THE DETERMINATION OF THE REFRACTIVE INDICES OF MINERALS BY THE IMMERSION METHOD

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The crystallographic-optical theory upon which the determination of the indices of refraction of a birefringent mineral by the immersion method is based, is very adequately treated in a number of texts, so it is not the purpose of this paper to approach the subject from that standpoint. But the application of this theory to the routine determination of minerals is an art which the student acquires chiefly by practice. The student finds himself confronted with the necessity of doing three things simultaneously, no one of which in itself would give him much difficulty, but taken together they contrive to delay his mastery of the petrographic microscope. The first essential, of course, is an understanding of the theory upon which the determinations of the indices of refraction are based; secondly, he must interpret his observations under the microscope in terms of this theory; and, thirdly, he must at the same time develop a manipulative technique or skill in the use of the microscope as a mechanical instrument. The present treatment is an attempt to bridge the gap between theory and practice.

In the great majority of cases the petrographic microscope is only a useful tool and the determination of the indices of refraction an important step in the identification of the mineral. Too often though, the emphasis is placed upon the refinement of procedure, and the main objective, the identification of the mineral, becomes subordinated to the method of attack. It is recognized that in certain types of research, accuracy in the determination of the optical constants becomes one of the main objectives of the problem. In general, however, the variations in the chemical composition within a single mineral species make extremely accurate determinations of little value, unless accompanied by a chemical analysis of the same material. It is hoped that nothing in this presentation will be interpreted as meaning that a thorough grounding in fundamental crystal optics is not desirable. The sole purpose is to present an exposition of a method that has been found satisfactory in the routine determination of the optical constants as a means of identifying minerals, in the hope that others may profit from it.

The use of the symbols o, e, $\mathfrak{a}$, $\mathfrak{h}$, $\mathfrak{c}$, X, Y, and Z are not essential to the practical or to the theoretical study of crystal optics. Hence these terms are dropped and the vibration directions within a crystal are denoted by ω and ϵ for uniaxial crystals, and α, β, and γ for biaxial crystals. No confusion arises when these terms are used to denote not only the principal indices of refraction (scalar properties) but also the vibration directions within the crystal (vector properties) for the rays possessing those indices of refraction.

By the time the student is sufficiently advanced to begin using the petrographic microscope, his knowledge of the megascopic physical properties and the general appearance of the common minerals will often give a preliminary idea as to the identity of most specimens. In most cases the microscope will be used to check and confirm megascopic impressions, or to decide upon one of a number of possibilities. Consequently any routine method should not be so rigid as to require that an inordinate amount of time be devoted to prescribed preliminary preparations. In other words, the method should be flexible enough to allow it to be adapted to the problem at hand. As experience is acquired, crushed mineral fragments under the microscope take on definite characteristics which convey to the observer impressions as diagnostic as the visual impressions he associates with hand specimens. Because of these facts no definite procedure is recommended but each step is determined by the sum total of knowledge that has been acquired up to that point. With this in mind the choice of the first immersion liquid depends upon the specimen to be determined.

If the mineral is uniaxial every fragment will give ω in one of the extinction positions. If the variable index is greater than ω, the mineral is positive, and if less than ω, negative. It is not necessary to determine the sign from an interference figure but the uniaxial character should be observed from an interference figure whose optic axis emerges within the field to demonstrate that the mineral is not biaxial with a small optic angle. The exact value of ϵ may be determined only from those fragments in which the c-axis lies in the plane of the microscope stage. These fragments, which are analogous to those perpendicular to the optic normal, give in the extinction positions (when the brushes are crossed) centered interference figures like Fig. E. In both instances the movement of the brushes on rotating the stage is very rapid. Except for this more rapid movement of the brushes, the figures are also similar to those from sections perpendicular to the obtuse bisectrix (Fig. J). If the interference figure is not exactly centered, a value very closely approximating ϵ may be determined. In minerals with low or moderate double refraction the approximation is extremely close. Fragments from which ϵ may be de-

termined extinguish very rapidly and, if the material is of approximately uniform thickness, will show higher interference colors than the fragments in which the *c*-axis is not horizontal. Every doubly refractive fragment will give ω in one extinction position and ε, or a value intermediate between ω and ε, in the other extinction position.
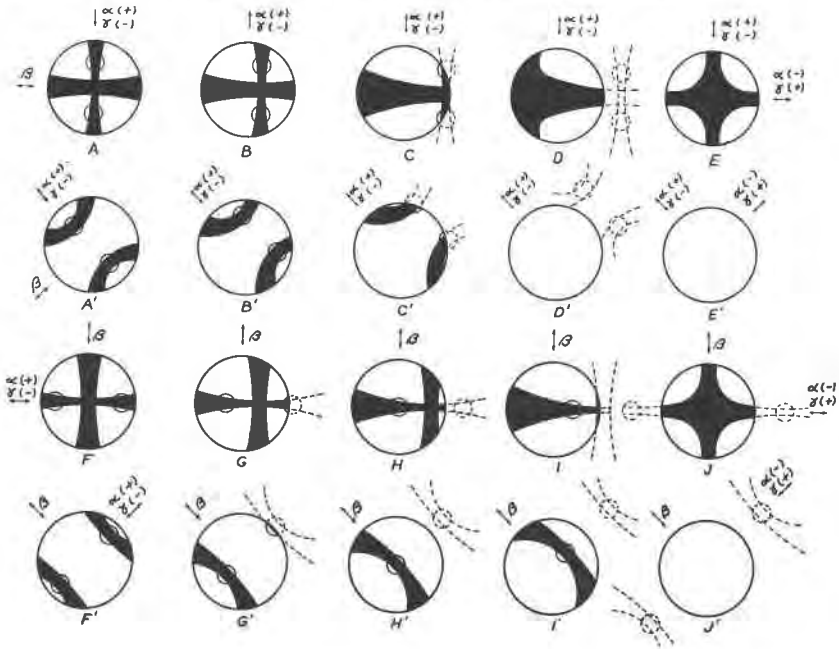

FIG. 1.

The value of ω can be easily determined with exactness and usually it is not necessary or advisable to determine ε with a corresponding accuracy in the routine determination of minerals. But whenever it is necessary to determine ε accurately, the orientation of the fragment should always be checked by observing an interference figure of the character described above.

In biaxial minerals α or γ may be determined from those fragments which are so oriented that *one* of the bisectrices lies in the plane of the microscope stage. Figures A–E show the types of interference figures given by fragments with the obtuse bisectrix lying in the plane of the microscope stage. In Fig. A, perpendicular to an acute bisectrix, the obtuse bisectrix is parallel to the plane of transmission of the polarizer. If we now think of the section as rotating to the right about the obtuse bisectrix as an axis of rotation we would obtain successively Figs. B, C, and D. Further rotation would bring the section perpendicular to the

optic normal as in Fig. E. Rotation to the left would have given similar figures but in reverse position. During the rotation the position of the obtuse bisectrix has remained fixed and the interference figure is always symmetrical to one direction of the field. Consequently any of these possible positions will permit α in a positive mineral and γ in a negative mineral to be compared with the liquid in which the fragment is immersed. Figures A′, B′, C′, D′, and E′ show the corresponding figures in the 45° position. Here the two brushes are still symmetrical to one direction in the field, when they fall within the field. When the interference figure is perpendicular to the optic normal (Fig. E), the acute bisectrix also lies in the plane of the microscope stage and therefore one extinction position will give α and the other γ.

The same argument may be developed for a similar series of interference figures starting with one cut perpendicular to the obtuse bisectrix in which case the acute bisectrix would lie in the plane of the microscope stage, and α would be determined from a negative mineral and γ from a positive mineral. In many cases when the optic angle approaches 90° it is impossible to distinguish the acute and obtuse bisectrices. This situation is covered by the following generalized conclusion. *If the observed bisectrix is positive* (as normally determined by the use of test plates) α *may be determined, and if negative* γ *may be determined.*[1]

In biaxial minerals, β may be determined from those fragments which are so oriented that the optic normal lies in the plane of the microscope stage. Figures F–J show the types of figures obtained from such fragments. In Fig. F, perpendicular to the acute bisectrix,[2] the optic normal is parallel to the plane of transmission of the polarizer. If we think of the fragment as rotating to the right about the optic normal as an axis of rotation we would obtain successively Figs. G, H, and I. Further rotation would bring the section perpendicular to the obtuse bisectrix as in Fig. J. Rotation to the left would give similar figures but in reverse position. During the rotation the position of the optic normal has remained fixed and consequently any of these possible positions will permit β to be compared with the liquid in which the fragment is immersed. When the interference figure is perpendicular to the obtuse bisectrix, Fig. J, the acute bisectrix also will lie in the plane of the microscope stage and on rotating the stage through 90° it will be parallel to the plane of transmission of the polarizer. Consequently, in that position, γ may be determined in positive minerals and α in negative minerals.

The student is apt to get the impression that only fragments showing interference figures perpendicular to either an optic axis, an acute or ob-

[1] This statement holds whether the mineral is positive or negative

[2] Compare with Fig. A.

tuse bisectrix, or the optic normal are available for the determination of the principal indices of refraction. Actually, if any one of the three principal optical *sections* is vertical, one of the principal indices may be determined in the direction normal to that principal section by rotating the stage so that the normal to the principal section is parallel to the plane of transmission of the polarizer (the principal section being in the E–W position).

In accordance with the foregoing discussion the following general rules may be laid down:

From any fragment giving an interference figure possessing one plane of symmetry with reference to the field of vision,[3] *one of the principal indices may be determined (Figs. B, C, D, G, H, and I).* With the plane of symmetry lying in the E–W position, the index of refraction is determined in the N–S position.

From any fragment giving an interference figure possessing two planes of symmetry with respect to the field of vision,[4] *two of the principal indices may be determined (Figs. A, E, F, and J).* These correspond to the two extinction positions.

In practice it is generally true that the student does not crush his fragments fine enough. He also is very apt to use far too many fragments in a single immersion mount. He expects his interference figures to resemble those pictured in texts. As a rule the average interference figures will resemble those obtained from feldspars in rock sections of standard thickness, in respect to the width and sharpness of the "brushes" and lack of rings. If, because of a distinct cleavage, it is difficult to find properly oriented fragments, finely ground glass may be added to the crushed mineral.[5] Some of the pieces of glass will lie under the edges of the fragments and give to some fragments the desired orientation. Because of the isotropic character of the glass, this method should not cause confusion.

The index of the mineral and that of the immersion liquid can be best compared under high magnification, using an objective giving 45× magnification, for instance. Because of the difference in dispersion between the liquid and the mineral a spectrum is observed along the contact when the indices of the two are close. When the indices of the immersion liquids are standardized for definite wave lengths of light, semi-monochromatic determinations may be made in white light by observing

[3,4] Strictly speaking, this holds only for monochromatic light. The moderate dispersion observed in some monoclinic and triclinic minerals offers no serious difficulty to such a generalized statement.

[5] Larsen, Esper S., and Berman, Harry: *U. S. Geol. Survey, Bull.* **848,** p. 22.

the movement of the colors of the spectrum along the contact between the mineral and the liquid.

In conclusion we wish to emphasize that there are in reality an infinite number of possible orientations available for the determination of each of the principal indices of refraction, that a routine procedure is not always desirable because experience points the way to "short-cuts," and that usually the errors involved in the method are smaller than the known variations of the indices within a mineral species. We also feel that methods based upon the use of fragments whose orientations have been observed are much to be preferred to statistical methods involving the determination of maximum and minimum indices of refraction exhibited by a large number of fragments. Where the orientation is known there can be no question about the vibration directions and indices in the fragments, and the method is free from the errors that pronounced cleavages are apt to introduce into the statistical method. We further believe that the use of fragments of known orientation usually requires no more time, but on the contrary generally saves time because one oriented section will give information obtainable only after the examination of a large number of unoriented fragments. For the student, the actual determination of a *specific* index of refraction gives him confidence in the accuracy of his work while the lack of a definiteness of purpose of a statistical method engenders uncertainty.