THE ALKALI FELDSPARS. III. AN OPTICAL AND X-RAY STUDY OF HIGH-TEMPERATURE FELDSPARS

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Abstract

A series of high-temperature alkali feldspars has been studied both optically and by x-rays. Almost all the specimens appear under the microscope to be optically homogeneous, but x-ray studies show that those in the composition range $Or_{60}Ab_{40}$–$Or_{25}Ab_{75}$ are unmixed to some extent. Single-crystal x-ray photographs of the unmixed specimens enable the separate phases to be studied, and in some cases the reciprocal lattice angles α^* and γ^* of the sodium feldspar phase can be measured. The values obtained for these angles correspond well with those of single-phase, high-temperature sodium-rich feldspars.

The effect on the mean value of the optic axial angle of heating at 900° C. for 24 hours has been studied and reveals a possible discontinuity in the series near the composition $Or_{60}Ab_{40}$, which has not been previously noted.

Introduction

It has thus far proved impossible to synthesize alkali feldspars with properties corresponding to those of the natural low-temperature[1] minerals, and therefore the complete phase relations in the system $KAlSi_3O_8$–$NaAlSi_3O_8$ have not been determined experimentally. However, field studies supplemented by more detailed laboratory investigations of the natural minerals may make it possible to deduce the sub-solidus relations in this system. Because of the complexity of these relations it has been found necessary to treat separately feldspars from differing geologic environments, and the optical and x-ray investigations reported in this paper are part of this systematic study.

Paper I of this series was devoted to a study of the orthoclase-microperthites, the name generally given to optically monoclinic feldspars

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[1] The use of the term low-temperature implies that, although the feldspar may have crystallized initially at high temperature, it has cooled sufficiently slowly to invert to a low-temperature form. Rapid cooling in a volcanic rock would quench the feldspar in its high-temperature form.

from supposedly moderate temperature environments. The present paper is concerned with feldspars from high-temperature environments and consists of an optical and *x*-ray study of twenty chemically analyzed or partially analyzed specimens.[2] The first-named author is responsible for the optical studies and part of the *x*-ray work, while the contribution of
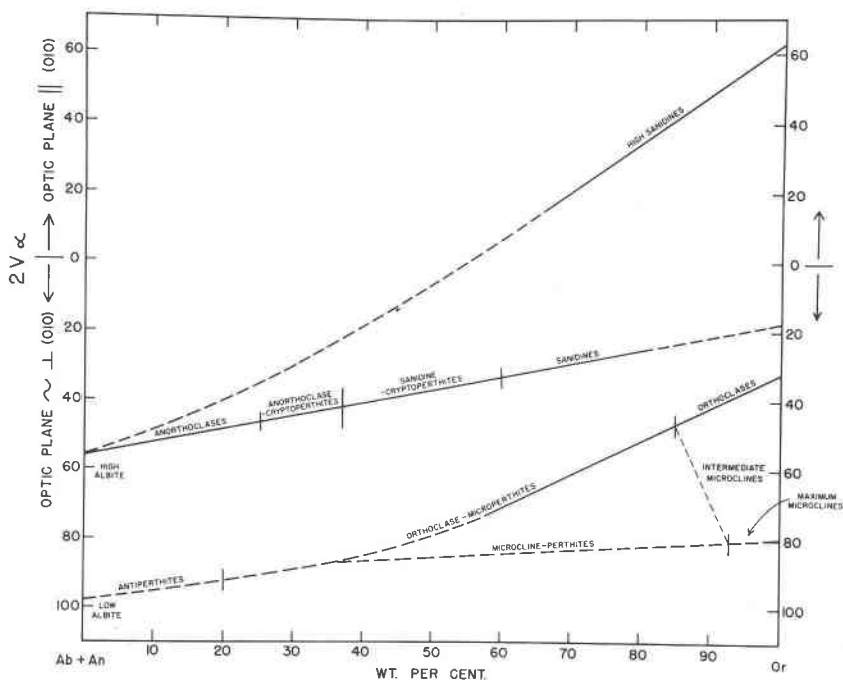

Fig. 1. Diagram showing the relation between optic axial angle and chemical composition in the four series of alkali feldspars (modified after Tuttle, 1952). The parts of each series in which homogeneous specimens occur are separated from those in which the specimens are generally unmixed.

the second author is mainly in the interpretation of the single-crystal *x*-ray photographs.

Tuttle (1952) divided the alkali feldspars into four series on the basis of the size of the optic axial angle and the orientation of the optic plane for a known chemical composition. Tuttle's curves relating optic axial angle with chemical composition have been adopted to define four series of feldspars and a slightly modified form of Tuttle's diagram, which was

[2] Two of the specimens studied here (Nos. 16 and 20) are not identical with those on which the chemical analyses were performed but were collected from the same localities as the analyzed samples.

given in paper I of this series, is reproduced again here (Fig. 1) since it is considered the only satisfactory method of classifying the alkali feldspars. Most of the specimens studied belong to the sanidine-anorthoclase-high-temperature albite series. When homogeneous the monoclinic members of this series are known as sanidines and the triclinic members are anorthoclases.[3] The vertical line in Fig. 1 at the composition $Or_{37}(Ab+An)_{63}$ separates the monoclinic from the triclinic feldspars.

The refractive indices of the alkali feldspars vary very slightly both with chemical composition and from one form to another. If the refractive indices are to be used in a study of the alkali feldspars they must be determined with much greater accuracy than is normally achieved.[4] In addition, the small amounts of other elements present, chiefly calcium, affect the refractivity to some extent. Spencer (1937) showed that heating orthoclase-microperthites at 850° C. may cause changes in refractive indices of as much as 0.002 with only very slight or no change in optic axial angle. It is clear from the work of Spencer (1937) and Tuttle (1952) that the most useful optical property for a study of the alkali feldspars is the optic axial angle.

Dr. O. F. Tuttle (personal communication) found that many natural sanidines and anorthoclases showed considerable variation in optic angle in different crystals from the same rock specimen. He also noted that this variation was in some cases reduced by heating the sample at 900° C. for a few hours. To make a more careful study of these effects, values of the optic angle were determined on a series of specimens both in their natural state and after heating at 900° C. for about 24 hours. At least five crystals from each sample were examined to obtain some indication of the variation in optic axial angle both in the heated and the unheated samples.

Many of the specimens studied showed a pale blue schiller in cleavage fragments, although under the microscope they appeared optically homogeneous. X-ray powder and single-crystal studies were made of most of the specimens to determine whether or not they were unmixed.

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[3] A great deal of confusion exists in the literature as to the precise meaning of the term anorthoclase. It is proposed to use the term here to denote a high-temperature alkali feldspar, more sodium-rich than $Or_{37}(Ab+An)_{63}$, which when heated inverts from triclinic to monoclinic symmetry and reinverts to the triclinic form even on rapid quenching. This definition makes possible a distinction between potassium-bearing albites and oligoclases on the one hand and calcium-bearing alkali feldspars on the other hand (see MacKenzie, 1952).

[4] The accuracy of ± 0.001, quoted by some workers for their refractive index determinations can be obtained only if very careful attention is given to control of temperature. In the sanidine-anorthoclase-high-temperature albite series the total change in n_β from $KAlSi_3O_8$ to $NaAlSi_3O_8$ is about 0.011 (Tuttle, 1952).

In all cases the unmixed specimens could be rendered homogeneous by heating at 700° C. for an hour or two and in some cases a few minutes were sufficient. In this respect the high-temperature feldspars differ from the orthoclase-microperthites of intermediate composition, some of which require prolonged heating at 1050° C. before they can be homogenized. The single-crystal x-ray photographs permit a more detailed study of the separate phases than do the powder photographs. Measurements made from the single-crystal photograph enable a high-temperature sodium feldspar phase to be distinguished readily from a low-temperature sodium feldspar phase and it has been found that all the sanidine- and anorthoclase-cryptoperthites studied here have a high-temperature sodium feldspar phase, as might be expected. Orthoclase-microperthites generally have a sodium feldspar phase corresponding to low-temperature albite (MacKenzie and Smith, 1955).

Methods

X-ray powder methods. A Norelco high-angle x-ray diffractometer was used for the powder diffraction studies. From the x-ray patterns it is possible to determine whether or not a feldspar is unmixed, since unmixed specimens generally have two or more peaks between $2\theta = 21°$ and $22°$ (approx.) (CuKα radiation) representing the $\bar{2}01$ reflections for the separate phases (Bowen and Tuttle, 1950).[5] Unmixed specimens were homogenized by heating at 900° C. for approximately 24 hours and then the orthoclase content of each specimen was determined from the spacing of the $\bar{2}01$ reflection (Bowen and Tuttle, 1950). The position of the $\bar{2}01$ reflection was determined using a vein quartz from Lake Toxaway as an internal standard. The $10\bar{1}0$ reflection of quartz at $2\theta = 20.876°$ (CuKα) is suitable for specimens having more than 20% by weight of sodium feldspar in their bulk composition; for more potassium-rich specimens the $\bar{2}01$ reflection of a sample of Amelia albite, Virginia, previously calibrated against quartz was used. The scanning of the x-ray diffractometer was set to give a change in 2θ of 0.25° per minute, and the recorder produced a chart in which 2 inches was equivalent to 1° in 2θ. The part of the x-ray diffraction pattern required was scanned four times, and the mean value of the angle between the $\bar{2}01$ reflection of the feldspar and the $10\bar{1}0$ reflection of quartz was determined. In the case of unmixed specimens the positions of the $\bar{2}01$ reflections for the separate phases

[5] Tuttle (1952) found that some cryptoperthites show only one $\bar{2}01$ reflection in the powder diffraction pattern, but Laves (1952) noted that this does not necessarily mean that this or other reflections might not be observed by single-crystal techniques. Very slight unmixing may not be detected from the powder pattern and may only be revealed by single-crystal methods.

were also obtained where possible. The measurements were reproducible to $\pm 0.02°$ in 2θ.

From the powder diffraction patterns the symmetry of homogeneous feldspars of composition near $Or_{37}Ab_{63}$ can be readily determined since the 111 and 1$\bar{1}$1 reflections are coincident for monoclinic symmetry and separate for triclinic symmetry (Donnay and Donnay, 1952).

X-ray single-crystal methods. Single-crystal x-ray oscillation photographs were made from most of the specimens, using a Unicam oscillation camera. Each photograph was taken in the same orientation so that they could be readily compared. Although many alkali feldspars consist of two phases, morphologically they appear as single monoclinic crystals, and the morphology may be used for alignment of the crystals in the x-ray camera. A b-axis oscillation photograph with the (001) cleavage set parallel to the x-ray beam in the center of a 15° oscillation arc was chosen as the standard orientation. Full details of the interpretation of the oscillation photographs and of a rapid method of determining the reciprocal lattice angles α^* and γ^* of the sodium feldspar phase are given in paper II of this series (Smith and MacKenzie, 1955).

Unmixing can be readily detected by the appearance of two or more reflections where a homogeneous monoclinic feldspar would show single reflections. If the unmixing is very slight, indistinct streaks on the x-ray photographs parallel to the layer lines are associated with each reflection.[6] Because of the simplicity of both the crystal setting and the interpretation of the x-ray photograph, the taking of single-crystal photographs has been used as a routine operation in the study of the feldspars.

Optical methods. Optical determinations were made on a Leitz five-axis universal stage. The conoscopic method was used to locate the postion of the optic plane and measure the size of the optic angle. The interference figure was observed using the Bertrand lens, and to obtain the full aperture of the objective a Leitz U. T. 5 sub-stage condenser was employed. The optic angle measurements were made in sodium light, except in a few cases where the optic angle was very small and the greater intensity obtainable with white light was necessary. In every case the optic angle was measured directly, the crystal fragments having been selected so that each showed the points of emergence of both optic axes and both cleavages well developed, i.e. the a crystallographic axis was approximately vertical. Both 45° positions were used in measuring the size of the optic angle, as proposed by Fairbairn and Podolsky (1951),

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[6] Crystals removed from thin sections frequently give diffuse streaks centered on the sharp reflections. These streaks are the result of misorientation of the surface layers caused by grinding and may be distinguished from streaks due to unmixing, since the former lie on curves of constant θ.

and there is no doubt that this precaution reveals an inaccurate setting of the optic plane. Readings on the outer E–W axis of the universal stage were made three times in each of the 45° positions and the mean value was taken. Optic axial angle measurements given here are reproducible to ±0.5°.

A parting approximately perpendicular to the *a*-axis is frequently developed in these high-temperature feldspars and this makes it possible to select crystals which are parallel sided and lie flat on the glass slide although both cleavages are vertical. Crystals of the order of 0.1 mm. in thickness or greater yield very good interference figures on the universal stage.

Unmixing in Natural High-Temperature Alkali Feldspars

Table 1 gives a list of the specimens studied with their compositions as calculated from chemical analyses.[7] The orthoclase content of each specimen after homogenization, as obtained from the $\bar{2}01$ spacing, is given for comparison with the results obtained from chemical analyses. In the case of unmixed specimens the orthoclase contents of the separate phases, as obtained from the $\bar{2}01$ spacings, are also given.

All the specimens studied here which contain between 60% and 25% of potassium feldspar in their bulk composition are unmixed to some extent as found in nature; two specimens of composition about $Or_{23}(Ab+An)_{77}$ are also unmixed. It may be noted here that in the low-temperature feldspars it was found that specimens ranging in composition from 84.5% to 19.5% of potassium feldspar were unmixed (MacKenzie and Smith, 1955). In the anorthoclase from Quatre Ribeiras, Azores (No. 15), which was almost certainly derived from a glassy rock (Fouqué, 1883), and in specimen S. C. XX (No. 6) from an obsidian in the San Juan Mountains (Larsen and Larsen, 1938) very slight unmixing was detected only from the single-crystal photographs. The anorthoclase from Grande Caldeira, Azores (No. 14), showed three $\bar{2}01$ reflections in the powder diffraction pattern, indicating the presence of three phases, one of which was found to correspond to the bulk composition of the specimen. This suggests either that the individual phenocrysts are only partially unmixed or, more likely, that some phenocrysts have unmixed more readily than others. The difference in properties of individual crystals from the same rock specimen has been noted frequently in the study of feldspars and will be mentioned further in this paper.

The graph relating the spacing of the $\bar{2}01$ planes with the orthoclase content of alkali feldspars was constructed by Bowen and Tuttle (1950)

[7] All compositions are given as weight % of orthoclase, albite and anorthite, and where necessary celsian.

for a series of synthetic feldspars. Comparison of the orthoclase contents of these natural feldspars as given by chemical analyses with the values obtained using the curve of Bowen and Tuttle, reveals that in fourteen out of twenty specimens the x-ray results are within 2% of those given

TABLE 1. CHEMICAL COMPOSITION OF FELDSPARS EXAMINED

	Chemical comp.			Comp. from x-ray method			Notes on powder diffraction patterns of unmixed specimens
				Bulk Or content	Separate phases		
	Or.	Ab.	An.		Or.	Or.	
1. Eifel	77.8	21.3	0.9	82.0	homogeneous		
2. Kokomo	72.5	24.0	3.5	76.5	homogeneous		
3. Alder Creek	72.0	25.0	3.0	72.5	homogeneous		
4. Mineral Creek	66.7	30.8	2.5	65.5	homogeneous		
5. Grant County	59.0	40.7	0.3	60.0	82.0	0	
6. S. C. XX	62.0	35.0	3.0	59.5	slight unmixing		
7. Pine Creek Mesa	61.2	36.0	2.8	57.5	72.0	—	No $\bar{2}01$ reflection for sodium phase
8. Nathrop	60.4	37.5	2.1	57.5	81.5	0	
9. Sparling Gulch	49.2	47.0	3.8	48.0	87.0	0	
10. Spring Creek	44.3	52.2	3.5	44.0	86.0	0	
11. Mitchell Mesa	42.9	56.3	0.8	44.0	92.0	0	
12. Old Baldy Mt.	41.5	55.5	3.0	42.5	95.0	0	
13. Cebolla Creek	40.3	57.6	2.1	39.0	88.0	0	
14. Grande Caldeira	31.7	66.5	1.8	31.5	56.0	8.0	In the unmixed specimen a third $\bar{2}01$ reflection gives a composition of Or_{51}
15. Quatre Ribeiras	31.9	64.7	3.4	30.5	slight unmixing		
16. Mt. Franklin	24.9	67.5	7.6	25.0	homogeneous		
17. Victoria	23.3	75.5	1.2	23.0	—	5.5	No $\bar{2}01$ reflection seen for potassium phase
18. Brownhills	25.7	70.8	3.5*	22.5	homogeneous		
19. Ropp	23.0	69.2	7.8†	21.0	—	8.0	No $\bar{2}01$ reflection seen for potassium phase
20. Mt. Anakie	18.2	75.1	6.7	19.5	homogeneous		

* Includes 0.8% Cs.
† Includes 0.3% Cs.

References

Specimens 1, 2, 5 and 17, Kracek and Neuvonen (1952).
Specimens 3, 4, 6, 7, 10, 12 and 13, Larsen and Larsen (1938).
Specimens 11 and 14, Tuttle (1952).
Specimen 9, Spencer (1930).
Specimen 15, Fouqué (1883).
Specimen 16, The specimen used here was not from the analyzed sample. Edwards (1938).
Specimen 19, Joyce and Game (1952).
Specimen 20, The specimen used here was not from the analyzed sample. Osten (1951).

by chemical analyses. Since the chemical analyses are themselves liable to error the agreement may be considered fair. In the case of low-temperature feldspars, however, considerable caution must be taken in using this x-ray method to find the orthoclase content, since many perthites can be homogenized only after prolonged heating at 1050° C. and erroneous results may be obtained if the specimens are not completely homogeneous.

THE SEPARATE PHASES OF HIGH-TEMPERATURE CRYPTOPERTHITES

A review of the status of knowledge of the structure of perthites as revealed by x-rays was given in the first paper in this series (MacKenzie and Smith, 1955), so that little need be added here. In the study
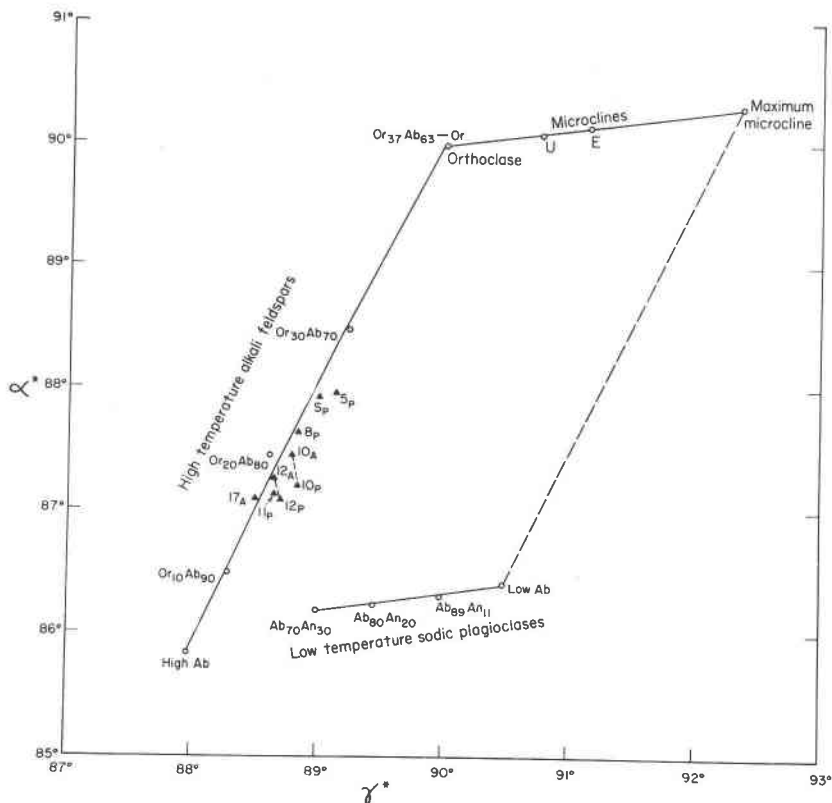

FIG. 2. Plot of the reciprocal lattice angles α^* and γ^* for triclinic alkali feldspars and three low-temperature plagioclase feldspars; a point representing monoclinic feldspars is also given. A point representing the sodium feldspar phase of each of seven high-temperature cryptoperthites is plotted; the numbers refer to the specimens listed in Table 1 and the subscripts A and P to the type of twinning (albite or pericline) from which the measurements of α^* and γ^* were made. S refers to specimen P of Spencer (1937).

of orthoclase-microperthites it was found that these consisted of two or more phases: a monoclinic potassium feldspar phase or a monoclinic and a triclinic potassium feldspar phase together with one or two sodium feldspar phases generally having lattice angles near those of low-temperature albite or oligoclase. The single-crystal x-ray studies of sanidine- and anorthoclase-cryptoperthites show that these usually con-

sist of only two phases. The potassium-rich phase is generally mono-
clinic and, in contrast with the low-temperature specimens, there is no
evidence of a triclinic phase with lattice angles similar to those of micro-
cline. The sodium feldspar phase may be untwinned, pericline twinned,
albite twinned, or both pericline and albite twinned. In sanidine-crypto-
perthites pericline twinning of the sodium-rich phase is most frequently
found, and in specimens having both types of twinning the intensity of
the pericline-twinned reflections is greater than that of the albite-twinned
reflections. When the sodium feldspar phase is untwinned it appears to
have monoclinic symmetry; this will be discussed more fully in a follow-
ing section.

When the sodium feldspar phase is twinned the reciprocal lattice angles
α^* and γ^* may be measured from the oscillation photograph by the

TABLE 2. RECIPROCAL LATTICE ANGLES OF SODIUM-RICH PHASE
OF CRYPTOPERTHITES

No.	Specimen	Albite twinning		Pericline twinning	
		α^*	γ^*	α^*	γ^*
5	Grant County			87° 58′	89° 8′
8	Nathrop			87° 39′	88° 50′
10	Spring Creek	87° 27′	88° 47′	87° 12′	88° 50′
11	Mitchell Mesa			87° 8′	88° 39′
12	Old Baldy Mt.	87° 16′	88° 39′	87° 5′	88° 41′
17	Victoria	87° 6′	88° 30′		
S	Spencer's specimen *P* (Spencer, 1937)			87° 56′	89° 0′

method described by Smith and MacKenzie (1955). This has been done
for six of the specimens studied here. The chemical compositions of the
separate phases in cryptoperthites are not known, and in order to com-
pare the reciprocal lattice angles of these specimens with each other and
with those of single-phase feldspars the method of plotting α^* against
γ^* has been adopted.

Figure 2 is constructed by plotting α^* against γ^* for the following feld-
spars: high-temperature albite and synthetic high-temperature alkali
feldspars of composition $Or_{10}Ab_{90}$, $Or_{20}Ab_{80}$, $Or_{30}Ab_{70}$ (Donnay and Don-
nay, 1952); low-temperature albite and three natural low-temperature
plagioclases of composition near $Ab_{89}An_{11}$, $Ab_{80}An_{20}$, $Ab_{70}An_{30}$ (Smith,
1956). Points representing a maximum microcline, two intermediate
microclines (MacKenzie, 1954) and orthoclase are also plotted. On this
diagram are plotted points representing the sodium feldspar phases of

six of the high-temperature cryptoperthites studied here and one high-temperature cryptoperthite described by Spencer (1937), specimen P. The reciprocal lattice angles α^* and γ^* for the sodium feldspar phase of these specimens are given in Table 2. The subscripts A and P refer to the type of twinning, albite or pericline, from which the measurements were made. In specimens 10 and 12 both albite and pericline twinning are present and the angles determined from both types of twinning show good agreement in each case.

The proximity of the points representing the sodium-rich phase of the cryptoperthites to the curve showing the variation of α^* and γ^* with chemical composition for the high-temperature synthetic feldspars is striking. In addition the points are spread out along this curve, and both these facts taken together suggest that the reciprocal lattice angles of the sodium-rich phases may be utilized in determining their compositions. Perpendiculars drawn from the points representing the sodium-rich phases to the curve for the high-temperature alkali feldspars give a range of compositions from about $Or_{15}Ab_{85}$ to $Or_{26}Ab_{74}$ for the specimens plotted in Fig. 2. The compositions derived in this manner show no relation to the values obtained for the sodium-rich phases of the same specimens as obtained from the spacing of the $\bar{2}01$ planes (see Table 1).

The discrepancy between the compositions of the sodium feldspar phases as determined by these two methods is rather disconcerting since it cannot yet be shown which method gives a closer approximation to the true compositions. It is known in the case of orthoclase-microperthites that the spacing of the $\bar{2}01$ planes sometimes gives impossible results for the compositions of both the sodium and potassium feldspar phases (Laves, 1952; Coombs, 1954). Even after allowing for the difference in $d_{\bar{2}01}$ for low- and high-temperature albite, impossible results may be obtained for the composition of the sodium feldspar phase of some orthoclase-microperthites. All the sanidine- and anorthoclase-cryptoperthites examined here give possible values, but it is not be be expected that the sodium feldspar phase would be almost pure albite in each case as has been found here (Table 1). Laves (1952) has suggested that the separate phases in a perthite cannot be expected to show the same lattice constants as the individually crystallized phases would exhibit and that the strain produced by unmixing is kept to a minimum by some distortion of the lattices of the separate phases. The same writer has also noted that a cryptoperthite may have a triclinic potash phase which is not microcline but potash feldspar forced to be triclinic by the influence of the triclinic soda phase which is the host material. One example of this has been found in this investigation (specimen No. 17) and will be discussed in a following section (p. 422).

Use of the spacing of the $\overline{2}01$ planes for determining the composition of alkali feldspars depends chiefly on the rather large change in the a^* parameter with change in chemical composition. From what has been noted above regarding the distortion of the lattice in the separate phases in cryptoperthites it would seem that the reciprocal lattice angles also may be unreliable for determining the composition of the sodium feldspar phase. However, from the close correspondence of the points in Fig. 2 to the curve showing the change in a^* and γ^* with chemical composition in sodium-rich feldspars, it is believed that the reciprocal lattice angles give a better approximation to the composition of the sodium feldspar phase than do the reciprocal lattice edges.

For comparison with Fig. 2, Fig. 3 shows the plot of a^* against γ^* for the sodium feldspar phases of eight orthoclase-microperthites. With the exception of specimen E, the positions of the points indicate that the sodium feldspar phase in the orthoclase-microperthites is a low-temperature albite or oligoclase. The case of specimen E has been discussed in the earlier paper (MacKenzie and Smith, 1955) from which this figure is reproduced.

A careful study of the b-axis x-ray oscillation photographs of high-temperature cryptoperthites makes it possible to deduce the probable sequence of events in the unmixing of a monoclinic feldspar. The first stage is shown by diffuse streaks associated with each of the main reflections and lying parallel to the layer lines. (It may be noted here that reflections from a pericline-twinned sodium feldspar phase in a perthite lie on the layer lines of the potassium-rich phase since the twin axis b coincides with the b-axis of the potassium feldspar phase.) This is followed by the appearance of an intensity maximum on each of the diffuse streaks and these maxima represent the untwinned sodium feldspar referred to on a preceding page. This must not be used as evidence for the existence of a monoclinic form of albite since this phase almost certainly has a considerable amount of potassium feldspar in solid solution and may represent a composition more potassium rich than $Or_{37}Ab_{63}$. The splitting up of these single reflections into a number of small well-defined spots gives the fine structure which is a common feature of the sodium-rich phase in the x-ray diffraction patterns of many perthites (Chao and Taylor, 1940; Laves, 1952; Ito and Sadanaga, 1952). The final stage is the development of a pericline-twinned sodium-rich phase which results from the merging of the fine structure into two sharp spots, a single spot sometimes remaining between the two pericline-twinned spots.[8]

[8] This discussion of the development of pericline twinning of the sodium feldspar phase would not be generally applicable to anorthoclase-cryptoperthites since twinning developed in the homogeneous feldspar would be expected to influence that in the unmixed phases.
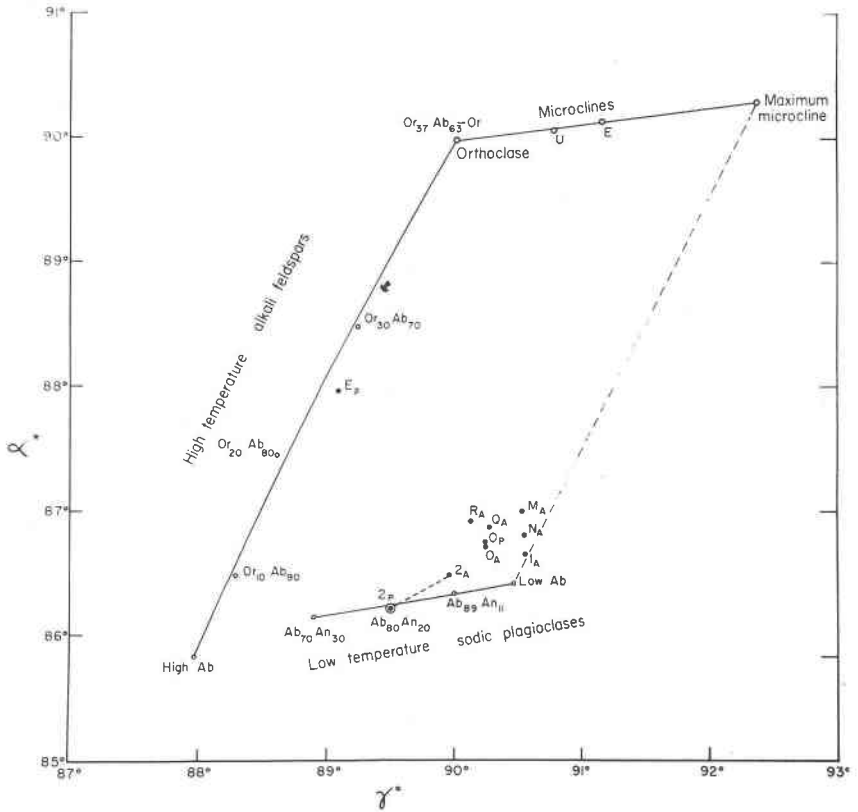
FIG. 3. This diagram is constructed in the same manner as Fig. 2. Points representing the sodium feldspar phases of eight orthoclase-microperthites are plotted and, with one exception, these have reciprocal lattice angles similar to those of low-temperature albite or oligoclase. Diagram reproduced from paper I of this series (MacKenzie and Smith 1955).

VARIATIONS IN OPTIC AXIAL ANGLE

Preliminary measurements indicated that there was frequently a considerable variation in optic angle in different crystals from a single rock specimen (Tuttle, personal communication). Since many of the specimens were known to be unmixed it was considered that this optic angle variation might be related to their inhomogeneity and so the effect of heating on the values of the optic angle was studied. The possibility that part of the variation in optic angle was the result of differences in chemical composition within individual crystals or between separate crystals was considered. The sharpness of the $\overline{2}01$ reflection in the x-ray powder diffraction patterns of homogenized specimens indicated that the range of chemical composition was very slight and could be neglected.

Although variations in optic angle between different crystals were found in most of the specimens, only in one case was an appreciable variation in a single crystal fragment found. The sanidine from Mineral Creek, San Juan region, Colorado (No. 4), described by Larsen and Larsen (1938) was considered by these writers to be foreign to the latite-andesite from which it was separated. One crystal of this sanidine showed a large variation in optic angle, being zoned from a high-sanidine[9] with $2V = 7.8°$ to a low-sanidine with $2V = 17.5°$. No discontinuity in the zoning was observed, and an intermediate zone was uniaxial. From the broken cleavage fragment it was impossible to determine which was the rim and which the core of the crystal.

Table 3 gives the measured values of the optic angle in a number of crystals from both the unheated and heated samples. Although sufficient measurements have not been made to obtain a good estimate of the variation in both the unheated and heated samples, there are in many cases indications of a reduction in the variation resulting from the heating. Specimen 3 is distinctive because there is a marked increase in the 2V variation in the sample heated at 900° C. for 24 hours; two of the heated crystals have the optic plane parallel to (010) so that this short period of heating has been sufficient to promote the transformation to the high-sanidine form. The increase in the variation in 2V in this specimen is undoubtedly due to the inversion to the high-sanidine form having proceeded fairly rapidly in this specimen and in some crystals to a greater degree than in others.

High-temperature cryptoperthites can be readily homogenized by heating at 700° C. for a few hours, and therefore the effects of homogenization alone have not been investigated since all these samples were heated at 900° C. for approximately 24 hours. As some of the homogeneous specimens show variations in optic angle in different crystals it is unlikely that these variations are related only to unmixing.

Tuttle and Keith (1954) have attributed variations in the optic axial angle of the alkali feldspars in a single specimen of granite to transitions from sanidine-cryptoperthite to orthoclase-microperthite, the change having progressed further in some grains than in others. Coombs (1954) has noted large variations in the optic axial angle of ferriferous potassium feldspars from Madagascar and he considers these to be due to states transitional between high-sanidine and sanidine or orthoclase. The variations in optic axial angle reported here are much smaller than those considered by Tuttle and Keith or by Coombs, but they undoubtedly

[9] The curve showing the relation between chemical composition and optic axial angle for the high-sanidine series (Fig. 1) is considered to define this series, but it is convenient to describe as a high-sanidine any potassium-rich feldspar in which the optic plane is parallel to (010).

TABLE 3. OPTIC AXIAL ANGLE MEASUREMENTS

	Unheated									Heated at 900° C. for 24 hours									Effect on mean value of optic angle of heating at 900° C.	
	1	2	3	4	5	6	7	Variation	Mean	1	2	3	4	5	6	7	Variation	Mean	Decrease	Increase
1. Eifel*	10.4	12.7	8.0	10.9	10.0			4.7	10.4	30.0	26.4	29.2	26.7	30.1			3.7	28.5	—	
2. Kokomo	31.6	32.4	32.6	35.4	27.0			8.4	31.8	15.5	11.4	21.0	25.3	19.0	(7.0‡)		13.9	18.4	3.3	
3. Alder Creek*	25.8	22.8	24.0	21.6	25.1	21.8		4.2	23.5										5.1	
4. Mineral Creek	11.8	12.4	11.5	15.2	(17.5†–7.8‡)			3.7	12.7										—	
5. Grant Co.	32.6	30.0	31.1	31.7	30.4	31.5	31.3	2.6	31.2	28.6	30.1	30.3	29.8	29.1	29.9		1.7	29.6	1.6	
6. S. C. XX	38.0	40.3	39.4	38.3	40.2			2.3	39.2	36.2	36.0	37.2	35.6	37.0			1.6	36.4	2.8	
7. Pine Creek Mesa	36.9	37.2	34.9	33.0	36.7			4.2	35.7	29.8	31.1	33.5	31.9	30.0	28.0		5.5	30.7	5.0	
8. Nathrop	30.9	30.7	29.4	34.6	29.0	32.2		5.6	31.1	32.6	33.5	32.3	31.5	31.7	34.4		2.9	32.7		1.6
9. Sparting Gulch	40.3	38.9	42.1	39.9	47.7	45.0		8.8	42.3	48.4	48.1	47.5	48.1	48.7			1.2	48.1		5.8
10. Spring Creek	37.4	40.2	37.1	38.0	36.8	38.1		3.4	37.9	44.9	46.5	44.6	46.9	48.2	45.7		3.6	46.1		8.2
11. Mitchell Mesa	35.0	34.7	34.2	35.5	33.9	32.6	37.4	4.8	34.8	42.3	42.3	41.6	42.0	42.1			0.7	42.0		7.2
12. Old Baldy Mt.	38.4	38.7	39.2	37.3	39.8	40.2		2.9	38.9	43.9	47.1	45.9	44.4	46.4	46.8	48.1	4.2	46.1		7.2
13. Cebolla Creek	33.9	36.5	32.4	33.7	36.4			4.1	34.6	47.3	47.8	48.2	48.4	48.1			1.1	47.9		13.3
14. Grande Caldeira	46.6	47.4	46.9	46.8	45.5	46.9	46.5	1.9	46.7	47.2	47.3	46.8	47.1	46.7	46.2		1.1	46.9		0.2
15. Quatre Ribeiras	44.4	45.2	46.0	43.3	44.1	45.0		2.7	44.7	45.2	44.9	45.1	45.0	46.6			1.7	45.3		0.6
16. Mt. Franklin	53.7	57.6	56.9	54.8	54.8			3.9	55.6	56.5	53.7	54.9	56.7	56.3	55.8		2.8	55.6		0.0
17. Victoria	48.0	48.3	48.4	46.9	47.8	49.1	47.6	2.2	48.1	47.8	47.7	49.2	48.0	49.2	49.2	50.0	2.3	48.7		0.6
18. Brownhills	38.9	39.5	41.6	41.4	42.2	42.6		3.7	41.0	44.3	41.2	42.5	43.7	42.3			3.1	42.8		1.8
19. Ropp	51.9	53.1	52.9	53.7	52.1			1.8	52.7	55.1	54.7	55.3	55.6	54.7	55.2		0.6	55.1		2.4
20. Mt. Anakie	56.7	56.5	56.7	56.0	56.4	56.3		0.7	56.4	61.4	58.7	59.1	58.6				2.8	59.4		3.0

* High sanidine in nature.
† Indicates optic plane perpendicular to (010).
‡ Indicates optic plane parallel to (010).

reveal the tendency for change in optic angle in the alkali feldspars with temperature of final crystallization. The sluggish nature of this change is reflected in the differing rate of response of different crystals to change. It is believed that the variation in optic angle in each specimen might be reduced to nearly zero if the specimen were held for a sufficient time at a fixed temperature.

EFFECT ON THE OPTIC ANGLE OF HEATING AT 900° C.

The mean values of the optic angles in the unheated and heated samples given in Table 3 are plotted in Fig. 4. The mean value of the optic angle before heating is represented by a circle and after heating by the point of an arrow head for eighteen of the specimens studied.
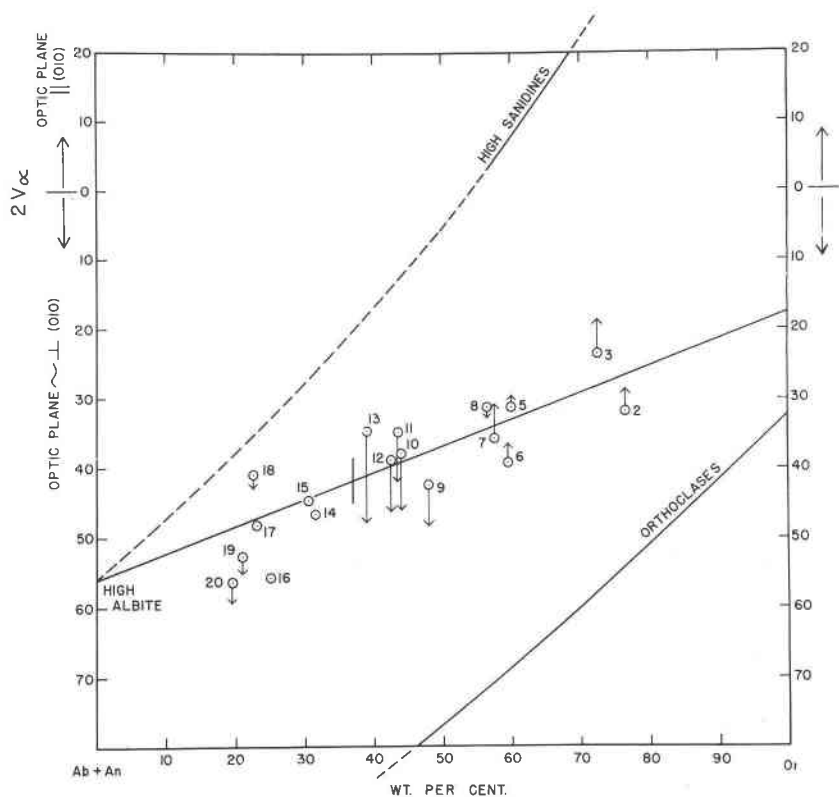
FIG. 4. Diagram showing the change in the mean value of the optic angle of high-temperature feldspars as a result of heating at 900° C. for 24 hours. The circles represent the mean value of the 2V for the unheated samples and the arrowheads the mean value of 2V for the heated samples. The numbers refer to the specimens listed in Table 1. Lines representing the variation in optic angle with chemical composition for three of the alkali feldspar series are shown.

With respect to the effect of heating at 900° C. this series of feldspars can be divided into three groups. Specimens with more than 60% potassium feldspar in their bulk composition show a slight but measurable decrease in the mean value of the optic angle. Feldspars in the compositional range $Or_{60}(Ab+An)_{40}$ to $Or_{40}(Ab+An)_{60}$ (approx.) show an increase in the mean value of the optic angle, and this increase reaches its maximum value in the most sodium-rich specimens. Alkali feldspars with less than 40% potassium feldspar show a very slight increase or no change in the mean value of the optic angle as a result of this heat treatment.

It is now fairly well established that any natural potassium-rich feldspar, if heated for a sufficiently long period at about 1050° C., is changed to the high-sanidine form by a decrease in the optic angle and rotation of the optic plane into a position parallel to the symmetry plane[10] (Spencer, 1937; Tuttle, 1952). The reduction of the optic angle in the potassium-rich specimens as a result of heating at 900° C. is the effect which would be expected since the change is in the direction of a high-sanidine, but the heat treatment has not been sufficient to convert any of the specimens completely to the high-sanidine form. The sanidine from Alder Creek, San Juan Mountains (No. 3), has a variation in optic angle in the unheated sample of 4.2° and in the heated sample it is 13.9°; it has already been noted that this is undoubtedly due to some of the crystals having been partly transformed to the high-sanidine form. Specimens 1 and 4 were transitional to the high-sanidine form in their natural state and so no optical measurements were made on the samples heated at 900° C. for 24 hours.

Specimens in the compositional range $Or_{60}(Ab+An)_{40}$ to $Or_{40}(Ab+An)_{60}$ (approx.) do not show a tendency to change to the high-sanidine form as a result of heating at 900° C. for 24 hours since the mean value of the optic angle increases. Additional evidence for a discontinuity in the effect of heat treatment at the composition $Or_{60}(Ab+An)_{40}$ is given by the results of prolonged heating at 1030° C. Heating a number of specimens at 1030° C. for seven months showed that specimens more potassium-rich than $Or_{60}(Ab+An)_{40}$ were changed to the high-sanidine form but more sodium-rich specimens were not thus changed. No systematic study has been made of the optic angle in the specimens heated at 1030° C. Slight increases in optic angle as a result of heat treatment of feldspars in this compositional range have been found by Kôzu and Suzuki (1925) and Spencer (1937). Spencer's studies indicate that such

[10] Some microclines are not changed to the high-sanidine form even after heating for 6 months at 1050° C. but it is believed that longer heating will effect this change (personal communication from Dr. F. Chayes).

feldspars may be changed to the high-sanidine form but that the process is very much more sluggish than in the case of the potassium-rich specimens.

The increase in optic angle resulting from heating at 900° C. reaches its maximum value in a feldspar of composition near $Or_{40}(Ab+An)_{60}$ (No. 13). At this composition there is a pronounced change in the effect of heat treatment since feldspars more sodium-rich than this composition show a very slight increase or no measurable increase in the mean value of the optic angle. It is possible that this alteration in the effect of heat treatment is related to the change in symmetry in the high-temperature alkali feldspars at the composition $Or_{37}(Ab+An)_{63}$ (Donnay and Donnay, 1952), but this is rather a surprising result since the other physical properties do not show an abrupt discontinuity at this composition, the symmetry change being temperature dependent (MacKenzie, 1952; Laves, 1952).

No explanation can be advanced at the present time for the differing response of these three groups of specimens to this heat treatment. Similar studies with differing times and temperatures of heating would undoubtedly go a long way toward solving this problem.

OPTICALLY MONOCLINIC ANORTHOCLASE-CRYPTOPERTHITES

It is frequently important to know the symmetry of an alkali feldspar, and petrologists have usually relied on optical methods of symmetry determination. In the absence of visible multiple twinning it may be difficult to determine the symmetry with certainty, and if the feldspar is unmixed on a sub-microscopic scale the optical symmetry may be quite misleading. Tuttle (1952) reported that some anorthoclase-cryptoperthites are optically monoclinic or have very small extinction angles in the zone [010] but that after heating to homogenize the crystals there is no doubt about their triclinic character because of the oblique extinction in the zone [010].

All sanidine-cryptoperthites investigated have optically monoclinic symmetry but anorthoclase-cryptoperthites may be either optically monoclinic or distinctly optically triclinic. Two of the anorthoclase-cryptoperthites studied here are optically monoclinic or have very small and variable extinction angles in the zone [010] before being homogenized. One of these is an anorthoclase-cryptoperthite from Victoria, Australia (No. 17), investigated by Tuttle (1952) and the other an anorthoclase-cryptoperthite from Ropp, Nigeria (No. 19), described by Joyce and Game (1952). All the Victoria anorthoclase crystals examined are untwinned, but some fragments of the Ropp anorthoclase show multiple twinning and others show straight extinction on the [010] zone. It is of

interest to determine whether there is any genetic reason for this differ-
ence in the optical character of anorthoclase-cryptoperthites.

The optical symmetry of an anorthoclase-cryptoperthite may depend
on the relative temperatures of the non-quenchable change from tri-
clinic to monoclinic symmetry and the temperature at which exsolution
begins. If the feldspar is monoclinic when it begins to unmix it is possible
that only the sodium feldspar phase will invert to triclinic symmetry and
the crystal might more readily appear optically monoclinic.[11] The tem-
peratures of inversion to monoclinic symmetry of the two specimens here
considered, viz. No. 17 ($Or_{23.3}Ab_{75.5}An_{1.2}$) and No. 19 ($Or_{23.0}Ab_{69.2}An_{7.8}$),
have been determined to be $360° \pm 10°$ C. and $540 \pm 10°$ C., respectively
(MacKenzie, 1952). From the experimentally determined alkali feldspar
solvus (Bowen and Tuttle, 1950) the temperature of commencement of
exsolution of a binary feldspar of composition $Or_{23}Ab_{77}$ is close to $610°$ C.
The effect of an increase in the anorthite content of an alkali feldspar is
to raise the temperature of the solvus, so that specimen 17 would be ex-
pected to unmix at a temperature slightly greater than $610°$ C. and speci-
men 19 at a much higher temperature. Both specimens should therefore
begin to unmix while still monoclinic in symmetry, and this may be the
reason for the optical symmetry shown by these anorthoclase-crypto-
perthites. It does not follow, however, that an optically triclinic crypto-
perthite must have been triclinic when unmixing began, since some of
the fragments of the Ropp anorthoclase are optically triclinic.

A single-crystal b-axis oscillation photograph of the Victoria anortho-
clase is reproduced in Fig. 5. The sodium and potassium feldspar phases
are each represented by sets of paired reflections in albite twin relation-
ship.[12] Diffuse streaks join the albite-twinned reflections of the sodium-
rich phase to the corresponding reflections of the potash phase. Between
each pair of reflections of the albite-twinned sodium feldspar phase are a
series of very faint spots giving the effect of a diffuse line joining the two
spots. One possible interpretation of this x-ray photograph is that the
two phases unmixed from an albite-twinned, and therefore triclinic,
crystal. This interpretation, however, is in disagreement with the con-
clusion already reached that the feldspar was still monoclinic when un-
mixing began.

[11] Laves (1952), in discussing ternary sodium-rich feldspars, has made a similar sug-
gestion, but this hypothesis applies equally well to potassium-sodium feldspars with a
negligible amount of calcium.

[12] This albite-twinned, and therefore triclinic, potassium feldspar phase is forced to be
triclinic by the influence of the sodium feldspar phase, which is present in much greater
proportion and so is the host structure (Laves, 1952). That the potassium feldspar phase
is constrained to be triclinic is shown by the values of α^* and γ^* for this phase, since these
fall on the curve representing the variation in α^* and γ^* for high-temperature alkali feld-
spars (Fig. 2) near the point $Or_{30}Ab_{70}$.

If we consider the temperature at which the monoclinic-triclinic inversion curve cuts the solvus for a binary alkali feldspar as 570° C. (MacKenzie, 1952) and neglect the small anorthite content of the Victoria anorthoclase, it is found that the temperature will have to fall only 40° C. from the beginning of unmixing until the sodium feldspar phase changing in composition along the solvus reaches the monoclinic-triclinic inversion curve and so inverts to triclinic symmetry. Thus, although unmixing may start from a monoclinic crystal, the greater proportion of
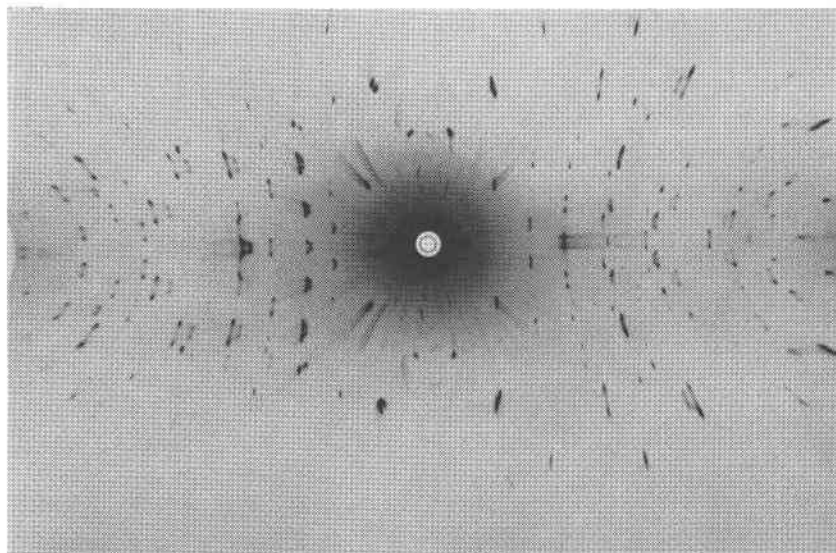
FIG. 5. A *b*-axis *x*-ray oscillation photograph of the anorthoclase-cryptoperthite from Victoria, Australia (No. 17). The (001) plane is set in the center of a 15° oscillation arc. Both the sodium and potassium feldspar phases are albite twinned (see text for further details).

the crystal will invert to triclinic symmetry after a fall in temperature of only 40° C. An interpretation of the *x*-ray photograph of the Victoria anorthoclase-cryptoperthite in harmony with this is that when the sodium feldspar phase became triclinic it developed albite twinning and the potassium-rich phase, under the influence of the predominant sodium-rich phase, also twinned. It is of interest to note that none of the crystals of a sample of the Victoria feldspar, heated until homogeneous, showed any twinning, either microscopic or on a sub-microscopic scale.

Summary and Conclusions

From the curves relating optic axial angle with chemical composition in the alkali feldspars (Tuttle, 1952) eighteen of the twenty specimens

described here belong to the sanidine-anorthoclase-high-temperature albite series, the remaining two specimens being transitional to the high-sanidine series. X-ray studies show that all the specimens in the composition range $Or_{60}Ab_{40}$-$Or_{25}Ab_{75}$ are unmixed to some extent, although in some cases the unmixing is very slight. Doubtless completely homogeneous specimens in this composition range could be found.

Those unmixed feldspars which have been classified, on the basis of the value of the optic axial angle, as belonging to the sanidine-anorthoclase-high-temperature albite series, have been found to have a *high-temperature sodium feldspar phase*. Orthoclase-microperthites, on the other hand, have, with one or two exceptions, *a low-temperature sodium feldspar phase* (MacKenzie and Smith, 1955). The importance of this difference cannot be overemphasized since this gives a useful basis for subdividing perthitic feldspars.

It is in many cases possible to decide whether a given feldspar has a high- or low-temperature sodium feldspar phase simply by comparing the x-ray single-crystal pattern with standard patterns; it is, of course, essential that all the photographs compared have been taken in identical orientation. From x-ray photographs showing albite and pericline twinning in a low-temperature sodium feldspar phase and in a high-temperature sodium feldspar phase, comparison of the separation of several sets of albite-twinned or pericline-twinned reflections in the unknown sodium-rich phase with those of the standard patterns readily indicates whether the phase is high or low temperature.

Laves (1952) has suggested that there are only two stable forms of potassium feldspar, viz. sanidine and microcline, and that "common" orthoclase is unstable. This may or may not be true, but for the purposes of petrographic description it seems advisable to retain the terms orthoclase and orthoclase-microperthite. The name orthoclase has generally been associated with the optically monoclinic feldspars of some granites and pegmatites, whereas the term sanidine has been used for the monoclinic feldspars of volcanic rocks. The curves drawn by Tuttle (1952) relating optic axial angle with chemical composition make it possible to define these terms more precisely and to remove the genetic significance attached to the names. Thus in certain granites the alkali feldspar may be a sanidine-cryptoperthite (Tuttle and Keith, 1954) instead of the more common orthoclase-microperthite or microcline and low-albite association.

The subdivision of the microperthitic and cryptoperthitic feldspars on the basis of the value of the optic axial angle is supported by the x-ray evidence of the difference in the nature of the sodium feldspar phase in the orthoclase-microperthite and sanidine-cryptoperthite series. The

existence of specimens whose optic angle places them intermediate be-
tween these two series in no way detracts from the usefulness of this sub-
division since these specimens have two sodium feldspar phases, one a
low-temperature phase and the other a high-temperature phase (Tuttle
and Keith, 1954). Further examination of specimens intermediate be-
tween the two series has revealed that the size of the optic angle is
proportional to the relative amounts of the high-temperature and the
low-temperature sodium feldspar phases. This will be discussed in more
detail in a subsequent paper.

The optical and x-ray studies, the results of which are reported in the
foregoing pages, are a part of a systematic study of alkali feldspars from
different geologic environments. It is believed that the feldspars, by
virtue of their apparent complexity and the sluggish nature of the
changes which they undergo, will be of the greatest value in eventually
unraveling the history of the rocks in which they occur.

APPENDIX

Notes on specimens 1, 5, 8 and 15

1. *Eifel sanidine.* The sample of the Eifel sanidine used here was that
studied by Kracek and Neuvonen (1952). It was found that this specimen
was transitional to the high-sanidine form, the optic plane being parallel
to (010). The studies of Des Cloizeaux (1861), Kôzu (1916), Kôzu and
Seto (1921) and Kôzu and Suzuki (1923) have shown that the optic axial
angles of sanidines from this locality are very susceptible to temperature
changes, and it is not surprising therefore to find natural samples transi-
tional to the high-sanidine form. Some of the specimens described in the
literature have the optic plane parallel to (010) and others have the
optic plane perpendicular to (010).

5. *Grant County sanidine.* This sanidine occurs in a pegmatite within
a rhyolite porphyry in Rabb Canyon, Grant County, New Mexico.
Kelley and Branson (1947) have described the pegmatites in this rhyolite
porphyry, and, noting the unusual feature of the presence of sanidine in

a pegmatite, have concluded that the pegmatites crystallized at high temperature and at shallow depth. Since the publication of their paper it has been found that the plagioclase of these pegmatites is also a high-temperature form (personal communication from Dr. Bowen). A specimen of this plagioclase has been analyzed by Mr. J. H. Scoon and its composition calculated to be $Or_{8.3}Ab_{78.8}An_{12.9}$.

8. *Nathrop sanidine.* Cross (1886) has briefly described the Nathrop rhyolite from Chaffee County, Colorado, because of the presence of topaz and spessartine in lithophyses. Although remarking on the sanidine, Cross does not mention the presence of a plagioclase. There is, however, in addition to the sanidine a high-temperature plagioclase in this rock, and a partial analysis of this plagioclase by Mr. J. H. Scoon gives a composition of $Or_{7.8}Ab_{81.2}An_{11}$.

15. *Quatre Ribeiras anorthoclase.* The sample of the anorthoclase from Quatre Ribeiras, Ile de Terceira, Azores, was part of the material originally described by Fouqué (1883) and was made available to the writers by Professor C. E. Tilley. The chemical analysis by Fouqué indicated that this mineral was almost pure albite, and Dana (1906) referred to it as an abnormal form of albite. Tuttle and Bowen (1950) suggested that Fouqué's chemical data were probably unreliable, and a new determination of the alkalies by Mr. J. H. Scoon gave the following values: $Na_2O = 7.65$ and $K_2O = 5.40$, indicating that this is anorthoclase and not albite.

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