Canadian Mineralogist,
Vol. 12, pp. 87-94 (1973)

PLAGIOCLASE FELDSPAR DETERMINATION IN A NONEQUILIBRIUM SYSTEM

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ABSTRACT

The anorthite content and distribution has been determined for seven zoned plagioclase phenocrysts from a tholeiitic diabase. Compositional determinations by both universal stage and electron microprobe techniques at the same locations within the phenocrysts indicate that optical techniques are of limited value in this type of material. Because all phenocrysts exhibit vicinal composition twin planes, the migration of poles to composition planes cannot be used as a composition or structural state indicator. Using electron microprobe analyses as a reference base, it was found that the twin axis method of composition determination is reliable. There are no reliable structural state indicators among the various universal stage techniques attempted for the plagioclase composition range $Ab_{60}An_{40}$ to $Ab_{18}An_{82}$.

INTRODUCTION

Traditionally, the universal stage has been a major tool in the study of zoned plagioclase in disequilibrium rock assemblages, particularly in hypabyssal and extrusive rock units. More recently, the electron microprobe has been applied as a more precise method of determining composition variations in zoned plagioclase. However, it would be desirable to retain the more rapid and less precise universal stage technique since optical measurements may give some indication of the structural state in addition to composition variation. The purpose of this study was to evaluate the usefulness of universal stage techniques in characterizing the compositional range and structural state of plagioclase from a hypabyssal environment. This was done by comparing the compositions determined by the universal stage with the compositions of the same locations as determined by the electron microprobe.

The Grand Manan Island, New Brunswick, tholeiite sheet is about 15 × 4 miles in area and is approximately 500 feet thick (Gunter 1967). The sample, chosen from the coarser-grained central portion of the sill, was a porphyritic diabase containing plagioclase and pyroxene phenocrysts up to 2 mm in length with interstitial glass and micropegmatite. The sample had a modal composition of 40% plagioclase, 42% clinopyroxene, 10% orthopyroxene and 8% mesostasis. Of the 7 phenocrysts chosen for detailed study, 4 consisted of a core, with an approximate composition of 75 mole % An, surrounded by a normally-zoned mantle that ranged in composition from 82 mole % An at the core boundary to 40 mole % An on the margins. Figure 1 includes a microprobe traverse on a phenocryst of this type. The remaining 3 phenocrysts were normally zoned from approximately 75% An in the center to 40 mole % An on the margins. The principal twin law in 5 of the 7 phenocrysts was Albite-Carlsbad ⊥[001] / (010). One phenocryst was twinned on the (010) plane according to the albite law and the remaining phenocryst was twinned on the (021) plane but not according to the Baveno law. All 7 phenocrysts had lamellar twins or cleavage traces visible on the (010) and (001) planes.

Universal stage techniques

The orientation of the indicatrix was determined in the selected locations using a five-axis universal stage. Stereographic plots of the indicatrix orientation were made, following the format given in Slemmons (1962), and the compositions corresponding to the orientations determined from the plutonic and volcanic curves of Burri *et al.* (1967). The five types of measurements used to estimate the composition and structural state are:

(1) migration of twin axes;
(2) migration of poles to composition planes;
(3) migration of poles to cleavage planes;
(4) extinction angles measured in the section ⊥*a* (Emmons 1943); and
(5) optic axial angle measurements.

As many of the five possible techniques as were applicable were used to estimate the composition and structural state at each sample location. Each type of measurement presents somewhat different practical problems and a subjective decision is involved in deciding whether or not a valid measurement can be made. For example,

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the geometric determination of an axis of twinning (Slemmons 1962) requires an indicatrix orientation from each twin member. The minimum requirement for a measurement of an indicatrix orientation is an area of about 0.03 mm diameter free of lamellar twins, inclusions and oscillation zones. In zoned phenocrysts, care must be taken to assure that the measurements come from areas of equal composition which usually restricts twin axis determinations to locations near the composition plane. As a result, only a limited number of locations are suitable for determinations of any of the optical parameters. For the 26 pairs of locations selected for twin axis determinations, the mean difference from the subsequent microprobe determinations was 2.1 mole % anorthite, thus indicating that the pairs of locations were within the same compositional zone.

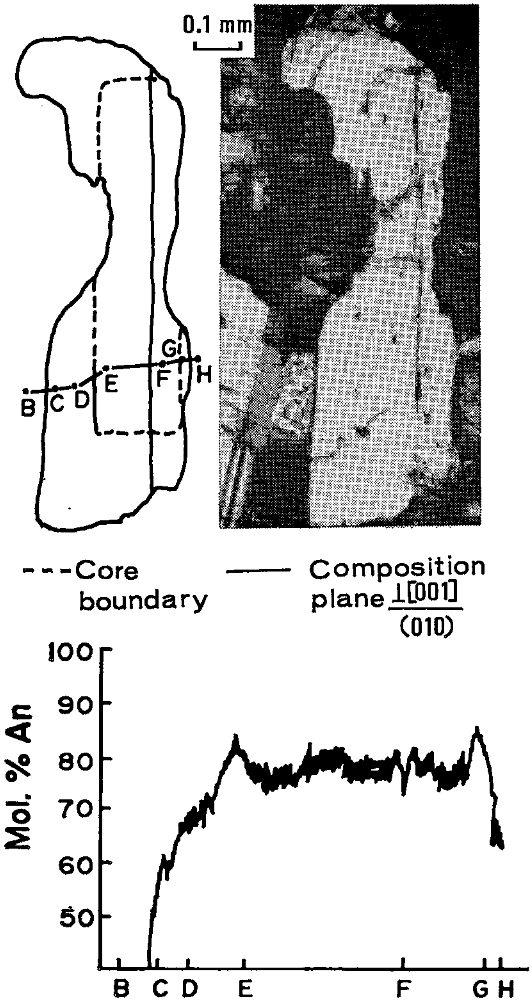

Fig. 1. Photomicrograph and sketch of plagioclase phenocryst 1, showing a microprobe traverse.

Precision of optical measurements

A phenocryst with a similar zoning profile to that shown in Figure 1 was chosen for the purpose of estimating the precision of the universal stage determinations. Figure 2 is a composite stereogram of 7 readings by G.J.P. and 6 readings by G.E.P. for two locations within the mantle area of the phenocryst. The stereogram of Figure 3 represents 5 determinations by G.J.P. of the mantle immediately adjacent to the core boundary. The estimated errors are given in Table 1. Readings in the mantle near the core boundary represent the most difficult determinations that were routinely attempted in this study. The experimental precision for the twin axis determination can be estimated as ±2 mole % anorthite content with better precision to be expected in areas of less marked zoning. This scatter corresponds to a maximum deviation of approximately ±2° in a universal stage measurement.

Electron microprobe technique

The plagioclase phenocrysts were analysed for the five major cations and iron using the ARL electron microprobe at Queen's University. These elements were determined at 15 kv, 0.024 μa sample current and a beam diameter of 5 μm. The total counting times were 30 seconds for silicon and calcium and 60 seconds for the remaining elements. Two elements were analysed at all locations before changing to the next two elements. Appropriate standards were read before and after the series of analyses for two elements on a phenocryst. The sample current was read-

TABLE 1. PRECISION OF OPTICAL DETERMINATIONS OF ANORTHITE COMPOSITION

Optical Elements	(a) Mole % An. Mean	*S.D.*	(b) Mole % An. Mean	*S.D.*
Twin Axis 1	63.4	0.9	74.4	1.1
Twin Axis 2	63.7	0.9	74.2	1.1
Composition Plane 1	67.4	1.3	80.2	1.1
Composition Plane 2	67.1	1.3	69.8	3.3
Optic Axis	76.4	2.0	92.0	5.5

S.D.=standard deviation
(a) two locations in the phenocryst mantle based on 7 measurements by G.J.P., 6 measurements by G.E.P.
(b) two locations near a core boundary based on 5 measurements by G.J.P.

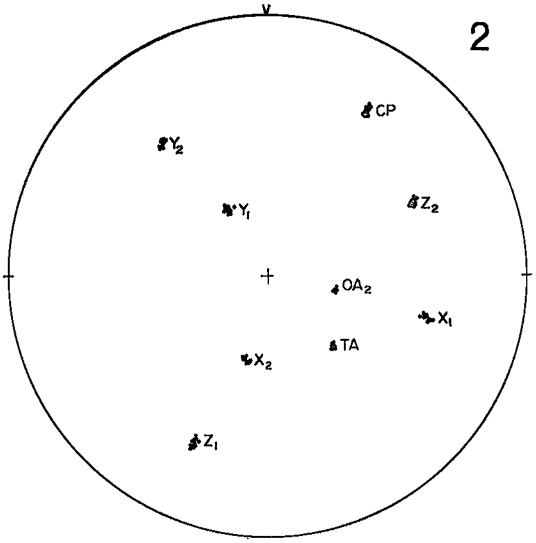

FIG. 2. Stereogram of all readings and constructed points in locations 1a and 2a, sample 4-230.5. Total of 13 readings by two operators.
X_1, Y_1, Z_1 = Indicatrix for location 1a
X_2, Y_2, Z_2 = Indicatrix for location 2a
X_2, Y_1 = Arrived at by construction
OA_2 = Optic axis in location 2a

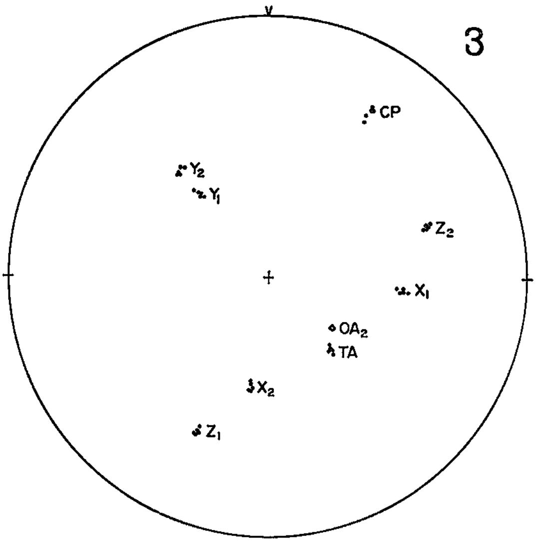

FIG. 3. Stereogram of all readings and constructed points for locations 1b and 2b, sample 4-230.5.
X_1, Y_1, Z_1 = Indicatrix for location 1b
X_2, Y_2, Z_2 = Indicatrix for location 2b
X_2, Y_1 = Arrived at by construction
OA_2 = Optic axis in location 2b

justed prior to reading the standard again and starting the analyses on the next phenocryst. Natural orthoclase, albite, bytownite and synthetic anorthite were used as standards. Care was taken to analyse precisely the same locations as were determined optically and to return to the same location for each successive pair of elements. Corrections for background, deadtime, drift, fluorescence, absorption and atomic number were applied using a program adapted by Dr. M. Corlett from that of Frazer *et al.* (1966) with the addition of the atomic number correction from Duncumb & Reed (1968). Weight % values for CaO, Na_2O and K_2O were recast to 100% and recalculated as mole % feldspar molecule. Based on the estimated precision of the Na_2O and CaO analyses, the precision of the anorthite values is estimated to be ±2 mole %.

Using the MAC microprobe at the Geological Survey of Canada with similar operating conditions and the same sample, it was determined that the count rate for sodium, silicon and calcium remained essentially stable for test periods of 300 seconds. Also at the Geological Survey, strontium, magnesium and barium were not detected in five locations that were checked. Titanium varied from the limits of detection to 0.1 wt. %.

Comparison of microprobe and universal stage determinations

If microprobe and optical determinations of anorthite content at the same location are compared, we will get an indication of the relative usefulness of the various optical techniques for the study of strongly zoned plagioclase. The precision of optical determinations under ordinary working conditions will give an estimate of the limits of the particular optical measurement (Table 1).

The microprobe and universal stage composition determinations are listed in Table 2 and a summary of the mean difference in anorthite content between the microprobe and the tested optical techniques is given in Table 3. The differences between microprobe and optical determinations of anorthite content are interpreted as a measure of accuracy of the optical technique, assuming that the microprobe results are "correct". The standard deviation of the mean differences is interpreted as a measure of the precision of the optical techniques (although it also contains a measure of the precision of the microprobe). Additionally, an examination of the mean differences should indicate whether the plutonic or volcanic curves of Burri *et al.* (1967) are more applicable to the phenocrysts under examination.

TABLE 2. PLAGIOCLASE COMPOSITIONS DETERMINED FROM MIGRATION CURVES (AFTER BURRI *et al.* 1967).

Pheno-cryst	Location		TA⊥[001]/(010)		TA(001)		CP(010)		CP(001)		CP(021)		⊥a	2V		Cl(001)		Micro-probe
	U*	M**	v	p	v	p	v	p	v	p	v	p		v	p	v	p	
1	1a	1	72	69	-	-	66	65	-	-	-	-	-	79	77	-	-	69.1
	2a	2	78	79	-	-	63	63	-	-	-	-	-	77	72	-	-	71.3
	1b	3	77	80	-	-	65	63	-	-	-	-	63	90	88	-	-	73.9
	2b	4	74	75	-	-	58	57	-	-	-	-	-	90	88	-	-	69.8
	1c	5	80	83	-	-	74	74	-	-	-	-	67	90	88	-	-	79.8
	2c	6	76	78	-	-	62	63	-	-	-	-	-	100	100	-	-	73.0
	13	7	-	-	-	-	62	60	-	-	-	-	42	68	62	-	-	60.4
	1f	8	-	-	-	-	nf	nf	-	-	-	-	30	56	55	-	-	56.3
	1h	9	-	-	-	-	57	53	-	-	-	-	32	57	62	-	-	53.4
	1g	10	79	86	-	-	70	64	70	69	-	-	63	90	88	-	-	74.6
	2g	11	76	76	-	-	66	65	-	-	-	-	-	78	76	-	-	71.0
	1i	12	-	-	-	-	71	68	72	70	-	-	64	90	88	-	-	74.8
	1j	13	-	-	-	-	nf	nf	-	-	-	-	59	79	79	-	-	71.4
	1k	14	-	-	-	-	75	72	75	75	-	-	66	94	93	-	-	76.9
	1l	15	-	-	-	-	57	58	60	59	-	-	42	50	55	-	-	51.0
	1m	16	-	-	-	-	nf	45	nf	49	-	-	21	45	38	-	-	45.8
2	1a	1	68	65	-	-	66	66	-	-	-	-	-	nf	nf	-	-	66.2
	2a	2	70	67	-	-	70	64	-	-	-	-	-	85	82	-	-	78.5
	1c	5	79	81	-	-	65	nf	-	-	-	-	-	77	74	-	-	80.5
	2c	6	79	82	-	-	69	65	-	-	-	-	-	100	100	-	-	79.5
	1b	7	66	64	-	-	70	69	-	-	-	-	-	71	65	-	-	69.5
	2b	8	71	68	-	-	70	65	-	-	-	-	-	80	79	-	-	68.8
	1e	9	74	70	-	-	72	nf	-	-	-	-	-	71	65	-	-	71.1
	2e	10	75	75	-	-	73	nf	-	-	-	-	-	73	68	72	70	70.3
	1d	11	74	69	-	-	66	66	-	-	-	-	-	72	65	-	-	72.3
	2d	12	74	69	-	-	69	66	-	-	-	-	-	69	62	76	77	74.7
3	1c	1	-	-	nf	nf	59	61	-	-	-	-	-	48	59	-	-	50.7
	2c	2	-	-	nf	nf	38	41	-	-	-	-	-	-	-	-	-	49.7
	3c	3	-	-	nf	nf	59	61	-	-	-	-	-	48	59	-	-	49.8
	1b	4	-	-	58	60	64	65	-	-	-	-	-	-	-	62	62	57.5
	2b	5	-	-	59	60	52	51	-	-	-	-	-	-	-	58	57	56.7
	3b	6	-	-	54	52	60	62	-	-	-	-	-	-	-	60	57	56.6
	1a	7	-	-	62	62	66	65	-	-	-	-	-	-	-	57	59	59.2
	2a	8	-	-	60	61	64	62	-	-	-	-	-	-	-	60	59	59.9
4	2d	1	60	59	-	-	60	57	-	-	-	-	-	nf	nf	-	-	56.2
	1d	2	60	59	-	-	53	nf	-	-	-	-	-	65	55	-	-	58.9
	2c	6	68	65	-	-	72	65	-	-	-	-	-	70	62	nf	nf	61.1
	1c	8	68	65	-	-	64	nf	-	-	-	-	-	nf	nf	nf	nf	63.6
	2a	9	55	52	-	-	60	58	-	-	-	-	-	nf	nf	-	-	52.8
	1a	10	55	53	-	-	52	nf	-	-	-	-	-	-	-	-	-	54.9
5	2a	1	-	-	65	65	-	-	76	nf	-	-	-	nf	nf	-	-	62.5
	3a	2	-	-	65	64	-	-	55	nf	-	-	-	65	55	-	-	65.6
	2b	3	-	-	75	76	-	-	95	nf	-	-	-	78	57	-	-	69.4
	3b	4	-	-	75	75	-	-	64	nf	-	-	64	73	68	-	-	70.0
	1e	5	-	-	-	-	53	nf	57	nf	-	-	-	nf	nf	-	-	53.0
	3c	6	-	-	nf	nf	-	-	68	nf	68	-	67	73	74	-	-	72.8
	1c	7	-	-	nf	nf	nf	nf	70	nf	nf	-	95	73	74	-	-	68.9
	3d	8	-	-	nf	nf	63	nf	61	nf	50	-	49	65	55	-	-	60.9
	1d	9	-	-	nf	nf	61	nf	63	nf	69	-	76	62	50	-	-	60.8
	3c	10	-	-	nf	nf	-	-	68	nf	68	-	67	73	74	-	-	80.2
	1c	11	-	-	nf	nf	nf	nf	70	nf	nf	-	95	73	74	-	-	81.0
	3h	12	-	-	nf	nf	54	nf	-	-	46	-	-	-	-	-	-	55.8
	1h	13	-	-	nf	nf	-	-	57	nf	62	-	-	nf	nf	-	-	55.7
	1g	17	-	-	-	-	60	nf	60	nf	-	-	-	nf	nf	-	-	58.9
	1f	18	-	-	-	-	60	nf	-	-	-	-	-	-	-	-	-	49.8
6	1a	1	62	60	-	-	52	nf	-	-	-	-	-	70	62	-	-	59.7
	2a	2	58	58	-	-	67	64	-	-	-	-	-	62	50	-	-	60.9
	1b	3	65	63	-	-	55	nf	-	-	-	-	-	67	59	-	-	64.1
	2b	4	65	63	-	-	70	65	-	-	-	-	-	65	55	-	-	65.6
7	2a	9	60	69	-	-	67	65	-	-	-	-	-	-	-	-	-	57.8
	1a	10	60	58	-	-	60	nf	-	-	-	-	-	nf	nf	-	-	58.4
	2b	12	57	54	-	-	64	62	-	-	-	-	-	-	-	-	-	55.8
	1b	13	57	54	-	-	54	nf	-	-	-	-	-	nf	nf	-	-	57.1
	2c	15	50	47	-	-	60	nf	-	-	-	-	-	-	-	-	-	49.2
	1c	16	55	51	-	-	52	nf	-	-	-	-	-	50	55	-	-	50.5

U*=universal stage locations 1a and 2a represent a pair of interdependent data points within twin members 1 and 2
M**= microprobe data point
V=volcanic curves, p=plutonic curves, TA=twin axis, CP=composition plane, Cl=cleavage, nf= no fit

TABLE 3. MEAN DIFFERENCES BETWEEN MICROPROBE AND OPTIC COMPOSITIONS

		Mean Differences	*S.D.* of Mean Difference
TA $\frac{\perp[001]}{(010)}$	v	2.7	2.0
	p	3.3	3.2
TA(001)	v	2.4	1.9
	p	3.3	1.8
CP(010)	v	5.3	3.7
	p	6.2	4.0
CP(001)	v	6.6	6.5
	p	4.7	2.3
CP(021)	v	8.7	2.9
Cl(001)	v	2.9	1.8
	p	1.3	1.6
2V	v	6.9	6.5
	p	7.7	5.6
a		14.1	7.7

* See Table 2 for explanation of symbols
S.D. = standard deviation

Composition determination

The best correlation with microprobe results is obtained by measuring the axis of twinning and comparing this with the volcanic migration curves given in Burri *et al.* (1967). The mean differences between the various composition plane determinations, ⊥a, 2*V* and the microprobe compositions, are considerably larger and Tables 1 and 3 indicate both a lower precision and accuracy. The values for the anorthite content derived from cleavage plane determinations appear to be more precise, but only one phenocryst in a suitable orientation was available and hence the method was not fully tested. Some types of measurement appear to lack precision and, therefore, it follows that a study utilizing a mixture of optical determinations could well be uneven in quality of data.

Structural state

Figure 4 is a stereogram of all the Albite-Carlsbad ⊥[001] / (010) twin axes that were determined, superimposed on the curves of Burri *et al.* (1967). The spread of the points and the limited separation of the volcanic and plutonic curves for compositions greater than 60 mole per cent anorthite preclude the estimation of structural state. With compositions of less than 60 mole per cent anorthite, the points generally fall within the area between the curves, indicating an intermediate structural state. The spread of points is comparable to the precision of measurement demonstrated in Figures 2 and 3. Figure 5, a plot of the same data in the format given in Slemmons (1962), gives essentially the same result, even though this plotting technique involves a further averaging of results. Each twin axis that was determined is plotted twice in Figure 4, that is, with respect to both the first and second twin members that were used to construct the twin axis. In Figure 5, the two readings generate only one plotting point which is the further averaging mentioned above.

Figure 6 is a plot of all the 2*V* measurements (measured on one optic axis only) versus the microprobe compositions for the same locations. The spread of points is comparable to those from which the curves are constructed by Burri *et al.* (1967). This spread is much larger than would be expected from the measurement precision depicted in Figures 2 and 3. The spread indicates (a) that the interrelationship among plagioclase composition, 2*V*, and structural state is not as simple as assumed in Burri *et al.* (1967), and (b) that a relationship among these factors may be evident if more detailed optical and microprobe measurements were made on the same locations in zoned materials.

Fairbairn & Podolsky (1951) determined that a precision of ±0.6° could be expected on direct measurements of optical axial angles in plagioclase. However, Crump & Ketner (1953) show that commonly V_1 and V_2 differ by as much as 2 or 3 degrees. If V_1 and V_2 are unequal, this could explain some of the spread. Because it is rare that both optic axes can be observed in the same location, and because the curves given in Burri *et al.* (1967) are averages of data with a

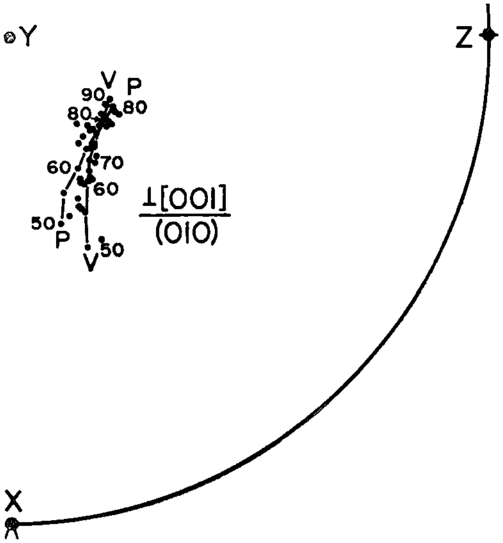

FIG. 4. Stereogram of all the Albite-Carlsbad twin axes for phenocrysts in sample 4-357.9, projected on the X-Z plane. The migration curves are in mole % An. (Burri *et al.* 1967). X,Y,Z = indicatrix axes; V = volcanic migration curve; P = plutonic migration curve.

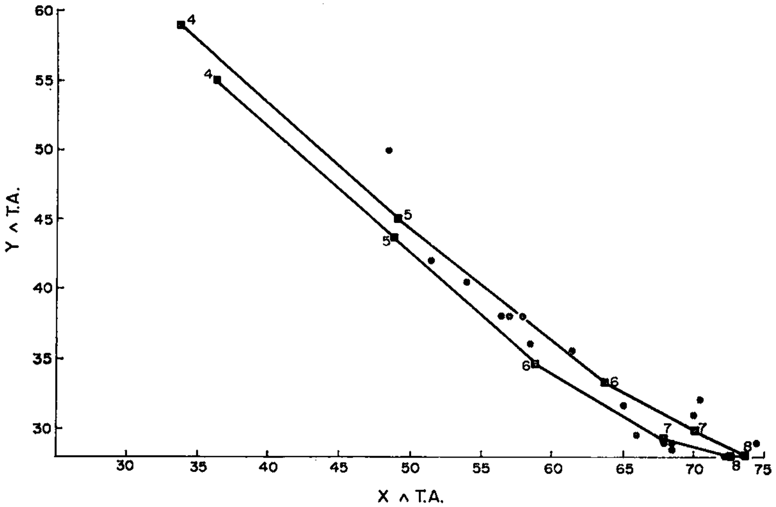

FIG. 5. Plot of the Albite-Carlsbad twin axes ⊥[001]/(010) for the phenocrysts in sample 4-357.9. Solid lines after Slemmons (1962).

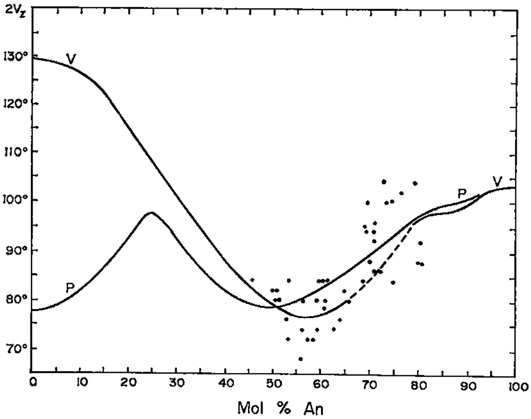

FIG. 6. Variation in 2*V* measurements in 7 phenocrysts from sample 4-357.9. The curves are from Burri *et al.* (1967).
V = volcanic curve P = plutonic curve.

broad scatter, the curves cannot be used to determine composition or structural state in the range of compositions being considered here.

Differences between twin members

Figure 7 is a stereogram of all measured normals to the (010) composition planes plotted with respect to the indicatrix orientations measured in each phenocryst. For example, the composition plane in each phenocryst is plotted with respect to each indicatrix measured in locations in the phenocryst near the composition plane. Points from different twin members fall on opposite sides of the curves; that is all the points from twin member 1 fall on the opposite side to those points derived from twin member 2. This pattern is consistent in all the phenocrysts that were studied and gives rise to the two groupings of points that can be seen in Figure 7. If the means of the dependent sets of (010) composition planes

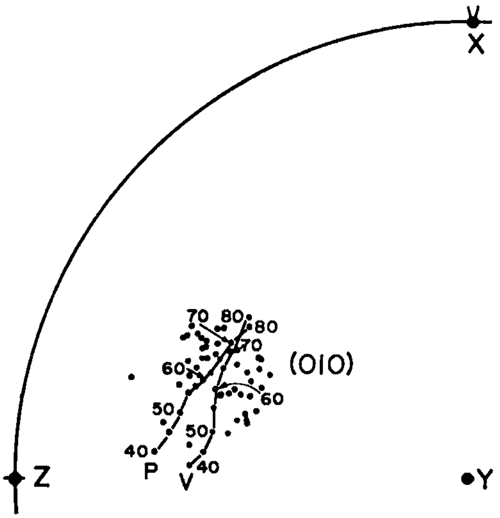

FIG. 7. Stereogram of all the Albite-Carlsbad composition planes (010) measured in crystals in sample 4-357.9 projected on the X-Z plane. The migration curves are in mole % An (Burri *et al.* 1967).
X, Y, Z = Indicatrix axes; V = volcanic migration curve; P = plutonic migration curve

are plotted, the points cluster around the migration curves and the variability is disguised.

Throughout the body of measurements (in the case of normal twin laws) the geometrically located twin axes does not coincide with the measured normal to the composition plane. Similarly, in the case of the Albite-Carlsbad twin axes, each measured axis does not fall in the composition plane. This deviation in each is greater than 5° but less than 10°. This feature can be explained by (a) structural state differences between twin members, (b) composition differences, or (c) vicinal composition planes, that is, composition planes that deviate from the geometry required by the particular twin law. If it can be assumed that structural state variations are due to differences in thermal history, then the first possibility can be discarded and, furthermore, the changes due to structural state variations would be of an insignifcant magnitude. As the mean difference between pairs of interdependent points is approximately 2 mole % anorthite, based on microprobe determinations, the compositional difference could not account for the 5-10° deviations mentioned above and, therefore, the principle twin planes in each of the 7 phenocrysts must be vicinal. A detailed account of the reasoning is included in Pringle (1972). This would be consistent with the exceptionally poor correlation between compositions determined by using the (010) composition plane and those determined using the microprobe. In addition, this would make the composition plane measurements useless as structural indicators for this compositional range.

Composition differences between twin members have been reported in literature by Emmons (1943), Bradley (1953), Crump & Ketner (1953), and Vogel (1964). Crump & Ketner interpreted discrepancies in their optical results as indicating differences of as much as 10% anorthite (Crump & Ketner, p. 42). Vogel (p. 617) investigated four grains that showed anomalous optics, or in his terminology, "internal scatter", where the composition plane measurements did not fit the twin law. Microprobe analysis disclosed composition differences of 2% An and 5% An in two cases and no difference in the other two. In this study, twin members within one compositional zone were examined and no consistent compositional differences between twin members were noted.

SUMMARY AND CONCLUSIONS

Optical techniques are, in general, severely restricted in their usefulness for determinations of composition and structural state of zoned plagioclase in the composition range from 40 to 80 mole % An. Of the possible methods of optically determining the composition, only the migration of twin axes and, possibly, the orientation of cleavage planes gives an acceptable correlation with microprobe results. As the location of a twin axis requires an indicatrix orientation from both twin members, and as care must be taken to assure that these readings come from zones of the same composition, only a limited number of determinations can be made on a single phenocryst. Consequently, it is difficult to fully delineate the zoning of a plagioclase phenocryst using this technique.

The presence of vicinal (010) composition planes precludes the use of this crystallographic feature either as a composition or as a structural state indicator. None of the remaining measurable optic features proved useful in either respect.

The scatter of twin axes determinations is such that the structural state cannot be reliably estimated at compositions greater than 60 mole % anorthite; only a general indication can be obtained at compositions between 40 and 60 mole % anorthite, the compositional range in which there is a greater separation of the migration curves.

The curves relating 2*V* and anorthite composition (Burri *et al.* 1967) represent averages of a spread of values. This study confirms that the spread of values is real and suggests that if 2*V* determinations and microprobe determinations are made on the same locations, it may be possible to unravel the complex relationships among composition, 2*V* and structural state.

It was brought to the attention of the authors by a reviewer of the manuscript that Schedler (1970) has published optical data for volcanic plagioclase in the range $Ab_{75}An_{25}$ to $Ab_{60}An_{40}$. Schedler found a scatter in 2*V* measurements similar to that presented in Figure 6, and a scatter in poles to (010) that is comparable to Figure 7 if the related measurements are averaged removing the effect of vicinal composition twin planes.

ACKNOWLEDGEMENTS

We wish to acknowledge the assistance of Dr. A. G. Plant, Geological Survey of Canada, for testing the effects of sample disintegration and checking for trace elements; Dr. J. Sutherland of the New Brunswick Research and Productivity Council for a preliminary survey of the analytical problem; and Dr. M. I. Corlett, Department of Geological Sciences, Queen's University, for providing microprobe facilities and assistance with the interpretation of the analytical data. D. Quigg prepared the diagrams and typed the manuscript. Funds for the project were supplied by a Geological Survey of Canada grant to Trembath and a National Research Council Bursary to Pringle.

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Manuscript received February 1973, emended April 1973.