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OPTIC ANGLE DETERMINED CONOSCOPICALLY ON THE SPINDLE STAGE: I. MICROMETER OCULAR METHOD[1]

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ABSTRACT

Optic angle may be determined if one or both melatopes of the optic axes pass through some part of the conoscopic field during rotation of the crystal fragment about the spindle axis. With the spindle pointed north, the orientation of each optic axis is established by the amount of rotation about the spindle axis required to place the melatope on the N-S crosshair and by the angular distance of the melatope north or south of the microscope axis as determined by a general extension of Mallard's method, using a calibrated ocular micrometer. After plotting the two optic axes, the value of $2V$ may be read off the stereogram. Should only one optic axis pass through the conoscopic field, a somewhat less precise value of optic angle may be obtained by doubling the angle V, measured between the plotted positions of the optic axis and one of the bisectrices.

The optic angle, determined independently of the principal refractive indices, is a useful characteristic of a mineral for identification or, in some isomorphous series, for inferring chemical composition. Whereas the three principal indices may be determined for the same fragment on the spindle stage (Rosenfeld, 1950; Wilcox, 1959), the value of optic angle calculated from these indices, as routinely determined, for example, to ± 0.001, is frequently not precise—usually not better than about $\pm 5°$ for minerals of moderate birefringence such as the clinopyroxenes, or $\pm 10°$ for minerals of low birefringence such as the feldspars. Several orthoscopic methods for determination of optic angle have already been proposed (Wilcox, 1960; Tocher, 1962, 1964a and 1964b; Joel, 1963, 1964, 1965; Garaycochea and Wittke, 1964). The conoscopic method outlined by us here and by Noble in Part II, in addition to one previously proposed by Noble (1965), are relatively rapid with precision adequate for routine work, at the same time providing additional useful optical information.

BASIS OF METHOD

For a large number of crystal fragments mounted at random on spindle, rotation under conoscopic illumination will bring one or both of the melatopes of the optic axes across the conoscopic field. Most other mounted fragments can, with a little practice, be nudged into such a desired approximate orientation on the spindle tip. The positions of each optic axis may then be determined accurately with respect to the spindle and microscope axes and plotted stereographically, whereupon the angle between them, $2V$, may be read from the stereogram. Procedures de-

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scribed here are based on the conoscopic techniques and mechanical design of the spindle stage of Wilcox (1959) but are adaptable to other one-axis rotating devices that provide for conoscopic illumination and for reading rotations about the spindle axis (*cf.* Fisher, 1962; Jones, 1962; Hartshorne, 1963).

Essential to the measurements of the position of the optic axis in these procedures is the accurate location of the melatope, which represents the pierce point of the optic axis in the conoscopic field and which is ordinarily to be found along the narrowest and darkest portion of the isogyre. To locate it precisely the polars rather than the microscope stage are rotated, whereupon the isogyre pivots about the melatope, marking its position. It is, of course, essential to return both polars to their cardinal positions before proceeding to conventional measurements.

As the crystal is rotated about the spindle axis, the optic axis A sweeps out a portion of a cone, represented by the small circle TAU of the stereogram of Figure 1. Its angle with the microscope axis (ψ) becomes minimum ($\psi_{\min}$) when the optic axis lies in the plane of the spindle axis P and microscope axis M, that is, at point A' of the stereogram. In the conoscopic field the linear distance d from the crosshair intersection to the melatope is related to the angle ψ by Mallard's equation $d = K\beta \sin \psi$ where d is the distance from the center of the field in divisions of the micrometer ocular, β is the intermediate principal index, and K is Mallard's proportionality constant determined for the particular lens system and micrometer ocular (Johannsen, 1918, p. 468).

The value of $\psi_{\min}$ may be found from the convenient alignment chart of Winchell (1946), or from a separate chart of ψ *vs* d constructed for several values of β (*cf.* Johannsen, 1918, Fig. 676). Stereographic plotting of the optic axis uses the value of $\psi_{\min}$ so determined, together with the reading of the spindle arm when the optic axis is in the plane of the spindle axis and microscope axis.

Procedure when both optic axes are accessible

Step 1. Make sure the microscope lens system, including the Bertrand lens, is centered.

Step 2. Determine and record the *Reference Azimuth*—that is, the reading of the microscope stage when the spindle axis is exactly N-S with the spindle tip pointing S.[1]

Step 3. Set the microscope stage exactly 180° from the Reference Azimuth.

Step 4. With the crystal fragment immersed in a liquid of similar refractive index (say ± 0.02) and under conoscopic illumination, rotate about the spindle axis until the narrowest and densest part of the isogyre (such as that of Fig. 2a lies approximately on the N-S crosshair.

Step 5. Rotate *both* polars the same amount to swing that portion of the isogyre which is near the melatope into parallelism with the N-S crosshair. Then refine the setting of the

[1] In this paper N will designate away from the operator, S towards, E to the right, and W to the left. "Horizontal" means parallel to the microscope stage.

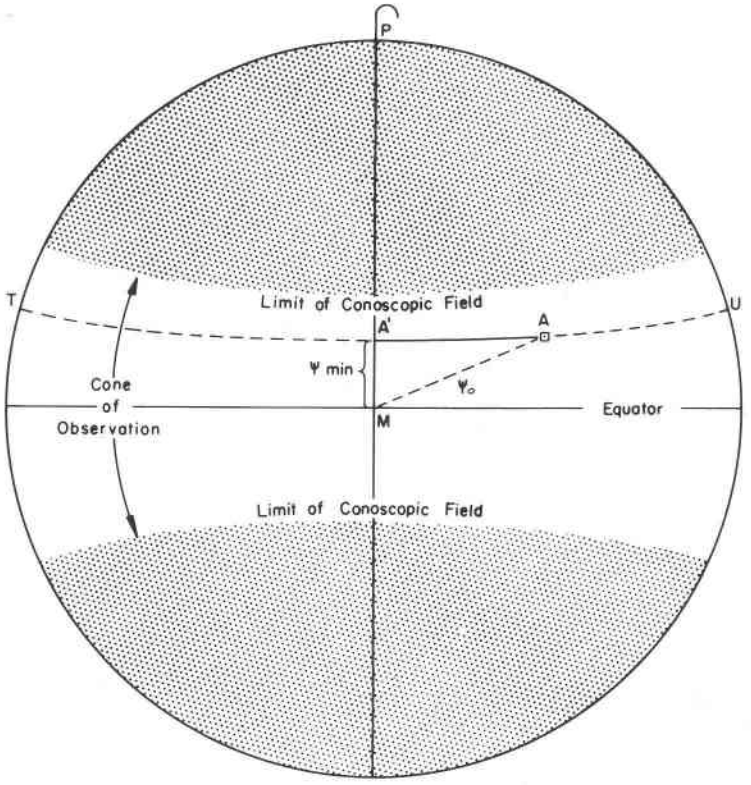

FIG. 1. Stereogram (plotted on equal-area net) showing position of optic axis A when spindle arm is at 0°, with ψ_0 the angle of optic axis with microscope axis M. Small circle TAU represents locus of optic axis during rotation about P, the spindle axis. ψ_{min} represents the angle between microscope axis and optic axis when latter is at A' in the plane defined by the microscope axis and spindle axis.

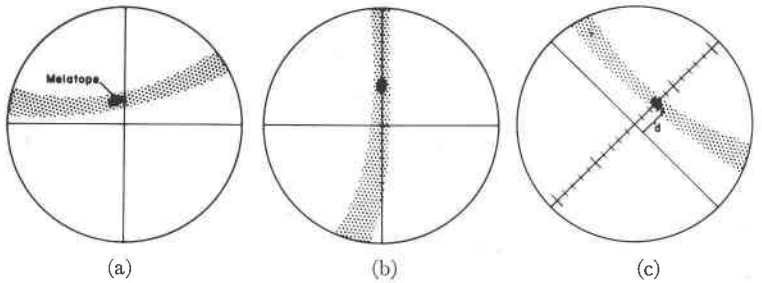

FIG. 2. Placement of melatope on N-S crosshair: (a) Preliminary approximate setting. (b) Final placement after appropriate rotation of both polars to make isogyre parallel to N-S crosshair. (c) Determination of distance d in divisions of micrometer after rotation to 45° position on microscope stage.

spindle arm so that this portion of the isogyre lies exactly on the N-S crosshair (such as Fig. 2b). Record the reading of the spindle arm for this optic axis OA_1 and record whether the melatope lies north or south of the crosshair.[1]

Step 6. Rotate on the microscope stage to the 45° position (as in Fig. 2c) and measure d, the distance in scale divisions from the crosshair intersection to the center of the melatope. It is good practice to repeat the determination with the microscope stage 180° from the first position (also for spindle rotations in the opposite hemisphere, if permitted by the construction of the spindle stage) and then use the average of the values of d. Convert this distance d to $\psi_{\min}$ by use of the alignment chart (Winchell, 1946) or the chart constructed for the microscope.

Step 7. Plot OA_1 on an overlay on a stereographic (Wulff) net or equal area (Schmidt) net: To plot on the upper hemisphere, as illustrated by Figure 3 and Table 1, start at the net center, count off the angle $\psi_{\min}$ northward or southward, as was noted in Step 5. (This direction is to be used literally, because the inversion of the image by the Bertrand lens has been canceled in Step 3 by setting the microscope stage at 180° from the Reference Azimuth.) Thence count eastward along the small circle an angle equal to the spindle arm reading of Step 5, plot and label the optic axis. Should the spindle arm reading be greater than 90° one will run off the eastern edge of the net, whereupon resume the count at a point *diametrically* opposite on the primitive circle, as in Figure 4. (In effect we are picking up the count for the other end of the optic axis.)

Step 8. Return the microscope stage to its original setting 180° from the Reference Azimuth and repeat Steps 3 through 7 for the second optic axis OA_2. Finally, return both polars to their cardinal positions, and determine optic sign by use of a retardation plate.

Step 9. Rotate the overlay to place both optic axes on the same great circle of the net and read off the optic angle $2V$ as the angular distance between OA_1 and OA_2.

As an example the data for a fragment of ferroaugite is presented in Table 1 and plotted in Figure 3 to give an optic angle $(+)\ 2V_z = 55°$.

Procedure when only one optic axis is accessible

In this case the orientation of the one optic axis is determined and plotted as before, Steps 1–7, then the following steps are carried out:

Step 8a. With the polars in their cardinal positions rotate spindle and microscope stage to place an isogyre symmetrically along the crosshair parallel to the analyzer vibration direction. Therewith an optic symmetry axis lies horizontal, and in the plane of the polarizer (Wilcox, 1959). Identify as X, Y, or Z and record readings of microscope stage and spindle arm. Similarly orient and identify the other two symmetry axes.

Step 9a. As illustrated by Figure 4 and Table 2, plot the symmetry axes on the stereogram: Subtract the Reference Azimuth from the microscope stage reading, start at the

[1] Polars may be rotated simultaneously or one at a time. Greater convenience and saving of time are offered by microscopes providing synchronous rotation of polars. For those microscopes in which both polars cannot be rotated, D. C. Noble suggests the following substitute for Step 5: After setting the melatope approximately on the N-S crosshair, read the isogyre intercept on the scale of a keyed crossline micrometer ocular. Rotate both the microscope stage and crossline ocular exactly 45° and again read the intercept. If not the same as before, rotate about the spindle axis to place the isogyre about midway between the two readings. Return the microscope stage and ocular to original positions and check the intercept. Continue to readjust the isogyre in this manner at alternating positions until the intercept remains the same for both, whereupon the melatope is known to lie on the crosshair. Yet another means for setting the melatope is offered by the "Benford plate" (Craig, 1961), provided its retardation equals that of the accessory plate with which it is used.

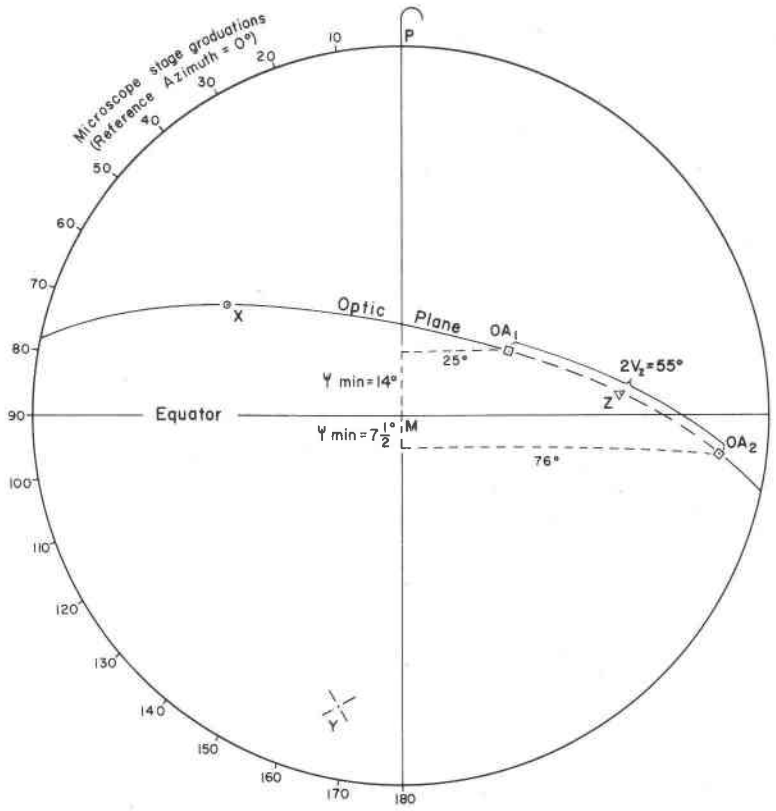

FIG. 3. Stereogram (on equal-area net) of ferroaugite of Table 1, in which both optic axes pass through conoscopic field. Spindle axis P at Reference Azimuth=0°.

north point of the overlay, count off the remainder counterclockwise about the primitive circle of the net, and then count inward along the small circle an angle equal to the reading of the spindle arm and plot the symmetry axis at this point and label.

TABLE 1. SPINDLE STAGE DATA FOR OPTIC ANGLE DETERMINATION OF A FERROAUGITE FRAGMENT, BOTH OPTIC AXES ACCESSIBLE (FIG. 3)

REF. AZIMUTH=*0°* $\beta=1.71$ MALLARD'S CONSTANT $K=18.0$

	Microscope stage reading	Spindle arm reading	d ocular microm. divs.	ψ_{min}
OA_1	180°	25°	7 1/2 N	14° N
OA_2	180°	76°	4 S	7 1/2° S

OPTIC ANGLE $2V_z=55°\pm1°$.

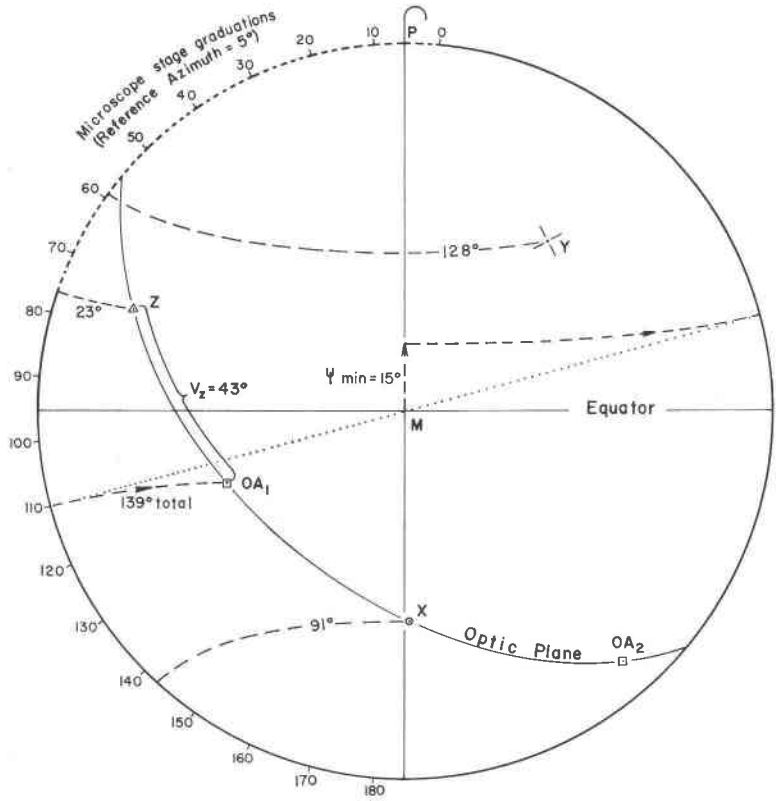

FIG. 4. Stereogram (on equal-area net) of cummingtonite of Table 2, in which only one optic axis passes through conoscopic field. Spindle axis P at Reference Azimuth = 5°.

TABLE 2. SPINDLE STAGE DATA FOR OPTIC ANGLE DETERMINATION OF A CUMMINGTONITE FRAGMENT, ONLY ONE OPTIC AXIS ACCESSIBLE (FIG. 4)

Ref. Azimuth = 5° $\beta = 1.648$ Mallard's Constant $K = 29.0$

	Microscope stage		Spindle arm reading	d ocular microm. divs.	ψ_{min}
	(reading)	Corr'd for REF. AZ.			
OA_1	(185°)	180°	139°	12 1/2 N	15° N
X	(143°)	138°	91°		
Y	(59°)	54°	128°		
Z	(76°)	71°	23°		

$2V_z = 86° \pm 3°$.

Step 10a. Rotate the overlay to place the optic plane on a great circle and read off the angle V between optic axis and bisectrix. Doubling this gives the value of $2V$, the optic angle.

Discussion

The conoscopic method described here is the result of a search for a more rapid and direct method than the orthoscopic (extinction curve) methods currently available. While not capable of the accuracy reported for some orthoscopic methods (Tocher, 1962, for instance estimates a possible accuracy of $\pm 0.25°$), the conoscopic method suffices well for routine work. We would estimate the precision of the present method, using two well-defined melatopes, to approach $\pm 1°$, provided the microscope is properly adjusted, Mallard's constant accurately established, and the spindle scale and plotting net accurately graduated. Time required for determination of $2V$ by an experienced operator may vary from 15 to 30 minutes depending largely on the number of readjustments of the mount to bring the two optic axes within range of the conoscopic field. The time required to establish the positions of the melatopes is considerably reduced using synchronous polars.

After several years test and practical use of the conoscopic method, the present writers do not share the doubts expressed by some (see for instance Wright, 1966) concerning the reliability of conoscopic measurements with the ocular micrometer. Certainly the micrometer must be properly calibrated, preferably under conditions similar to the application, and a check made to establish that Mallard's constant does not vary significantly for different parts of the field. And certainly crystals showing broad diffuse isogyres in the vicinity of the melatope are less favorable for measurement because of difficulties in choosing the exact location of the melatope. Likewise the melatope cannot be located reliably in an isogyre so close to the edge of the field that no illuminated area is visible beyond.

When only one optic axis is accessible the precision of the optic angle value is probably not better than $\pm 2°$ or $3°$, because uncertainties already accrued in establishing the orientation of the bisectrix are doubled in obtaining the final value of optic angle. It is good practice here to determine the positions of both X and Z and to determine V from the one which appears most reliable. When this degree of inaccuracy cannot be accepted, it may be expedient to change the fragment's position on the spindle so that both optic axes are accessible. With a water-sensitive mounting adhesive (Wilcox, 1959, p. 1276), the practiced operator may accomplish the desired change without remounting by (1) estimating from the interference figure what amount and direction of movement is needed, (2) removing the spindle from the stage and rinsing off the im-

mersion oil with acetone, (3) breathing gently on the mount to soften the adhesive, and (4) while holding it under a stereomicroscope, nudging the fragment into what is estimated to be the desired position. Such a manipulation to bring the optic plane into some large angle with the spindle axis is considerably less difficult than might appear and is an expeditious alternative to the task of making it exactly perpendicular to the spindle for a reading of optic angle by direct rotation (*cf.* Wood and Ayliffe, 1935; Roy, 1965).

Finally, in addition to instrumental and observational errors, it is necessary to keep in mind that a fragment of a natural crystal itself may vary chemically from zone to zone with parallel variations in the optic properties. Such differing parts of the crystal may be superposed at the different selected positions at which measurements are made, and thus may affect the values obtained. If the inhomogeneities are not too great, however, conoscopic illumination tends to average out these effects, and although the isogyre in this case may be broader, it is nonetheless readable, and the resulting value of optic angle more often than not will approach an "average" optic angle for the fragment. Such an abnormal broadening or distortion of the isogyre in the vicinity of the melatope is itself a warning that the crystal may not be optically homogeneous, and suggests that a larger margin of error should be assigned the results.

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