rho < v$, small.....	{X=c, Z=b.
Al ₂ SiO ₅ (cyanite).....	Triclinic.....	1.712	1.720	1.728	Blue, colorless, and variable.....	82	$\rho > v$, slight.....	{X almost \perp (100). Z∧c=-30°.
Ca, Al, Fe (silicate, epidote).....	Monoclinic.....	1.729	1.754	1.768	Green.....	(?)	$\rho > v$, rather strong.....	{Y=b, X∧c=-2.5°.

¹ Large.

LITERATURE CITED

- (1) ANDERSON, M. S., and FRY, W. H.
1920. SOLID PHASES OBTAINED BY THE EVAPORATION OF CERTAIN SOIL EXTRACTS. *Jour. Indus. and Engin. Chem.* 12: 663-669.
- (2) CHAMOT, E. M. and MASON, C. W.
1930. HANDBOOK OF CHEMICAL MICROSCOPY. v. 1, 474 p., illus. New York and London.
- (3) COUCH, J. F.
1923. LUPINE STUDIES. IV. ISOLATION OF D-LUPANINE FROM LUPINUS KINGII (S. WATSON). *Jour. Amer. Chem. Soc.* 47: 2584-2587.
- (4) DANA, E. S.
1916. A TEXT-BOOK OF MINERALOGY, WITH AN EXTENDED TREATISE ON CRYSTALLOGRAPHY AND PHYSICAL MINERALOGY. New ed., entirely rewritten and enlarged, 593 p., illus. New York.
- (5) FRY, W. H.
1914. IDENTIFICATION OF COMMERCIAL FERTILIZER MATERIALS. U. S. Dept. Agr. Bul. 97, 13 p.
- (6) HENDRICKS, S. B., and FRY, W. H.
1930. THE RESULTS OF X-RAY AND MICROSCOPICAL EXAMINATIONS OF SOIL COLLOIDS. *Soil Sci.* 29: 457-479, illus.
- (7) JOHANNSEN, A.
1918. MANUAL OF PETROGRAPHIC METHODS. Ed. 2, 649 p., illus. New York and London.
- (8) KEENAN, G. L.
1924. THE OPTICAL PROPERTIES OF SOME AMINO ACIDS. *Jour. Biol. Chem.* 62: 163-172, illus.
- (9) KELLY, W. P., DORE, W. H., and BROWN, S. M.
1931. THE NATURE OF THE BASE-EXCHANGE MATERIAL OF BENTONITE, SOILS, AND ZEOLITES, AS REVEALED BY CHEMICAL INVESTIGATION AND X-RAY ANALYSIS. *Soil Sci.* 31: 25-55.
- (10) LARSEN, E. S.
1921. THE MICROSCOPIC DETERMINATION OF THE NONOPAQUE MINERALS. U. S. Geol. Survey Bul. 679, 294 p., illus.
- (11) McCaughey, W. J., and FRY, W. H.
1913. THE MICROSCOPIC DETERMINATION OF SOIL-FORMING MINERALS. U. S. Dept. Agr., Bur. Soils Bul. 91, 100 p., illus.
- (12) MERWIN, H. E.
1913. MEDIA OF HIGH REFRACTION FOR REFRACTIVE INDEX DETERMINATIONS WITH THE MICROSCOPE; ALSO A SET OF PERMANENT STANDARD MEDIA OF LOWER REFRACTION. *Jour. Wash. Acad. Sci.* 3: 35-40, illus.
- (13) MIERS, Sir H. A.
1929. MINERALOGY; AN INTRODUCTION TO THE SCIENTIFIC STUDY OF MINERALS. Ed. 2, rev. by H. L. Bowdler. 658 p., illus. London.
- (14) SALOMON, W.
1896. UEBER DIE BERECHNUNG DES VARIABLEN WERTHES DER LICHTBRECHUNG IN BELIEBIG ORIENTIRTEN SCHNITTEN OPTISCH EINAXIGER MINERALIEN VON BEKANNTER LICHT- UND DOPELRECHUNG. *Ztschr. Kristallographie u. Mineralogie* 26: [178]-187, illus.
- (15) SHORT, M. N.
1931. MICROSCOPIC DETERMINATION OF THE ORE MINERALS. U. S. Geol. Survey Bul. 825, 204 p., illus.
- (16) STORY-MASKELYNE, M. H. N.
1895. CRYSTALLOGRAPHY; A TREATISE ON THE MORPHOLOGY OF CRYSTALS. 521 p., illus. Oxford.
- (17) WATSON, W.
1905. A TEXT-BOOK OF PHYSICS. Ed. 4, 929 p., illus. New York, London [etc.].
- (18) WHERRY, E. T.
1918. THE APPLICATION OF OPTICAL METHODS OF IDENTIFICATION TO ALKALOIDS AND OTHER ORGANIC COMPOUNDS. U. S. Dept. Agr. Bul. 679, 9 p.

(19) WINCHELL, A. N.

1931. THE MICROSCOPIC CHARACTERS OF ARTIFICIAL INORGANIC SOLID SUBSTANCES OR ARTIFICIAL MINERALS. Ed. 2, 403 p., illus. New York and London.

(20) WRIGHT, F. E.

1911. THE METHODS OF PETROGRAPHIC-MICROSCOPIC RESEARCH, THEIR RELATIVE ACCURACY AND RANGE OF APPLICATION. 204 p., illus. Washington, D. C. (Carnegie Inst. Wash. Pub. 158.)

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