THE ALKALI FELDSPARS: I. ORTHOCLASE-MICROPERTHITES

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Abstract

A study of the lamellar structure of a number of analyzed feldspars belonging to the orthoclase-microperthite series has been made using *x*-ray oscillation photographs. Differences in the *x*-ray diffraction patterns have been correlated with the bulk composition of the feldspars. Measurements of the reciprocal lattice angles α^* and γ^* of the soda phase give results which indicate that the composition of the soda phase may be determinable from these angles.

The variations in optic axial angle for a known chemical composition have also been correlated with differences in the *x*-ray diffraction patterns.

Introduction

The importance of the soda-lime or plagioclase feldspars in the classification of igneous rocks has been recognized for a long time, but the alkali feldspars, probably because of their more limited distribution in igneous rocks, have not received the same detailed attention until very recently.

In 1950 Bowen and Tuttle made the most significant advance in our knowledge of the alkali feldspar series by their determination of liquidus, solidus, and sub-solidus relations in the system $KAlSi_3O_8$—$NaAlSi_3O_8$—H_2O. It had long been suspected that at high temperatures the alkali feldspars formed a complete series of solid solutions, whereas, in rocks thought to have been formed at low temperatures or slowly cooled from high temperatures, two feldspars were found either intimately intergrown or as separate crystals. Bowen and Tuttle were able to demonstrate that complete solid solution did pertain at high temperatures, but that at low temperatures there was only limited miscibility between the two end members of the series. These writers made it clear, however, that the optical properties of the synthetic feldspars were similar to those of some natural high-temperature forms, and that in no case were they able to synthesize material similar to the natural low-temperature feldspars. The sub-solidus relations are thus still only imperfectly known, and it is only by detailed study of natural minerals that we can hope to obtain a clearer understanding of these relations.

Tuttle (1952*b*) divided the alkali feldspars into four series on the basis of the value of the optic axial angle and orientation of the optic plane for a known chemical composition. A slightly modified form of the diagram given by Tuttle to show these relations is reproduced in Fig. 1 and the curves on this diagram have been adopted to define the four series of feldspars. The intermediate members of each series are frequently unmixed and consist of intimate intergrowths of a potash- and a soda-rich phase. These intimate intergrowths are referred to as perthites. For the high-temperature feldspars (high sanidines, sanidines, and anorthoclases) the two phases can rarely be detected optically and the term cryptoperthite is suitable.[1] The term microperthite is generally applicable to the low-temperature feldspars orthoclase and microcline.

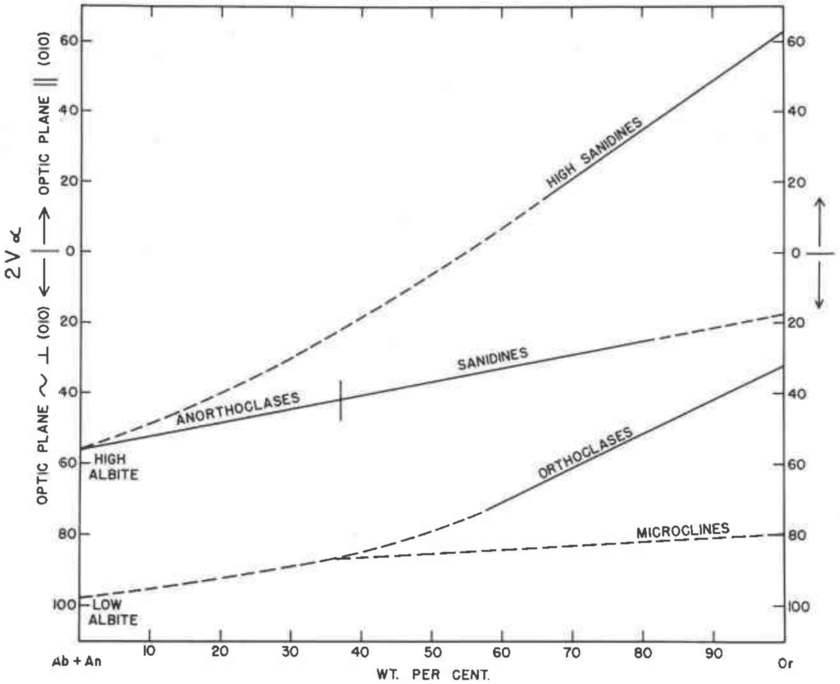

FIG. 1. Diagram showing the relation between optic axial angle and chemical composition in the alkali feldspars (after Tuttle, 1952*b*). The curves are used to define four series of alkali feldspars: microcline-low albite, orthoclase-low albite, sanidine-anorthoclase-high albite, high sanidine-high albite. The dashed portions of the curves indicate where the data are limited or absent.

To name a particular alkali feldspar using the curves in Fig. 1, it is not necessary to know whether or not the feldspar is unmixed, the optic axial angle being that of either a homogeneous crystal or the aggregate

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[1] The term cryptoperthite is used here to include perthites which appear optically homogeneous under the highest magnification although *x*-ray studies show them to be unmixed (Tuttle, 1952*a*), and to include perthites in which optical examination suggests unmixing although the boundaries of each phase cannot be accurately delineated by optical methods.

effect produced by the intergrowth of the separate phases. Thus a feldspar of composition $Or_{45}Ab_{55}$ with a mean optic axial angle of 40° will be either a sanidine or a sanidine-cryptoperthite; in some cases only by *x*-ray methods can one decide whether or not the feldspar is unmixed. Specimens which fall between two of the curves (Fig. 1) are considered as intermediate between the two series defined by the curves. Examples of such feldspars are described by Tuttle and Keith (1954).

This is the first of a series of papers devoted to a systematic study of the alkali feldspars. This study consists of two parts—first a purely mineralogical investigation of selected specimens, and second a petrologic investigation of the alkali feldspars from granites and related rocks belonging to the same suite. The present paper is an investigation by single-crystal *x*-ray methods of a number of feldspars belonging to the orthoclase-microperthite series. The second paper (Smith and MacKenzie) describes a simple but accurate *x*-ray technique developed in the course of this work for the study of the triclinic phases in perthites. The third paper will be devoted to an optical and *x*-ray study of sanidine- and anorthoclase-cryptoperthites. A paper on the relation between orthoclase and microcline has already been published (MacKenzie, 1954), so the mineralogical aspects of the alkali feldspars have been treated in some detail.[2]

With the data obtained from the purely mineralogical study of the alkali feldspars a detailed petrologic study of the alkali feldspars in a few selected granites and related minor intrusions has been undertaken. It is believed that this study will provide further information as to the changes which take place in the alkali feldspars in the solid state.

PREVIOUS STUDIES OF MICRO- AND CRYPTOPERTHITES

The existence of micro- and cryptoperthitic intergrowths of a soda- and a potash-rich feldspar has long been interpreted as the result of unmixing of an originally homogeneous feldspar. Kôzu and Endô (1921) were the first to study perthites by *x*-ray methods and they found that the two phases could be homogenized and partially unmixed again by suitable heat treatment. Spencer (1930, 1937) made very careful optical, chemical, and thermal studies of a number of alkali feldspars, and he observed that in many cases the microperthitic structure could be made to disappear by heat treatment. Chao, Smare, and Taylor (1939) found from a single-crystal *x*-ray study of some of Spencer's specimens that in many cases the two phases in microperthites had lattice parameters

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[2] Alkali feldspars in which the optic plane is parallel to the symmetry plane, defined by Tuttle (1952*b*) as high sanidines, are much rarer in occurrence than most mineralogy textbooks indicate. Such feldspars have not yet been studied in detail.

which corresponded with nearly pure potash feldspar and soda feldspar.

In 1940 Chao and Taylor classified Spencer's specimens into two groups: those having an albite-twinned soda phase whose lattice angles were close to those of low-temperature albite, and those having a pericline-twinned soda phase whose lattice angles did not agree with low-temperature albite. At the time this work was done the existence of a high-temperature form of albite had not been clearly established, although Spencer (1937) had found an appreciable change in the optical properties of a specimen of albite from Amelia, Va., as a result of prolonged heating at 1080° C. Tuttle and Bowen (1950) proved without doubt that a high-temperature form of albite did exist. They showed that synthetic albite crystallized at about 800° C. had optical properties similar to those of the material produced by prolonged heating of natural low-temperature albite and to those of the natural sodic plagioclase phenocrysts from lavas. Laves and Chaisson (1950) determined the lattice angles of high-temperature albite, and Taylor (personal communication, 1951) suggested that the soda phase of some perthites corresponded to the high-temperature form of albite. Laves (1951) reported that the soda phase of a sanidine cryptoperthite had lattice angles close to those of high-temperature albite.

Ito and Sadanaga (1952) did not distinguish between high- and low-temperature albite in perthites but concluded that the type of twinning shown by the soda phase was dependent on the bulk chemical composition of the feldspar. Their conclusion that potash-rich perthites showed an albite-twinned soda phase and soda-rich perthites showed a pericline-twinned soda phase was directly contrary to the observations of Chao and Taylor (1940) in their study of low-temperature feldspars.

Laves (1952) thought that the different lattice parameters of high- and low-temperature albite controlled the type of twinning shown by the soda phase of perthites so that high-temperature albite showed pericline twinning and low-temperature albite showed albite twinning. Smith and MacKenzie (1954) have since shown that the soda phase of perthites may be albite twinned, pericline twinned, or both albite and pericline twinned, whether it is near high- or low-temperature albite.

Tuttle and Keith (1954) have described feldspars which contain, in addition to a monoclinic potash phase, two soda phases, one near low-temperature albite and the other near high-temperature albite. Smith and MacKenzie (1954) have briefly described an additional complexity in the structure of perthites by noting a specimen consisting of two potash phases, one monoclinic and the other triclinic, with a soda phase close to low-temperature albite.

From this brief review of the status of knowledge of the structure of perthites it is clear that only by examination of a large number of specimens of known chemical composition and from all manner of geological environments will the full story of the development of the different types of structure be unravelled. When this has been done the information obtainable from a study of the alkali feldspars will be of considerable value in any petrologic study.

PRESENT INVESTIGATION

This paper deals with a series of optically monoclinic perthites from presumed low-temperature geologic environments and for such specimens the term orthoclase-microperthite is generally applicable. Spencer (1937) and subsequently Tuttle (1952*b*), using most of the specimens which are studied here, constructed curves relating the variation in optic axial angle to chemical composition in the alkali feldspars. The curve drawn by Tuttle (1952*b*) for the orthoclase—low-temperature albite series is here considered as a definition of this series, since it is not always possible on geologic grounds to distinguish between a high-temperature and a low-temperature environment. It has been suggested (MacKenzie in Tuttle and Keith, 1954) that perthites be subdivided on the basis of the nature of the soda phase; thus an orthoclase-perthite has a soda phase near low-temperature albite and a sanidine-perthite has a soda phase near high-temperature albite.[3]

Twelve of the specimens used here are from Dr. Edmondson Spencer's series of alkali feldspars on which he did much careful work (Spencer, 1930, 1937). These specimens were received from Drs. Bowen and Tuttle and the writers are much indebted to Drs. Spencer, Bowen, and Tuttle for the opportunity to use these specimens. Many of them have already been studied by *x*-ray single-crystal techniques by Chao, Smare, and Taylor (1939) and by Chao and Taylor (1940), but some of the samples not available to these investigators have been studied. The two soda-rich specimens were received from Professor C. E. Tilley, whose kindness is gratefully acknowledged.

It was found that the simplest method of studying a large number of alkali feldspars by single-crystal *x*-ray methods was to use *b*-axis oscillation photographs. In each case the (001) plane was made parallel to the *x*-ray beam in the center of the 15° oscillation arc. Figure 2 shows a *b*-axis oscillation photograph of a homogeneous feldspar crystal taken in this orientation.[4] For each crystal investigated a photograph taken in

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[3] A division of perthites based on the size of the optic angle may be preferable since it is not dependent on the unmixing of the specimen. It will be seen (p. 724), however, that these two alternative definitions are not always complementary for specimens in the compositional range $Or_{90}Ab_{10}$—$Or_{75}Ab_{25}$.

[4] The completely indexed photograph is reproduced in the following paper by Smith and MacKenzie.

identical orientation was obtained and they could be readily compared. Albite and pericline twinning of the soda phase can be distinguished at a glance and in almost every case there are slight differences which can be found after careful examination of the photographs. The reciprocal lattice parameters α^* and γ^* can be readily measured if albite- or pericline-twinned reflections occur (see following paper).

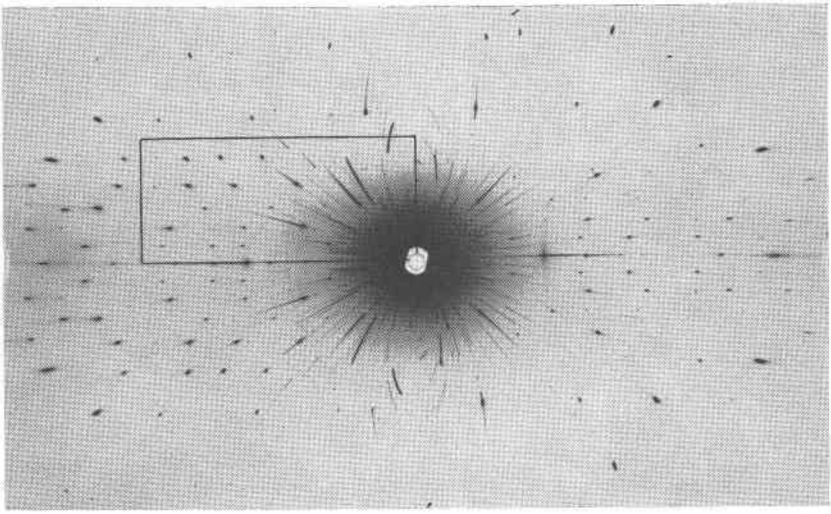

FIG. 2. *b*-axis oscillation photograph of a crystal of specimen *F* previously heated until homogeneous. The *x*-ray beam was set parallel to (001) in the center of a 15° oscillation arc. The rectangular area shows the reflections which appear in the small parts of the *x*-ray photographs in Fig. 3.

A small part of the *x*-ray photograph of each of the 14 specimens studied is reproduced in Fig. 3. The area of the photograph selected is marked on Fig. 2. The photographs are arranged in order of increasing soda content of the feldspars, and the letters used to designate the specimens are those used by Spencer (1937); the specimens numbered 1 and 2 are those received from Professor Tilley.

Table 1 gives the chemical composition and optic axial angle for each specimen, together with the values of the reciprocal lattice angles α^* and γ^* of the soda phase where these could be measured. To compare these values with each other and with the values of low- and high-temperature albite and adjacent feldspars the method selected has been to plot the value of α^* against γ^*.

Figure 4 shows a plot of α^* against γ^* for the following feldspars:

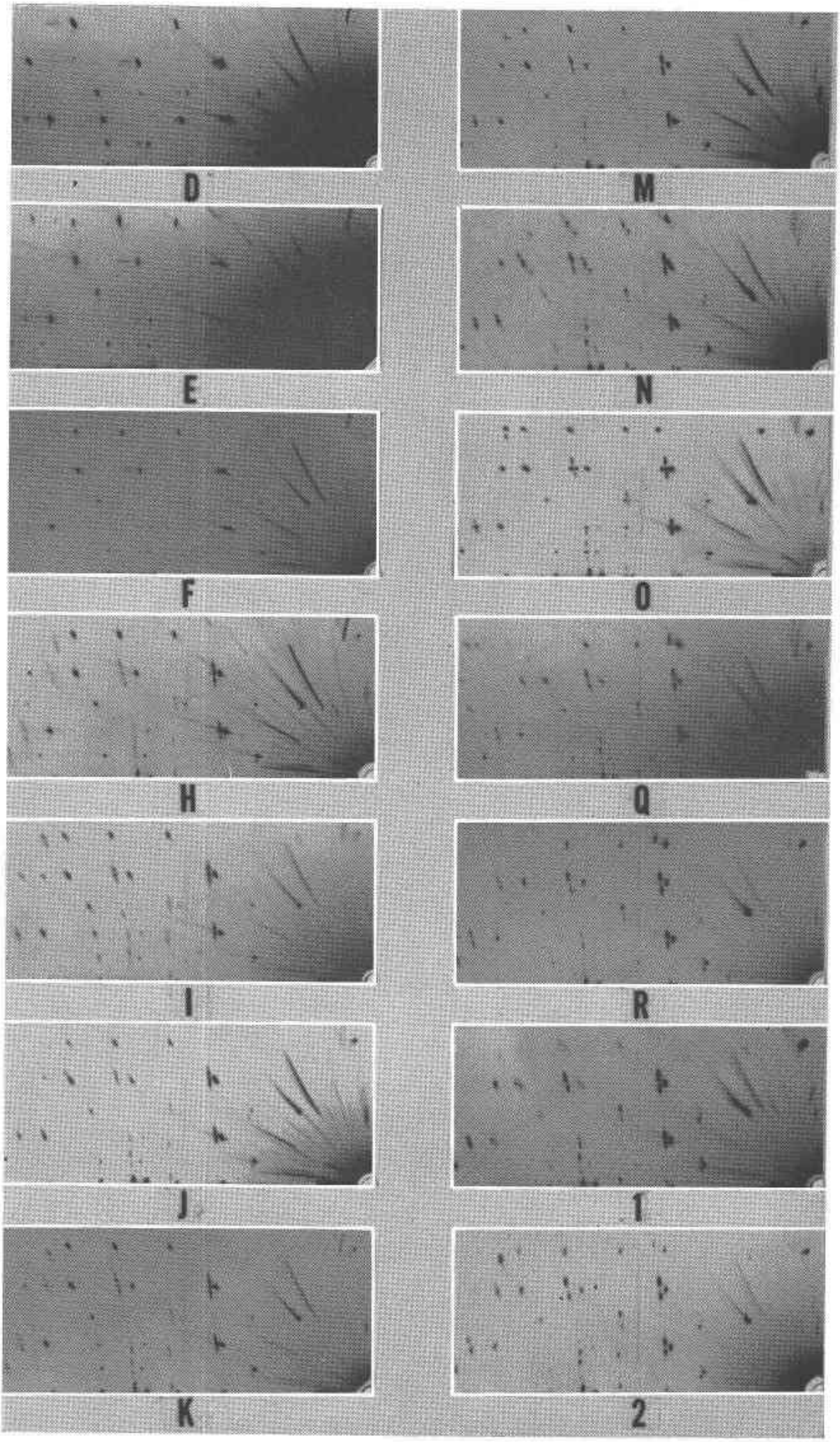

FIG. 3. Small parts of the *b*-axis *x*-ray oscillation photographs of 14 low-temperature feldspars. The letters and numbers refer to the specimens described in the text.

TABLE 1. DATA ON ORTHOCLASE-MICROPERTHITES

Specimen	Chemical composition weight %			$2V_\alpha$	Reciprocal lattice angles of soda phases		Type of twinning of soda phase
	Or	Ab	An		α^*	γ^*	
D	84.5	13.8	1.7	46.2	not measured		(pericline type superstructure)
E	83.3	14.9	1.8	57.6	87° 58′	89° 05′	pericline
F	78.8	18.9	2.3	52.9	not measured		(pericline type superstructure)
H	72.5	25.8	1.7	61.5	not measured		(albite-twin type superstructure)
I	69.4	28.9	1.7	69.1	not measured		(albite-twin type superstructure)
J	66.6	32.5	0.9	75.0	not measured		(albite-twin type superstructure)
K	64.4	33.8	1.8	61.4	not measured		(albite-twin type superstructure)
M	57.3	40.3	2.4	73.7	87° 00′	90° 32′	albite
N	53.7	45.6	0.7	83.5	86° 48′	90° 33′	albite
O	48.5	47.3	4.2	82.8	86° 45′ 86° 43′	90° 15′ 90° 15′	pericline albite
Q	45.6	50.2	4.2	81.7	86° 52′	90° 17′	albite
R	44.1	51.6	4.3	71.3	86° 55′	90° 08′	albite
1	31.5	68.3	0.2	82.0	86° 39′	90° 34′	albite
2	19.8	72.7	7.5*	78.5	86° 13′ 86° 29′	89° 30′ 89° 58′	pericline albite

* Includes 1.5% Cs.

orthoclase; maximum microcline;[5] two intermediate microclines; high-temperature albite and synthetic feldspars, $Or_{10}Ab_{90}$, $Or_{20}Ab_{80}$, $Or_{30}Ab_{70}$; low-temperature albite and three natural low-temperature plagioclase feldspars of composition near $Ab_{89}An_{11}$, $Ab_{80}An_{20}$, and $Ab_{70}An_{30}$. The angles α^* and γ^* for these feldspars are given in Table 2. The values of

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[5] A microcline with maximum deviation from monoclinic symmetry has been described as a maximum microcline (MacKenzie, 1954) and it is proposed that any triclinic potash feldspar having less than the maximum deviation from monoclinic symmetry should be described as an intermediate microcline.

the reciprocal lattice angles of the soda phase of the orthoclase-perthites are also plotted. This diagram shows that some of the specimens have a soda phase which corresponds fairly closely with low-temperature albite but others show considerable departure from the lattice angles of low-temperature albite. One specimen (E) has a soda phase corresponding to a high-temperature feldspar of composition near $Or_{25}Ab_{75}$. This will be discussed more fully after the specimens used in this study are described.

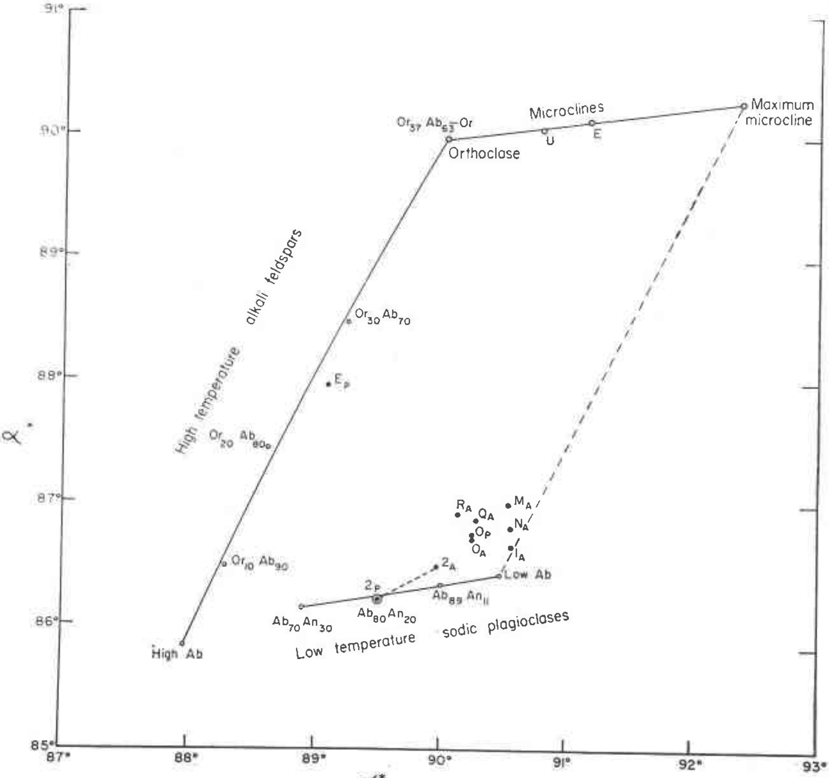

FIG. 4. Plot of the reciprocal lattice angles α^* against γ^* for triclinic alkali feldspars and three low-temperature sodic plagioclases. The point marked "orthoclase" at $\alpha^*=\gamma^*=90°$ includes all homogeneous monoclinic feldspars. The value of α^* is plotted against γ^* for the soda phase or phases of eight low-temperature feldspars. The suffixes A and P denote the type of twinning (albite or pericline) from which the measurements were made. Specimen *2* has two soda phases, one albite twinned and the other pericline twinned. Specimen *O* has one soda phase twinned according to both the albite and pericline laws.

Certain differences in the small parts of the x-ray patterns shown in Fig. 3 suggest a subdivision of the 14 specimens based on their bulk chemical composition. The groups are as follows: (i) *D*, *E*, and *F*, (ii) *H*, *I*, *J*, and *K*, (iii) *M*, *N*, *O*, *Q*, *R*, *1* and *2*.

Specimens D, E, and F. These specimens were grouped together by Chao and Taylor (1940) as representing one type of structure, and specimen *F* was described in some detail. The small parts of the *x*-ray photographs in Fig. 3 show that these specimens are distinct from the remaining specimens, in that reflections representing the soda phase lie only on the main layer lines of the photograph.

TABLE 2. RECIPROCAL LATTICE ANGLES α^* AND γ^* FOR SELECTED FELDSPARS

	α^*	γ^*	Reference
Microclines			
Blue Mountain, Ontario (maximum microcline)	90° 18′	92° 22′	MacKenzie (1954)
Specimen *E* (Spencer, 1937)	90° 09′	91° 09′	
Specimen *U* (Spencer, 1937)	90° 05′	90° 46′	
Synthetic high-temperature alkali feldspars (crystallized hydrothermally)			
$Or_{30}Ab_{70}$	88° 29′	89° 14′	Donnay and Donnay (1952)
$Or_{20}Ab_{80}$	87° 27′	88° 37′	
$Or_{10}Ab_{90}$	86° 29′	88° 17′	
Ab	85° 50′	87° 58′	
* *Synthetic high-temperature plagioclasses*			
Ab (crystallized hydrothermally)	85° 58′	87° 54′	Smith (in preparation)
$Ab_{90}An_{10}$ (crystallized dry)	85° 57′	87° 59′	
$Ab_{70}An_{30}$ (crystallized dry)	86° 04′	88° 00′	
$Ab_{50}An_{50}$ (crystallized dry)	86° 04′	87° 54′	
Natural low-temperature plagioclases			
Ab	86° 24′	90° 29′	
$Ab_{89}An_{11}$	86° 18′	89° 59′	
$Ab_{80}An_{20}$	86° 14′	89° 27′	
$Ab_{70}An_{30}$	86° 11′	89° 00′	

* These values are included to show the very slight differences in the angles α^* and γ^* of high-temp. plagioclases.

Specimens *D* and *F* were found by Spencer in the gem-washing residues of the Mogok Ruby Mines, Burma (Spencer, 1930). Specimen *E* was obtained from a garnetiferous granite-gneiss in the railway cutting near Ombadowla, Kalahandi State, Orissa, India (Spencer, 1937). Although specimen *E* was classified by Spencer as an orthoclase-microperthite and the crystal used to make the *b*-axis *x*-ray photograph, part of which is shown in Fig. 3, was optically monoclinic and has a monoclinic potash phase, it has been found that much of this sample should be described as an intermediate microcline with somewhat variable lattice angles (MacKenzie, 1954). A crystal of specimen *E* with a $7\frac{1}{2}°$ extinction angle on an (001) cleavage fragment gave the *x*-ray pattern of an untwinned microcline with diffuse streaks indicating only very slight unmixing.

The *b*-axis oscillation photograph of specimen *E* shows, in addition to the monoclinic potash phase, two sets of two closely spaced reflections lying on the layer lines of the monoclinic potash host. If the two closely spaced reflections are considered as a single reflection then the soda phase can be interpreted as twinned on the pericline law. The reciprocal lattice angles α^* and γ^* measured on this assumption are set down in Table 1, and from Fig. 4 it can be seen that these correspond closely to a high-temperature feldspar of composition near $Or_{25}Ab_{75}$.

The oscillation photographs of specimens *D* and *F* are very similar to each other and have, in addition to a monoclinic potash phase, a soda phase represented by three diffuse reflections. These cannot be interpreted as due to pericline twinning. In the crystal of specimen *F* studied by Chao and Taylor (1940) the soda phase was pericline twinned and the lattice angles corresponded more nearly with a high-temperature soda feldspar than with low-temperature albite (Taylor, personal communication). The type of structure shown by specimens *D* and *F* will be described as a pericline type superstructure, since the reflections are aligned in the direction given by pericline-twinned reflections. It is believed that this is an intermediate stage in the development of pericline twinning of the soda phase. The fine structure noted in the soda phase of specimen *E* may be a further stage in this process.

Specimens H, I, J, and K. The *x*-ray patterns of these specimens have one feature in common which distinguishes them from the remaining specimens. In each case the soda phase is represented by an odd number of reflections usually connected by diffuse streaks, the center reflection lying on the layer lines of the monoclinic potash phase. This structure is described as an albite-twin type superstructure for the reflections are aligned in the direction given by albite-twinned reflections. It is probably somewhat analogous to the pericline type superstructure already mentioned. Previous writers have noted the presence of a fine structure in the soda phase of some perthites. Laves (1952) has explained this as a result of the strain produced in the triclinic soda feldspar by the monoclinic potash structure. The strain is reduced by the growth of twin lamellae only a few unit cells across; this produces a superstructure which results in the complex pattern of reflections. The lattice angles of the soda phase cannot be measured by the simple method devised for twinned crystals (see following paper).

Specimen *H* is from the gem-washing residues of the Mogok Ruby

Mines, as are specimens *D* and *F*. Spencer (1930) noted that the extinction on (001) is sometimes oblique and may be as much as 4° from straight extinction but that there is no sign of microcline twinning.

Specimens *I* and *J*, two moonstones from Ambalangoda, Ceylon, are of very similar chemical composition. They occur in pegmatites within a region of feldspathic gneisses which appear to have been decomposed by hydrothermal solutions (Spencer, 1930).

Specimen *K* is from the contact of a pegmatite with a limestone at Myo Taung, $3\frac{1}{4}$ miles northeast of Mogok, Burma.

A careful examination of the *x*-ray photographs of specimens *I* and *J* reveals that the reflection representing the potash phase is not sharp but shows a diffuse streak at about 45° to the main layer lines. This will be discussed in detail in a following section.

Specimens M, N, O, Q, R, 1, and *2*. These specimens show either albite twinning or, in some cases, both albite and pericline twinning of the soda phase. Specimens *M* and *Q* show a fine structure of the albite-twinned soda phase but, if the centers of the two groups of reflections are measured, the reciprocal lattice angles are very similar to those of low-temperature albite.

Specimen *M* is from Ambalangoda, the same locality as that of specimens *I* and *J*. This sample was used by Chao and Taylor (1940) as an example of a perthite with an albite-twinned soda phase with lattice angles similar to those of low-temperature albite. The reciprocal lattice angles of the soda phase are given in Table 1 and plotted in Fig. 4, and their similarity to those of low-temperature albite can be readily seen.

Specimen *N* is from a locality $3\frac{1}{4}$ miles east-northeast of Mogok, Burma. The small part of the *x*-ray photograph (Fig. 3) shows that the potash phase is represented by three reflections; the relations in this specimen have already been briefly described (Smith and MacKenzie, 1954) and further details are given below.

Specimen *O* is described by Spencer (1930) as *Burma Black I*, but no locality is given for this specimen. The reciprocal lattice angles α^* and γ^* were measured for both the pericline-twinned reflections and the albite-twinned reflections. The results obtained were almost identical and are close to those of low-temperature albite.

Specimen *Q* is described by Spencer (1930) as *Burma Black II* and shows a blue schiller. In the single-crystal photograph a fine structure of the soda phase is present; the reciprocal lattice angles were measured by considering the centers of the two groups of reflections.

Specimen *R* is from Fredricksvärn, Norway.[6] Spencer (1937) noted

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[6] One pegmatite in the Langesundsfjord area provides most of the specimens of microperthite from this region. Oftedahl (1948) gives a sketch-map showing the location of the pegmatite.

that in thin section this material has an appearance similar to that described by Alling (1921) as incipient microcline twinning. The *x*-ray photograph shows that the *b*-axis of the potash phase is not exactly normal to the twin plane of the albite-twinned soda phase.

Specimen *1* was separated from the lestiwarite from north of Kvelle church, Laagendal, Norway. Brögger (1898, p. 216) gave a chemical analysis of this rock from which he calculated the mineral content as 91% microperthite, 7½% aegirine and 1½% sphene, and derived the composition of the feldspar from this mode as $Or_{35.8}Ab_{64.2}$. The analysis of the rock shows 0.85% CaO and thus the anorthite content of the feldspar is less than 4%.[6a] In thin section the feldspar is cryptoperthitic except for a narrow zone of microperthite at the grain boundaries where the two phases are distinctly visible and give a serrated border to most of the crystals. Brögger (1898) gives a drawing of this type of structure as it appears in a lestiwarite from Lyseböfjord. In the single-crystal *x*-ray photograph the reflections due to the potash phase show diffuse streaks in a direction at about 45° to the main layer lines (cf. specimens *I*, *J*, and *N*). The soda phase is albite twinned and has lattice angles very close to those of low-temperature albite.

Specimen *2* is an unusually soda-rich feldspar from a nepheline syenite in Mogok, Burma, recently studied by Tilley (1954). The feldspar has been described by Tilley as an orthoclase-microperthite, since most of the crystals are optically monoclinic despite the high soda content. A few crystals have been found showing albite twinning and others showing albite and pericline twinning when examined under the petrographic microscope. Single-crystal *x*-ray photographs show a monoclinic potash phase and a soda phase which is albite twinned or both pericline and albite twinned. One crystal which was albite twinned as observed under the microscope gave a single-crystal *x*-ray pattern having a monoclinic potash phase and an albite-twinned soda phase, i.e. the *x*-ray pattern was identical with that produced by an optically untwinned crystal.

A powdered sample of this feldspar was heated at 1050° C. for 65 hours and then *x*-rayed at elevated temperatures on the Philips high-angle spectrometer. Although the preliminary heat treatment had not completely homogenized the sample, only one triclinic phase could be detected in the *x*-ray powder patterns and this became monoclinic at elevated temperature. When homogeneous, this feldspar would be described as an anorthoclase (MacKenzie, 1952).

The reciprocal lattice angles α^* and γ^* (of the soda phase) were measured from an *x*-ray photograph which showed both albite- and pericline-

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[6a] Through the courtesy of Professor Tilley, a chemical analysis of this mineral was made by Mr. J. H. Scoon, after completion of the manuscript. Its composition is calculated as $Or_{31.5}Ab_{68.3}An_{0.2}$.

twinned reflections. The values differ by an amount greater than the error in measurement and the difference is sufficient to warrant describing these as two distinct phases. It can be seen also, from Fig. 4, that the angles measured from the pericline-twinned phase depart further from the values of low-temperature albite than any of the other specimens studied.

Comparison of the relative intensities of the soda and potash reflections in the *x*-ray photographs made from different crystals of this specimen indicates that the chemical compositions of the individual crystals differ. This difference has been neglected in the present study, but an *x*-ray method of determining the composition of individual crystals is being investigated.

RELATION BETWEEN CHEMICAL COMPOSITION AND THE NATURE OF THE SODA PHASE

From examination of the single-crystal photographs (Fig. 3) a division of these feldspars into three groups on the basis of the arrangement of the reflections representing the soda phase has been suggested. In the first group, only in the case of specimen *E* have the reciprocal lattice angles been measured, and these correspond to a high-temperature soda-rich feldspar. Specimen *F* was found by Taylor (personal communication) to have lattice angles close to a high-temperature soda-rich feldspar. It is believed that specimen *D* has a soda phase with similar lattice angles. The existence of a high-temperature soda phase in these specimens, which are presumed to be from low-temperature environments, presents a problem for which no completely satisfactory explanation is at present available. This difficulty might, of course, be overcome in the case of specimens *D* and *F* by describing them as sanidine-microperthites, since the optic axial angles of sanidines in the compositional range Or_{100} to $Or_{75}Ab_{25}$ are not known and the curve for orthoclases and orthoclase-microperthites in this compositional range is based partly on specimens *D* and *F* (Tuttle, 1952*b*). It has already been noted, however, that specimen *E* partly consists of an intermediate microcline, and the term sanidine has invariably been used to denote a high-temperature feldspar. Although the lattice angles of the soda phase were not determined on the crystal having a triclinic potash phase, this does necessitate a fairly close association of the assumed lowest temperature modification of potash feldspar with the high-temperature form of soda feldspar.

The lattice angles of the soda phase of specimen *E* are close to those of a high-temperature feldspar of composition about $Or_{25}Ab_{75}$. *If this represents the true composition of the soda phase, it may be impossible for it to invert to the low-temperature form if the structure of low-temperature albite* *cannot accommodate more than a very limited amount of potash.*[7] Low-temperature alkali feldspars having less than about 25% soda feldspar in their bulk composition might be expected in many cases to have a soda phase which is not pure $NaAlSi_3O_8$ and so would not invert to the low-temperature form. This does not exclude the possibility of specimens in this compositional range being completely unmixed to almost pure potash feldspar and pure soda feldspar, in which case the soda phase would be expected to be low-temperature albite if the specimen occurred in a low-temperature environment. Specimens of this type have been found.

Specimens in the composition range Or_{75}–Or_{60} (approx.) are characterized by the albite-twin type superstructure. If this type of structure is due to a periodicity of the albite cells reducing the strain caused by the presence of triclinic cells in a monoclinic host structure, it is to be expected that the existence of the superstructure will be dependent on the bulk composition of the sample, since the greater the potash content the greater will be the strain on the soda phase. The appearance of the albite-twin type superstructure in only the four specimens in this composition range gives further support to this explanation of the superstructure.

Specimens having less than 60% potash feldspar in their bulk composition have a soda phase which is albite twinned or albite and pericline twinned. Specimens *M* and *Q*, instead of having single spots representing the albite-twinned reflections, have groups of two spots. This may be a relict of the superstructure formed during the exsolution process. Since the proportion of soda feldspar in the remaining specimens is almost equal to or greater than the potash feldspar content, the soda phase should be considered as the host structure. The strain in the soda phase should therefore be small and the tendency to form a superstructure correspondingly less.

The tendency to form a superstructure is probably highest at the beginning of the unmixing process. As the unmixing proceeds, the size of the lamellae of the soda phase should increase, thus reducing the value of the strain per unit volume. It is thus reasonable to suppose that the formation of a superstructure is an intermediate step in the formation of a twinned crystal. We have, however, no evidence to prove this hypothesis.

It should be made clear at this point that the subdivision of these low-temperature perthites suggested here is based on only a limited number of specimens and may have to be modified as other samples of known composition are investigated.

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[7] Low-temperature alkali feldspars of composition near $Or_{25}Ab_{75}$ are comparatively rare and those that do exist are almost certainly unmixed.

Chao and Taylor (1940) gave a tentative explanation of the difference in the twinning and in the lattice angles of the soda phase in low-temperature perthites with relation to the bulk chemical composition. On the basis of the change in length of the *a*-axis they concluded that when the soda feldspar content is between 10 and 30%, only the soda feldspar in excess of the 10%, which might be held in solid solution in the potash phase, is exsolved. When the soda feldspar is in excess of 30% in the bulk composition they considered that all of it was exsolved and formed a separate soda phase with lattice angles close to those of low-temperature albite. In an attempt to determine the composition of the unmixed phases in the present investigation, using the change in spacing of the $20\bar{1}$ reflection in an *x*-ray powder pattern (Bowen and Tuttle, 1950), it was found that some specimens gave impossible results for the composition of the potash phase. A similar effect has been noted by Laves (1952) and explained by him as resulting from the unmixed phases not showing the same lattice parameters as they would if crystallized independently. Since the lattice edges of the unmixed phases do not give the values which would be expected if the phases had crystallized independently, it may be argued that the lattice angles also give incorrect values. From the present study, taken in conjunction with a study of high-temperature cryptoperthites, it is believed that a closer approximation to the composition of the soda phase is given by the lattice angles than by the lattice edges.

ORTHOCLASE-MICROPERTHITES WITH A TRICLINIC POTASH PHASE

Previous studies of orthoclase-microperthites have all indicated that the potash phase in such specimens is monoclinic. Four[8] of the specimens described here have a triclinic potash phase in addition to a monoclinic potash phase. It must be emphasized that these specimens would not be described as microcline-microperthites by the petrologist since the triclinic potash phase cannot be detected optically either by twinning or by oblique extinction. Even from *x*-ray powder patterns is it not possible to detect with certainty the existence of two potash phases.

Specimens *I*, *J*, and *1* show diffuseness of the reflections representing the potash phase, causing an elongation of the spots in a direction at about 45° to the main layer lines. In specimen *N* the potash phase is represented by three distinct spots and this material has been studied in detail. The reciprocal lattice angles α^* and γ^* of the triclinic potash phase are given in Table 3 and plotted in Fig. 5 along with the values for the

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[8] Specimen *E* will be excluded from this discussion since the optically monoclinic crystals examined have a monoclinic potash phase and optically triclinic crystals have a triclinic potash phase.

TABLE 3. EFFECT OF HEAT TREATMENT ON RECIPROCAL LATTICE ANGLES OF SPECIMENS *N*, *O* AND *R*

Specimen	Heat treatment	Soda phase α^*	Soda phase γ^*	Potash phase α^*	Potash phase γ^*
N	unheated	86° 52′	90° 35′	90° 50′	92° 35′
	heated at 800° C. for 6 hrs.	87° 31′	90° 45′	90° 48′	92° 16′
	then heated at 950° for 6 hrs.	88° 09′	91° 12′	90° 39′	92° 06′
	then heated at 1025° for 5 hrs.	88° 27′	91° 16′	90° 21′	91° 51′
	then heated at 800° for 24 hrs.	87° 41′	90° 49′	—	—
	then heated at 600° for 48 hrs.	87° 21′	90° 42′	90° 48′	92° 17′
O	unheated	86° 45′	90° 15′		
	heated at 900° C. for 1½ hrs.	88° 11′	90° 47′		
R	unheated	86° 55′	90° 08′		
	heated at 900° C. for 240 hrs.	87° 46′	90° 23′		

soda phase. The values of α^* and γ^* are comparable with those of a maximum microcline, but both α^* and γ^* depart further from 90° than do those of any microcline so far reported. This may result from the intimate intergrowth of the three phases affecting the true values of the lattice parameters.

From Laue, precession and Weissenberg *x*-ray photographs the following relations were found between the three phases of specimen *N*. The triclinic potash phase and the soda phase are oriented so that the b^*-axes of the potash phase are symmetrical about the common b^*-axis of the albite-twinned soda phase and make angles of 1° 24′ with it. The a^*-axes of the triclinic potash phase are also symmetrical about the two a^*-axes of the soda phase and are at angles of 48′ to the a^*-axes of the soda phase. The monoclinic potash phase has no simple crystallographic relation to either the triclinic potash phase or the soda phase.

Specimen *N* has been shown to consist of three phases, and it is of interest to determine the possible sequence of events in the exsolution process. With this in view the crystal, whose lattice angles had been carefully determined, was heated for 6 hours at 800° C., 6 hours at 950° C., and 5 hours at 1025° C. After each period of heating, the lattice angles of the two triclinic phases were measured. The values are given in Table 3 and plotted in Fig. 5. In this diagram the solid circles represent the plot of α^* against γ^* after heating at the temperature indicated beside the circles. In the case of the soda phase the triangles represent the plot of α^* against γ^* after heating the same crystal at progressively lower temperatures, i.e. at 800°C. for 24 hours and 600° C. for 48 hours. The triangle in the top right-hand corner of the diagram represents the plot of α^* against γ^* for the triclinic potash phase after heating at 600° C. for 48 hours. From Fig. 5 it can be seen that the change in the reciprocal lattice angles of the soda phase with heating is in the direction of a maximum microcline. The angles of the triclinic potash phase do not change directly toward low-temperature albite as would be expected if complete solid solution exists between microcline and low-temperature albite (Laves, 1952). After heating at 1025° C. measurement of the reciprocal lattice angles became difficult, and it was judged that further heating would make it impossible to measure the angles without introducing considerable error.

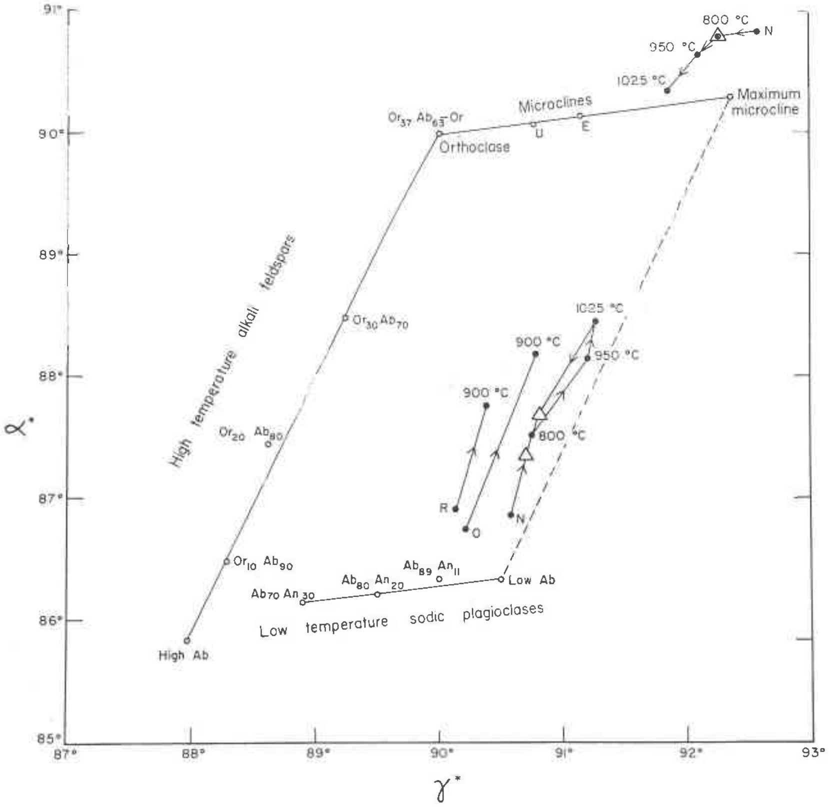

FIG. 5. Diagram to show the effect of heating at progressively higher temperatures on the values of α^* and γ^* of the soda phase in specimens *N*, *O*, and *R* and of the triclinic potash phase of specimen *N*. The triangles represent the points obtained by reversal of this process in specimen *N* by heating the same crystal at 800° C. for 24 hours and then at 600° C. for 48 hours.

To determine whether these changes were reversible the same crystal which had been heated at 1025° for 5 hours was heated at 800° for 24 hours and 600° for 48 hours. The results given in Table 3 and Fig. 5 indicate that the changes produced in both the soda and potash phases are reversible, although heating at 600° did not restore the angles to their original values; prolonged heating at lower temperature might have this effect since this is undoubtedly a rate process.

Two other specimens were heated for varying lengths of time, and from the figures given in Table 3 and plotted in Fig. 5 it can be seen that the angles of the soda phase of these specimens also change in the direction of those of microclines.

In the case of the soda phase of specimen *N* it is certain that the changes in the lattice as a result of heat treatment are due to the solid solution of potash in the soda phase, and it is assumed that the changes in the lattice of the potash phase result from the solid solution of soda.[9] It is now fairly well known that prolonged heating of a microcline at a temperature fairly near its melting point produces a change in the lattice, the final product being a monoclinic feldspar. The heat treatment to which specimen *N* was subjected was insufficient to cause any change in the lattice unless it be due to the solid solution of soda feldspar.

In the single-crystal *x*-ray photographs the appearance of streaks, or two sharp spots lying at the extremities of the streaks, making an angle of approximately 45° with the main layer lines is the characteristic feature of these four specimens. This is to be contrasted with the development of microcline from a potash-rich orthoclase where the first sign of a departure from monoclinic symmetry is indicated in the *x*-ray oscillation photographs by the appearance of diffuse streaks lying on curves of constant ζ or curves of constant ξ representing pericline or albite twinning, respectively, or in many cases both types of twinning appear together. The association of orthoclase and microcline in a feldspar from the Bear Paw Mountains, Montana, has already been described (MacKenzie, 1954) and it has been shown that there is a simple crystallographic relationship between the two potash phases. The evidence that the triclinic form was derived from the monoclinic form is fairly conclusive.

In the case of specimen *N* the crystallographic relationship between the triclinic potash phase and the triclinic soda phase suggests that these two phases are the result of the same period of exsolution but that the monoclinic potash phase was probably exsolved at an earlier stage. If the temperature of the final period of exsolution is within the stability

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[9] The monoclinic potash phase also takes some soda feldspar into solid solution with heat treatment.

field of microcline and the composition of the potash phase is nearly pure $KAlSi_3O_8$, then the potash phase would be expected to be a microcline (MacKenzie, 1954).

These small differences found in the single-crystal *x*-ray patterns of specimens *I*, *J*, *N*, and *1* almost certainly have some petrologic significance which is not yet fully understood. Further work on specimens of this type from carefully investigated geologic environments may help to solve this problem and enable future investigators to make use of these small differences which are easily detected on an *x*-ray oscillation photograph.

RECIPROCAL LATTICE ANGLES OF THE SODA PHASE

In a study of a series of high-temperature sanidine-cryptoperthites (to be described in paper III of this series) it has been found that the reciprocal lattice angles of the soda phase of these specimens correspond closely with the values expected from high-temperature soda-rich feldspars, and it is believed that from these angles the amount of potash feldspar in the soda phase may be determined. In the case of perthites whose soda phase corresponds approximately with low-temperature albite the points representing α^* plotted against γ^* are distributed in an apparently random manner near the point representing low-temperature albite (Fig. 4). The values of α^* and γ^* of the soda phase of a perthite will permit making a distinction between a high- and a low-temperature soda phase, but it would be desirable to have an explanation for the cause of the spread of values near low-temperature albite.

Consideration of the reciprocal lattice angles of the soda phase of these low-temperature feldspars with respect to those of low-temperature albite (Table 1) along with the total anorthite content of the samples, suggests that the value of γ^* of the soda phase decreases with an increase in the total anorthite content. That the effect of solid solution of potash feldspar in the soda phase is to increase the value of α^* has been shown by the heating experiments already described. Thus the values of α^* and γ^* of the soda phase may give an indication of its chemical composition.

The measurements made from both the albite-twinned and pericline-twinned phases of specimen *2* are very different from those of low-temperature albite, and it is seen (Fig. 4) that the plot of the pericline-twinned phase falls approximately halfway between high- and low-temperature albite with reciprocal lattice angles equivalent to those of a low-temperature plagioclase of composition $Ab_{80}An_{20}$. From the values of α^* plotted against γ^* for soda-rich low-temperature plagioclases it may be seen that the anorthite molecule has an effect on low-temperature albite very similar to that which would be expected from materials transitional between the two forms of albite. The lattice angles of the soda phases of specimen *2* may therefore deviate from those of low-temperature albite, either because these phases are transitional to the high-temperature form or because they have a high content of anorthite.[10] The total anorthite content of specimen *2* is 6% and is greater than that of any of the other specimens studied.

It is almost certain that the deviations of γ^* of both the albite- and pericline-twinned phases from γ^* of low-temperature albite are due to the high anorthite content of this specimen and not to a transition to the high-temperature forms. The soda-rich part of this specimen may thus be considered as a plagioclase of bulk composition near $Ab_{85}An_{15}$ which consists of two phases of approximate composition $Ab_{90}An_{10}$ and $Ab_{80}An_{20}$ (see Fig. 4). It is interesting to note that, although the temperature of final crystallization of this feldspar has been low enough to form two low-temperature plagioclase phases (peristerite), there is no evidence of the development of a triclinic potash phase. Laves (1952) has briefly noted the existence of three-phase feldspars of this type.

Specimens *O*, *Q*, and *R* each have about 4% of the anorthite molecule in their bulk composition (Table 1). These are represented in Fig. 4 by points lying considerably to the left of a line joining low-temperature albite to maximum microcline. The remaining specimens *M*, *N* and *1* (see footnote 6*a*) have much smaller anorthite contents and are represented by points lying fairly close to the line joining low-temperature albite to maximum microcline. This suggests that increase in the bulk anorthite content of the feldspar does reduce the value of γ^* of the soda phase.

Because of the very limited solid solution between lime feldspar and potash feldspar (Schairer and Bowen, 1947) it may be assumed that in a perthite almost all the lime feldspar is held in the soda phase. Unfortunately, the proportion of lime feldspar to soda feldspar in this phase cannot be determined since it will depend on the amount of soda in the potash phase, and at present we have no means of determining this amount accurately.[11]

Specimens *M*, *N*, *O*, *Q*, and *R* have values of α^* differing from that of low-temperature albite by amounts greater than the error in measurement, whereas specimens *1* and *2* have values close to that of low-temper-

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[10] These two alternatives are not mutually exclusive since the effect of lime on the values of α^* and γ^* of high-temperature albite is negligible (see Table 3). Thus the soda phases might have a high lime content and also be transitional to the high-temperature form.

[11] It has been noted on a previous page that the $20\bar{1}$ spacing cannot be used to determine the composition of the potash phase in many perthites.

ature albite. The heating experiments on specimens *N*, *O*, and *R* indicate that the effect of solid solution of potash in the soda phase is to increase the value of α^*, and so it is believed that specimens *M*, *N*, *O*, *Q*, and *R* have soda phases which are not pure $NaAlSi_3O_8$ but contain small amounts of potash in solid solution. From what has already been stated in discussing the soda phase of specimen *E* (page 724) is it assumed that the amount of potash which can be held in solid solution in a low-temperature albite is rather small. The solid solution of potash in the soda phase of specimens *N*, *O*, and *R* as a result of heat treatment probably represents metastable equilibrium.

If the deviations in the values of γ^* and α^* in the soda phases of low-temperature perthites are due, as has been proposed above, to the lime and potash feldspar contents respectively, it may eventually be possible to determine accurately the composition of the soda phase and so calculate the composition of the potash phase of a specimen of known bulk composition.

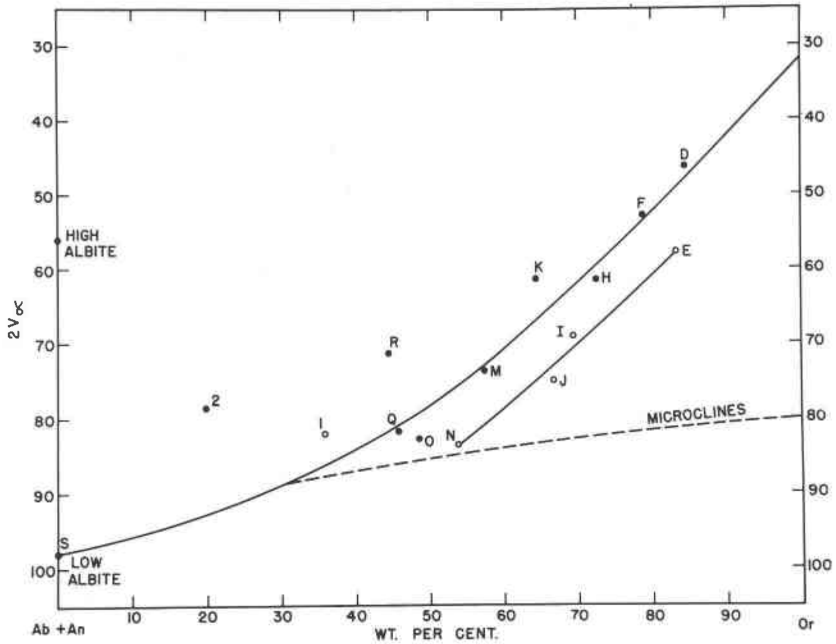

FIG. 6. Plot of the optic axial angle against chemical composition for the orthoclase-microperthites investigated. The closed circles denote specimens having a monoclinic potash phase and the open circles denote specimens having a triclinic potash phase in addition to a monoclinic potash phase. The point indicated by the letter *S* is the value of 2V for Amelia albite given by Spencer (1937). A point for high-temperature albite is given for comparison.

THE OPTIC AXIAL ANGLE OF ORTHOCLASE-MICROPERTHITES

In Fig. 6 the values of the optic axial angle of each of 14 specimens investigated have been plotted against their orthoclase content as obtained from chemical analyses. The points representing specimens which have a monoclinic potash phase are represented by closed circles and those which have a triclinic potash phase in addition to a monoclinic phase are represented by open circles. The curves relating the optic axial angle with chemical composition for the "orthoclases" and "microclines" are reproduced from Fig. 1 and a separate curve has been drawn through the points marked by open circles, representing specimens *E, I, J,* and *N*. Specimens whose bulk compositions lie in the range $Or_{84.5}$–$Or_{45.6}$ fall fairly close to the curve for orthoclases if they have only a monoclinic potash phase. Specimens in this range which have a triclinic potash phase in addition to the monoclinic potash phase have values of optic angle greater than would be expected.

The three specimens more soda-rich than $Or_{45.6}$ show a rather large scatter of the values for their optic axial angles. Specimen *2* is very much displaced from the curve, and it has already been noted that the reciprocal lattice angles of the soda phase of this specimen deviate considerably from those of low-temperature albite. Specimen *1* falls above the orthoclase curve although it has a triclinic potash phase and is similar to specimens *E, I, J,* and *N* in this respect. The scatter of the values of optic axial angle in this compositional range cannot be accounted for by any one variable.

Tuttle and Keith (1954) have shown that the optic axial angle of some alkali feldspars may be intermediate between the expected value for an orthoclase-microperthite and a sanidine-cryptoperthite of corresponding composition and have attributed this to the soda phase having partly inverted to the low-temperature modification, with part remaining as high-temperature albite. Further investigation of the specimens studied by Tuttle and Keith has shown that the value of the optic angle of an alkali feldspar for a known composition is a function of the ratio of high- to low-temperature albite. From the data given here it is suggested that the optic axial angle of low-temperature perthites may also be affected by the nature of the potash phase. Thus the value of the optic angle will be greater in a feldspar which has a triclinic potash phase than it will be if no triclinic potash phase is present.

In specimen *E* the soda phase is near a high-temperature soda-rich feldspar and the potash phase is sometimes triclinic. These two factors should have the opposite effect on the value of the optic angle. It appears that the number of variables affecting the value of the optic axial angle is too great to permit using the 2V as an indication of the nature of the potash phase. A single-crystal *x*-ray oscillation photograph will give important information as to the nature of both the potash and the soda phase.

SUMMARY AND CONCLUSIONS

To describe the feldspar specimens studied, the subdivision of the alkali feldspars into four series as proposed by Tuttle (1952*b*) has been adopted and the curves relating optic axial angle with chemical composition have been used to define members of these series. Single-crystal *x*-ray studies of a number of chemically analyzed orthoclase-microperthites have shown that the reciprocal lattice angles of the soda phase can be used to indicate whether the soda phase is a high- or low-temperature form. In addition, an approximation to the chemical composition of the soda phase may be determinable from these angles.

Most of the orthoclase-microperthites, in which the nature of the soda phase could be determined, have a soda phase with lattice parameters close to those of low-temperature albite.[12] Studies of sanidine-cryptoperthites, to be reported in paper III of this series, reveal that these have soda phases comparable with high-temperature soda feldspar. Tuttle and Keith (1954) have shown that specimens which fall intermediate between the orthoclase-microperthite series and the sanidine-cryptoperthite series have two soda phases, one a high-temperature form and the other a low-temperature form. Thus the subdivision of the alkali feldspars into the orthoclase-microperthites and sanidine-cryptoperthites based on the value of the optic angle for a known chemical composition is not merely an arbitrary subdivision, but has a genetic significance, particularly relative to the temperature of final crystallization.

No perthites have been found having a soda phase which gives conclusive evidence of stable states transitional between high- and low-temperature soda feldspar, although such transitional forms have been postulated by other workers from both optical and *x*-ray studies for single-phase soda feldspars.

Many of the specimens which have been classed as orthoclase-microperthites do not always show straight extinction on (001) cleavage fragments. In addition, some specimens have a triclinic potash phase as well as a monoclinic potash phase and the term orthoclase has generally been understood to apply to monoclinic potash feldspar. It is thought that, until the significance of these slight differences in orthoclase-microperthite

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[12] The exceptions have been discussed on a previous page.

specimens can be elucidated, no useful purpose can be served by giving special names to such specimens.

A mineralogical study of this type can merely indicate a possible sequence of events in the crystallization history of the alkali feldspars. It is hoped, however, that by using the *x*-ray technique, adopted here and described in detail in the following paper, the petrologist investigating alkali feldspar-bearing rocks will obtain considerable help in deducing the history of the rocks. Conversely the detailed study of the alkali feldspars from a carefully investigated geologic environment will give a more accurate picture of the sub-solidus equilibria in this series.

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