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USE OF THE ANGLE $A_1 \wedge c$ IN OPTICAL DETERMINATION OF THE COMPOSITION OF AUGITE

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ABSTRACT

The use of the angle between an optic axis and the *c* crystal axis, as described for aegirine-augites by King (1962), is adapted to determination of the composition of augites. The technique is described and curves for pertinent optical data are given.

INTRODUCTION

King (1962) has shown that the angle between an optical axis and *c* crystal axis—designated $A \wedge c$—is just as critical an optical character as the two angles—Z or $X \wedge c$ and 2V—normally determined and correlated with the chemical composition of monoclinic pyroxenes. Optical measurement of $A \wedge c$ was found to be the most satisfactory in the determination of aegirine-augites, since this angle is easily, accurately and quickly determined, and varies systematically with the chemical composition in this mineral series. The advantage of King's method is that it eliminates the necessity of locating Z (or X)—a procedure always subject to considerable error.

The same procedure has now been applied by the present writer in a systematic study of augites from Brazilian diabases. It was found that variation in $A \wedge c$ permits close estimation of the chemical composition in the augite-salite-diopside-endiopside field (nomenclature after Poldevaart and Hess, 1951). This new approach eliminates the need for refractive indices in the determination of these pyroxenes because the procedure is completely accomplished through optical measurements made on a universal stage.

CURVES FOR $A \wedge c$ IN AUGITES

The optic axis nearest to *c* will be referred to as A_1 to distinguish it from the farther axis A_2. Variation curves for $A_1 \wedge c$ in the four component system diopside-hedenbergite-clinoenstatite-clinoferrosilite have been constructed from 105 recorded measurements of $Z \wedge c$ and 2V in analyzed pyroxenes. These optical and chemical data have been collected from the literature using as a main source of reference Deer *et al.* (1963). The values of $A_1 \wedge c$ so obtained were plotted in the four component field of clinopyroxenes on the classic $CaSiO_3$-$MgSiO_3$-$FeSiO_3$ triangle.

Smooth curves most closely fitting the plotted data are shown in Fig. 1 for pyroxenes in which $Fe/Mg < 1$. Here they trend across the curves for 2V, permitting determination of a unique composition from universal-

—stage measurements alone—without the necessity of locating Z. But in the field of more ferriferous pyroxenes the curves $A_1 \wedge c$ and 2V are so nearly parallel that this procedure is inapplicable, and refractive indices must also be determined.

Figure 2 is a plot of curves for $A_1 \wedge c$ superposed on 2V curves after Hess (1949) as given by Tröger (1959, p. 62). The accompanying curves for $Z \wedge c$ represent values calculated from the corresponding smooth 2V and $A_1 \wedge c$ curves; so that Fig. 2 is internally consistent.

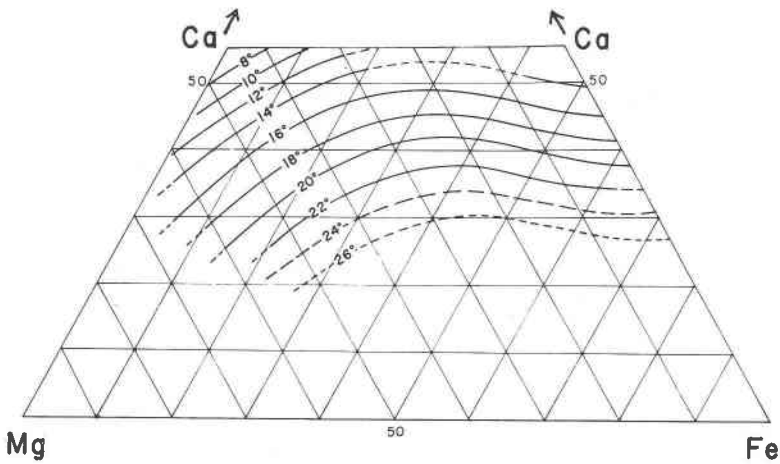

FIG. 1. Curves for $A_1 \wedge c$ in Ca-Mg-Fe clinopyroxenes based on 105 measurements of 2V and $Z \wedge c$. In the lower half of the diagram, Ca-poor clinopyroxenes, the available data are scanty and inconsistent. The 24° was based on a small number of points and the 26° curve is highly inferred.

Optical Procedure

For accurate estimation of the chemical compositions of the common pyroxenes, optical measurements on a universal-stage must be confined to twinned grains. Moreover, attention must be paid to avoid common sources of error due to equipment used, or measurement techniques, following the suggestions and observations of Munro (1963).

The angle $A_1 \wedge c$ must be measured in sections of twinned crystals cut at high angles to c. They are also inclined at high angles to an optic axis in both individuals, in both of which the interference colors are therefore of a low order. The b axis, common to both subindividuals can be brought precisely into coincidence with the EW axis of the stage (Turner, 1942, p. 576) by matching the two in complete extinction for any tilt on the EW axis. With b aligned thus EW, rotate the whole stage into the 45° position and tilt on EW until both halves precisely match in color. The c axis is now vertical. The A_1 axis can now be determined in at least one, and in favorable cases in both halves by tilting to extinction on EW in the usual manner. The angle $A_1 \wedge c$ can now be read directly from a stereographic plot (Fig. 4). The stage is now returned to zero position and c is redeter-

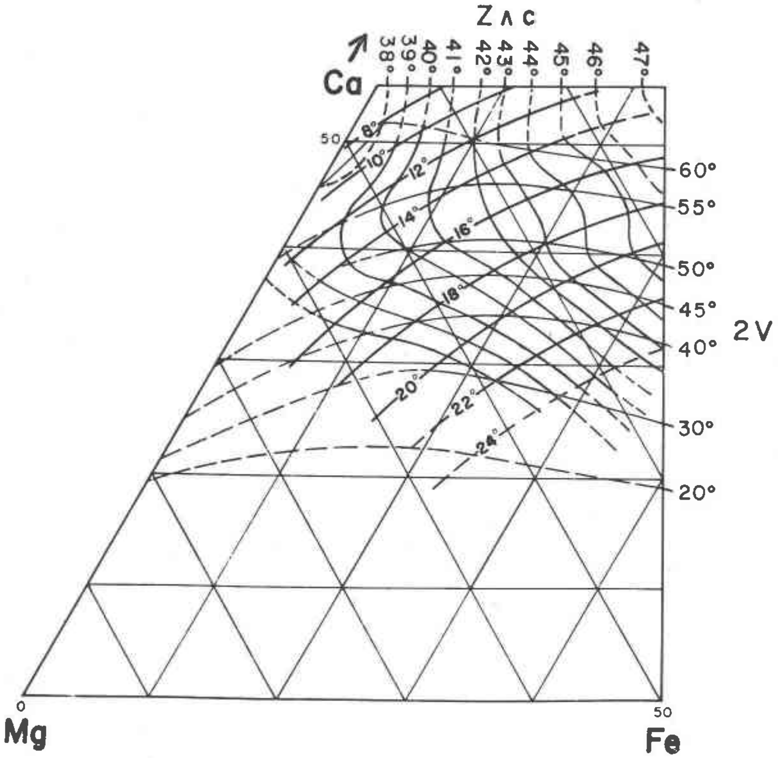

FIG. 2. $A_1 \wedge c$ curves (trending NE–SW: 8°–24°) in the fields of augite-salite-diopside-endiopside of Fig. 1, plotted against 2V curves (after Hess, 1949), (trending EW, 20°–60°) and corresponding calculated curves for $Z \wedge c$ (38°–47°).

mined independently by rotating on the innermost axis to bring the trace of the twin plane horizontal, and tilting on NS to give exact matching of interference color in both halves for all positions of tilt on EW. The normal to {100} is now EW; and c is the pole of the great circle containing the pole of {100} and b as previously determined. Data plotted in Fig. 4 are as follows

$$\left.\begin{array}{r} b = \text{EW},\ 92° \rightarrow 2\text{:}\ \ c \text{ vertical } 10° \downarrow \\ A_1 \text{ vertical } 10° \uparrow \\ A_1 \text{ vertical } 30° \downarrow \\ \perp \{100\}\,\text{EW},\ 181° \leftarrow 10° \qquad\qquad\qquad \end{array}\right\} A_1 \wedge c = 20°$$

There is nothing to add regarding measurements of 2V, except that the best section for measurement of two optic axes in one crystal has a somewhat different orientation from that just described. To avoid high tilts it should be nearly normal to Z in one half of the twin.

Turner's (1942) procedure for measuring $Z \wedge c$ involves location of Z by bringing X or Z parallel to EW (when the crystal remains in extinction

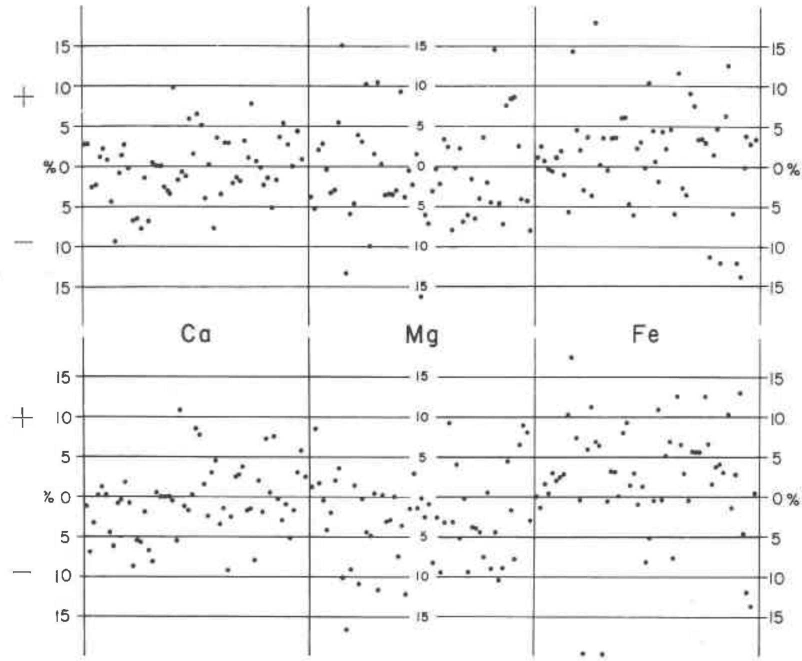

FIG. 3. Positive and negative departure from the chemical analyses (0% line) of 64 estimations based on optical data (Table 1) of clinopyroxenes. *Above:* Estimations using $A_1 \wedge c$ and 2V (or $Z \wedge c$) curves (Fig. 2). *Below:* estimations using 2V and β curves (after Hess, 1949—quoted from Tröger, 1959).

for all tilts on EW). This procedure is subject to error of at least 1° even under the most favorable circumstances. Less time-consuming is the method of Bambauer (1959). In a section of a twinned crystal showing maximum interference colors, locate the twin plane {100} by bringing its trace NS and tilting on the NS axis until both halves match precisely for all tilts on EW. The {100} plane is now normal to EW. Now tilt to various angles on EW and for each position determine the angle Z′ to trace of {100} by rotating the whole stage in the appropriate direction to extinction. The minimum value is $Z \wedge c$ and this is obtained when c is in the plane normal to the vertical axis of the microscope.

Accuracy

The variation curves of $A_1 \wedge c$ here presented are by no means precise. Aside from the chemical and structural factors (see Deer, Howie, and Zussman, 1963, v. 2, pg. 131) which interfere in the optical properties of

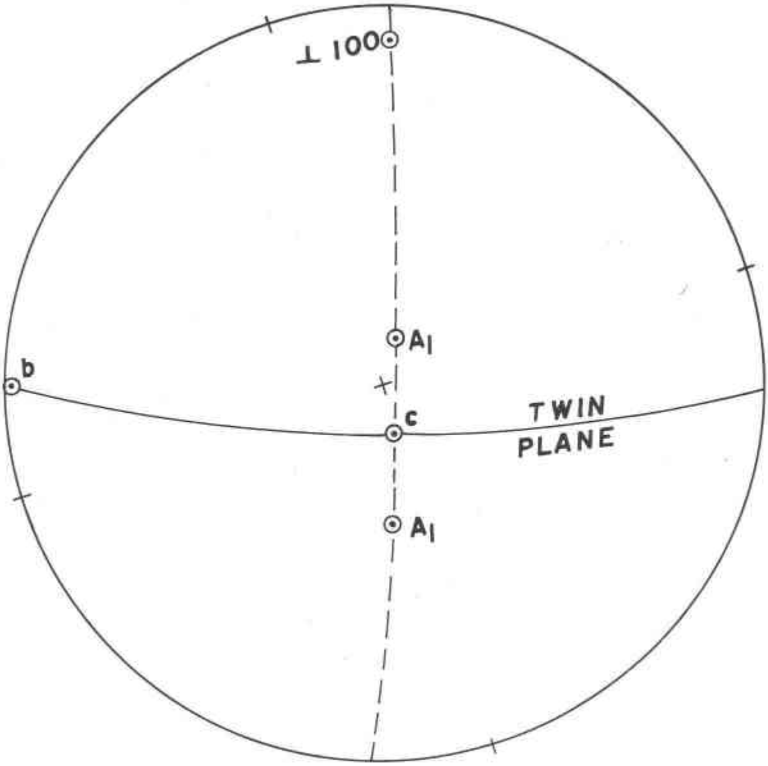

Fig. 4. Equal-area projection (lower-hemisphere) of augite crystal suitably oriented for measuring $A_1 \wedge c$ (data in text).

the pyroxenes, many other sources of error in the data from which the curves have been deduced must be considered. Those factors are the previously mentioned measurements techniques, the equipment used, and even the quality of the chemical analyses. Nevertheless, the curves drawn by Hess are still in use and are considered the more reliable approach for chemical composition estimations.

Table 1 gives optical data and chemical analyses recorded for 64

TABLE 1[1]

No.	Optical Measurements				Chemical Analyses			Field
	$Z\wedge c$	2 V	$A\wedge c$	β	Ca	Mg	Fe	
1	38	60	8	1.673	49.2	49.8	1.0	
2	39	58	10	—	46.6	51.7	1.7	
3	39	57	10.1/2	1.672	51.1	45.5	3.4	
4	39	56.1/2	11.1/4	1.678	48.8	46.8	4.4	
5	39	57.3/4	10.1/4	1.678	47.8	47.5	4.7	
6	40	60	10	1.683	49.3	45.7	5.0	
7	40.1/4	55.1/2	12.1/2	1.680	45.4	49.6	5.0	
8	39	56	11	1.681	50.9	44.0	5.1	
9	38	50.1/2	12.3/4	1.684	47.8	43.5	8.7	
10	46	60	16	1.701	48.9	41.3	9.8	
11	44	60	14	1.708	48.1	41.3	10.6	
12	43	59	13.1/2	1.696	46.2	43.2	10.6	Diopside-
13	41	58	12	1.686	49.3	39.6	11.1	Salite
14	41	48	17	1.707	46.8	42.0	11.2	Series
15	39.1/4	48	15.1/4	1.691	45.5	42.3	12.2	
16	45	48	21	1.698	46.3	41.4	12.3	
17	42	53	15.1/2	1.697	45.4	40.5	14.1	
18	39.1/2	46.3/4	16.1/4	1.695	45.3	39.6	15.1	
19	55	48	31	1.714	45.1	39.2	15.7	
20	43	55	15.1/2	1.692	45.6	37.8	16.6	
21	45	59	15.1/2	1.698	48.0	35.1	16.9	
22	45	59	15.1/2	1.698	48.0	35.0	17.0	
23	45.3/4	54.1/2	18.1/2	1.698	45.0	35.0	20.0	
24	47.1/2	62	16.1/2	1.714	49.5	26.5	24.0	
25	44	56	16	1.714	49.5	26.7	23.8	
26	40.3/4	50	15.3/4	1.684	41.0	52.0	7.0	
27	40.1/2	49	16	1.685	39.5	52.2	8.3	Endiopside
28	40.1/2	48.3/4	16.1/4	1.685	36.2	54.9	8.9	
29	39	55.1/4	11.1/4	1.686	35.6	54.3	10.1	
30	40.3/4	49	16.1/4	1.686	41.7	47.6	10.7	
31	40.3/4	48	16.3/4	1.686	40.7	48.3	11.0	
32	41	51.1/2	15.3/4	1.687	42.3	46.0	11.7	
33	46	61	15.1/2	1.678	43.1	44.7	12.2	
34	35	58.1/4	6	1.682	41.2	46.1	12.7	
35	42.1/2	51.3/4	16.3/4	1.687	41.5	45.5	13.0	
36	48	52	22	1.700	44.5	42.4	13.1	
37	42	52	16	1.687	40.0	46.1	13.9	
38	43.1/2	60.1/2	13.1/4	1.700	45.0	39.6	15.4	
39	42	46.1/2	18.3/4	1.697	43.0	41.3	15.7	
40	42	48.1/2	17.3/4	1.678	40.4	43.8	15.8	
41	44	52.1/2	17.3/4	1.708	50.8	31.7	17.5	
42	39.1/2	45.1/2	16.3/4	—	45.0	37.1	17.9	Augites
43	43.1/2	43.1/2	21.3/4	1.697	39.0	43.0	18.0	
44	42	51	16.1/2	1.692	39.6	42.2	18.2	
45	43	55.1/2	15.1/4	1.695	43.7	35.8	18.5	
46	50	63	18.1/2	1.711	46.1	35.0	18.5	
47	44	46.3/4	20.3/4	1.698	39.7	41.4	18.9	
48	44	47	20.1/2	1.698	40.0	41.1	18.9	
49	44	51.1/2	18	1.707	44.4	36.6	19.0	
50	43	46	19.1/4	1.698	35.9	45.1	19.0	
51	44.1/2	50.1/2	17.1/4	1.697	43.5	36.5	20.0	

[1] The data of this table are quoted from Deer *et al.* (1963) with the exception of analyses numbers 4, 5, 22, 23, 24, 25, 26, 31, 32, 43, 45, 47, 48, 51, 53, 54, 55, 56, 58, 61, 64 which are quoted from Hess (1949).

TABLE 1—(*continued*)

No.	Optical Measurements				Chemical Analyses		
	Z∧c	2 V	A∨c	β	Ca	Mg	Fe
52	41	55	13.1/2	1.701	37.8	41.9	20.3
53	43.1/2	49	19	1.700	39.5	39.5	21.0
54	50	66	17	1.705	44.5	34.5	21.0
55	44	47.1/2	20.1/4	1.695	38.7	41.0	21.3
56	51	77	12.1/2	1.711	44.0	34.0	22.0
57	41	52	15	1.700	44.9	32.6	22.5
58	43.1/2	43.1/2	21.3/4	1.699	37.0	39.7	23.3
59	44	40	24	1.700	36.7	38.3	25.0
60	43	50	18	1.700	42.8	31.4	25.8
61	43	57.1/2	14.1/4	1.705	44.5	29.5	26.0
62	42	55	14.1/2	—	40.3	33.5	26.2
63	62	74	25	1.732	44.7	20.0	35.3
64	43.1/2	44	21.1/2	1.701	33.0	38.0	29.0

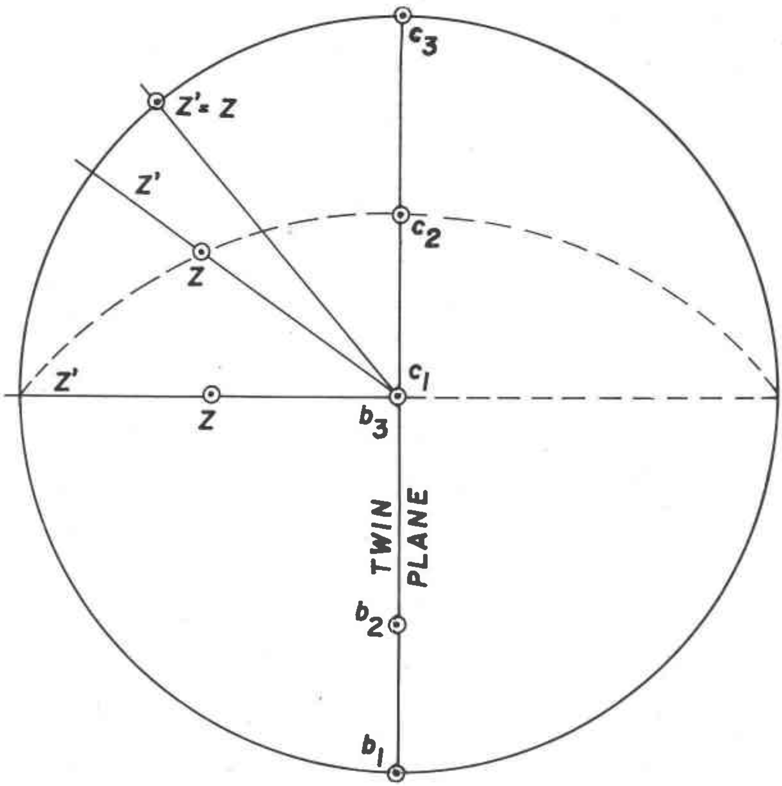

FIG. 5. Equal-area projection (lower-hemisphere) of augite twinned crystal with composition plane vertical and oriented NS. c_1, c_2, c_3, and b_1, b_2, b_3, different positions for crystal axes while tilting about EW axis of the stage and the correspondent extinction angle (Z′) for each position. When c crystal axis is normal to axis of microscope (c_3) Z′ = Z.

clinopyroxenes selected from the literature. For each pyroxene the composition has been redetermined from the optical data in two ways: (1) using the curves for $A_1 \wedge c$ and 2V(or $Z \wedge c$) of Fig. 2; (2) using the standard curves for 2V and the β refractive index (Tröger, 1959, p. 62). For each pyroxene the departure of the contents of Ca, Mg and Fe so determined from the values given by chemical analyses has been plotted in Fig. 3. The spread of points in the upper diagram (based on $A_1 \wedge c$) is more even than that of the lower diagram (based on β index.) it appears that the ratio Mg/Fe in particular is more satisfactorily determined using the method described in this paper than from refractive index determinations. Later correction of refractive index data might remove this anomaly.

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References

Bambauer, H. S. (1959) Direkte Bestimmung der Auslöschungsschiefe nach (hol) verzwillingter monokliner Kristalle von allgemeiner Schnittlage, dargestellt an Pyroxenen und Amphibolen. *Zeit. Krist.* **3**, 421.

Deer, W. A., Howie, R. A. and J. Zussman (1963), *Rock-Forming Minerals: 2.* Longmans, London.

Hess, H. H. (1949) Chemical composition and optical properties of common clinopyroxenes. *Am. Mineral.* **34**, 621.

King, B. C. (1962) Optical determination of aegirine-augite with universal stage. *Mineral. Mag.* **33**, 132.

Muir, I. D. (1951) The clinopyroxenes of the Skaergaard intrusion, eastern Greenland. *Mineral. Mag.* **29**, 690.

Munro, M. (1963) Errors in the measurement of 2V with the universal stage. *Am. Mineral.* **48**, 308.

Poldevaart, A. and H. H. Hess (1951) Pyroxenes in the crystallization of basaltic magma. *Jour. Geol.* **59**, 472.

Tröger, W. E. (1959) *Optische Bestimmung der gesteinsbildenden Minerale.* Stuttgart.

Turner, F. J. (1942) Determination of extinction angles in monoclinic pyroxenes and amphiboles. *Am. Jour. Sci.* **240**, 571.

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