The jeweler's refractometer as a mineralogical tool

C. S. Hurlbut, Jr.

Department of Geological Sciences
Harvard University, Cambridge, Massachusetts 02138

Abstract

The jeweler's refractometer offers a simple method of determining the refractive indices of any mineral having a single polished surface of at least 1 mm^2 to a precision of about 0.002. For some crystallographic orientations of the polished surface of anisotropic crystals, it is necessary to determine the angles the vibration directions of the measured refractive indices make with the polished surface. This is accomplished by viewing the refractometer scale through a rotatable polarizing filter on which the transmission direction is indicated. With the knowledge of these angles, it is possible to tell if a crystal is uniaxial or biaxial: in uniaxial crystals to distinguish ω from ϵ and tell the optic sign, and in biaxial crystals to identify all three refractive indices and thus determine the optic sign. Similar measurements can be made on a single mineral grain in a polished thin section. Also the indices of refraction of immersion liquids can be quickly determined with the refractometer.

Introduction

By the end of the nineteenth century the Abbé-Pulfrich refractometer was in use in many laboratories for the determination of the optical properties of minerals. It is an elaborate instrument requiring careful adjustment, but in the proper hands the three refractive indices of biaxial crystals could be measured with an accuracy of 0.0002. Numerous papers written describing its use and reporting data obtained with it were summarized briefly by Wright (1911, p. 98–100). But with the advent of the immersion method and its wide adoption as a means of refractive index determination, the mineralogist gradually abandoned the refractometer. Most modern textbooks on optical crystallography mention the instrument and give the principle on which it operates but do not elaborate on it as a working tool. However, the gemologist, eager for nondestructive tests on cut and polished gemstones, recognized the potential of the refractometer in gem identification. The first efficient jeweler's refractometer was developed by G. F. Herbert Smith (1905). With various improvements in design and construction, the refractometer is today the most important instrument used for gem determination.

The mineralogist could also profit by use of this simple instrument in determining the optical properties of minerals. The only requirement, and perhaps the reason the refractometer is little used, is that the crystal under study must have a flat polished surface with a minimum area of 1 mm^2. Having met this requirement, the following information can be obtained: for isotropic substances, the single refractive index; for uniaxial crystals, both principal refractive indices and the optic sign; and for biaxial crystals, the three principal refractive indices and the optic sign. Using the refractometer, the same data can be obtained on a single mineral grain in a polished thin section. The refractometer also offers a quick and easy way to determine the refractive index of an immersion liquid.

The simplicity of the refractometer and its straightforward method of determining refractive index was recognized by McKague (1971). However, he was apparently unaware of the extent to which optical properties of crystals were obtained by early users of the Abbé-Pulfrich refractometer. Had he been, he could have presented a more compelling case, not only for the use of the jeweler's refractometer in teaching mineralogy, but also for mineral identification.

McKague (1971) gives examples of the measurements obtained when the polished surface of the crystal is parallel to one or another of the principal optical planes or has a *random* orientation, that is, is inclined to them all. Four examples are given for uniaxial crysals and ten for biaxial crystals. In only three of the fourteen examples does he interpret the measurements to give unequivocal results. For the remaining eleven examples, the measurements leave in doubt the uniaxial or biaxial character of the crystal, its optic sign, or both.

The following discussion illustrates how for *any orientation* of a polished surface on a uniaxial or biaxial crystal definitive answers can be obtained. The basic design of the jeweler's refractometer and the principle on which it operates are given by McKague (1971) and in most gemology texts (e.g., Hurlbut and Switzer, 1979, p. 66).

However, these will be restated briefly to aid those unfamiliar with the instrument in interpreting the measurements.

The refractometer

Several jeweler's refractometers are commercially available with which refractive index (n) is determined to ±0.002 on the principle of total reflection and the critical angle. Central to them all is a polished, high refractive index ($n \approx 1.90$) glass prism, hemisphere or hemicylinder. The instrument in most common use in the United States is the Duplex II, manufactured by Gem Instruments, Santa Monica, California, which employs a hemicylinder. A schematic, longitudinal section through the instrument is shown in Figure 1. The polished surface of the mineral under study (here referred to as plane P) is placed on the flat polished surface of the hemicylinder but separated from it by a film of liquid. The liquid is to ensure optical contact and must have a refractive index higher than that of the mineral. The index of the contact liquid supplied with the refractometer is about 1.81. Since the liquid must have a higher index than that of the mineral, the maximum measurable refractive index is about 1.80. The index liquids with $n > 1.78$, commonly present in mineralogical laboratories, should not be used; they are corrosive and etch the lead-glass hemicylinder.

Light enters through a ground glass at the back of the instrument and passes through the hemicylinder, striking the mineral at varying angles of incidence. When the light rays are at angles less than the critical angle (C.A.), they pass upward through the mineral, but when greater than the critical angle, they are totally reflected back through the hemicylinder to fall on a transparent scale. The image of the scale is reflected by a mirror and is observed through a lens system. The position on the scale of the boundary separating light from dark positions, called the shadow edge, indicates the mineral's refractive index (Fig. 2). When using white light, the shadow edge is a narrow band of spectral colors caused by dispersion of both hemicylinder and mineral. Thus, for precise readings, monochromatic light should be used.

For isotropic substances the single refractive index can be read directly from the scale as shown for spinel in Figure 2, where $n = 1.720$. The faint shadow edge in the figure at 1.81 indicates the refractive index of the contact
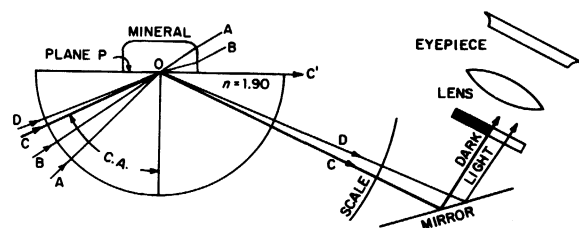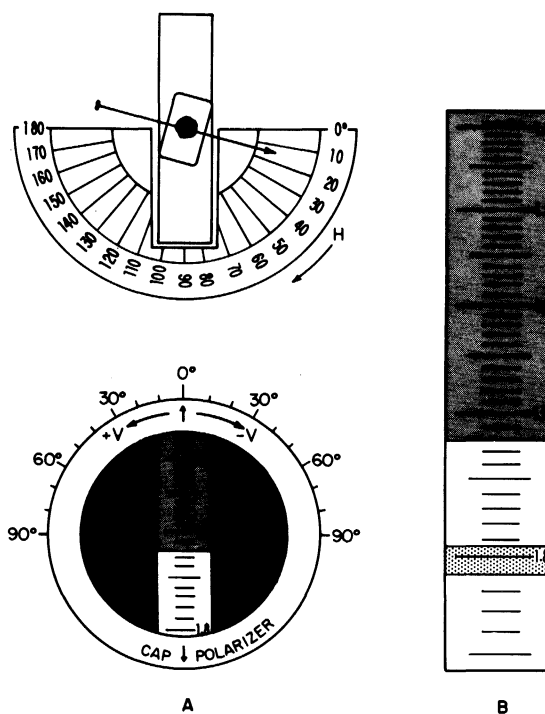

Fig. 2. (A) Top view of refractometer hemicylinder and scale image as seen through eyepiece. Angles H, rotation of mineral on hemicylinder, and V, rotation of cap polarizer, are shown. Arrows on polarizer indicate transmission direction. Angles H and V are used in determining indices of anisotropic crystals. In the illustration H = 15°, V = 0°. (B) Enlarged scale with reading for spinel, 1.720. The shadow edge at 1.810 indicates the index of the contact liquid.

liquid. The determination of the refractive indices of anisotropic crystals is not as simple as for isotropic but can be easily accomplished as explained below.

Anisotropic crystals

In working with anisotropic crystals, keep in mind that light traveling through them in any direction, except along an optic axis, is broken into two rays vibrating at right angles to each other and to the direction of propagation. Light moves through the refractometer from left to right (Fig. 1), parallel to the long dimension of the instrument. At the critical angle, it is moving through the crystal in direction OC' (Fig. 1). and, in general, is vibrating as two mutually perpendicular rays at right angles to OC'. Because these polarized rays have different refractive indices, their total reflection gives rise to two shadow edges on the scale. *When the scale is viewed through a polarizing filter placed over the eyepiece, one edge disappears as the polarizer is turned; a 90° rotation of the polarizer will eliminate the other edge* (see Fig. 5). The elimination of one edge tends to sharpen the reading of the other, and for this purpose the refractometer is supplied with a

Fig. 1. Longitudinal section through jeweler's refractometer showing light reflected at the critical angle (C.A.) for spinel.

rotatable cap polarizer. If the transmission direction of the cap polarizer is known, it is possible to determine the vibration direction of each ray and its orientation with respect to the contact plane, P. The ability to do this makes possible the determination of all refractive indices of anisotropic crystals.

For any anisotropic crystal, except for special orientations that will be noted, one or both of the observed refractive index readings change as the crystal is rotated on the surface of the hemicylinder of the refractometer. The difference between the greatest reading of the higher index and the least reading of the lower index in all cases is the birefringence. This information suffices for identification of some minerals. However, to determine whether a crystal is uniaxial or biaxial and its optic sign, it is necessary in many instances to know the angle the vibration direction of the observed refractive index makes with plane P. For simplicity in the following discussion, this vertical angle will be designated as angle V, and the horizontal angle through which a crystal has been rotated on plane P will be designated as angle H (Fig. 2A).

Angle V can be measured using a polarizing cap on which the transmission direction is indicated. When a vibration direction is perpendicular to plane P, $V = 0°$; when it is parallel to P, $V = 90°$ (see Fig. 5). Rotation of the polarizer to determine intermediate vibration directions is $(-)$ if clockwise, $(+)$ if counterclockwise. An adequate interpretation can be made knowing that V is 0°, 90°, or merely has some intermediate value. Only for a complete optical orientation of a biaxial crystal must the values of both V and H be determined to within a few degrees.

Since we are concerned with determining refractive indices in vibration directions, an indicatrix offers an ideal model to help visualize the results obtained with
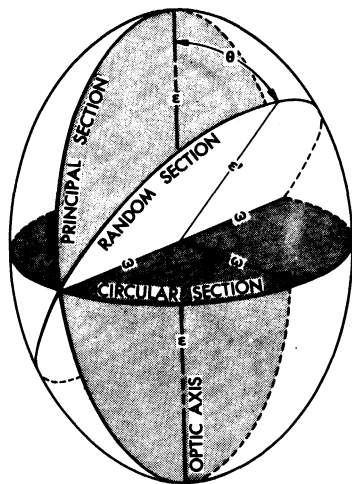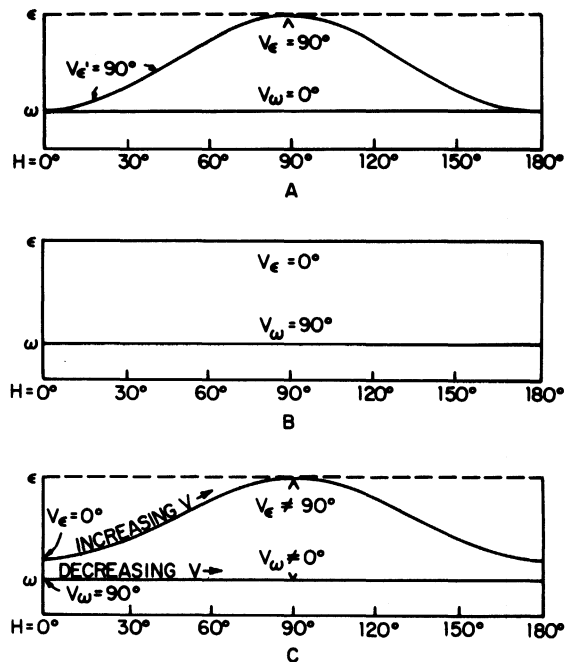

Fig. 4. Variations of refractive index readings of a positive uniaxial crystal as it is rotated on the surface of the refractometer hemicylinder. (A) Optic axis lies in plane P. (B) Optic axis is perpendicular to plane P. (C) Random orientation of plane P.

different orientations of plane P. Indicatrices, both uniaxial (Fig. 3) and biaxial (Fig. 7), are figures constructed by plotting the refractive indices in the directions of their vibrations. In each of the several orientations that will be discussed, one should picture plane P as passing through the center of the indicatrix. Most readers will be familiar with indicatrices which are used to aid interpretation of observations made with the polarizing microscope. Those unfamiliar with them are referred to Bloss (1961, p. 70, 152).

Uniaxial crystals

Light moving through uniaxial crystals is broken into the ordinary (O) ray vibrating at right angles to the optic axis, the c crystal axis, and the extraordinary (E) ray vibrating in the principal section, that is, a section containing the optic axis. The index of the O ray, ω, is constant; the index of the E ray, ϵ', varies with orientation and is designated as a principal index, ϵ, only when vibrating parallel to the optic axis. When $\omega < \epsilon$, the crystal is $(+)$, as in Figures 3 and 4; when $\omega > \epsilon$, the crystal is $(-)$.

For uniaxial crystals there are three possible conditions for the orientation of plane P with respect to the indicatrix (Fig. 3). (1) The optic axis lies in plane P. (2) The optic axis is perpendicular to plane P. (3) A random orientation, i.e., any orientation other than 1 or 2.

1. The optic axis lies in plane P (Fig. 4A). When the

Fig. 3. Uniaxial indicatrix of a positive crystal. After Bloss (1961, p. 76).

optic axis is parallel to the long dimension of the refrac-
tometer (H = 0°, Fig. 4A), there is a single index reading,
ω. As the crystal is turned, ω remains constant but a
second reading ϵ', appears. The difference between the
two indices reaches a maximum after a rotation of 90°. In
this position ϵ is measured vibrating parallel to the optic
axis. Figure 4A illustrates the variation of the refractive
index of quartz with plane P a prism face. With $\omega < \epsilon$, the
crystal is optically positive.

2. The optic axis is perpendicular to plane P (Fig. 4B).
In this special orientation there are two constant readings
for all values of H. The vibration direction of ϵ is vertical
with V = 0°; the vibration direction of ω is horizontal with
V = 90°. One can, therefore, tell which index is greater
and thus the optic sign. Figure 5 shows the refractometer
readings for a negative crystal, tourmaline, when the
optic axis is perpendicular to plane P.

3. Random orientation of plane P (Fig. 4C). As the
crystal is turned on the refractometer, one index, ω,
remains constant; the other, ϵ', varies in a range either
higher or lower, but in no position does it equal ω. Note,
however, that this situation, with one variable and one
constant index, may also obtain in a biaxial crystal (see
below). A distinction can be made by determining the V
angle of the constant index at any H position. If V = 0°,
the crystal is biaxial. If V has any other value, the crystal
is uniaxial and the highest (or lowest) value of the variable
index is ϵ.

The cleavage planes of calcite have a random orienta-
tion with respect to the indicatrix. It is thus nearly
impossible to measure ϵ using the immersion method,
because 99+% of the mineral grains lie on a cleavage
surface. But if a smooth cleavage plane is placed on the
hemicylinder of the refractometer, values of both ω and ϵ
can be obtained in a few seconds. Figure 6 illustrates the
orientation of a cleavage rhobohedron of calcite in which
both indices can be measured simultaneously. $V\omega \approx$
$-45°$; $V\epsilon \approx +45°$.

Biaxial crystals

The relation of the three refractive indices of biaxial
crystals and their vibration directions can be best visual-
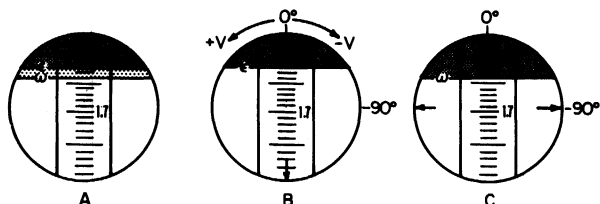ized by reference to the biaxial indicatrix, Figure 7. This

Fig. 6. Calcite rhombohedron in position to give readings of ω
and ϵ.

is a triaxial ellipsoid so constructed that the three mutual-
ly perpendicular semiaxes coincide with the vibration
directions of the principal refractive indices and have
lengths proportional to these indices. The principal indi-
ces, α, β, and γ, are represented in Figure 7 respectively
by OX, OY, and OZ. Index α is the least, γ the greatest,
and β intermediate. The birefringence is $\gamma - \alpha$. A crystal
is (+) if β is closer to α than to γ, and (−) if β is closer to γ
than to α. If β lies midway between α and γ, the optic sign
is indeterminate.

For any orientation of a single polished surface P on a
biaxial crystal, the three indices can be obtained. Indices
α and γ, and for some orientations β, can be determined
without noting angle V. For other orientations it is
necessary to determine V to identify β.

In general there are two readings observed for a biaxial
crystal, both of which vary as the crystal is rotated on
plane P. Two variable readings indicate the crystal is
biaxial, not uniaxial. But there are three special orienta-
tions in which one reading remains constant. These are
when one of the principal optical directions, X, Y, or Z, is
perpendicular to plane P.

Fig. 5. Refractive indices of tourmaline as observed with the
optic axis perpendicular to plane P. (A) Readings of ω and ϵ. (B)
Reading for ϵ only with polarizing cap at V = 0°. (C) Reading for
ω only with polarizing cap at V = 90°. Arrows indicate
transmission direction.

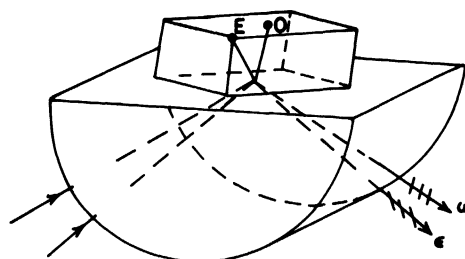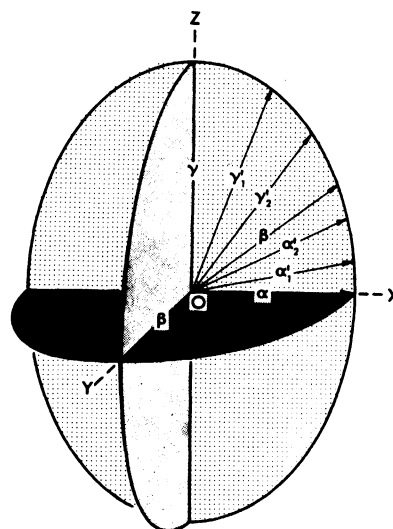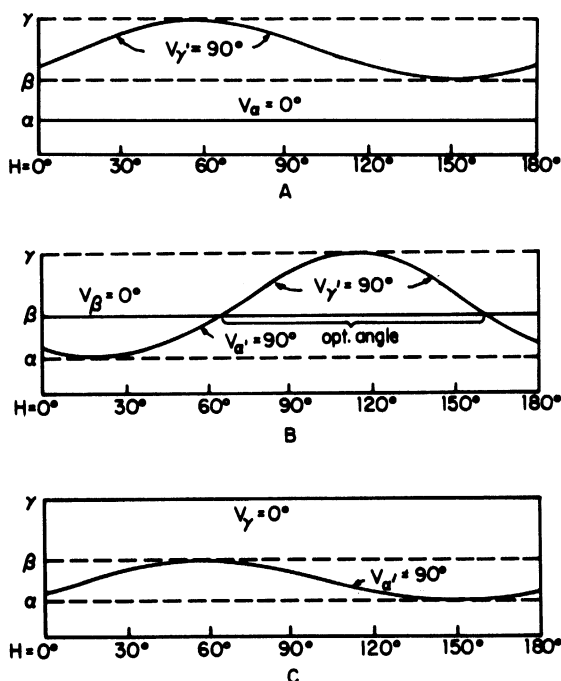Fig. 7. Biaxial indicatrix. After Bloss (1961, p. 152).

Fig. 8. Variations of refractive index readings of a positive biaxial crystal with special orientations of plane P. (A) X perpendicular to P. (B) Y perpendicular to P. (C) Z perpendicular to P.

1. X is perpendicular to P, the YZ plane. In this case α, vibrating in the X direction is constant (Fig. 8A). The variable reading will always be greater than α and range from β, the least, to γ, the greatest. One constant and one variable reading also result from a uniaxial crystal when P is a random plane. That the crystal is biaxial can be determined by noting angle V of the constant index. If V = 0°, the crystal is biaxial.

In the micas X is perpendicular or nearly perpendicular to the excellent cleavage. Thus, using the cleavage surface as plane P, α (V $\approx$ 0°) can be readily obtained (Fig. 9). Such a determination is nearly impossible with the immersion method using random grain mounts.
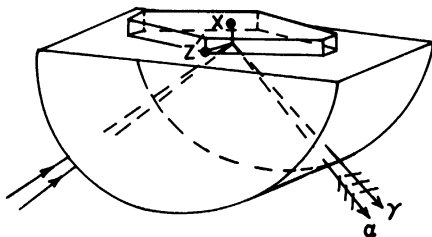
2. Y is perpendicular to P, the XZ plane. In this

Fig. 9. Mica cleavage on refractometer in position to give α and γ readings.

orientation β, vibrating in the Y direction, is constant and V = 0° (Fig. 8B). The lowest reading of the variable index is α and the highest reading is γ. On rotating through an angle of 180° on plane P, there are two positions at which the variable index will equal β and only one reading is observed. These are when light moves parallel to the optic axes and vibrates in the circular sections. The difference between the H readings at these two positions is equal to the optic angle.

3. Z is perpendicular to P, the XY plane. With this orientation, the reading for γ, vibrating in the Z direction, is constant (Fig. 8C). On rotating the crystal, the variable reading will range from α, the least, to β, the greatest. The same ambiguity exists as when X is perpendicular to P. That is, is the crystal uniaxial or biaxial? If for the constant reading V = 0°, the crystal is biaxial. For a uniaxial crystal, V of the constant reading would have some other value.

McKague (1971) illustrates several partially random orientations for biaxial crystals but does not interpret them to obtain β and the optic sign. When these orientations are considered as sections through the indicatrix, it is possible to arrive at unambiguous solutions without determining V angles. However, they will not be considered individually here, for they can be resolved in the same manner as the general case, that is, as completely random orientations of plane P, described next.

When P is a random section, two variable readings will be observed in the refractometer (Fig. 10); β is either the lowest reading of the higher index or the highest reading of the lower index. After obtaining values for α and γ, the shadow edges are observed as the crystal is rotated. If the higher reading decreases to a value less than the midpoint between α and γ, β is obviously closer to α than to γ and the crystal is positive (Fig. 10). (Similarly, if the lower reading passes the midpoint, the crystal is negative.) *The passing of the midpoint between α and γ by the curve indicating the higher index (Fig. 10) indicates only that the crystals is positive; it does not necessarily mean that the curve minimum is β.* The maximum of the lower curve could be β. The method of determining which reading is β is given in the following paragraph.

With P a random plane, a second situation may exist in which neither shadow edge passes the midpoint between α and γ as the crystal is rotated on the hemicylinder. Is β the lowest reading of the higher index or the highest
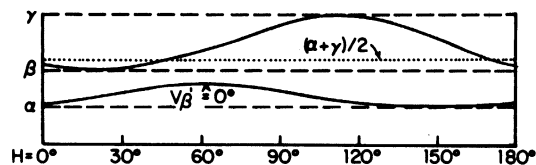

Fig. 10. Variation of refractometer readings with P a random section of a biaxial crystal. Since the minimum reading of the higher index is less than $(\alpha + \gamma)/2$, the crystal is positive.
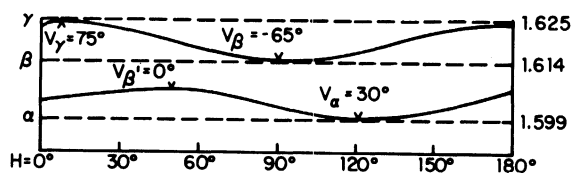
Fig. 11. Variation of the observed refractive indices of tremolite as it is rotated on the refractometer. Plane P is (110), a random section; the c axis is taken as H = 0°, V angles are noted at significant H positions.

reading of the lower index? There is a simple solution to the problem. The V angles of the two possible β readings are determined. For one reading, V = 0°; for the other, V $\neq$ 0°. The index measured at V = 0°, called β', is ignored, and the index measured at the other position is β, as shown in Figure 11.

Checking the validity of the method of obtaining β with P a random plane is an interesting and instructive exercise. It involves determining two angular coordinates, H and V, for both α and γ, respectively the X and Z directions of the indicatrix, and projecting them stereographically. H is the horizontal angle through which the crystal is rotated on the hemicylinder in a clockwise direction from a zero position. V is the angle of a vibration direction from the vertical: (−) clockwise, (+) counterclockwise (see Fig. 2A).[1]

The normal procedure, as has been described, of obtaining refractive indices with the refractometer is to rotate the crystal on the hemicylinder until the highest and lowest index readings are observed and noting the V angles at these positions. It is generally not necessary to measure V precisely but to note only that it is 0°, 90°, or an intermediate value. Except for special reasons (see Fig. 8B), it is unnecessary to determine angle H. However, for a complete optical orientation of the crystal, the angular coordinates, V and H, must be determined to within a few degrees.

The vibration directions of the observed indices, the V angles, can be obtained by rotating the cap polarizer. Angle H is less easily determined but can be measured in the following way. Radial lines about 0.75 in. long are scored on a plastic sheet (0.005–0.007 in. thick) at 10° intervals. The plastic sheet is then cut to fit around the polished surface of the hemicylinder which is 1 in × 0.25 in. and extends about 0.010 in. above the top plate of the refractometer. The plastic sheet is then cemented to the top plate with the 0° mark at the right, as shown in Figure

2A. A bit of wax is stuck on the mineral opposite the polished surface and a pin pressed into the wax to lie parallel to plane P. In its initial setting, the mineral is placed on the hemicylinder with the point of the pin above the 0° mark on the scale. As the crystal is rotated, H angles are determined by the position of the pin point.

The method of obtaining the angular coordinates of the X and Z directions is illustrated using tremolite as an example with plane P a {110} cleavage surface. The c axis, the intersection of the {110} cleavages, is taken as H = 0°; that is, the pointer pin would be parallel to c, the length of the cleavage fragment. Thus in the zero position, the c axis is at right angles to the long dimension of the hemicylinder. The observations on tremolite are shown in Figure 11.

The highest index, γ (1.625), is observed at H = 7°. At this position, V = 75° (Fig. 12A). The lowest index, α (1.599), is reached at H = 120°; here V = 30° (Fig. 12C). These two sets of angular coordinates—H = 7°, V = 75°, and H = 120°, V = 30°—determine respectively the Z and X directions and can be plotted stereographically. Since the X, Y, and Z directions are mutually perpendicular, great circles drawn on the stereographic projection at 90° to X and Z will intersect at Y (Fig. 13). From the position of this point, the H and V angles for the vibration direction of β can be obtained. For tremolite the coordinates of Y are H = 90°, V = −65°. With the crystal turned to H = 90°, one will find the lowest value of the higher reading with V = −65°, as shown in Figures 11 and 12B. This is the β index (1.614). The highest value of the lower reading, β' (n = 1.606), has coordinates of H = 50°, V = 0°, which in no way correspond to the projected direction of Y.

The stereogram (with (110) polar) of the H and V angles is constructed on tracing paper overlying a stereographic net. In its initial position, a zero mark on the tracing is placed over H = 0° of the net. To locate Z, the tracing is rotated to bring its zero mark to H = 7° and V plotted at +75° along the horizontal diameter. For X, zero of the tracing is rotated to H = 120° and V plotted at +30° along the horizontal diameter. Figure 13 illustrates the completed stereogram rotated to the initial zero position.

Determination of refractive index of minerals in thin sections

A technique for the determination of the refractive indices of minerals in thin sections (without coverslips) using dispersion staining and oil immersion was developed by Laskowski and others (1979). The accuracy obtained is impressive: refractive indices to ±0.001. However, the method is involved, requiring special microscope accessories. Also, before measurements can be made, a thin cut must be made through a properly oriented grain of the thin section to the glass below and the correct immersion liquid selected by trial and error.

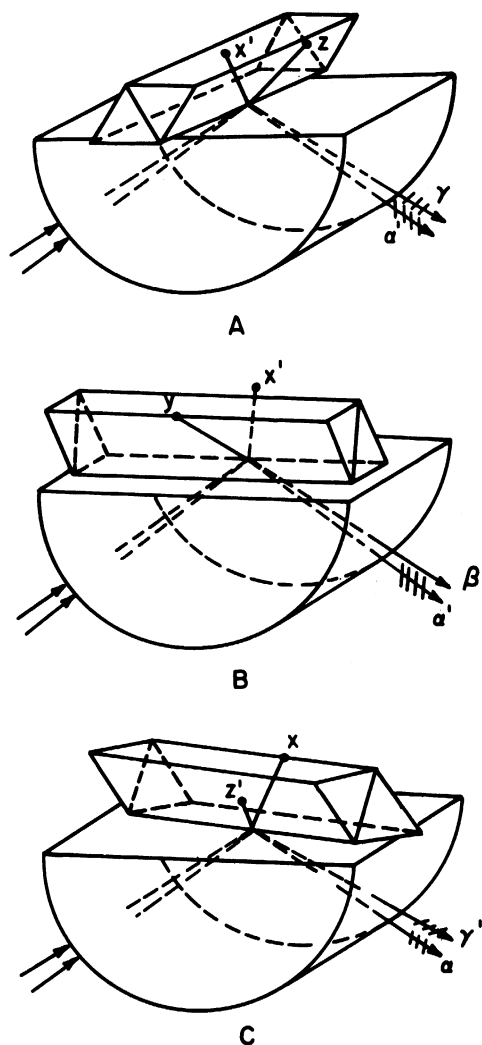Although slightly less accurate, the jeweler's refrac-

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[1] If observed directly, a clockwise rotation of the polarizer gives a (+) V reading. However, because one observes the refractometer scale as a reflected image, it is the mirror image of the vibration that is measured by angle V. Thus a counterclockwise rotation of the polarizer is recorded as (+) V and a clockwise rotation as (−) V.

A

B

Fig. 13. Stereographic projection of the principal optical directions of tremolite. X and Z are projected from H and V readings obtained with the refractometer. Y is located by the intersection of great circles drawn through X and Z. H is the observed horizontal angle. V is the observed vertical angle with $+V$ to the right and $-V$ to the left.

C

Fig. 12. Tremolite on refractometer at positions to give readings of the three refractive indices. (A) Reading for γ. (B) Reading for β. (C) Reading for α. The trace of the symmetry plane (010), is given to help visualize the optical orientation. Rays incident to the cleavage fragment are shown striking edges rather than face centers so that the orientation of the vibration directions can be better illustrated.

viewing the section using a low-power objective, the grain is outlined with an opaque, water-soluble ink, and the surrounding grains for a radius of 5 mm are coated with the ink. When the ink is dry, the section is placed, polished side down, on the hemicylinder with the grain at its center. Any immersion liquid with n greater than that of the mineral may be used as contact liquid between section and hemicylinder. Refractive index measurements of all indices can then be made in the manner described on the previous pages.

I have determined refractive indices of mineral grains in only a few (20) polished thin sections, but the results have been most satisfying. In only eleven cases was it possible to check the refractive indices by the immersion

tometer offers a simpler and less time-consuming method of making refractive index measurements on minerals in thin sections. However, one must work with a *polished* thin section; but today, with the preparation of sections for the electron microprobe, making of polished thin sections has become routine.

The grain of the mineral for study is selected using the petrographic microscope, the larger the grain the better, but it must present a minimum area of about 1 mm². Any grain of the mineral is acceptable, for its optical orientation with respect to the slide is unimportant. While
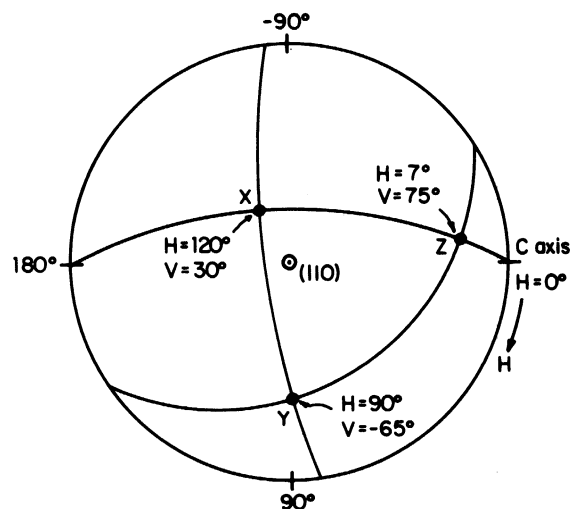
Table 1. Summary of refractometer observations which identify the refractive indices and distinguish uniaxial from biaxial crystals.

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Uniaxial:  ε > ω (+);  ε < ω (-).
   Two constant readings.  Vε = 0°; Vω = 90°.
   One constant reading (ω) with V ≠ 0°.
      ε is maximum (or minimum) of variable reading.

Biaxial:  (γ-β) > (β-α) (+);  (γ-β) < (β-α) (-).
   One constant reading with V = 0° (indicates biaxial).
      α constant.  Variable reading maximum, γ; minimum β.
      β constant.  Variable reading maximum, γ; minimum α.
      γ constant.  Variable reading maximum, β; minimum α.
   Two variable readings (indicate biaxial).
      α is minimum of lower reading.
      γ is maximum of higher reading.
         The maximum of the lower reading or the minimum of
         the higher reading is β.  V is determined for both
         possibilities.  For one, V = 0° and is ignored.
      β is the reading where V ≠ 0°.
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method, but in all they agreed to within ±0.003. In two instances the refractometer-determined indices were made on the same grains on which electron microprobe analyses had been made by Dr. David Walker of Harvard University. One was of anorthite, which by microprobe analysis gave 95.4% An. The refractive indices $\alpha = 1.576$, $\beta = 1.583$, $\gamma = 1.588$, indicated, according to the chart of Chayes (1952), 96% An. The other was an olivine for which the microprobe analysis gave 14.6% Fa. The refractive indices $\alpha = 1.661$, $\beta = 1.1680$, $\gamma = 1.700$, indicated, according to the chart of Bowen and Schairer (1935), 15% Fa. These examples suggest that for some purposes a simple $300 instrument may be as effective in yielding certain information as an elaborate $300,000 apparatus.

Determination of refractive indices of immersion liquids

The refractive indices of immersion liquids are subject to change with time and should be checked periodically. The jeweler's refractometer offers a quick and easy method of doing this. A drop of liquid on the hemicylinder, with or without an overlying mineral, will give its own shadow edge and thus a reading of its refractive index (see Fig. 2B). The highest reading obtainable on most Abbé refractometers, designed for the determination of the refractive indices of liquids, is 1.70. Using the jeweler's refractometer, the range is extended to 1.80. However, with a jeweler's refractomer employing a hemicylinder of chemically inert cubic zirconia, $n = 2.16$ (Hurlbut, 1981), the refractive indices of corrosive liquids in the range 1.80–2.10 can be measured. This refractometer also permits determination of the refractive index of minerals as high as 2.08. Unfortunately, at present the instrument is not commercially available.

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