NOTE ON DETERMINATION OF OPTIC AXIAL ANGLE AND EXTINCTION ANGLE IN PIGEONITES

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During the past decade the work of several petrologists on the course of crystallization of pyroxene in basic magmas has drawn attention to the importance of estimating accurately the composition of augites occurring in basalts and dolerites (e.g., see T. F. W. Barth,[1] W. Q. Kennedy[2] H. Kuno[3]). Determination of 2V and the extinction angle is an essential part of such estimations (cf. Deer and Wager[4]) and should be carried out as accurately as possible. In pigeonites of low axial angle ($2V=0°–20°$) which give sensibly uniaxial interference figures in convergent light, it is difficult to determine the exact positions of X, Y and Z if the standard universal stage procedure, as described for example by Nikitin,[5] is followed. As a result of close approach to the uniaxial condition, any direction in the plane XY (perpendicular to Bx_a) has properties that approximate to those characteristic of a principal axis of the indicatrix. If any such direction is placed parallel to the EW axis (A_4) of a universal stage, the section remains approximately in extinction when tilted about that axis. Further, if the stage is now rotated into the 45° position and the section is again tilted on the EW axis, near-extinction is achieved over a short arc of rotation as the optic axes approach, but not necessarily attain, parallelism with the vertical axis of the microscope.

To overcome the resulting ambiguity as to the location of X and Y, the writer has found the following procedure effective. Select a crystal showing interference tints of a low order—preferably one in which the salite structure, orthopinacoidal twinning or two sets of cleavages are developed. Set the inner circle of the stage at any convenient reading (say, 20°) and tilt about the NS axis (A_2) so as to bring some direction in the XY plane parallel to the EW axis; the interference colour falls as extinction is approached, and the section remains almost or quite dark on subsequent tilting about the EW axis. The optical reaction is sharp, and the requisite tilt on NS can be determined to within less than one degree.

[1] Barth, T. F. W., The crystallization process of basalt: *Am. Jour. Sci.*, **31,** 321–351 (1936).

[2] Kennedy, W. Q., Trends of differentiation in basaltic magmas: *Am. Jour. Sci.*, **25,** 239–256 (1933).

[3] Kuno, H., On the crystallization of pyroxenes from rock magmas with special reference to the formation of pigeonite: *Jap. Jour. Geol. and Georg.*, **13,** 141–150 (1936).

[4] Deer, W. A., and Wager, L. R., Two new pyroxenes included in the system clinoenstatite, clinoferrosilite, diopside and hedenbergite: *Min. Mag.*, **25,** 15–22 (1938).

[5] Nikitin, W., *Die Fedorow-Methode*, Berlin, Borntraeger, 31–38 (**1936**).

Now rotate on the inner vertical axis through successive intervals of 20° or 30° and repeat the above procedure for each position of the section, provided that the tilt on the EW axis does not exceed about 35°. The points so obtained (poles of lines in the plane XY) are now plotted on a stereographic net,[6] preferably using the lower hemisphere of projection, and they will be found to lie on a great circle of the net (AA in Fig. 1). If any point departs from the circle, the discrepancy is due to error in measurement, and the corresponding axis should be measured again. The acute bisectrix Z is perpendicular to the great circle so determined and can now be plotted. The writer finds that Z can be located more accurately by this method than by direct measurement, especially since in sections suitable for measuring 2V the direct method must involve high angles of tilt on the NS axis.

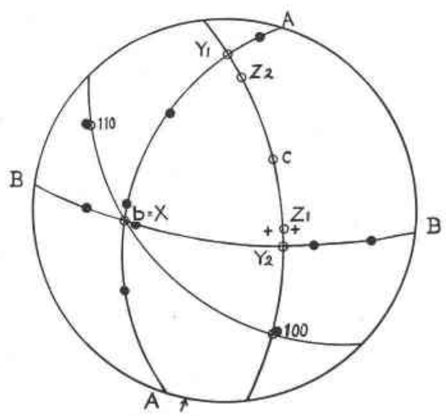

FIG. 1. Stereographic projection (lower hemisphere) of twinned pigeonite from diabase, West Rock, New Haven, Connecticut. Solid circles = observed points; open circles = deduced points; crosses adjacent to Z_1 = observed points of emergence of optic axes in the first half of the twinned crystal.

The positions of X and Y have now to be determined. One of these directions is perpendicular to (010), while the other is parallel to (010), so that if this latter plane is located and plotted its intersection with the plane XY will be either X or Y, usually the former. To do this it is necessary to measure either (a) the basal plane as indicated by salite structure, or (b) the twinning-plane (100) and corresponding twinning axis *c* in orthopinacoidal twins, or (c) the intersection of two sets of prismatic cleavages.

(a) If salite structure is present, as is commonly the case with pigeonite in dolerites, the position of (001) can be observed directly, usually

[6] A Schmidt equal-area net will do equally well.

with great accuracy on account of the sharp definition of the planes of parting involved. Its pole is plotted on the projection and the great circle (010) is drawn through this pole and the pole of Z.

(b) When the crystal shows orthopinacoidal twinning, the position of Z is determined in both halves of the crystal, and the twinning plane (100) is observed directly. The poles of Z_1, Z_2 and (100) should lie on the great circle (010). This is probably the most accurate of the three methods.

(c) The prismatic cleavages are usually less sharply defined than the basal parting, and their positions can therefore be determined only to within one or two degrees. Their intersection on the projection gives the position of the *c* axis to within about 3°, and the great circle through this point and Z is (010).

On the great circle perpendicular to Z the poles of X and Y lie at the intersection with (010) and the point 90° distant from this. By rotation on the inner circle and tilting about the NS axis of the stage, bring one of these axes parallel to the EW axis. Rotate the whole stage into the 45° position using the vertical microscope axis, then tilt to extinction (or near-extinction) on the EW axis. If the crystal axis in question is X, a narrow zone of near-extinction is attained as the acute bisectrix Z is brought parallel to the microscope axis. If the crystal axis is Y, then extinction prevails over a wider arc of tilting as first one optic axis and then the other is brought parallel to the vertical axis of the microscope. In this case the axial angle 2V can be measured directly. If the value of 2V is greater than about 10° a zone of very faint illumination can usually be distinguished between the axial points, but for smaller values of 2V there is darkness over the whole arc between the optic axes.

The extinction angle $Z \wedge c$ may be determined by direct measurement from the projection (see Fig. 1):

(a) Where (001) has been plotted, $Z \wedge c =$ the angle between Z and the pole of (001) plus 16° (since in augites the crystallographic angle $\beta = 74°$).

(b) In twinned crystals the bisectors of the angles between Z_1 and Z_2 are the *c* axis and the normal to (100), respectively. The extinction angle $Z \wedge c$ is thus one-half the appropriate angle $Z_1 \wedge Z_2$ (cf. T. Nemoto[7]). This is probably the most accurate method of determining $Z \wedge c$.

(c) If no crystals showing salite structure or twinning are available, $Z \wedge c$ is best determined in a section approximately parallel to the plane (010). Here the position of Z is measured directly and *c* is given by the trace of the vertical cleavages.

[7] Nemoto, T., A new method of obtaining extinction angle of monoclinic minerals, especially of pyroxenes and amphiboles, by means of random sections: *Jour. Fac. Sci. Hokkaido Imp. Univ.*, (4), **4**, 107–111 (1938).

In order to obtain the composition of the pigeonite under consideration it is of course still necessary to determine either refractive indices or birefringence.

As an example, measured data are given for a twinned crystal of pigeonite in diabase from West Rock, New Haven, Conn., in which pigeonite is associated with a normal augite having $2V = 42°–56°$. The readings cited are those for which the measured direction or plane is parallel to the EW axis of the stage; if the measured element is a plane it is also parallel to the vertical axis of the microscope. Tilts on the NS axis from the right-hand side are recorded thus ←; tilts on the EW axis away from the observer are indicated thus ↑.

	Measured Direction or Plane	Reading on Inner Circle	Tilt on NS Axis	Tilt on EW axis
First half of crystal.	Directions in Plane XY	8°	35°→	
		50	22→	
		90	4←	
		130	28←	
	Twinning-plane (100).	34	0	22° ↑ (±3)
	Cleavage (110).	70	0	8 ↓ (±3)
Second half of crystal.	Directions in Plane XY	20	38→	
		10	18→	
		0	13←	
		350	36←	
	Z	274	18→	
	Cleavage (110).	70	0	8 ↓ (±3)

From the projection based on these data (Fig. 1) the positions of various crystallographic directions may be read as follows:—

Crystallographic Direction	Reader on Inner Circle	Tilt on NS Axis
b ($=X_1$ and X_2)	18°	34°→
c	58	49←
Y_1	$279\frac{1}{2}$	11→
Y_2	341	50←
Z_1	354	54←
Z_2	274	19→

Extinction angle $Z \wedge c = 40°$.

Optic axial plane transverse to (010).

2V (measured with Y_1 parallel to the EW axis of the stage) $=14°$ (± 2).

Applying these data to the diagram of Deer and Wager,[8] two alternative compositions are possible for the pyroxene in question, viz., $Wo_6En_{50}Fs_{44}$, or $Wo_{10}En_{67}Fs_{23}$. The birefringence $(\gamma-\alpha)$ determined with a Berek compensator, assuming birefringence of 0.007 for an adjacent crystal of labradotite (An_{57}), is 0.026. This favors the composition $Wo_6En_{50}Fs_{44}$.

The accuracy of the data obtained in the above-described investigation can be checked to some extent by plotting the observed cleavages parallel to (110). The angle between the pole of (110) and *b* should be 43°35′; that between the pole of (110) and *c* should be 79°10′; the angle measured on the projection between *b* and the pole of the observed cleavage (110) is actually 43°, though the latter departs slightly from the great circle perpendicular to *c*.

As a further check on the position of the axial plane, $\gamma-\beta$ was determined with a Berek compensator as .0245, as compared with $\gamma-\alpha = .026$. This corresponds to $2V=$ about 22°, using the Boldyrew chart as given by Nikitin.[9]

The same procedure on a second twinned crystal gave the following results: $2V=20°$; axial plane perpendicular to (010); $Z\wedge c=39°$; $\gamma-\alpha = .027$.

[8] *Loc. cit.*, 22, Fig. 3.
[9] *Loc. cit.*, pl. IV.