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DETERMINATION OF THE COMPOSITION AND STRUCTURAL STATE OF PLAGIOCLASE WITH THE FIVE-AXIS UNIVERSAL STAGE[1]

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ABSTRACT

Anorthite content and structural state of plagioclase may be determined rapidly on the five-axis universal stage. Angles between optical and crystallographic directions are measured directly on the universal stage and are plotted on rectangular determinative graphs. Stereographic plotting, normally required in using both the Fedorow method and the standard five-axis method, is eliminated. The method is particularly useful for routine compositional determination of plagioclase from volcanic, hypabyssal, and epizonal and mesozonal plutonic environments, in which marked variation in shape and orientation of the indicatrix with structural state render extinction angle techniques inaccurate, and optical determination of structural state.

Determinative charts and procedures for resolving ambiguities are given.

INTRODUCTION

This paper describes a rapid and accurate method of determining the composition and structural state of plagioclase on the five-axis universal stage. The relatively simple sequence of universal-stage manipulations here outlined is adequate for routine work in the great majority of cases. The adaptation of rectangular determinative charts to the five-axis method increases both speed and accuracy.

The five-axis universal stage provides three horizontal and two vertical axes of rotation in addition to the microscope axis. The reader is referred to Emmons (1929, 1943) for a detailed description of the instrument. The following modification of Berek's (1924) nomenclature of axes is used in this paper.

	This paper	Emmons (1943)
Inner vertical axis	A_1	I. V.
Inner horizontal axis	A_{aux}	I. E-W
Middle horizontal axis	A_2	N-S
Outer vertical axis	A_3	O. V.
Outer horizontal axis	A_4	O. E-W
Microscope axis	A_5	M

OPTICAL PARAMETERS USED

The procedure here described is based on (a) the angles separating the principal axes X and Y and ⊥(010), the twin axis of the albite twin law (Fig. 1), (b) the angle between X and ⊥(001), and (c) 2V. Measurement of the orientation of the indicatrix with respect to ⊥(010) is probably

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the most commonly used method of determining the composition and structural state of plagioclase (Köhler, 1942a; 1942b; Marfunin, 1960; Slemmons, 1962a; 1962b; Uruno, 1963). The angle separating X and ⊥(001), when plotted versus the angle Y to ⊥(010) (Fig. 2), is also very useful for determining composition and structural state, particularly of albite and oligoclase. For the more sodic compositions, 2V (Fig. 3) is a sensitive indicator of structural state.

Measurement Procedure

By the procedure here described, the angles separating optical and crystallographic directions are measured directly on the universal stage and plotted on rectangular determinative graphs. No stereographic manipulations are required.

Orientation of the indicatrix. The optical indicatrix of the twinned sub-individual or cleaved grain is oriented by the standard five-axis procedure (Emmons and Gates, 1939; Emmons, 1943). The procedure here described requires that the indicatrix be oriented with either (a) Y

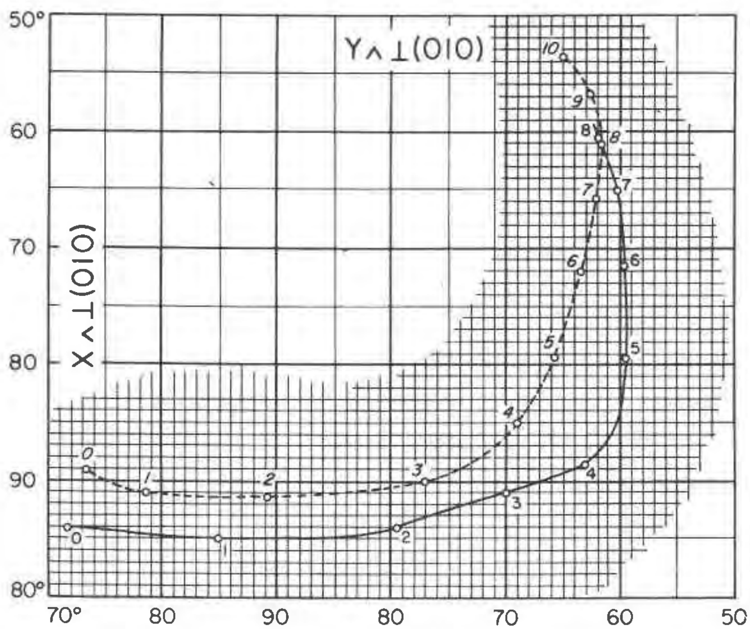

FIG. 1. Plot of X to ⊥(010) versus Y to ⊥(010) for plutonic (dashed line) and volcanic (solid line) plagioclase. Composition, from An_0 to An_{100}, is indicated by the numbers 0 to 10.

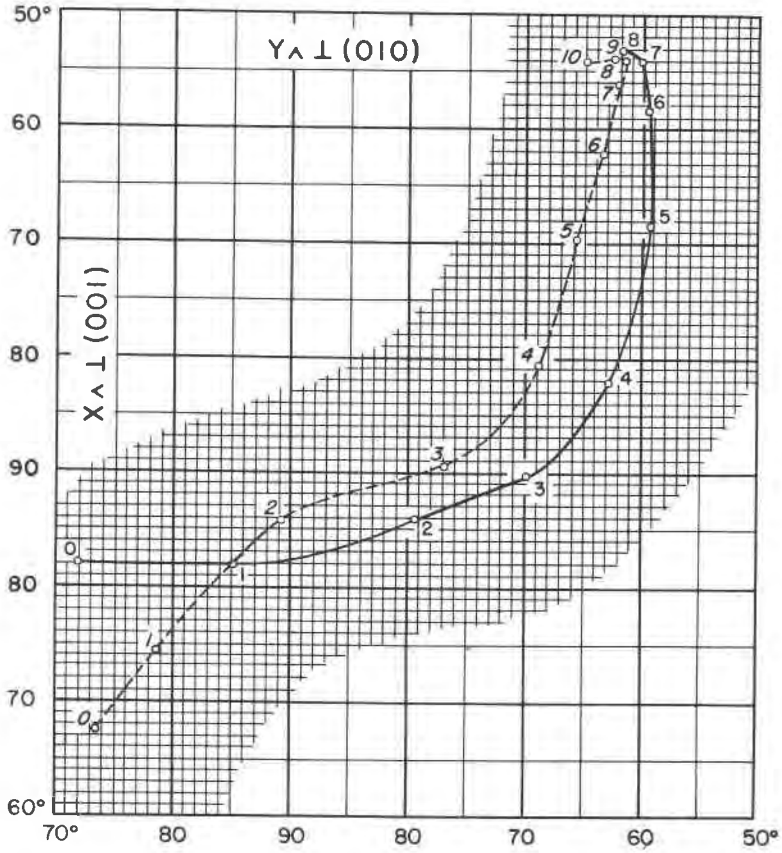

FIG. 2. Plot of X to ⊥(001) versus Y to ⊥(010) for plutonic (dashed line) and volcanic (solid line) plagioclase. Composition, from An_0 to An_{100}, is indicated by the numbers 0 to 10.

parallel to A_2 and X parallel to A_3 or (b) X parallel to A_2 and Y parallel to A_3. Because both X and Y lie at a relatively low angle to (010) in all but the most calcic plagioclases (Fig. 4), one of the two orientations will result if a grain having (010) at a high angle to the plane of the thin section is selected. If the angle X to ⊥(001) is to be measured, the indicatrix must be in orientation (a). As may be seen from Fig. 4, this orientation will result in most cases if a grain is chosen in which both (001) and (010) are at a moderately high angle to the plane of the thin section.

As grains having composition or cleavage planes at a high angle to the plane of the thin section are the most easily and accurately measured by three-axis techniques, there are few grains accessible to three-axis techniques that cannot be studied by five-axis methods.

Measurement of the angle X to ⊥(001). To measure the angle between X and ⊥(001), a (001) cleavage or composition plane is made vertical (parallel to A_5) and parallel to A_4 by rotation about A_3 and A_4 (Fig. 5). As X is vertical when the A_4 scale is set at zero, the amount of rotation about A_4 required to orient (001) is equal to the complement of the angle X to ⊥(001).

Measurement of 2V. The optic angle can be measured directly if Y is parallel to A_2. By rotation about A_3, Y is placed parallel to A_4 and is then placed in the 45° position with respect to the nicols by rotation about A_5. One, and preferably both, optic axes are then made vertical by rotation

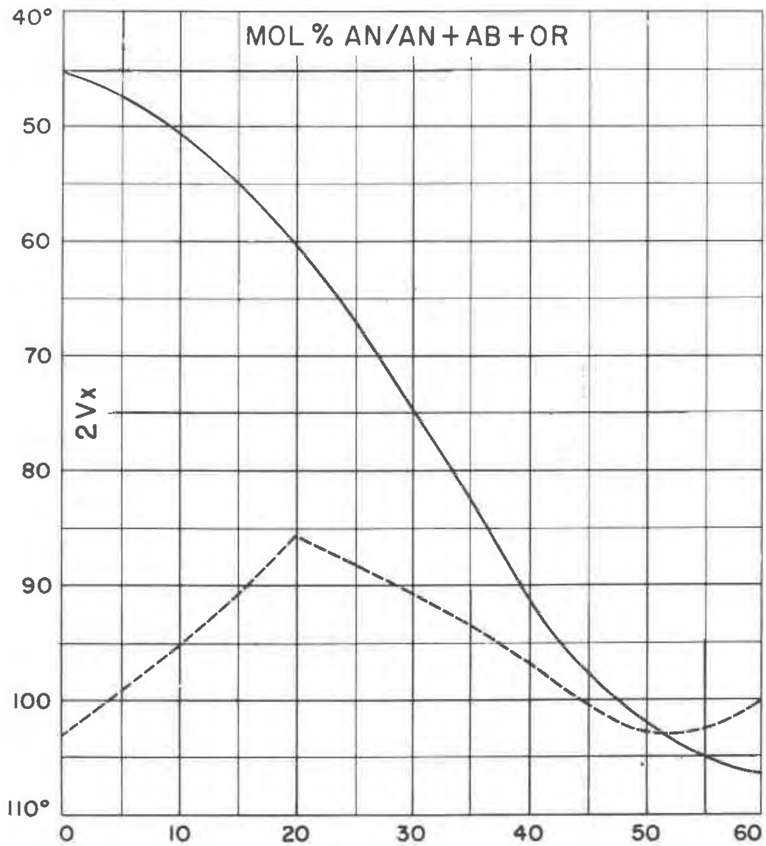

FIG. 3. Plot of $2V_x$ for plutonic (dashed line) and heated plutonic (solid line) plagioclase of sodic and intermediate composition. Data for plutonic plagioclase from Smith (1960); for heated plagioclase from Smith (1958).

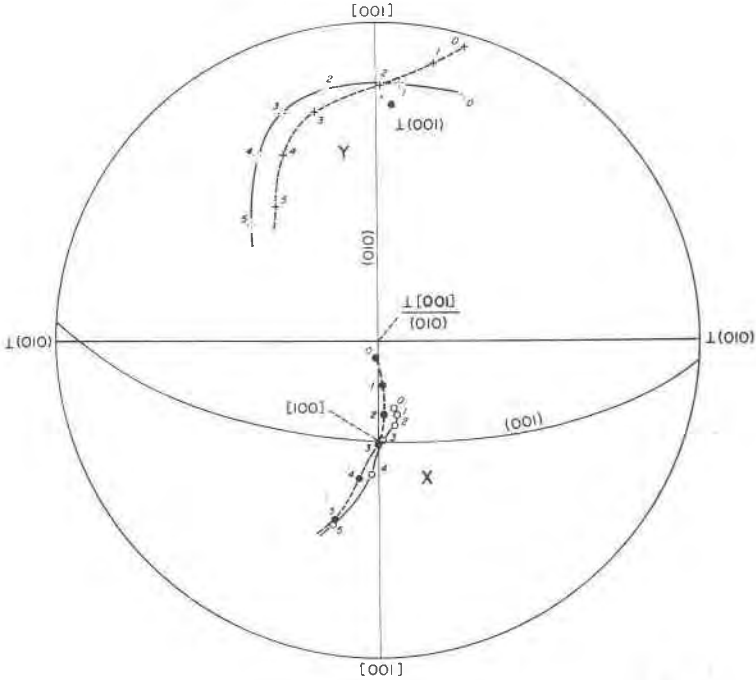

FIG. 4. Equal-area plot of the orientations of X (circles) and Y (crosses) for plutonic (dashed line) and volcanic (solid line) plagioclase of composition An_0 to An_{50}.

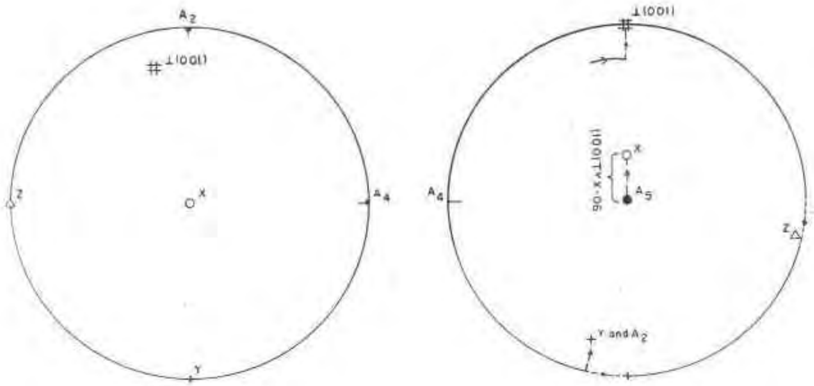

FIG. 5. Equal-area plot of the position of the indicatrix of plutonic albite An_0 (a) before and (b) after ⊥(001) has been made normal to A_4 and A_5 by rotation about A_3 and A_4.

about A_4, and V_x is read directly on the A_4 scale. Accuracy is increased if measurements are made in both 45 degree positions and averaged (Fairbairn and Podolsky, 1951).

If Y is vertical (parallel to A_5) the indirect Berek-Dodge method (Berek, 1923; 1924; Dodge, 1934) must be used. The principal axes X and Z are both placed 45 degrees from A_4 by rotation about A_3. By rotation in either direction about A_4, Y is inclined 50, 60, 70, or 75 degrees from A_5. The extinction angle from X′ to A_4 is then measured and 2V and sign are determined using Fig. 6.

Although the sensitivity of the extinction-angle reading increases with increased separation of Y and A_5, the magnitude of the errors introduced both by differences in the index of refraction of the crystal and the universal stage hemispheres and by strain in the hemispheres (Vogel, 1964a) increases rapidly with increase in the angle between A_1 and A_5. For this reason, rotation about A_4 should normally be limited to 50 or 60 degrees. If hemispheres with an index of refraction of approximately 1.554 are used, rotation corrections may be ignored for all but the most sodic and calcic plagioclases.

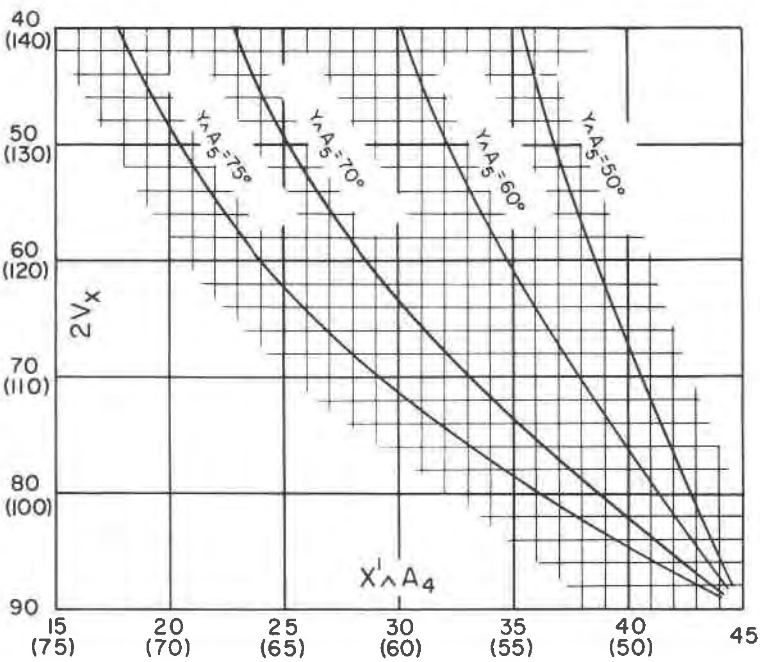

FIG. 6. Chart for determining 2V by means of the Berek-Dodge method when X and Z are both normal to A_3 and 45 degrees from A_4.

Direct determination of the orientation of the indicatrix with respect to $\perp$*(010)*. The orientation of the indicatrix with respect to $\perp(010)$ may be determined directly on the universal stage in one operation requiring no intermediate graphical construction.[2]

By rotation about A_2 and A_3, $\perp(010)$ is placed parallel to A_4 (Fig. 7) by the standard five-axis procedure. As X or Y remains parallel to A_2 during

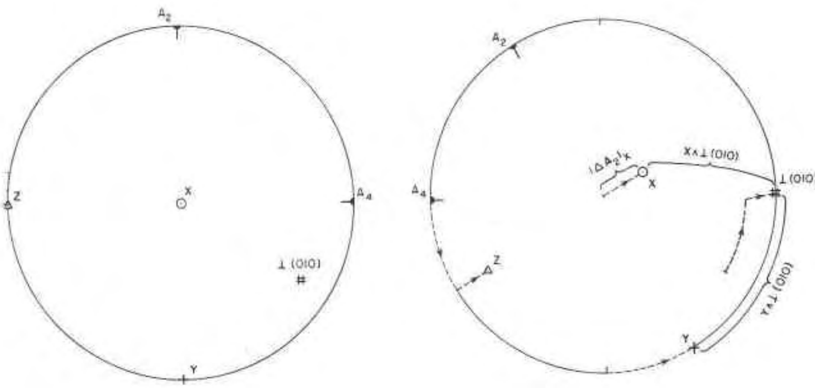

FIG. 7. Equal-area plot of the position of the indicatrix of volcanic labradorite (a) before and (b) after $\perp(010)$ has been made parallel to A_4 by rotation about A_2 and A_3.

the orientation of $\perp(010)$, the angles between the principal axis parallel to A_2 and $\perp(010)$ can be read directly on the A_3 scale.

Rotation about A_2 is necessary to place $\perp(010)$ parallel to A_4. If the angle Y to $\perp(010)$ is measured directly on the A_3 scale, the amount of rotation is termed $|\Delta A_2|_x$; if X to $\perp(010)$ is measured directly, the amount of rotation is termed $|\Delta A_2|_y$. The magnitude of $|\Delta A_2|_x$ and $|\Delta A_2|_y$ depends solely on the angles X to $\perp(010)$ and Y to $\perp(010)$. The relations are given by the equations:[3]

$$\cos X \wedge \perp(010) = \sin Y \wedge \perp(010) \cdot \sin |\Delta A_2|_x \quad (1)$$

$$\cos Y \wedge \perp(010) = \sin X \wedge \perp(010) \cdot \sin |\Delta A_2|_y \quad (2)$$

The relation for $|\Delta A_2 \Delta_x$ is shown stereographically on Fig. 7; an

[2] Zavaritsky (1942, 1943) has described a somewhat similar method of directly determining the orientation of the indicatrix with respect to $\perp(010)$ or $\perp(001)$. His method utilizes A_3 and A_4 to orient the crystallographic direction. This is not as accurate as the use of the axes A_2 and A_3, because the grain cannot be rotated about A_4 during the orientation of the crystallographic direction.

[3] The angle Z to $\perp(010)$ may also be calculated using the equations:

$$\cos Z \wedge \perp(010) = \sin Y \wedge \perp(010) \cdot \cos |\Delta A_2|_x$$

$$\cos Z \wedge \perp(010) = \sin X \wedge \perp(010) \cdot \cos |\Delta A_2|_y$$

analogous relation holds for $|\Delta A_2|_y$. From An_0 to An_{40} $|\Delta A_2|$ is, for all practical purposes, equal to the complement of X to $\perp(010)$ or Y to $\perp(010)$. From An_{40} to An_{100} $|\Delta A_2|$ becomes progressively greater than the complement, exceeding it by approximately 20 per cent in the range An_{80-100}.

Reduction of $|\Delta A_2|_x$ and $|\Delta A_2|_y$ to X to $\perp(101)$ and Y to $\perp(010)$, respectively, is not required for routine plagioclase study. Since the orientation of the indicatrix with respect to $\perp(010)$ is completely defined by the angle pairs Y to $\perp(010)$, $|\Delta A_2|_x$, and X to $\perp(010)$, $|\Delta A_2|_y$, determinative curves can be constructed by plotting $|\Delta A_2|_x$ versus Y to $\perp(010)$ (Fig. 8) and X to $\perp(010)$ versus $|\Delta A_2|_y$ (Fig. 9) in the rectangular coordinate method of Turner (1947).

Alternatively, the angles X to $\perp(010)$ and Y to $\perp(010)$ may be computed quickly on a slide rule equipped with a sine scale.

Determination of Composition and Structural State

Composition is determined by plotting $|\Delta A_2|_x$ versus Y to $\perp(010)$ on Fig. 8 or X to $\perp(010)$ versus $|\Delta A_2|_y$ on Fig. 9. In addition, for sodic plagioclase, X to $\perp(001)$ is plotted versus Y to $\perp(010)$ (Fig. 2). This plot may be used also to check the composition of more calcic plagio-

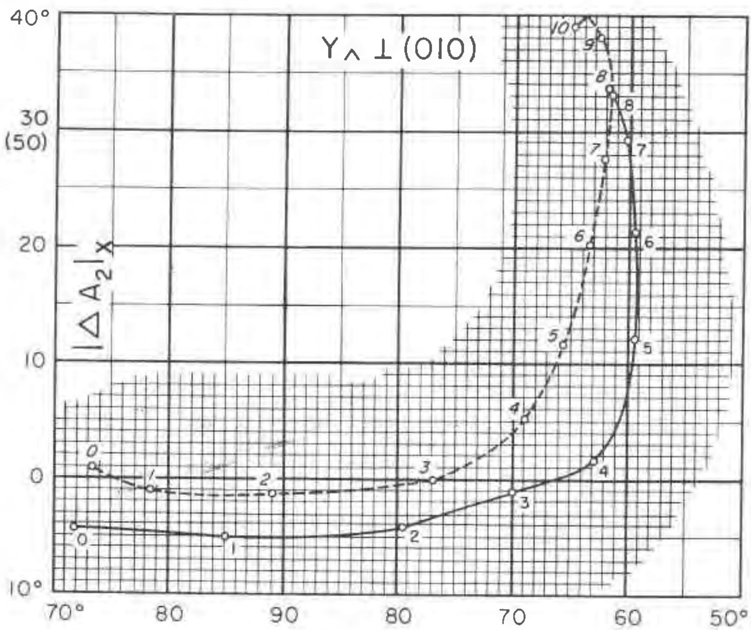

FIG. 8. Plot of $|\Delta A_2|_x$ versus Y to $\perp(010)$ for plutonic (dashed line) and volcanic (solid line) plagioclase. Composition, from An_0 to An_{100}, is indicated by the numbers 0 to 10.

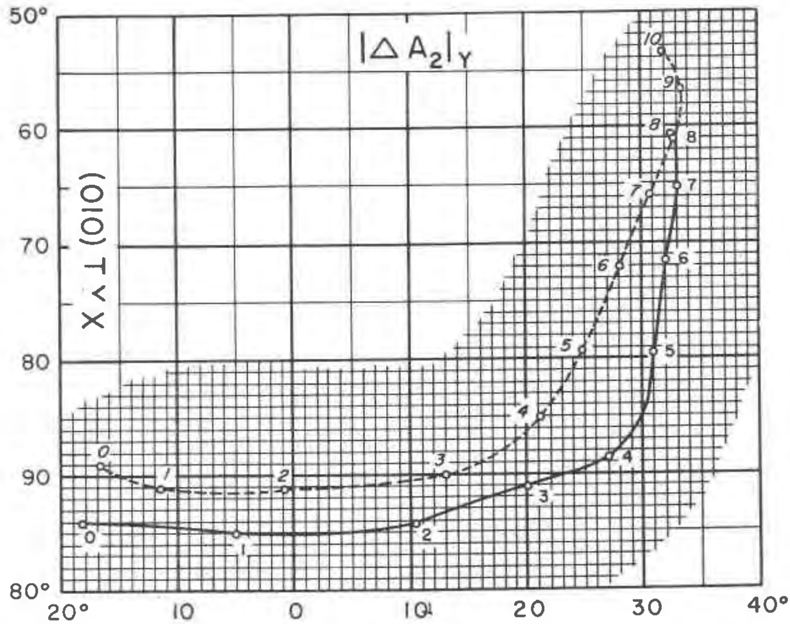

FIG. 9. Plot of X to $\perp(010)$ versus $|\Delta A_2|_Y$ for plutonic (dashed line) and volcanic (solid line) plagioclase. Composition, from An_0 to An_{100}, is indicated by the numbers 0 to 10.

clases. If the data fall on either the plutonic curve or the volcanic curve, interpolation is made between the points which represent 10 per cent increments of An content. If the point falls between, or slightly outside of the curves, composition is determined by constructing a straight line through the point that intersects both the plutonic and volcanic curves at the same An value.

Structural state is determined by the degree to which the plotted data approach the plutonic or volcanic curves. The position of $\perp(010)$ with respect to the indicatrix is probably the most sensitive of all optical indicators of structural state for plagioclase which is more calcic than approximately An_{35}; for the more sodic compositions 2V (Fig. 3) is most sensitive. The plot of X to $\perp(001)$ versus Y to $\perp(010)$ (Fig. 2) is a sensitive indicator of structural state for albites. Although most plagioclases will plot near either the plutonic curve or the volcanic curve, plagioclases having intermediate optic orientations are not uncommon (Muir, 1955). As the optics of plagioclase from a single rock often show some scatter normal to the curves, several grains must be measured to obtain a reliable estimate of the average structural state of the plagioclase in a rock.

For sodic plagioclase, the composition indicated by a given value of Y to $\perp(010)$ is greatly affected by small errors in X to $\perp(010)$. If the value of structural state determined from the orientation of the indicatrix disagrees with the value determined by the more sensitive 2V measurement, the value of structural state reflected by the optic angle should be taken into account in estimating composition.

The plutonic and volcanic curves on Figs. 1, 2, 4, 8, and 9 are average curves constructed from data obtained from analyzed feldspars from plutonic and volcanic environments. The data are from Slemmons (1962a, Table 3).[4]

More precise data on the optical orientation of plagioclase continually become available (Carmichael, 1960; Gay and Muir, 1962; Uruno, 1963; Burri *et al.*, 1962; Vogel, 1964b). The worker is urged to construct determinative curves from the best data that are available.

Resolving Ambiguities

The ambiguities inherent in the use of X to ⊥(010), Y to ⊥(010), and X to ⊥(001) as determinative parameters may in most cases be resolved during the course of measurement if (001) can be made vertical by rotation about A_4.

Values of Y to ⊥(010) from 70° to 90° may represent either of two compositions. The correct one may be determined by noting if Y lies within the acute or within the obtuse angle formed by (010) and (001). For plutonic and volcanic plagioclase more sodic than An_{20} and An_{13}, respectively, Y will lie within the obtuse angle formed by (010) and (001), whereas, for more calcic compositions Y will lie within the acute angle. The relative relief of the grain against the mounting media may also be used to determine the correct composition.

In most instances the position of Y with respect to (010) and (001) shows immediately on which side of the ordinate X to ⊥(001) = 90° (Fig. 2) the measured value of X to ⊥(001) is to be plotted.

In sodic plagioclase X is very close to (010), equivalent to the ordinate $|\Delta A_2|_x = 0$ on Fig. 8. The side of this line on which $|\Delta A_2|_x$ is to be plotted may be determined by qualitatively noting the relationship of X

[4] Slemmons (oral communication, 1963), in collecting data for his curves, did not discriminate between data given in mol per cent An and those given in weight per cent An. However, the data of Becke (1906), cited by Duparc and Reinhart (1924), are given in mol per cent, and the analyses of Smith (1960), on which Slemmons' plutonic curves are almost wholly based, are also given in mol per cent An/An+Ab+Or. Likewise, the analyses of the Linosa feldspars (Köhler, 1942a) were given by Ernst and Neiland (1934) in mol per cent An/An/+Ab+Or, and the index of refraction curves of Smith (1958), used to adjust the data of Kano (1955), are in mol per cent An/An+Ab+Or. The positions of An_0, An_{10}, and An_{20} for plutonic plagioclase given on Plate 2 of Slemmons (1962a) do not agree with their positions on Fig. 4 of Slemmons (1962b). The latter orientation, which agrees with that of the classic plagioclase migration curves, has been used in constructing the figures in this paper.

to (010) and (001) (Fig. 4). The position of X relative to (010) and (001) is obtained from the sense of the rotations about A_2 and A_4 made to place (010) and (001), respectively, vertical. For albite, sodic oligoclase, and for calcic oligoclase and sodic andesine having Y to ⊥(010) greater than approximately 82 degrees, $|\Delta A_2|_x$ plots above the line $|\Delta A_2|_x=0$ if X lies within the acute angle formed by (010) and (001), and below the line if X lies within the obtuse angle.

For compositions near An_{30}, however, the position of X relative to [100] and ⊥[001] /(010) must be qualitatively determined before $|\Delta A_2\Delta_y$ is plotted versus Y to ⊥(010), or X to ⊥(001) is plotted versus Y to ⊥(010). For such compositions X is nearly parallel to (010). Thus the projection of X on (010) is virtually parallel to A_3 after ⊥(010) has been made parallel to A_4. The direction [100] is the line of intersection of (010) and (001). The direction ⊥[001]/(010) may be determined if a Carlsbad or albite-Carlsbad twin is present in the individual grain being studied. The interference tints in the Carlsbad or albite-Carlsbad twinned subindividuals will match when ⊥[001]/(010), which lies 26° from [100], is made vertical by rotation about A_4.

The measured value of $|\Delta A_2|_x$ is plotted above the ordinate $|\Delta A_2|_x=0$ if X lies to the left of (010), *as oriented in Fig. 4*, and below the ordinate if X lies to the right of (010). The measured value of X to ⊥(001) is plotted above the ordinate X to ⊥(001) = 90° if the projection of X on (010) lies within the acute angle formed by [100] and ⊥[001]/(010), and below the ordinate if X lies within the obtuse angle.

Detailed Outline of Measurement Procedure

In the following section the measurement procedure is outlined sequentially. A knowledge of basic universal stage procedure (Haff, 1942; Wahlstrom, 1960) is assumed.

Orientation of indicatrix.

(1-A) Select a grain with (010) at an angle of more than 60°, and with (001) preferably at an angle of more than 50°, to the plane of the thin section.

(1-B) Lock A_2 exactly parallel to A_4.

(1-C) Place the principal axis lying nearest to (010) in one twin individual exactly parallel to A_2 by rotation about A_1 and A_{aux}. This principal axis will be either X or Y. It is not necessary to orient the principal axes in one of the albite-twinned individuals that will be used to orient ⊥(010). Rather, one subindividual related to these units by a twin law having (010) as the composition plane may be used.

(1-D) Lock A_1 and A_{aux} having Y or X parallel to A_2; unlock A_3 and rotate 90° about A_3 to the zero position; lock A_3.

(1-E) Place Z parallel to A_4 by rotating about A_2; lock A_2. Record the reading on the A_2 scale.

Measurement of X to $\perp$*(010)*

The angle X to $\perp$(010) may be measured if Y and Z have been made parallel to A_2 and A_4, respectively.

(2) Place a (001) cleavage or composition plane parallel to A_4 and A_5 by rotation about A_3 and A_4. Record the reading on the A_4 scale, which is 90°——X to $\perp$(001).

Measurement of 2V

If Y has been made parallel to A_2 in the orientation procedure, 2V is measured directly.

(3-A) Unlock A_3 and place A_2 parallel to A_4 by rotation about A_3; lock A_3.

(3-B) Having A_5 in the 45° position, make one, or if possible, both optic axes vertical by rotation about A_4. Since X is vertical when A_4 is set at zero, V_x is equal to the amount of rotation about A_4 required to reach the optic axis. Repeat in other 45° position and average values obtained.

If Y has been made parallel to A_3, 2V is determined indirectly by the Berek-Dodge method.

(4-A) Unlock A_3 and place X and Z 45 degrees from A_4 by rotation about A_3; lock A_3.

(4-B) Place Y 50, 60, 70, or 75 degrees from A_5 by rotation in either sense about A_4; lock A_4.

(4-C) Measure the extinction angle from X′ to A_4; determine 2V and sign using Fig. 6.

Measurement of X to $\perp$*(010) and Y to* $\perp$*(010).*

(5-A) Unlock A_3; place $\perp$(010) parallel to A_4 by rotation about A_2 and A_3.[5]

(5-B) Read the angle separating A_2 and A_4, which is either Y to $\perp$(010) or X to $\perp$(010), directly on the scale of the A_3 axis. Record the reading on the scale of the A_2 axis. The parameter $|\Delta A_2|$ is the absolute value of the difference between this reading and the reading recorded in step (1-E).

Resolving ambiguities.

(6-A) Make (001) vertical by rotation about A_4 and qualitatively note the position of Y with respect to (010) and (001).

(6-B) For sodic plagioclases qualitatively note the position of X with respect to (010) and (001) from the sense of rotation about A_2 and A_4 required to make (010) and (001), respectively, vertical.

(6-C) If necessary, qualitatively determine the position of X with respect to [100] and $\perp$[001]/(010).

Applications, Advantages, Precision and Accuracy

The procedure here described is particularly useful for routine determination of composition and for determination of structural state.

Extinction angle techniques (Rittmann, 1929; Bordet, 1963), which give a single parameter by which to estimate composition, are not accurate for determining the composition of plagioclase from volcanic,

[5] Either a (010) cleavage or a (010) composition plane may be used. Because they are more regular, the composition planes of albite twins are preferable to those of Carlsbad or albite-Carlsbad twins. The normal to (010) may also be oriented by adjusting the crystal until the interference tints in adjacent albite-twinned subindividuals match exactly throughout a wide rotation about A_4. Comparison should be made in both the zero and 45° positions; the insertion of a first-order red compensator sometimes increases the sensitivity in the 45° position. This method of orientation is very precise.

hypabyssal, and epizonal and mesozonal plutonic rocks; the structural state of the plagioclase cannot be accurately inferred from the presumed cooling history of the rock. Errors of as much as 13 per cent anorthite may result, for example, by applying extinction angles measured on volcanic plagioclase in the zone ⊥(010) to curves prepared for plutonic plagioclase.

The angles measured in the procedure here described, X to ⊥(010), Y to ⊥(010), X to ⊥(001), and 2V are those most useful in determining the composition and structural state of plagioclase. If the position of ⊥[001]/(010) is determined quantitatively, these four angles completely determine the optical orientation of the plagioclase. Little additional data useful in determining composition or structural state would be obtained by a more complete study.

The main advantage of the method here described over other universal stage methods is its speed. It is approximately twice as fast as the classic Fedorow method as modified by Turner (1947; Slemmons, 1962a), and because stereographic plotting is eliminated, it is somewhat faster that the five-axis method as described by Emmons. In addition, the use of rectangular graphs greatly facilitates the recording and presentation of orientation data (*cf.* Vogel, 1964b, Fig. 10). In the five-axis method the orientation of the indicatrix is not double-checked by plotting. This disadvantage is offset, at least in part, by the elimination of plotting errors.

The five-axis universal stage is best adapted to measuring the angles between the normals to (010) and (001) and the principal axes of the indicatrix. Because plotting errors are eliminated, these angles can be determined more accurately by the five-axis method than by three-axis methods in which the crystallographic directions are located by direct measurement.[6] Where both sets of twinned lamellae are properly oriented and sufficiently wide to be accurately measured, the Fedorow procedure, in conjunction with careful plotting on an accurate net, is potentially slightly more accurate.

The angles separating the axes of complex and parallel twins from the principal axes of the indicatrix cannot be measured directly on the five-axis stage; a rather complex sequence of measurement and stereographic

[6] Doubt has been cast both on the usefulness of the optical orientation of plagioclase as a petrologic tool and, in the minds of some workers, on the accuracy of the five-axis method of indicatrix orientation by the abnormally large scatter of the data obtained by workers using the method (Crump and Ketner, 1953; Emmons *et al.*, 1960). This scatter, however, appears to be in large part the result of using grain mounts prepared from rather fine-grained material (Vogel, 1963). The present writer has found the five-axis method surprisingly precise. Even in routine work on material of only moderate quality, the scatter of points obtained from measuring 10 or so grains in a thin section of either volcanic or deep-seated plutonic rock is in most cases less than 2° measured normal to the migration curves.

plotting is required. Moreover, the method by which a parallel or complex twin axis is oriented on the five-axis stage (Emmons and Gates, 1939; Emmons, 1943) is probably relatively inaccurate. For these reasons, the classic Fedorow method (Nikitin, 1936; Haff, 1942; Slemmons, 1962a) is preferred for measuring the Köhler angles of complex and parallel twins.

The location of the composition points on the plutonic curves in Figs. 1, 2, 4, 8 and 9 is based on fairly abundant data, and, therefore, compositional determinations for plutonic feldspars should be accurate to approximately ±3 per cent An. The location of the composition points on the volcanic curve, however, is based on very scanty data, and compositional determinations for feldspar plotting on or near the volcanic curves at best are probably accurate to only ±5 per cent An.

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