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X-RAY AND OPTICAL STUDY OF ALKALI FELDSPAR: I. DETERMINATION OF COMPOSITION AND STRUCTURAL STATE FROM REFINED UNIT-CELL PARAMETERS AND 2V[1]

THOMAS L. WRIGHT AND DAVID B. STEWART, *U. S. Geological Survey, Hawaii National Park, Hawaii, and Washington, D. C.*

Computer-refined unit-cell parameters and optical angle measurement of several series of alkali feldspars of intermediate structural state (prepared by alkali-exchange techniques), together with similar data obtained by Orville for the limiting series high sanidine-high albite and maximum microcline-low albite, now provide a comprehensive method to study alkali feldspars from all geologic environments. All samples of equivalent structural state prepared by alkali exchange from the same starting material ("alkali-exchange series") show a continuous variation in unit-cell parameters and optic axial angle with composition, but slightly different alkali-exchange series are obtained for samples of intermediate structural states when the starting material is K-feldspar than when the starting material is Na-feldspar. The evidence from the physical properties measured indicates that, although it is theoretically permissible to have an infinite number of intermediate structural states between the limiting series, in nature certain structural states have a relatively high frequency of occurrence while certain others have not yet been observed. Nonetheless, previous classifications based only on small numbers of feldspar series should be modified.

A revised terminology and format, based on cell parameters, for description of alkali feldspar is given for all natural alkali feldspars. Determinative curves of b vs c (and contoured for a) permit both the estimation of the structural state and the detection of "anomalous" unit cells, that is, if $a_{(\text{observed})} - a_{(\text{estimated from } b \text{ and } c)} > 0.02$Å. Composition may be determined directly from a if a is not crystallographically "anomalous," or from unit-cell volume if a is "anomalous." An appendix describes in detail the measurement and indexing of the X-ray powder diffraction patterns of an alkali feldspar preparatory to computer refinement of unit-cell parameters.

INTRODUCTION

A new cycle of study of the physical properties of alkali feldspars is underway, utilizing recently developed alkali-exchange techniques and computer refinement of unit-cell parameters from powder diffraction data. Techniques of exchanging the alkali ions in pulverized feldspars (Ashcroft, 1918; Laves, 1951; Wyart and Sabatier, 1956a, b; Orville, 1960, 1962, 1964, 1967) have now been developed to the point where it is possible to prepare a composition with any specified Na/K ratio from any alkali feldspar without altering the original aluminum-silicon arrangement of the starting material. Recently, computer programs that yield refined unit-cell dimensions from least-squares analysis of powder diffraction data have become available (Evans, Appleman, and Handwerker, 1963, and subsequent oral communications), and it is now possible routinely to obtain precise measurements of unit-cell parameters

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[1] Publication authorized by the Director, U. S. Geological Survey.

from the fine-grained samples most suitable for alkali exchange and collected from many geological environments.

Recently Professor P. M. Orville of Yale University has measured unit-cell parameters for the maximum microcline-low albite structure series and for the high sanidine-high albite structure series (Orville, 1967). We have performed alkali exchange experiments on many varieties of alkali feldspar that are structurally intermediate between these two limiting series and have measured the compositions and unit-cell parameters of both the starting material and of the exchanged products. Orville's data as well as our own were refined using the Evans *et al.* (1963) computer program at the Geological Survey, and may thus be compared directly. We have made extensive use of Orville's data, and have also been aware of data for various alkali feldspars prepared by D. R. Waldbaum of Harvard University.

In addition to new data for alkali-exchanged feldspars, a re-refinement of the powder-diffraction data of Donnay and Donnay (1952) for the high albite series is presented.

We will describe alkali feldspars in terms of composition and structural state. Composition will be stated throughout in terms of weight percent $KAlSi_3O_8$, denoted by the symbol Or.

Each alkali feldspar composition may exist as a number of polymorphic modifications, which are usually called *structural states*. We will use the term *structural state* for any one particular polymorphic modification of the feldspar structure. Crystal structure analysis of feldspars has shown that the various polymorphic modifications differ principally in their aluminum-silicon distributions. For example, high sanidine and high albite have essentially random Al-Si distributions, whereas maximum microcline and low albite have almost completely ordered Al-Si distributions. Between these limiting cases many polymorphs with different ordering schemes and amounts of order may occur, each of which is a different structural state.

From any initial alkali feldspar composition and structural state, most other alkali feldspar compositions may be prepared by rapid alkali exchange and homogenization techniques. Our results and those of previous workers demonstrate that the aluminum-silicon distribution of the starting material can be retained in these experiments. Thus we may refer to alkali feldspars of various compositions which have *equivalent* structural states, that is, which have identical Al-Si distributions to the starting feldspar. The various compositions may not form an isostructural series, for any of several reasons, for example, a symmetry change or differences in the alkali positions in the structure.

The structural states of feldspars that have been subjected to crystal structure analysis have been compared by means of a long range order parameter calculated from the aluminum contents of the various tetrahedral sites, deduced from the average tetrahedral sizes in the structures. One such parameter, S, was defined by Smith and MacKenzie (1961, p. 42) so that completely ordered feldspars have $S=1$, and completely disordered feldspars have $S=0$. Unfortunately, the relationship between tetrahedral size and aluminum content is not known exactly, and the calculation of S may be uncertain by at least five and perhaps ten percent for this reason. Complications also may result from the many possible ways in which a feldspar may change the distribution of Al and Si in going from a completely disordered to completely ordered arrangement or vice versa. Different ordering schemes may yield the same value of S, so that the structural state is not completely specified by knowing S. Stated another way, the aluminum: silicon distribution may be quite different in two feldspars with the same value of the long range order parameter, or degree of order. Our alkali exchange data indicate that the ordering schemes that control the formation of intermediate structural states of potassium feldspar are slightly different from the ordering schemes that control intermediate structural states of sodium feldspar. Lacking structural studies of intermediate structural states of sodium feldspar, the long range ordering parameter is useful only to compare the polymorphs of potassium feldspar whose structures have been determined.

Our study demonstrates that the axial dimensions of homogeneous alkali feldspars vary smoothly with composition and with structural state in such a way that if b and c are known, a can be closely estimated. It is known from studies by previous workers and confirmed by us that the a of certain alkali feldspars is too long relative to b and c to fit the series defined by homogeneous starting materials. The a axis of the potassic phase of some perthites may even exceed that for any known polymorph of $KAlSi_3O_8$. Thus anomalous cell dimensions are known to occur in natural alkali feldspars and their origin in phases of perthites has been discussed by Smith (1961). For descriptive purposes in this paper we state that if, for any alkali feldspar, the quantity [a (observed)-a (estimated from b and c)] exceeds 0.02 Å then the feldspar is described as having *anomalous* cell dimensions.

The available data permit certain broad correlations to be made among composition and the physical properties we have measured, which are useful in estimating the compositions and structural states of natural samples. We present herein a number of tables and graphs for the purpose of describing natural alkali feldspar phases; simplifications of some of these are reported by Wright (1968) as part II of this study. Such problems as the dependence of the monoclinic $\rightleftharpoons$ triclinic symmetry change on composition and structural state, the occurrence of preferred structural states in natural alkali feldspar polymorphs, and the identification of alkali feldspar polymorphs formed by metasomatism can be solved from our X-ray data for alkali feldspar series of constant structural state.

The preparation of samples with known composition and structural state has made it possible to relate other physical properties of alkali feldspars to these variables. The optic axial angle is given for several alkali feldspars, both synthetic and natural, and an approximate correlation of unit-cell parameters with optic axial angle is made. Comparison of the properties of our samples with those of feldspars studied less precisely, or before many of the complexities introduced by variable structural state were recognized, reveals that extensive modifications are needed for determinative curves based on optical data.

METHODS

Alkali exchange. Natural alkali feldspars as nearly homogeneous as obtainable were used as starting materials for alkali exchange in anhydrous NaCl or KCl melts. The method described by Orville (1967) was used with only minor modifications. Each batch of end-member composition was prepared by two or three exchanges in fresh alkali chloride melt, at $\sim$ 850°C, for one day. Most of the exchange occurred during the initial 6 hours, but the rate varied from specimen to specimen. Exchanges were considered as complete when the composition as estimated from 2θ $(\bar{2}01)$ became constant in successive exchanges. Not all feldspars could be exchanged to pure $NaAlSi_3O_8$ or $KAlSi_3O_8$. Possible reasons for this are discussed in a later section.

Determination of unit-cell parameters. Smear mounts were made of finely ground feldspar mixed with CaF_2 as a standard ($a = 5.4620$ at 25°C) and were run on a high-angle X-ray diffractometer at a goniometer speed of 1/2° per minute. Chart speed was set so that $1°\ 2\theta = 1$ inch. Peaks were measured as near their tops as practicable, and a wavelength of $CuK\alpha_1$ ($\lambda = 1.5405$ Å) was used for all peaks. The values of 2θ were the average for three traverses run from 57°–10° 2θ.

Unit-cell parameters were refined from the measured 2θ values using the computer program developed by Evans, Appleman, and Handwerker (1963), with subsequent modifications by Appleman and Handwerker. The 2θ values used were selected with criteria developed by Wright and given in detail by Orville (1967). Initial starting dimensions were taken from the literature or from Orville's results. The ambiguity in indexing reflections was resolved with Tables 11–14 and also with single-crystal intensity data from Cole, Sorum and Kennard (1949), Jones and Taylor (1961), Finney and Bailey (1964), and Ferguson, Traill and Taylor (1958). Both computer and fixed indexing were used in the early stages; the final unit-cell parameters were determined by least-squares refinement of unambiguously indexed 2θ values[1] using the fixed-index routine of the computer program. All 2θ values were given unit weight.

The standard errors reported for the unit-cell parameters of a given sample reflect the internal consistency of line measurements from a particular pattern of that sample. The true precision of determination of the cell parameters for the sample could be obtained more accurately by measuring and refining the data from several patterns, made from different splits of the sample. We lack such data. However, in many experiments on the reversibility of exchange reactions and in three cases where three or four separate measurements and refinements were performed on the same sample, we observed that the results normally agree to within twice the standard errors obtained from the individual patterns, and without exception fall within three such intervals. We conclude that the best estimate of the precision of our cell-parameter determinations is twice the standard errors.

Since the unit-cell parameters that we obtain are of course "averaged" for each sample by the powder-diffraction technique, the possibility of a range of parameters existing within a "homogeneous" sample has not been treated. Such variation may well occur on a small scale due to the complex types of domain structures that have been found in feldspars. Furthermore, many potassic phases of intermediate structural state may actually be triclinic, but must be treated as monoclinic by powder-diffraction methods. Both of these factors may contribute to the standard errors obtained from the refinements.

RESULTS

Presentation of data. So far as is known, the limiting structural states of alkali feldspar are the series high sanidine-high albite and maximum microcline-low albite. Our data will be presented first for series of equivalent structural state from potassic starting materials, and then for those from sodic starting materials, in sequence from highest to lowest

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[1] A document listing the computer input (fixed Miller index and associated observed 2θ) and the final cycle of refinement for each sample studied has been deposited as Document No. 9739 with the American Documentation Institute, Auxiliary Publications Project, Photo Duplication Service, Library of Congress, Washington, D. C. 20540. Copies may be secured by citing the document number, and remitting in advance $6.25 for photoprints or $2.50 for 35 mm microfilm.

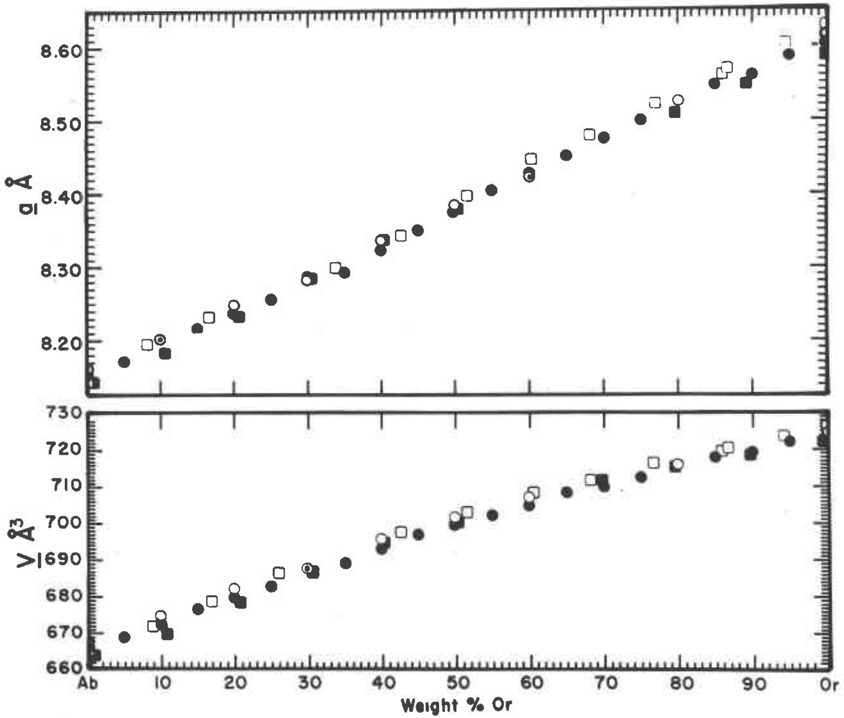
apparent structural states as estimated from their positions on the plot of the *b* and *c* axial dimensions (Fig. 2b). For potassic feldspar the sequence from highest structural state is high sanidine, Puye, P50-56F, Benson, SH 1070, Spencer B, Spencer U, and maximum microcline. For sodic feldspars the sequence from highest structural state is high albite, S62-34, Albite III, and low albite.

The X-ray, chemical, and optical data for feldspars used in our exchange experiments are summarized in Tables 1–7. Understanding of the interrelations of the various feldspar series will be made clearer, however, by referring to the graphical presentation of Figures 1–3. In Figure 1 cell data for an exchange series equivalent to orthoclase are plotted against Or content. Data for the high sanidine-high albite and maximum microcline-low albite series are shown for comparison. The presentation is similar to that of Orville (1967, Figs. 3–5).

Simultaneous examination of the axial dimensions, interaxial angles, and unit-cell volumes is a somewhat cumbersome procedure, and we have sought to plot pairs of these parameters against each other, and to contour such plots for one or more additional parameters. We make particular use of the opposite variation of the *b* and *c* axes with changing structural state (Fig. 2), and of the variation of α and γ, which we have chosen to represent by α^* and γ^* (Fig. 3) in a slight modification of the way first plotted by MacKenzie and Smith (1955). The line generated on such plots by the variation of any two unit-cell parameters for samples of equivalent structural state we call an *alkali-exchange path*, and these form the basis for distinguishing structural states. Figure 2b is contoured for *a*. Feldspars whose cell dimensions do not plot at possible intersections of *a* with alkali exchange paths are called *anomalous* as defined above.

The high sanidine-high albite series. Alkali feldspars in the high sanidine-high albite series can be synthesized hydrothermally from glass or gel, or can be inverted from lower structural states hydrothermally or by long heating at over 1000°C. Anhydrous alkali-exchange techniques were used by Wyart and Sabatier (1956b) to convert high sanidine to high albite and vice versa, but the unit-cell parameters of these materials were not given. We utilize cell data for two series of feldspars prepared by direct synthesis and cell data for alkali-exchanged equivalents of synthetic $KAlSi_3O_8$ and $NaAlSi_3O_8$.

Donnay and Donnay (1952, Tables 6–9) give powder-diffraction data for four synthetic alkali feldspars of high structural state. They have provided us with the 2θ measurements for the other samples studied in their investigation, and we have determined the refined unit-cell param-



(a)

FIG. 1. Unit-cell parameters for three structure-equivalent series of alkali feldspars plotted as a function of *Or* content. Figure 1a, *a* (top), *V* (bottom); Figure 1b *c* (top), *b* (bottom); Figure 1c, *α* (top), *γ* (middle), *β* (bottom). Symbols for all figures as follows:

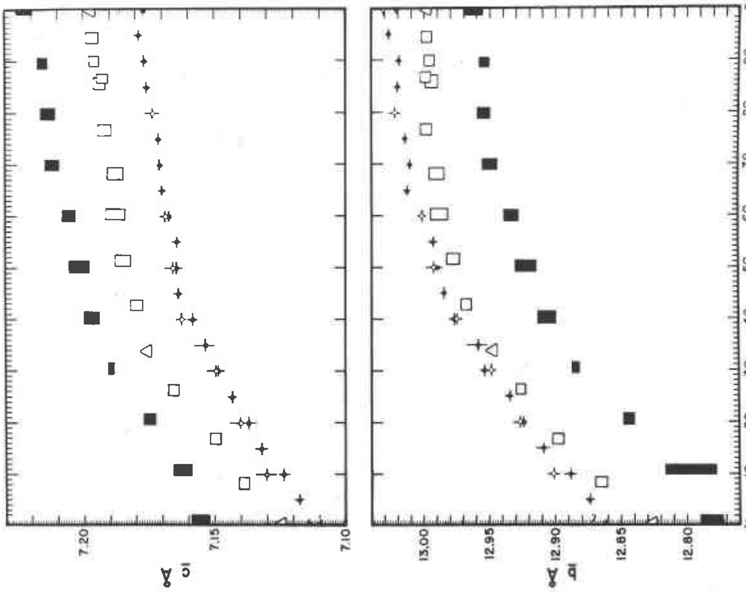
Open circles. High sanidine—high albite. Data of Donnay and Donnay (1952) re-refined (Table 1, this paper).

Solid circles. High sanidine—high albite. Data of Orville (1967).

Open rectangles. Orthoclase series structurally equivalent to P50-56F. Data of Table 7, this paper. Open triangles are interpolated or extrapolated points in this series.

Solid rectangles. Maximum microcline-low albite. Data of Orville (1967).

All data points are drawn to ±2 percent *Or* and to ±2 standard deviations of the cell parameter.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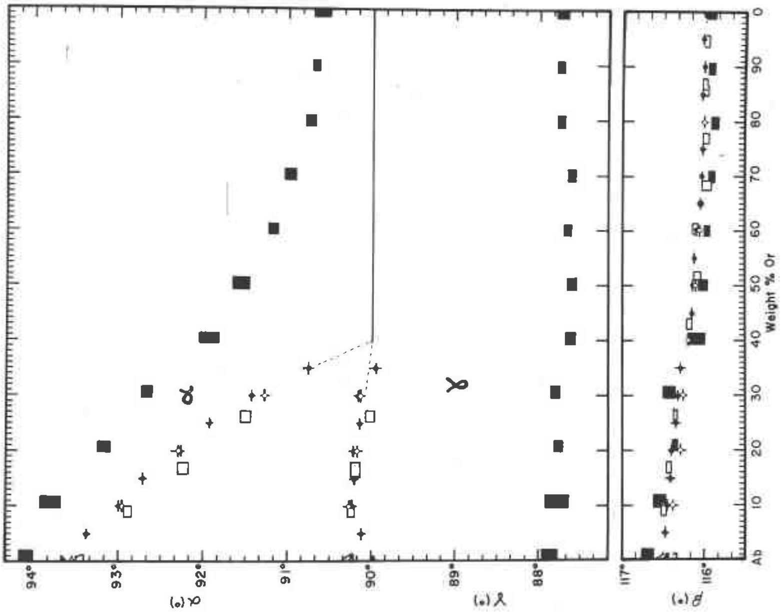
(b)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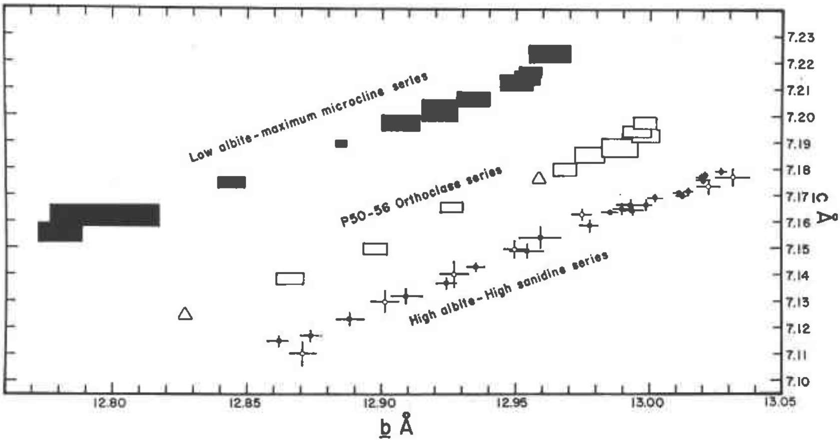

FIG. 2a. *b* plotted against *c* for three structure-equivalent alkali feldspar series. Symbols and references are the same as for figure 1.

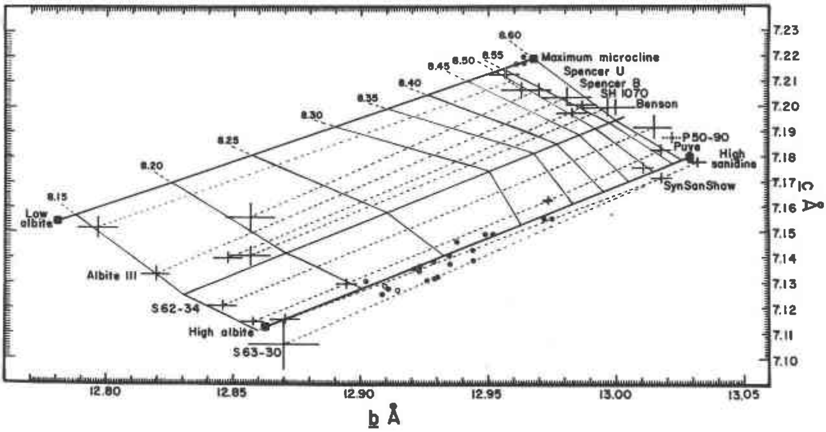

FIG. 2b. *b* plotted against *c* for alkali exchanged feldspars, data from Table 2, this paper, and for natural maximum microclines and anorthoclases. Dashed lines connect feldspars of equivalent structural state (each named on the diagram), except for P50-90 where the symbols are dotted. Solid squares are approximate positions of the end members; low albite, maximum microcline, high albite, and high sanidine. Heavy lines are drawn by eye for the three series shown in figure 2a. Cross contours are values of *a*, interpolated for the three complete series. Small circles represent natural maximum microclines and anorthoclases as follows:

Solid circles. Maximum microcline (upper right), unpublished data of T. L. Wright; anorthoclases, data of Carmichael and MacKenzie, 1964.

Open circles. Anorthoclase, data of Boudette and Ford, 1966.

Half-solid Circles. Anorthoclase, unpublished data of D. B. Stewart.

All symbols for alkali-exchanged felsdpars are drawn to ±2 standard deviations in *b* and *c*.

eters in Table 1 by the computer method. Our results agree with their hand refinement within the stated standard error in all but a few instances. This is an impressive testament to the quality of their measurements and to the meticulous calculations that they performed before machines were programmed to compute unit-cell dimensions. The suggestion of Smith (1956, p. 537) that 0.025° 2θ should be added to the Donnays' powder-diffraction data for high albite to yield dimensions in better accord with those obtained since 1952 for high albite was used to get the value for high albite given in Table 1.

The data of Table 1 are plotted in Figures 1–3 together with the corresponding data for the high sanidine-high albite exchange series gathered by Orville (1967).

These two sets of unit-cell parameters for the high sanidine-high albite series agree within twice the stated standard errors in 89 percent of the measurements. We consider the agreement to be excellent considering that the measurements were collected by different methods. Furthermore, the most sodic samples measured by Orville yield parameters that deviate from the smooth curves obtained for the rest of the series, indicating that these samples have begun to change toward lower structural states, as described in detail by MacKenzie (1957). At least the high albite sample therefore should not be compared rigorously with the Donnays' sample because it is not of equivalent structural state.

We exchanged high sanidine in molten NaCl to prepare high albite, using sanidine prepared by H. R. Shaw (SynSanShaw, Table 2). Unit-cell parameters determined for the starting material and the sodic exchange product are given in Table 2. The cell parameters of the synthetic sanidine are anomalous when compared to those reported in Table 1 and by Orville (1967).[1] The sodium-rich product, however, plots on the high sanidine-high albite series (Fig. 2b, 3b).

A sample of synthetic high albite (S63-30, Table 2) was exchanged in molten KCl. The parameters of the starting material and of the exchange product are those of high albite and high sanidine, respectively. It is concluded that products of equivalent structural state in the high sanidine-high albite series can be obtained by direct synthesis, pyrosynthesis from lower structural states, and alkali exchange.

The cell data for the high sanidine-high albite series plot as a line in

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[1] Seven samples of sanidine synthesized from glass or gel with $KAlSi_3O_8$ composition have the following range of unit-cell dimensions: $a=8.600$–8.626, $b=13.011$–13.034, $c=7.164$–7.178; according to data from Lindsley, 1966, Orville (1967), Donnay and Donnay (1952), and Stewart (unpub.). This range of values exceeds the precision of measurement and may indicate that slight differences in structure result from different conditions of synthesis.

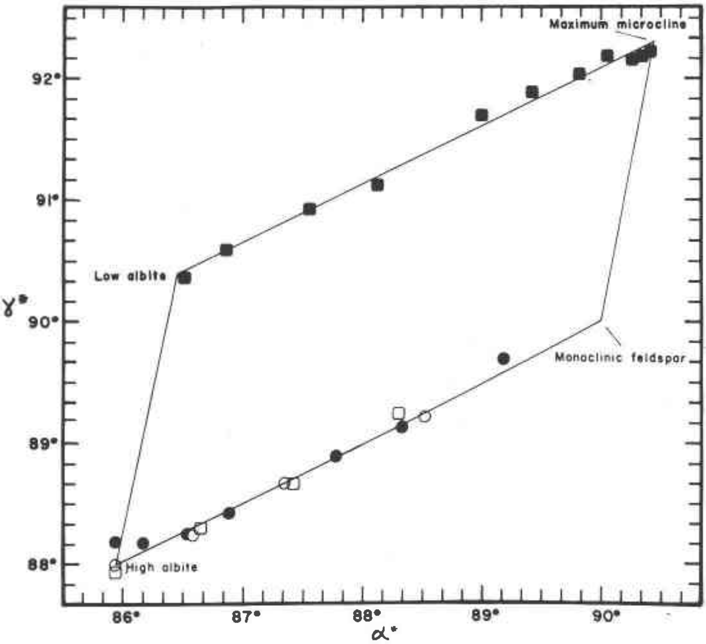

FIG. 3a. α^* plotted against γ^* for three structure-equivalent series of alkali feldspars. Symbols and references are the same as for figure 1. In this and figure 3b α^* and γ^* have been reversed from the conventional metohd of plotting introduced by MacKenzie and Smith (1955) in order that the feldspar end members plot in the same *relative* positions in figures 2 and 3.

Figures 1 and 2. The line represents feldspars of the highest possible structural state.

Alkali-exchanged equivalents of natural sanidines. An analyzed sample of natural sanidine (Puye), homogeneous to X rays, was made available to us by R. L. Smith and his co-workers. The unit-cell parameters of this feldspar are given in Table 2 and are plotted in Figures 2b and 3b. Optical data are summarized in Table 3. The analysis and calculated composition are given in Column 1 of Table 4. The approximate alkali exchange path on Figure 2b is not equivalent to that of the high sanidine-high albite series but is slightly displaced toward the maximum microcline-low albite series. α^*–γ^* for the sodium-exchanged equivalent, however, fall on the same line as for the high sanidine-high albite series (Fig. 3b).

Large (to 8 cm) crystals of potassic sanidine (P50–90) from trachytic dikes, supplied by W. T. Pecora, were also examined. Unit-cell para-

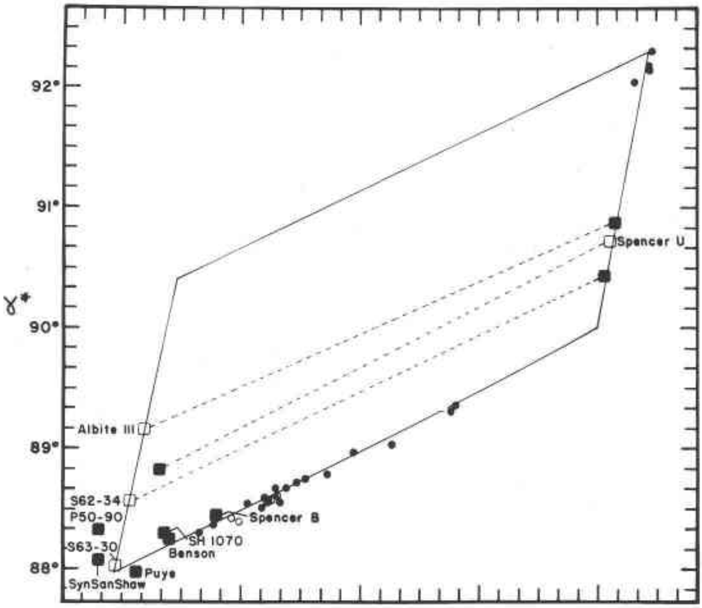

FIG. 3b. α^* plotted against γ^* for alkali-exchanged feldspars, data from Table 2, this paper, and for natural maximum microclines and anorthoclases. Open squares represent data for triclinic starting materials (all starting material with monoclinic symmetry plot at the point $\alpha^* = \gamma^* = 90°$); solid squares represent data for triclinic equivalents after exchange in either NaCl or KCl. Other symbols are as in figure 2b.

All symbols are drawn larger than ±2 standard deviations in α^* and γ^*.

meters are summarized in Table 2, optical axial angle in Table 3, and chemical data in Table 4. The starting material and the sodic exchange product fall on the alkali exchange path of the Puye sample (Fig. 2b). The potassic exchange product plots slightly outside the range of standard series on Figure 2b and a observed (8.589) is lower than that indicated from the plot ($a = 8.60$). 2V (see Figure 4) lies on the line for P50-56 equivalents rather than that for Puye equivalents. Both deviations are possibly due to the high content of the non-exchangeable cations Ba^{++} and Sr^{++}. We assume provisionally that this sample is structurally equivalent to the Puye sample but because of the compositional difference a detailed crystal structure would be necessary to prove this.

Alkali-exchanged equivalents of orthoclase. In our search for natural material suitable for our exchange experiments, we attempted to locate a homogeneous feldspar having optical and X-ray properties typical of those ascribed to 'orthoclase.' One such feldspar is specimen "C," from

TABLE 1. HIGH SANIDINE-HIGH ALBITE SERIES MEASURED BY DONNAY AND DONNAY (1952) REFINED BY THE COMPUTER PROGRAM OF EVANS *et al.* (1963)

Composition	a (Å)	b (Å)	c (Å)	α	β	γ	V (Å^3)	No. of Lines Used	Std. Error (°2θ)
Or 100	8.6154	13.0314	7.1771	90°	115°58.9′	90°	724.34	23	.0171
	±.0030	.0032	.0016		1.7′				
Or 80	8.5230	13.0228	7.1739	90°	115°59.8′	90°	715.69	36	.0171
	±.0016	.0022	.0014		1.1′				
Or 60	8.4435	13.0021	7.1691	90°	116°02.7′	90°	707.12	17	.0074
	±.0017	.0016	.0008		1.0′				
Or 50	8.3832	12.9930	7.1663	90°	116°05.4′	90°	701.04	17	.0128
	±.0039	.0027	.0014		1.4′				
Or 40	8.3353	12.9784	7.1627	90°	116°11.1′	90°	695.15	17	.0099
	±.0018	.0019	.0010		1.2′				
Or 30	8.2815	12.9493	7.1497	91°16.0′	116°15.4′	90°08.0′	687.39	17	.0095
	±.0023	.0020	.0016	1.6′	1.1′	1.6′			
Or 20	8.2464	12.9273	7.1400	92°17.9′	116°16.9′	90°10.7′	681.73	16	.0118
	±.0035	.0026	.0024	2.4′	1.8′	2.4′			
Or 10	8.1995	12.9014	7.1302	92°57.0′	116°22.5′	90°14.7′	674.54	19	.0126
	±.0035	.0024	.0020	2.0′	1.8′	2.3′			
Ab	8.1598	12.8707	7.1098	93°32.5′	116°21.7′	90°14.1′	667.36	15	.0097
	±.0028	.0022	.0024	2.1′	1.6′	1.9′			

Mogok, Burma, described by Spencer (1937). The structure of Spencer C is known to have partial ordering of aluminum atoms among the tetrahedral sites (Cole, Sorum and Kennard, 1949; Jones and Taylor, 1961, A. A. Colville and P. H. Ribbe, written communication, 1967). The structural state should therefore be intermediate between high sanidine and maximum microcline. It would have been most desirable to use Spencer C for alkali exchange experiments, but we were unable to obtain sufficient material.[1]

Another sample of homogeneous orthoclase was donated by W. T. Pecora, and has been described by him (Pecora, 1962, sample P50-56F). The compositions of P50-56F and Spencer C are compared in Table 5, and their unit cell parameters and optic axial angles are compared in Table 6. The $2V_\alpha$ and unit-cell parameters of P50-56F are indistinguishable from those of Spencer C. The principal difference between the two specimens other than ~3% in the ratio Or/Or+Ab is slightly more

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[1] Dr. H. S. Yoder of the Geophysical Laboratory, Washington, D. C., loaned us the smear mount of Spencer C used to determine unit-cell parameters by our method (Table 6).

TABLE 2. UNIT CELL PARAMETERS FOR ALKALI FELDSPARS AND FOR THEIR EQUIVALENTS AFTER EXCHANGE IN MOLTEN KCl OR NaCl

Sample[a]	Or[b]	Unit cell parameters									No. of Lines Used	Std. error (°2θ)
		a (Å)	b (Å)	c (Å)	α	β	γ	V (Å)³	α*	γ*		
				STARTING MATERIAL = K-FELDSPAR								
1. SynSanShaw	(100)	8.606	13.018	7.172	90°	116°02.6′	90°	721.86	90°	90°	20	.0087
		±.002	.002	.001		0.8′		.16				
SynSanShaw+NaCl	1	8.152	12.871	7.116	93°44.6′	116°33.0′	90°02.0′	666.15	85°47.9′	88°05.4′	10	.0111
		±.003	.003	.001	3.1′	1.7′	2.4′	.27				
2. Puye	(42)	8.333	12.974	7.163	90°	116°15.2′	90°	694.52	90°	90°	16	.0067
	41	±.002	.001	.001		0.7′		.12				
Puye+KCl	95	8.593	13.018	7.183	90°	116°02.3′	90°	721.98	90°	90°	24	.0108
		±.001	.002	.001		0.7′		.14				
Puye+NaCl	(2)	8.161	12.858	7.115	93°19.9′	116°28.5′	90°19.3′	666.75	86°07.1′	87°58.7′	17	.0141
	2	±.003	.003	.001	2.4′	1.4′	2.2′	.26				
3. P50-90 KF	(60)	8.444	13.011	7.176	90°	116°00.8′	90°	708.50	90°	90°	23	.0126
	63	±.002	.002	.001		1.0′		.20				
P50-90+KCl	98	8.589	13.022	7.188	90°	115°56.6′	90°	722.89	90°	90°	22	.0099
		±.002	.002	.001		0.8′		.15				
P50-90+NaCl	12	8.203	12.895	7.130	92°44.9′	116°22.4′	90°16.1′	674.66	86°47.9′	88°20.2′	16	.0081
		±.002	.002	.001	1.4′	1.0′	1.2′	.19				
P50-56F (see Table 7)												
4. Benson Or	95	8.595	12.997	7.200	90°	115°59.3′	90°	723.06	90°	90°	28	.0198
		±.002	.003	.002		1.1′		.24				

(Continued on following page)

TABLE 2—(*continued*)

Sample[a]	Or[b]	Unit cell parameters									No. of Lines Used	Std. error (°2θ)
		a (Å)	b (Å)	c (Å)	α	β	γ	V (Å)³	α*	γ*		
Benson+NaCl	7	8.178 ±.003	12.857 .004	7.141 .002	93°10.8′ 2.0′	116°34.2′ 1.6′	90°07.9′ 1.9′	670.27 .27	86°22.7′	88°15.7′	16	.0169
Benson NaCl+KCl	97	8.606 ±.002	13.000 .004	7.200 .002	90°	116°02.0′ 1.3′	90°	723.79 .27	90°	90°	26	.0201
5. SH 1070	88	8.559 ±.003	12.983 .003	7.198 .001	90°	116°00.2′ 0.9′	90°	718.97 .22	90°	90°	18	.0127
SH 1070+KCl	96	8.599 ±.002	12.987 .003	7.201 .001	90°	116°01.2′ 0.8′	90°	722.72 .18	90°	90°	21	.0124
SH 1070+NaCl	6	8.165 ±.002	12.848 .003	7.140 .001	93°11.5′ 1.6′	116°30.5′ 1.4′	90°07.4′ 1.7′	668.96 .19	86°22.3′	88°16.1′	14	.0112
6. Spencer 'B'	(89) 89	8.554 ±.001	12.970 .002	7.207 .001	90°	116°00.4′ 0.6′	90°	718.65 .13	90°	90°	23	.0092
Spencer 'B'+NaCl	11	8.172 ±.005	12.857 .005	7.156 .003	92°48.6′ 4.6′	116°22.7′ 3.5′	90°08.2′ 2.4′	672.49 .42	86°47.7′	88°27.1′	21	.0309
7. Spencer 'U'	94	8.578 ±.004	12.957 .003	7.213 .001	90°15.1′ 1.3′	116°01.6′ 1.2′	89°13.5′ 1.5′	720.33 .27	90°05.9′	90°44.4′	21	.0138
Spencer 'U'+KCl	94	8.574 ±.003	12.963 .004	7.207 .002	90°17.7′ 2.5′	115°54.6′ 2.9′	89°16.5′ 2.5′	720.43 .42	90°01.4′	90°39.7′	26	.0251
Spencer 'U'+NaCl	0	8.134 ±.004	12.797 .004	7.152 .002	93°30.9′ 2.6′	116°30.8′ 1.7′	89°29.3′ 2.6′	664.71 .31	86°19.6′	88°49.0′	22	.0261

TABLE 2—(*continued*)

Sample[a]	Or[b]	Unit cell parameters									No. of Lines Used	Std. error (°2θ)
		a (Å)	b (Å)	c (Å)	α	β	γ	V (Å)^3	α^*	γ^*		
		STARTING MATERIAL = NA-FELDSPAR										
8. S63-30	(0)	8.160	12.870	7.106	93°32.7′	116°21.8′	90°11.3′	667.0	85°57.0′	88°01.8′	20	.0200
		±.005	.007	.005	1.6′	3.6′	0.5′	0.4				
S63-30+KCl	98	8.595	13.032	7.178	90°	115°53.3′	90°	723.29	90°	90°	15	.0099
		±.003	.002	.001		1.7′		.25				
9. S62-34	(0)	8.151	12.846	7.121	93°41.7′	116°34.5′	89°37.2′	665.27	86°03.5′	88°34.5′	25	.0151
		±.002	.003	.001	1.8′	0.9′	1.5′	.20				
S62-34+KCl	100	8.609	13.015	7.192	90°09.0′	115°58.1′	89°32.2′	724.44	90°03.6′	90°26.6′	17	.0194
		±.004	.004	.002	2.6′	2.2′	2.5′	.41				
10. Albite III	(0)	8.151	12.820	7.134	93°51.9′	116°31.9′	89°01.4′	665.36	86°10.0′	89°09.7′	29	.0173
		±.002	.003	.001	1.3′	1.1′	1.2′	.17				
Albite III+KCl	100	8.618	12.981	7.204	90°17.1′	115°51.0′	89°04.9′	725.11	90°07.7′	90°53.0′	12	.0212
		±.007	.005	.002	5.4′	3.2′	5.2′	.55				

[a] Sources of feldspars used for alkali exchange as follows:

1. SynsanShaw: Sanidine, Or$_{100}$ gel crystallized hydrothermally at 700°, 2 kb, for a week by H. R. Shaw. Gel described by Shaw (1963, Table 1).
2. Puye—Sanidine, rhyolite pumice fall (Guaje member of the Bandelier Tuff) Pumice mine, 1 mile SE of Puye Cliff ruins, Jemez Mountains, New Mexico, collected by R. L. Smith.
3. P50-90—Sanidine phenocrysts, trachytitic dikes, Camel's Back Mountain, Bearpaw Mountains, Montana. Collected by W. T. Pecora and J. H. Kerr.
4. Benson: Orthoclase from orthoclase—magnetite rock, Benson Mine, St. Lawrence County, New York. Collected by D. R. Wones.
5. SH 1070: Faintly perthitic orthoclase from a pegmatite in the contact aureole of the Eldora Stock, Colorado. Collected and described by Hart (1964). Further X-ray and optical data given by Wright (1967).
6. Spencer 'B': Specimen 'B', adularia from St. Gothard, Switzerland, described by E. Spencer (1937). Or content from Smith and Ribbe, 1966, p. 209. Diffraction data for natural material obtained from a smear mount donated by H. S. Yoder, Jr., material for exchange donated by J. V. Smith.
7. Spencer 'U': Specimen 'U', a faintly perthitic intermediate microcline from Kodarma, Bihar, India, described by E. Spencer (1937). H. S. Yoder, Jr. donated both a smear mount and enough material for exchange.
8. S63-30: High albite synthesized from glass of $NaAlSi_3O_8$ composition at 925°C, 3500 psi steam pressure, 3 hrs., by D. B. Stewart.
9. S62-34: Intermediate albite synthesized from $NaAlSi_3O_8$ gel at 700°C, 2 kb, for 1050 hrs.
10. Albite III. Intermediate albite synthesized from $NaAlSi_3O_8$ glass at 500°C, 2 kb, for 1335 hrs.

[b] Compositions in parentheses from analysis—others are estimated from V, using data of figure 1 and interpolating to take account of structural state. SH 1070 and Spencer 'U' are perthitic with bulk compositions from analysis of Or$_{83}$ and Or$_{87}$ respectively. The compositions given are for the potassic phase estimated from V.

TABLE 3. VARIATION OF $2V_x$ IN ALKALI FELDSPAR SERIES OF EQUIVALENT STRUCTURAL STATE

Sample Type	Sample No.	Or Content	$2V_x$[a] range and (average)	No. of determinations
Natural Sanidine	Puye	42	40.5°–49° (45.5°)	8
	Puye+KCl	95	Zoned: rims have $2V_x$ of 29–38° (Av. 34° with the optic plane ⊥ (010). Cores range from 19°, O.P. ⊥ (010), to 52°, O.P. ∥ (010).	13
	Puye+NaCl	2	42.5–52° (48.0°)	23
Natural sanidine	P50–90	60	Oscillatorily zoned. core: 46.5–47.0; intermediate zones: 43.5°–56.5° (51°); rim: 45.5°	11
	(No data for exchanged equivalents of P50–90)			
Orthoclase	P50–56F	86	41.5°–52° (44.5°)	21
	P50–56+KCl	94.5	35°-42° (39.0°)	20
	P50–56+NaCl	8.4	61.5°–67° (65.0°)	20
Orthoclase	Benson	95	37.5°–51.5° (44.5°)	10
	Benson+NaCl	7	64°–67° (66°)	5
	Benson NaCl+KCl	97	38.5°–45.5° (42°)	9
Orthoclase	SH 1070	88	50°–60° (55.5°)	30
	SH 1070+KCl	96	48°–48.5° (48°)	4
	SH 1070+NaCl	4	66.5°–74.5° (69.5°)	4
Orthoclase	Spencer B	89	68.4° (Spencer, 1937; Table II)	—
	Spencer B+NaCl	11	72.5°–77° (75.0°)	6
Intermediate microcline	Spencer U	94	76.2° (Spencer, 1937, Table II, 69°–72° (70.5°), Finney and Bailey, 1964, p. 425)	—
	Spencer U+KCl	94	67.5°–71° (70°)	6
	Spencer U+NaCl	0	78.5°–86° (82.5°)	6

[a] Optic plane perpendicular to or approximately perpendicular to (010) except where noted.

$BaAl_2Si_2O_8$ (Cs) component in sample P50-56F. We therefore assume that the exchange series produced from P50-56F starting material is typical of that which would be produced from orthoclases like Spencer C.

End-member compositions were made by alkali exchange of the P50-56F starting material. Intermediate compositions at intervals of 10 weight percent were then prepared by dry homogenization of weighed

TABLE 4. CHEMISTRY OF TWO NATURAL SANIDINES

Sample No. Oxide	Puye[a]			P50–90[b]		
	1	2	3	4	5	6
SiO_2	67.45			62.9		
Al_2O_3	19.08			19.9		
Fe_2O_3	.19	.02		.30		
MgO	—			.16		
CaO	.24	.03		.50		
Na_2O	6.31		6.4	2.8	0–4.0 Av. = 3.0	
K_2O	7.08	6.9	7.1	10.2	7.2–12.1	9.9
BaO	—					
SrO	.00					
$\sum H_2O$	.08					
Total	100.43			96.76		
Feldspar components (Wt. %)						
Or	42.0			60.2		
Ab	56.8			23.7		
An	1.2			2.5		
Cs	—			≈8		
Sr-F	—			≈4		

[a] Sanidine, rhyolite pumice fall (Guaje member of the Bandelier Tuff), 1 mile southeast of Puye cliff ruins, Jemez Mountains, New Mexico. Analyses: Column 1, wet chemical analysis by L. Reichen; Column 2, X-ray fluorescence analysis by R. Brown; Column 3, flame photometry by J. Dinnin.

[b] Sanidine, trachytic dike, Camel's Back Mountain, Bearpaw Mountains, Montana. Analyses: Column 4, Analyses were made by chemists of the U. S. Geological Survey using the methods of Shapiro and Brannock (1962); Semiquantitative spectrographic analysis showed 2% Ba and 1% Sr. Column 5: Electron microprobe analysis by C. Mead. Column 6: X-ray fluorescence analysis by H. Rose and R. Brown.

amounts of the potassium and sodium end members, which had been prepared separately from the same starting feldspar. Homogenization in sealed platinum capsules was found to be complete after 48 hours at 900°–950°C. Splits were submitted for chemical analysis, and the unit-cell parameters were measured. Flame-photometer analyses for K_2O and Na_2O by J. I. Dinnin showed $Or + Ab = 95.9\%$ (with $\sigma = 0.8\%$) for all eleven compositions studied. This sum should be nearly constant[1] across the series, and indicates the amount of other feldspar components present: $An + Cs + Sr\text{-feldspar} = 4.1\%$. The amount so indicated is more than

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[1] 4.1 weight percent of the additional components in orthoclase would be present, after exchange of K for Na, as 4.3 weight percent of the resulting albite.

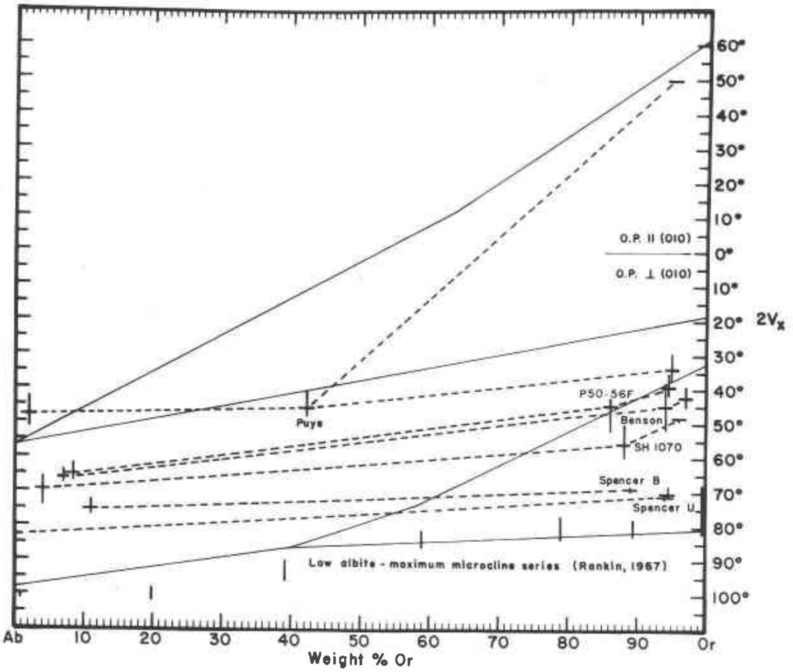

FIG. 4. $2V_x$ plotted against Or content for alkali-exchanged feldspars, data from Table 3, this paper. Light solid lines are series of Tuttle (1952) and MacKenzie and Smith (1955) from top to bottom as follows: high sanidine, low sanidine, orthoclase, maximum microcline. Heavy dashed lines connect $2V_x$ measurements on feldspars of equivalent structural state. Symbols are drawn as a vertical bar representing the range of $2V_x$ intersected by a horizontal bar at the average $2V_x$. Two dashed lines are drawn from the Puye samnle to points representing the extreme 2V measurements on the K-exchanged Puye sample.

twice that shown in the original analysis of the starting material (Table 5) which may be in error. Analysis of P50-56 Ab by flame photometer indicated 6.4% Or present, while X-ray fluorescence analysis by H. J. Rose, Jr. indicated 8.4% Or to be present. When the latter value is used to recalculate the weighed quantities to chemical compositions, better agreement is obtained with the flame-photometric compositions for intermediate members of the series, so 8.4% is taken in Table 7 as the Or content of the sodic end member. In figures where cell data are plotted against composition, the composition range is taken as ±1% Or which in every case encompasses the difference between the observed composition and the recalculated weighed composition (Table 7).

Unit-cell parameters of the orthoclase-equivalent exchange series are

TABLE 5. CHEMISTRY OF TWO NATURAL ORTHOCLASES

Sample No. oxide	P50–56F[a]	Spencer 'C'[b]	Spencer 'C'[c]
SiO_2	n.d.	63.66	64.2
Al_2O_3	n.d.	19.54	18.3
Fe_2O_3	0.29	0.10	0.0
CaO	0.08	0.50	0.1
Na_2O	1.24	0.80	0.9
K_2O	14.56	15.60	15.3
BaO	0.48	—	0.1
SrO	0.007	—	0.1
Rb_2O	0.04	—	—
$\sum$	—	100.20	99.0
Feldspar components (to 100 Wt. %)			
Or	87.7	90.9	90.8
Ab	10.7	6.7	8.0
An	0.4	2.4	0.7
Cs	1.2	—	0.3
Other	tr	—	0.2

[a] Orthoclase, Big Sandy Creek, Bearpaw Mountains, Montana. (Pecora, 1962, p. 95).
[b] Orthoclase, Mogok, Burma, Sample 'C' (Spencer, 1937, Table 1).
[c] Spencer 'C' analyzed by electron probe methods by Smith and Ribbe (1966).

given in Table 7, and are plotted on Figures 1–3. Because of a loss of peak resolution near the transition from monoclinic to triclinic symmetry, the unit-cell parameters for $\mathrm{Or}_{33\cdot7}$ composition could not be refined, and *a*, *b*, and *c*, have been estimated from the positions of $(\bar{2}01)$, (060), and

TABLE 6. UNIT-CELL PARAMETERS AND OPTIC AXIAL ANGLE OF SAMPLES OF ORTHOCLASE

Sample	*a*, (Å)	*b*, (Å)	*c*, (Å)	β	*V*, ($Å^3$)	Optic axial angle, 2Vx
P50–56[a] (this paper)	8.5610 ±.0017	12.9951 ±.0026	7.1941 ±.0011	115° 59.6′ ±0.9′	719.39 ±.17′	44°
Spencer C[a] (Spencer, 1937)	8.5607 ±.0011	12.9924 ±.0015	7.1921 ±.0007	116° 1.1′ ±0.6′	718.86 ±.11	43.6°
Spencer C (Cole *et al.* 1949)	8.5616 ±.0002	12.9962 ±.0004	7.1934 ±.0002	116° 0.9′ 0.3′	719.294	43.6°

[a] Unit-cell parameters measured against fluorite, $a=5.4620$ at 25°C.

Table 7. Unit Cell Parameters for 'Orthoclase Exchange Series Using P50–56F Starting Material

Or content[a]		a (Å)	b (Å)	c (Å)	α	β	γ	V (Å³)	No. of Lines Used	Std. Error (° 2θ)	Remarks
Anal.	Calc.										
94.5	—	8.6023 ±.0017	12.9982 .0021	7.1970 .0011	90°	115°59.4′ 0.8′	90°	723.36 .16	23	.0121	P50–56F+KCL (Or-rich end member=*P50–56 Or*
87.6	85.9	8.5694 ±.0015	12.9989 .0019	7.1929 .0010	90	116°0.4′ 0.7′	90	720.11 .14	21	.0107	
85.9	—	8.5610 ±.0017	12.9951 .0025	7.1941 .0011	90	115°59.6′ 0.9	90	719.39 .17	22	.0130	Starting material *P50–56F*
76.0	77.3	8.5206 ±.0017	12.9987 .0025	7.1922 .0012	90	115°59.1′ 0.9′	90	716.06 .17	25	.0146	
67.6	68.7	8.4774 ±.0043	12.9907 .0030	7.1881 .0015	90	115°58.7′ 2.2′	90	711.62 .34	14	.0148	
60.9	60.1	8.4451 ±.0041	12.9892 .0034	7.1879 .0018	90	116°05.8′ 1.7′	90	708.09 .32	17	.0182	
51.7	51.5	8.3952 ±.0033	12.9775 .0027	7.1851 .0014	90	116°05.5′ 1.5′	90	703.02 .26	16	.0146	
42.6	42.9	8.3434 ±.0025	12.9682 .0021	7.1798 .0012	90	116°10.8′ 1.2′	90	697.15 .20	14	.0111	
33.6	34.3	8.298[c]	12.949[c]	7.176[c]	—	—	—	—	—		

TABLE 7—(*continued*)

Or content[a] Anal.	Or content[a] Calc.	a (Å)	b (Å)	c (Å)	α	β	γ	V (Å.)	No. of Lines Used	Std. Error (°2θ)	Remarks
26.8	25.7	8.2690 ±.0014	12.9263 .0020	7.1656 .0010	91°30.6′ 1.9′	116°21.2′ 0.9′	90°0.9′ 1.7′	686.01 .14	13	.0084	
16.5	17.1	8.2288 ±.0019	12.8975 .0023	7.1495 .0010	92°14.2′ 2.0	116°26.3′ 1.0	90°12.0′ 1.9	678.72 .18	16	.0099	
8.4[b]	—	8.1859 ±.0038	12.8656 .0025	7.1387 .0011	92°53.2′ 1.3	116°29.4′ 1.1	90°14.5′ 1.7	671.74 .29	16	.0113	P50–56F+NaCl Ab-rich end member=*P50–56 Ab.*
	100.0	8.620	12.998	7.198	90°	115°59.5′	90°	725.0			$KAlSi_3O_8$ equivalent (extrapolated)
	0.0	8.149	12.842	7.125	93°28′	116°30′	90°17′	665.6			$NaAlSi_3O_8$ equivalent (extrapolated)
Est. 91		8.584 ±.001	12.996 .002	7.196 .001	90°	115°59.9′ 0.7′	90°	721.51 .14	30	.0121	P50–56F+NaCl reexchanged with KCl

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[a] Composition given as Or divided by (Or+Ab+An+Cs) recalculated to 100 weight percent assuming a constant value of 0.4 for An and 3.7 for Cs. Values in the column labeled "Anal" were obtained from flame-photometer determination of K_2O and Na_2O by J. Dinnin. Calculated values were obtained by using end-member compositions of $Or_{94.5}$ and $Or_{8.4}$ and the weighed amounts of the end members which were homogenized to produce each intermediate composition

[b] X-ray fluorescence determination by H. J. Rose, Jr.

[c] No satisfactory refinement. a, b, and c estimated from the positions of $(\bar{2}01)$, (060), and $(\bar{2}04)$, respectively.

($\bar{2}04$), respectively, from equations given by Wright (1968). The cell angles α and γ for $Or_{33.7}$ composition differ from 90°, but could not be estimated quantitatively.

The alkali-exchange path of P50-56F falls between the high-sanidine and maximum-microcline equivalent series in Figures 1 and 2a. α^*–γ^* of the triclinic Na-rich exchange equivalents fall on the same line as for the high sanidine-high albite series (Fig. 3a).

Three other samples of orthoclase (Benson, SH-1070, and Spencer 'B' of Table 2) were exchanged in molten halides. These samples were selected because they were homogeneous or nearly homogeneous phases, and although monoclinic to powder X-ray methods and of similar Or content, had larger optic axial angles than P50-56F. Unit-cell parameters of the starting materials and alkali-exchange products are given in Table 2 and optical data for these samples are given in Table 3.

None of the sodium-exchanged orthoclases was free of potassium. All of the samples of orthoclase and adularia except Spencer B were re-exchanged in KCl; the results (Tables 2, 7) show that the original dimensions can be recovered, except for small differences in *a* attributable to slightly different K/Na ratios in the original and KCl-exchanged material. Only 60 mg of Spencer B was initially available for the alkali-exchange studies, and this was all used to prepare intermediate compositions for study of the symmetry change as a function of composition.

A. A. Colville and P. H. Ribbe (written communication, 1967) have performed a three-dimensional structure determination on Spencer B, and have found it to be significantly more ordered than Spencer C. On the basis of unit-cell dimensions and optic axial angle, Spencer B is probably almost as highly ordered as any natural 'monoclinic' (to X-ray powder diffraction) potassic alkali feldspar. The estimated alkali exchange paths for Benson, SH-1070, and Spencer B fall between the series equivalent to P50-56F orthoclase and to maximum microcline (Fig. 2b). Like the exchange series for P50-56F, the sodic triclinic equivalents have α^* and γ^* equivalent to those of the high sanidine-high albite series (Fig. 3b).

Exchange equivalents of intermediate microcline. The structure of a sample of intermediate microcline with α and γ angles approximately halfway between 90° (monoclinic symmetry) and the angles farthest from 90° of those so far observed ("maximum microcline" of MacKenzie, 1954) was determined by Bailey and Taylor (1955). They used sample U described by Spencer (1937). Through the courtesy of H. S. Yoder, Jr., we were able to obtain sufficient Spencer U for our exchange experiments. The sample is slightly perthitic, and the amount of exsolution varies from one area to another. Our determination of the unit-cell parameters (Table 2) agree well with those reported by Bailey and Taylor (1955, Table 2), and MacKenzie (1954, p. 357).

Sodium-exchanged Spencer U yields an X-ray powder-diffraction pattern with somewhat broadened peaks. This may result from some compositional zoning, and may also indicate that a range of structural states occurs in the sample, reflecting its perthitic nature. Refinement of the unit-cell parameters proceeded only to a relatively high error level (Table 2). 2V showed a reasonable range (Table 3). The dimensions indicate that the sample contains very little potassium, in marked contrast to the sodic equivalents of monoclinic potassic feldspars after the same exchange treatment.

Sodium-exchanged Spencer U was re-exchanged with KCl to yield material (Tables 2, 3) with nearly the same structural state as the starting sample. The small change observed was in the direction of higher structural state. The estimated alkali-exchange path of Spencer U (Fig. 2b) falls close to the maximum-microcline equivalent series but toward the orthoclase-equivalent series. α^* and γ^* (Fig. 3b) fall between the high-sanidine and the maximum-microcline equivalent series.

The maximum microcline-low albite series. Laves (1951) first showed that low albite could be converted to maximum microcline by alkali exchange. Wyart and Sabatier (1956b), Goldsmith and Laves (1961), Orville (1967), and D. R. Waldbaum (written communication, 1965) have prepared various compositions in the low albite-maximum microcline solid solution series, and have shown that the exchange reaction is reversible.

Orville's data are plotted in Figures 1–3 and represent a close approximation to the lowest structural state attainable in natural alkali feldspar. Optical data for some of Orville's samples have been obtained by Rankin (1967).

Exchange equivalents of intermediate albites. It is convenient to classify polymorphs of albite by means of the angular separation of the 131 and $1\bar{3}1$ diffraction lines. In high albite this separation is ~2 degrees, and in low albite about 1.1 degrees. Albites with intermediate separations can be produced by various heating or hydrothermal experiments (Baskin, 1956; MacKenzie, 1957; McConnell and McKie, 1960; McKie and McConnell, 1963).

Correlation between the aluminum-silicon distribution and the 131–$1\bar{3}1$ separation is not yet possible because no intermediate albite structure has been determined.[1] Stewart synthesized two samples of albite with intermediate structural states by hydrothermal crystallization of $NaAlSi_3O_8$ glass. The first sample (S62-34, Table 2) had a $131-1\bar{3}1$ separation of 1.778° 2θ ($CuK\alpha_1$ radiation); the second (Albite III, Table 2) had $131-1\bar{3}1=1.565° \ 2\theta$. Neither sample was sufficiently coarse-grained for optical studies. Unit-cell dimensions of both samples and of their potassium-exchanged equivalents are given in Table 2.

The alkali exchange paths of the two intermediate albites fall between the high-albite and low-albite equivalent series both on a b–c plot (Fig. 2b) and on an α^*–γ^* plot (Fig. 3b).

D. R. Waldbaum (written communication, 1965) has obtained preliminary unit-cell dimensions for an intermediate albite with $131-1\bar{3}1=1.380° \ 2\theta$ prepared by heating low albite from Amelia, and for its potassium-exchanged equivalent. The alkali exchange path indicated for this sample is parallel to and closer to the low albite-equivalent series than the alkali exchange path for albite III. It is evident that nearly parallel exchange paths apply over the whole range of $131-1\bar{3}1$ separations in albites of intermediate structural state.

DISCUSSION

Discussion of the data for alkali-exchanged feldspars is directed toward two major topics: (1) a re-examination of the number of equivalent structural-state series of alkali feldspars, and (2) a method for identifying and describing natural alkali feldspar phases, including those in perthitic intergrowth, by means of computer-refined X-ray powder diffraction data. Discussion of the first topic will be based largely on the alkali-exchange paths observed for the feldspars studied. Many intriguing questions raised by the alkali exchange paths must be answered chiefly by detailed crystallographic work. We confine ourselves to describing the paths and offering tentative explanations for some of their peculiarities.

In spite of the complexities in the alkali-exchanged series, the data for the potassic or sodic end members may be employed to estimate structural state and Or content, and to recognize anomalous cell dimensions in natural alkali feldspars. On the basis of the alkali-exchange data we suggest a revised terminology for alkali feldspars and a procedure for

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[1] It can be demonstrated from the approximate results of Baskin (1956, Table 3) and from unpublished results of D. B. Stewart that there is a regular variation of all unit-cell parameters with change of $131-1\bar{3}1$ separation, such that it is possible to estimate all the unit-cell parameters of $NaAlSi_3O_8$ knowing only the $131-1\bar{3}1$ separation. This makes it appear probable that the aluminum-silicon distribution and the $131-1\bar{3}1$ separation are simply related.

describing and naming natural alkali feldspar phases from their unit-cell parameters.

Common properties of the alkali-exchange series. The unit-cell parameters for all alkali feldspars of constant structural state vary similarly and regularly with composition within the limits of measurement, Figures 1–3. Modern cell-refinement techniques are sufficiently precise that significant differences in unit-cell parameters can readily be recognized between different structural states of the same composition. We emphasize here some of the properties of the alkali-exchanged phases that are revealed by the alkali-exchange paths shown on Figure 2 and 3.

(1) All alkali-exchange paths are continuous, no matter which cell parameters are plotted against each other or the structural state of the starting material. Alkali-exchange paths do not cross each other, though they may coincide on some plots.

(2) Each of the series high sanidine—high albite and maximum microcline—low albite forms one limit on any plot of possible alkali-exchange paths. These limiting paths are unique because all of the unit-cell parameters can be specified for any point along the path whether the starting material was potassic or sodic.

(3) The total variation of the interaxial angles from those of the pure potassic phase to those of its pure sodic equivalent is nearly the same for *all* structural states of either potassic or sodic starting materials, and amounts to $\sim 3°30'$ for α, $\sim -4°$ for α^* $\sim 30'$ for β, $\sim -35'$ for β^*, $\sim 10'$ for γ, and $-2°30'$ for γ^*. Thus to a first approximation the amount of variation of the angular parameters is independent of structural state and depends on alkali content. It can be observed on Fig. 3 that monoclinic potassium feldspars of a wide range of structural states all yield sodic equivalents with the angles of high albite, and high albite is the only structural state of $NaAlSi_3O_8$ that yields a monoclinic potassic phase on alkali exchange. From crystal-structure analysis both high sanidine and high albite are known to have Al-Si distributions compatible with either monoclinic or triclinic symmetry, and we infer that the sodic exchange equivalents of all originally monoclinic alkali feldspars (sanidines, orthoclases, adularias) retain Al-Si ordering schemes compatible with monoclinic symmetry, even if the symmetry of the crystal as a whole becomes triclinic. We do not, however, imply that the Al-Si distribution is the same in all monoclinic structural states that yield sodic equivalents with the interaxial angles of high albite.

(4) A plot of alkali-exchange paths in terms of the *b* and *c* dimensions can be used to state structural state quantitatively. Our data for alkali-

exchanged feldspars of intermediate structural state combined with that for the limiting series collected by Orville (1967) indicate that the unit-cell volume for a given composition varies only slightly with change of structural state, largely owing to the opposite variation of the *b* and *c* axes. Stewart and Ribbe (unpublished data) have established that the relative position of alkali-exchange paths on the *b–c* plot depends on the quantity of aluminum in the two T_1 sites of the feldspar structure, and that the ordering scheme in sodium feldspar is actually quite similar to that in potassium feldspar. That the ordering scheme is *not identical* in both compounds is clear because of the nonequivalence of the products of alkali-exchange of intermediate structural states demonstrated in this paper. Therefore, for the relative ranking of structural state of all alkali feldspars we will utilize the positions of the alkali-exchange paths on the *b–c* plot, Figure 2.

Ranking of structural states by means of the *b–c* plot is similar to that obtained by several other ranking schemes, but has the advantage of being consistent for all compositions. Within the potassic feldspars studied relative ranking by means of the *b–c* plot is in agreement with what is known of the Al-Si distribution from refined structure determinations. Relative ranking by means of the *b–c* plot of the potassic feldspars studied also agrees with relative ranking on the basis of the size and orientation of the optic axial angle, Figure 4 and Table 3. (See also Tuttle, 1952; Hewlett, 1959; Brown, 1962; Finney and Bailey, 1964). The ranking of triclinic potassic feldspars or ranking of polymorphs of $NaAlSi_3O_8$ by means of their $131-1\bar{3}1$ separations is the same as could be obtained by reference to the *b–c* plot, and is also comparable to the ranking that would be obtained from an $\alpha^*-\gamma^*$ plot.

The relative positions of the alkali-exchange paths may change if plots are made that include angular parameters. This is illustrated in Table 8 in which the feldspars of Table 2 are ranked in two ways according to the position of their alkali-exchange path between the limiting series plotted on Figures 2 and 3. The relative ranking of a group of potassic and sodic starting materials by means of the $\alpha^*-\gamma^*$ plot is not possible because of the wide range of structural states of monoclinic potassic feldspars, and the fact that the pure sodic equivalent of an intermediate monoclinic feldspar with a given structural state (as defined by the *b–c* plot) has different interaxial angles than the equivalent structural state of intermediate albite. There can be no consistent ranking of the structural states of triclinic phases between Figures 2b and 3b, because the unit-cell angles depend on both structural state and composition of the starting material.

TABLE 8. RANKING OF EXCHANGED FELDSPARS ACCORDING TO STRUCTURAL STATE OF THE POTASSIC END MEMBER ON THE BASIS OF CELL DIMENSIONS, CELL ANGLES, AND OPTIC AXIAL ANGLE 2V

Structural State	*b vs c* (Fig. 2)	α^* *vs* γ^* (Fig. 3)	2V (Fig. 4)
Highest	1. High sanidine	1. High sanidine=Puye, P50–90, P50–56KF, SH 1070, Benson, and Spencer B. (all monoclinic)	1. High sanidine
	2. Puye=P50–90	2. S62–34+KCl	2. Puye
	3. S62-34+KCl	3. Spencer U	3. P50-90=P50-56F
	4. P50-56KF	4. Low AbIII+KCl	4. Benson
	5. Benson	5. Maximum microcline	5. SH-1070
	6. SH 1070		6. Spencer B
	7. Low Ab III+KCl		7. Spencer U
	8. Spencer 'B'		8. Maximum microcline
	9. Spencer 'U'		
Lowest	10. Maximum microcline		

A revised terminology for alkali feldspar polymorphs. It is possible now, with the aid of Figure 2 and the above discussions, to set down a consistent terminology for defining and describing alkali feldspars. The definitions listed below are based on properties of homogeneous phases that contain no greater than 5% of feldspar components other than $KAlSi_3O_8$ and $NaAlSi_3O_8$. In a later section we indicate that the effect of additional components is negligible and that these definitions may be applied to any naturally-occurring alkali feldspar. We have used only terms that are well-accepted in the literature but these may now be defined more precisely than was previously possible.

We apply the following principles in setting up our terminology: Feldspars are to be named on the basis of composition and structural state. Structural state will be specified by reference to the alkali-exchange paths on a *b–c* plot (Fig. 2). However, the definitions necessarily encompass the symmetry of the particular composition studied.

The named structural states or ranges of structural states of potassic feldspar are, from highest to lowest, high sanidine, low sanidine, orthoclase, intermediate microcline, and maximum microcline. These are defined as follows:

High sanidine. Monoclinic. Axial dimensions *b* and *c* correspond to those in the high sanidine-high albite series (Fig. 2a).

> *Low sanidine.* Monoclinic. Axial dimensions *b* and *c* fall between those which define the P50-56F equivalent and the high sanidine-equivalent series (Fig. 2a).
>
> *Orthoclase.* Monoclinic. Axial dimensions *b* and *c* fall along the curve for P50-56F equivalents or between the P50–56F and maximum-microcline equivalent series, if $\alpha=\gamma=90°$ (Fig. 2a).
>
> *Intermediate microcline.* Triclinic. α, γ, *b*, and *c* are distinct from the maximum microcline-low albite series (Figures 1c and 2a).

Maximum microcline. Triclinic. Unit-cell parameters α, γ, *b* and *c* correspond to the maximum microcline-low albite series (Figures 1c and 2a).

The structural states or ranges of structural states of sodic feldspar from highest to lowest are high albite, intermediate albite, and low albite. Albite is arbitrarily restricted to those feldspars containing less than 5 percent Or component. Anorthoclase is distinguished from albite by its more potassic composition and from high and low sanidines by triclinic symmetry. Definitions are as follows (all triclinic):

> *High albite.* Unit-cell parameters *b* and *c* correspond to the sodic end-member of the high sanidine-high albite series (Fig. 2a).
>
> *Intermediate albite.* *b* and *c* fall between the curves for the two limiting series, Figure 2a.
>
> *Low albite.* Unit-cell parameters *b* and *c* correspond to the sodic end-member of the maximum microcline-low albite series (Fig. 2a).

Anorthoclase. Triclinic with bulk composition containing greater than 5 percent Or component, but less than 40 percent *Or*, the composition of the symmetry change in series containing monoclinic K-feldspar.

Because of the changes in cell parameters with increasing *Or* content, definitions of structural state based on separation of the 131–1$\bar{3}$1 lines (2.03°–2.00° = high, 2.00°–1.15° intermediate, 1.15°–1.06° low; MacKenzie 1957, p. 484) are applicable only to the polymorphs of $NaAlSi_3O_8$.

Variation of Optical Axial Angle with Composition and Structural State. The optical axial angle is sensitive to small differences between the principal refractive indices and has been recognized as being especially useful in studying alkali feldspars (Spencer, 1937; Tuttle, 1952; MacKenzie and Smith, 1955; Hewlett, 1959; Finney and Bailey, 1964). In Figure 4 we have plotted the optical axial angle, 2V, against composition for our alkali-exchanged potassic starting materials where sufficient data were available, and we have included pertinent data obtained by other investigators. Points for samples of equivalent structural state are connected by lines, but the lack of data for sodic starting materials makes this representation tentative.

Inspection of the curve for the high sanidine-high albite series (Fig. 4) shows that compositionally zoned high sanidines with uniform structural state will have potassic parts with the optical axial plane parallel to (010) and more sodic parts with the optic axial plane perpendicular to (010). This has been reported (for example, MacKenzie and Smith, 1956, p. 417) as two structural states within the same crystal, but is probably only compositional zoning. The term "high sanidine" should refer to feldspars with the highest possible structural state as determined from cell parameters, not applied merely to those with the optical axial plane parallel to (010).

The Puye sample of low sanidine, exchanged with KCl, was found to have quite variable optical properties (Table 3) which apparently represent both a compositional inhomogeneity in the exchanged feldspar and possibly also a subtle structural inhomogeneity in the starting material. Because of these complications, we are not sure what the optical properties of the potassic exchange equivalent of natural low sanidine aree. The only evidence we have that most natural sanidines differ from synthetic sanidine in structural state are small differences in the axial parameters of the unit cell, and in the optical axial angle in the starting material.

For homogeneous feldspar whose composition is known from analysis, optical angle may be used to estimate structural state. In all other feldspars, particularly those in perthitic intergrowth, X-ray data are necessary to fix structural state accurately. We find that perthitic feldspars with anomalous cell dimensions also have anomalous optic angle. Therefore, it is unwise to use optic angle to estimate structural state of perthites.

Effect of structural state on the monoclinic-triclinic symmetry change along alkali-exchange paths. In all exchange series from potassic monoclinic feldspar toward more sodic equivalents, the symmetry becomes triclinic, and it is desired to know at what composition this occurs. This may be done by studying many compositions at one temperature, or a few compositions at many temperatures (Laves, 1952; MacKenzie, 1952).

The powder-diffraction method is not adequate for precise determinations of the composition at which the symmetry change takes place in alkali feldspar solid solutions. As the angles α and γ approach 90° (monoclinic symmetry) pairs of diffraction lines begin to interfere with each other, distorting the true positions of each line. Orville (1967) has discussed this problem in detail. The same phenomenon occurs when triclinic feldspars become monoclinic on heating, and discussions are given by MacKenzie (1952) and Stewart and von Limbach (1967). In general the convergence is more rapid than would be expressed by linear relationships; straight-line projections from the interference-free patterns through and beyond the interfering patterns will indicate that the Or content for the transition point is too high.

In the high sanidine-high albite series, Orville estimated the monoclinic-triclinic inversion to be at $Or_{43.5} \pm 2.0$ weight percent. This estimate differs from the estimate of Or_{35} by Donnay and Donnay (1952), but the discrepancy is less serious than it appears. It is probable that the Donnay and Donnay patterns for both $Or_{34}Ab_{66}$ and $Or_{35}Ab_{65}$ are for triclinic phases with low obliquities. Their pattern for $Or_{40}Ab_{60}$ (1952, p. 123) shows some peaks that may be slightly broadened, but nonetheless refinement of monoclinic unit-cell parameters to normal standard error values ($\sim$0.02 °2θ) is easily accomplished. The same was true for the pattern Orville obtained from $Or_{40}Ab_{60}$ composition. There is thus no substantial difference in the two sets of X-ray diffraction patterns for the sanidine-high albite series, and it follows that the symmetry change occurs at the same composition in both sets of samples. Whether the change takes place at a few percent higher or lower Or contents than 40% is thus a matter of interpretation.

The symmetry change in the alkali-exchange series equivalent to orthoclase P50-56F was estimated in the same way as for the high sanidine-high albite series, the result being Or 40 ± 3 percent, not recognizably different from the series with the highest structural state.

Although complete data were not collected, the exchange series equivalent to Spencer B is monoclinic at Or$=45$ and triclinic at Or$=35$. Compositions were estimated from the $\bar{2}01$ reflections, and symmetry determined by inspection for broadening of lines known to be most sensitive to this phenomenon (130, 111, 131). These patterns have not been refined.

One can also note that there is a distinct change of slope at Or_{40} in the maximum microcline-low albite series on a plot of any cell parameter against composition (Fig. 1). Evidently this triclinic series mimics the change of structural arrangement which causes the symmetry change in series of higher structural state.

We conclude that the composition of the symmetry change in the sodium-exchange equivalents of monoclinic potassic feldspars is independent of the Al:Si order of the monoclinic phase.

Effect of symmetry on the completeness of alkali exchange. In an earlier section, we commented on the difficulty in obtaining complete exchange of sodium for potassium in some of our originally monoclinic feldspars. Essentially complete exchanges using NaCl were obtained for SynSan-Shaw, Puye, and Spencer U and for all samples of albite exchanged with KCl. Exchanges using NaCl were notably incomplete when the starting material was monoclinic K-feldspar other than sanidine. This is probably in part due to nonexchangeable cations requiring different Al-Si ratios for charge balance but other factors may apply also. We suggest that the incomplete exchanges result from restraints placed on the alkali coordination polyhedron by the monoclinic-compatible Al-Si distribution in the tetrahedral framework. It has been noted above that the cell angles of the NaCl-exchanged monoclinic K-feldspars are always those of the high albite series. It is quite possible that the Al-Si distributions of these samples require potassium. For complete exchange to occur the feldspar framework would have to be reorganized with an Al-Si distribution similar to that observed for intermediate albites.

Volume of mixing for the orthoclase-equivalent series. The maximum excess volume of mixing for our orthoclase-equivalent series is 6.8 ± 0.4 Å^3 ($1.02 \pm .06$ cm^3/gfw X $AlSi_3O_8$) at Or 55 ± 5 mole percent, equal to $0.97 \pm 0.06\%$. This result is comparable to that found by Orville for the low albite-maximum microcline series and high albite-high sanidine series. As expected, the solvus for our orthoclase equivalent series will be between the solvi for the limiting series, will be raised by increasing pressure, and the crest will move toward more Or-rich compositions as the pressure is increased.

Number of alkali feldspar 'series'. Our data for alkali-exchanged feldspars lead logically to a review of the number of alkali feldspar 'series' proposed by Tuttle (1952), with subsequent modifications by other authors. In the original paper Tuttle subdivided potassic feldspars into four series using optical data (principally 2V). The data from our sodium-exchange experiments on potassic phases are quite different than could be predicted from Tuttle's graph (1952, Fig. 2) and it is evident that reclassification of many of these samples is required.

Tuttle's named series were high sanidine, low sanidine, orthoclase, and microcline, which were extended at least hypothetically to the albite sideline. MacKenzie (1957) tacitly disputed the extension of Tuttle's series to the albite sideline by presenting evidence for a continuum of structural states in albite. Later Smith and MacKenzie (1958, p. 888) argued the case for a continuum of structural states in both potassium-bearing and sodium-bearing feldspars.

The observation that led Tuttle to enumerate his series of alkali feldspar is important and is reinforced by the data presented in this paper; namely that certain structural states are greatly preferred in naturally occurring samples of potassium feldspar. There may be no thermodynamic restrictions on a continuum of stable structural states but geologic conditions or crystallography or both evidently impose restrictions on the frequency of occurrence of the various structural states. For example, we have found no natural samples whose cell parameters would indicate a structural state falling between the P50-56F equivalent and Puye equivalent series. Among the naturally occurring polymorphs of potassium-rich feldspar low sanidine is far more common than high, orthoclase is common (particularly the equivalents of SH-1070 and Spencer B), intermediate microcline is rare while maximum microcline is common. Natural homogeneous albites with very rare exceptions have the properties of low albite. It is probable despite the occurrence of preferred states that natural alkali feldspar having compositions near the sidelines could be found with *any* structural state between and including that of the limiting series high sanidine-high albite and maximum microcline-low albite.

It is tempting to hypothesize that the preferred states represent specific kinds and amounts of aluminum-silicon ordering. Many more highly-refined structure determinations will be necessary to substantiate this hypothesis. The Al-Si distribution has not yet been determined quantitatively for low sanidine and no intermediate structural states of albite have been subjected to crystal structure analysis.

APPLICATIONS OF THE GRAPHS TO THE DESCRIPTION AND NAMING OF NATURAL ALKALI FELDSPARS

Determination of composition and structural state of binary ($Ab+Or > 95\%$) alkali feldspar phases. Although one must be cautious about anomalous cell dimensions when using alkali-exchange paths to determine structural state and composition, it is clear that much use can be made of precise unit-cell parameters of the usual intermediate structural states of potassic alkali feldspars found in nature and also for the heat-treated natural or synthetic albites. Because of the nature of the variation of the unit-cell parameters with composition, it is possible to determine the Or content and structural state independently using Figure 1.

If *a* is used to determine the approximate Or content and *b* and *c*, plotted at this Or content, yield the *same* structural state, then the structural state and composition are considered to be known.

A surprisingly large number of natural alkali feldspars do not, however, fit this simple picture. For these it is found that once composition is fixed from *a*, *b* and *c* do *not* yield similar estimates of structural state on Figure 1. Conversely, if *b* and *c* are made to fit a consistent structural state the composition corresponding to this fit is different from that indicated by *a*. In every such case we find that *b*, *c* or both are too *low* relative to *a* to define a consistent structural state, and as defined earlier, the feldspar is considered to have anomalous cell dimensions.

In practice Figure 2b is set up for rapid identification of structural state and also provides for immediate recognition of anomalous cell dimensions. If *b* and *c* for any natural feldspar are plotted on Figure 2b, *a* can be read approximately from the contours. This value of *a* should be compared with that obtained in the refinement. If the two values agree within 0.02 Å then there are no significant anomalies. In this case composition can be found from *a* using Figure 1 and structural state can be specified directly from Figure 2b.

In anomalous feldspars, *a* cannot be used for composition even though the structural state normally seems to be correctly specified from Figure 2.[1] The 'apparent' structural state may be specified as above. However, cell volume may also be used to obtain composition and is particularly useful in estimating the composition of anomalous phases, on the premise that the atoms occupy the same volume regardless of the configuration of the unit cell (see Smith, 1961). This premise should, however, be rigorously tested by electron microprobe determination of Or content combined with computer refinement of cell parameters of anomalous phases.

All alkali feldspars, whether or not they are anomalous, can be named from Figure 2b using the definitions presented earlier (p. 65ff). The description may be keyed more closely to the figure by specifying the cell dimensions and their relation to the closest designated alkali-exchange path. As examples, the cell parameters for three natural feldspars are listed in Table 9. These might be described as follows:

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[1] We find from study of natural feldspars (Wright, unpublished data) that the apparent structural state derived from Figure 2b agrees with what would be guessed from the geological setting of the specimen. For example, the *b* and *c* cell dimensions of a distorted cryptoperthite from a pegmatite (a 'moonstone') indicate a structural state equivalent to that of Spencer B. The *b* and *c* cell dimensions of a cryptoperthite from a tuff indicate a structural state close to that of high sanidine.

TABLE 9. CELL PARAMETERS OF THREE NATURAL FELDSPARS

Specimen	a(Å)	b(Å)	c(Å)	α	β	γ	V(Å^3)
X (560-Ely)	8.516	13.006	7.176	90°	115°59′	90°	714.40
Y (TP-5)	8.565	12.975	7.202	90°	116°01′	90°	719.28
Z (Moonstone #1)	8.611	12.930	7.188	90°	116°08.4′	90°	718.46

Specimen X is a homogeneous feldspar with a structural state close to the high sanidine-equivalent series. The cell dimensions are not anomalous and Or content estimated from a is Or_{78}, from V is Or_{79}.

Specimen Y is the potassium-rich phase of a microperthite. It is slightly anomalous with a structural state lower than equivalents of SH-1070 and near the limit of resolution for intermediate microclines (broadened (131) and (130)). Approximate composition is Or_{91} (a), Or_{87} (V).

Specimen Z is the potassium-rich phase of a cryptoperthite. It is highly anomalous; a *refined*$-a$ (estimated from Fig. 2b) = 0.29 Å. The specimen has an apparent structural state equivalent to Spencer B. Composition, judging from cell volume, is Or_{88}.

Perthites represent a special problem of description and nomenclature in that they must be described in terms of the two phases present, neither of which may have the structural state of the original feldspar formed at temperatures above the solvus. In practice the properties of the potassium-rich phase may be determined quite easily whereas the character of the sodium phase is usually much more poorly known. Thus although it is a logical and common practice to describe and name a perthitic feldspar according to the properties of the potassic phase, this does not imply in any way the existence of a homogeneous feldspar, of bulk composition equal to that of the sample, which is structurally equivalent to the potassic phase.

Effect of additional components on unit-cell dimensions. The principal additional feldspars are $CaAl_2Si_2O_8$ (An), $BaAl_2Si_2O_8$ (Cs), and $SrAl_2Si_2O_8$ (Sr-f). Unit-cell parameters are available for some natural alkali feldspars containing more than 5 percent An, and these are by far the most important ternary solid solutions geologically. Or-rich feldspars and An-rich feldspars contain less than 5% of ternary solid solution, so the problem of describing the composition and structural state of ternary solid solutions is only serious for feldspar containing more than 50 percent Ab.

We have compared the unit-cell dimensions of 21 ternary feldspar solid solutions reported by Carmichael and MacKenzie (1964), Boudette and Ford (1966), and determined by Stewart for anorthoclases submitted by J. M. Hoare (written communication, 1965) with the unit-cell parameters of alkali feldspars on Figure 2b. The unit-cell parameters of eleven of the analyzed triclinic sodic feldspars that contained from 4 to 19 weight percent An all plotted within two standard errors of the appropriate curves for the exchanged equivalents of high sanidine on Figure 2b, and the Or content indicated by *a* from Figure 1 differed from the amount found by analysis (after recalculation to 100 percent feldspar components) with a standard deviation of 1.96% Or. More than half the observed standard deviation is due to Carmichael and MacKenzie's specimen number 12, which they indicate (1964, pp. 955–957) has a suspect analysis. If this sample is omitted, the standard deviation becomes 0.87%, well within agreement with the estimated limit of Or determination by unit-cell parameters of 2% Or. There is a tendency for some samples to have small *c* and large *b* relative to the *b*–*c* curve for the high sanidine-high albite series (Fig. 2b), but this tendency cannot be correlated with the An content of the sample. The cause is probably in part the An content and small variations in structural state and in part the different methods used to collect and refine the data. In every case the displacement from the curve is less than twice the standard deviation of the individual measurements.

Carmichael and MacKenzie (1964, p. 954) have remarked that α^* is in general most sensitive to change of Or-content of the unit-cell parameters of ternary triclinic feldspars. The values of α^* obtained for the new refinements of the data of Donnay and Donnay (1952) as well as those obtained by Orville (1967) require shifts in the contours of α^* plotted on the ternary feldspar composition diagram that tend to decrease the sensitivity of α^* to change in Or content. As pointed out by Smith (1956) all the parameters of high plagioclases in the range Ab_{100} to $Ab_{60}An_{40}$ are nearly constant. Because most ternary natural feldspars appear to be close to the highest possible structural state, their Or-contents can be estimated from the curves for the binary alkali feldspar solid solutions. Thus the Or-contents of the high plagioclases studied by Carmichael and MacKenzie (1964, p. 957–960) are adequately determined by the *a* axial dimension when referred to curves for the high structural state.

Structural state of sodic phases of perthites. The cell parameters of sodic phases of perthites are not generally obtainable from powder diffraction data, as commonly less than the 6 uniquely indexed reflections necessary for a determination can be measured. Determination of α^* and γ^* by the single crystal method of Smith and MacKenzie (1955) has been used commonly to indicate structural state of the sodic phases of perthites. Our results suggest that there may be complications in the application of this method to certain perthites. The interaxial angle γ for alkali feldspar phases of any one structural state is nearly independent of composition, but the angle α varies with both composition and structural state. From what has already been said about the fact that the sodic equivalents of many structural states of monoclinic feldspar yield unit-cell angles like those in the high albite-high sanidine series it should be obvious that it may not be possible to determine unequivocally the structural state of certain sodic phases of perthite from these angles, as attempted by MacKenzie and Smith (1962). In the many instances that two sodic phases have been reported in perthites it is quite possible that one phase represents the sodium-enriched equivalent of the structural state of *whatever monoclinic* potassium-enriched phase is present (MacKenzie and Smith's "anorthoclase phases" are therefore not necessarily members of the high albite-high sanidine series), and the second sodic phase is a lower structural state. Thus one need not infer that during exsolution the sodium-rich feldspar has a higher structural state than the coexisting potassic feldspar. The reverse is in better agreement with the observation that sodic feldspars normally have lower structural states than the coexisting potassic phases, when only one sodic phase is present (MacKenzie and Smith, 1962). The interpretation suggested above for perthites with two sodic phases implies that exsolution takes place by a two-step process, with unmixing of K- and Na-rich phases taking place before ordering of Al and Si. The measurement of α^* and γ^* of the phases of perthites by the method of Smith and MacKenzie (1955) may also be subject to errors resulting from irregular anomalous variations in the unit-cell parameters of the phases due to strains that accompany unmixing. The calculations required by their method assume that normal unit-cell parameters exist during unmixing.

With our present knowledge it is not possible to specify with certainty the structural state of sodium feldspar in a perthitic intergrowth, except when all the cell parameters can be supplied, either by single crystal study or from measurement of six uniquely indexed lines on an X-ray diffraction pattern; and when it can be shown that the phase has normal cell dimensions.

SUGGESTIONS FOR FUTURE RESEARCH

The data for alkali exchanged series suggest a number of problems as subjects of future research on alkali feldspars. The principal need is for additional complete structure determinations of both natural and exchanged feldspars, so that a consistent ranking scheme for structural states can be established on a sound basis. Some of the needed crystal structures are: 1. Intermediate albites 2. Low sanidines 3. Na-exchanged structural equivalent of a monoclinic potassium feldspar with intermediate structural state 4. K-exchanged structural equivalent of an intermediate albite 5. Structures of the cryptoperthitic phases with anomalous cell dimensions.

The optical properties of our 'low' sanidine (Puye) are puzzling enough to suggest a search for a more suitable specimen with which to prepare a complete series by alkali exchange.

The break in slope of all data for the maximum microcline-low albite series near Or_{40} should be studied with structure determinations of compositions at Or_{30} and Or_{50} in this series.

A crystallographic explanation for the particular features of the feldspar structure that control the specific observed kinds and amounts of interdependencies between unit-cell parameters is needed.

Studies such as those outlined above should lead eventually to an understanding of the factors that stabilize preferred structural states in the alkali feldspars. This will enlarge greatly the usefulness and scope of the methods we have described for the characterization and interpretation of these minerals; methods that enable the petrologist to employ modern crystal-chemical data in a rapid and routine manner in unravelling the genesis of igneous rocks.

APPENDIX: MEASUREMENT AND INDEXING OF X-RAY POWDER DIFFRACTION PATTERNS OF ALKALI FELDSPARS FOR COMPUTER REFINEMENT OF CELL PARAMETERS

This section is appended as an aid to the geologist who is not intimately familiar with X-ray diffraction patterns of feldspars but who wishes to identify and describe a natural alkali feldspar by the methods given in this paper. The position, intensity, and indices of reflections encountered in X-ray diffraction patterns of alkali feldspar phases may be obtained by referring to Tables 10–15. Tables 11–16 are derived empirically from measurement of nearly 100 X-ray diffraction patterns of natural alkali feldspar phases for which cell parameters have been computed. Many of the feldspar phases are in perthitic inter-growth as are the samples most likely to be encountered in nature. Descriptions of the feldspars from which the data of Tables 11–15 are derived will be reported later.

Measurement of X-ray diffraction patterns. The following procedure is recommended for measurement of unknown feldspar patterns. The

TABLE 10. GUIDE TO PUBLISHED DATA ON INDEXING AND INTENSITIES FOR ALKALI FELDSPARS

Sanidine	
Donnay and Donnay (1952)	Indexed X-ray powder diffraction pattern
Onorato, Penta, and Sgarlata (1963)	3-dimensional intensity data
Cole, Sorum, and Kennard (1949)	2-dimensional intensity data
Orthoclase	
Jones and Taylor (1961)	3-dimensional intensity data
Maximum microcline	
Goldsmith and Laves (1954)	Indexed X-ray powder diffraction pattern
Finney and Bailey (1964)	3-dimensional intensity data
Anorthoclase	
Donnay and Donnay (1952)	Indexed X-ray powder diffraction patterns
Carmichael and MacKenzie (1964)	Indexed X-ray powder diffraction pattern
High and low albite	
Smith (1956)	Indexed X-ray powder diffraction patterns
Ferguson, Traill, and Taylor (1958)	2-dimensional intensity data

measurement procedure is that used by the authors and if followed allows the closest comparison with the data given in the present paper. Other procedures may be equally valid (for example running X-ray patterns from low to high values of 2θ) but could introduce some bias in the identification and description of an unknown feldspar. Tables 10–15 should be consulted when necessary during evaluation and measurement of the patterns.

1. A standard pattern should be run from $2\theta=60°$ to $2\theta=15°$ using CuKα radiation.

TABLE 11. GUIDE TO INDEXING X-RAY DIFFRACTION PATTERNS OF PERTHITIC ORTHOCLASE, SANIDINE, AND HOMOGENEOUS ORTHOCLASE

Rating[a]	Miller Index[b]	Observed 2θ (range)	Intensity (range and average)	Computer statistics[c]		
				Used	Not used	Not Observed
	(110) (020) (001)	13.5 –13.7	5–15 (10)	—	40	—
	$(\bar{1}11)$	15.1	5	—	5	35
**	$(\bar{2}01)$	20.87–21.13	15–100 (35)	40		—
**	(111)	22.52–22.64	10–40 (20)	33	7	—

TABLE 11—(*continued*)

Rating[a]	Miller Index[b]	Observed 2[b] (range)	Intensity (range and average)	Computer statistics[c]		
				Used	Not used	Not Observed
	(200)	23.06–23.14	5–10 (8)	9	3	28
**	(130)	23.54–23.64	25–100 (65)	40	—	—
*	$(\bar{1}31)$	24.58–24.69	10–25 (15)	29	9	2
*	$(\bar{2}21)$	25.12–25.22	5–15 (10)	17	2	21
**	$(\bar{1}12)$	25.65–25.82	25–100 (60)	40	—	—
**	(220)	26.83–27.04	30–100 (70)	36	4	—
**	$(\bar{2}02)$	27.04–27.22	25–100 (55)	34	6	—
	(040)	≈27.5	I<I (002)	3	10	27
**	(002)	27.51–27.74	≫100	39	1	—
**	(131)	29.82–29.97	25–100 (50)	40	—	—
	$(\bar{2}22)$	30.46–30.52	10–25 (15)	8	2	30
*	(041)	30.79–30.99	15–60 (25)	35	5	—
	(022)	≈30.85	usually 10	2	8	30
**	$(\bar{1}32)$	32.31–32.46	10–40 (20)	38	1	1
*	$(\bar{3}12)$	34.39–34.51	10–30 (15)	25	9	6
*	$(\bar{2}41)$	34.80–34.91	10–60 (30)	31	8	1
*	(112)	35.10–35.22	10–45 (15)	27	4	9
*	(310)	35.58–35.74	5–15 (10)	19	5	16
	(240)	36.14–36.22	5–10 (8)	5	3	32
*	$(\bar{1}51)$	37.16–37.25	5–20 (10)	19	3	18
	$(\bar{3}31)$	37.64–37.78	5–15 (10)	12	7	21
**	$(\bar{1}13)$	38.60–39.00	5–15 (8)	34	3	3
	(151)	≈41.0	<10	1	4	35
**	(060)	41.60–42.00	10–60 (30)	40	—	—

TABLE 11—(*continued*)

Rating[a]	Miller index[b]	Observed 2θ (range)	Intensity (range and average)	Computer statistics[c]		
				Used	Not used	Not observed
*	(241)	42.46–42.67	10–20 (12)	19	2	19
	$(\bar{4}02)$ $(\bar{4}01)$	≈42.8	≈10	—	5	35
	(202) (311)	≈43.8	<10	—	6	34
	(061)	44.04–44.14	5–15 (8)	10	3	27
	$(\bar{4}22)$	45.06–45.29	5–15 (10)	12	6	22
	$(\bar{4}21)$	≈45.1	<10	—	3	—
*	(222)	45.96–46.11	10–25 (15)	21	3	16
	(400)	≈47.3	<10	3	3	34
	$(\bar{4}03)$	47.50–47.58	5–15 (10)	6	1	33
	(260)	≈48.2	<10	—	2	38
*	(113)	49.01–49.14	5–25 (10)	21	1	18
	$(\bar{2}62)$	≈50.5	10	1	2	37
	(170)	≈50.6	10	—	2	38
	(062)	50.63–50.75	10–40 (20)	7	1	32
	(043)	50.78–50.88	10–20 (15)	4	2	34
**	$(\bar{2}04)$	50.50–51.10	15–55 (30)	38	1	1

[a] Doubly starred (**) reflections are observed in all or nearly all patterns and should be used in any unit-cell refinement. Singly starred (*) reflections should be used in a unit-cell refinement only where they can be measured accurately. All other reflections should be checked carefully for indexing before using in a unit-cell refinement (see text).

[b] Reflections listed in order of increasing 2θ. Single-spaced groups of reflections are those with overlapping ranges of 2θ.

[c] Computer statistics for reflections observed in 40 powder diffraction patterns;

Used = Number of times the reflection was used in a unit-cell refinement.

Not used = Number of times the reflection was observed but not used because of inaccurate measurement or ambiguous indexing.

Not observed = Intensity less than 5, or obscured by a neighboring, high-intensity reflection.

TABLE 12. GUIDE TO INDEXING X-RAY DIFFRACTION PATTERNS OF INTERMEDIATE MICROCLINES

Rating[a]	Miller index[b]	Observed 2θ (range)	Intensity (range and average)	Computer statistics[c]		
				Used	Not used	Not observed
**	$(\bar{2}01)$	21.00–21.05	30–65 (45)	4	—	—
**	(111)	22.46–22.56	15–30 (20)	4	—	—
	$(1\bar{1}1)$	≈22.55	10	—	1	3
**	(130)	23.44–23.51	20–40 (30)	4	—	—
**	$(\bar{1}30)$	23.67–23.73	20–40 (30)	4	—	—
	$(\bar{1}\bar{3}1)$	≈24.5	10	1	1	2
*	$(\bar{1}31)$	≈24.8	15	2	—	2
**	$(\bar{1}\bar{1}2)$	25.62–25.70	40–100 (65)	4	—	—
**	(220)	26.71–26.80	40–70 (50)	3	1	—
**	$(\bar{2}02)$	27.07–27.11	60–100 (80)	4	—	—
**	(002)	27.50–27.59	>100	4	—	—
**	(131)	29.72–29.82	25–45 (40)	4	—	—
**	$(1\bar{3}1)$	29.92–30.01	15–45 (35)	4	—	—
	(041) $(\bar{2}22)$ $(0\bar{2}2)$ $(0\bar{4}1)$	30.81–30.87	25–65 (40)	—	4	—
**	$(\bar{1}\bar{3}2)$	32.25–32.30	15	3	—	1
**	$(\bar{1}32)$	32.37	15	3	1	—
	$(\bar{3}\bar{1}2)$ $(\bar{3}12)$	≈34.5	15	—	2	2
*	$(\bar{2}\bar{4}1)$	≈34.65	15	2	1	1
	(112) $(\bar{2}41)$	≈35.1	25	— 1	3 3	1 —
**	$(\bar{1}13)$	38.61–38.76	10–20 (15)	3	1	—
**	(060)	41.72–41.79	15–45 (30)	4	—	—
	(241) $(2\bar{4}1)$	≈42.7 ≈42.8	10 10	1 1	1 —	2 3
	(311) $(3\bar{1}1)$	≈43.7	10	—	1	3
	$(\bar{4}22)$ $(\bar{4}21)$	≈44.2	10	—	1	3
*	(113)	48.96–49.10	15	2	1	1
**	$(\bar{2}04)$	50.58–50.78	20–40 (30)	4	—	—

[a,b,c] See footnotes for Table 11. Data of this table based on X-ray diffraction patterns of 4 intermediate microclines.

2. The position and shape of the $(\bar{2}01)$ reflection(s) should be checked to find out whether the feldspar consists of a potassic phase, sodic phase, or both, and whether the phase(s) have a limited or a broad range of composition. The $(\bar{2}01)$ reflection will be sharp for samples in which the range of Or content is 5% or less. Samples with greater variation will show broadening of the top of the $(\bar{2}01)$ reflection.

3. If a potassic phase is present the (131) reflection should be checked. If it is a single, sharp reflection then the potassic phase may be indexed in monoclinic symmetry with the aid of Table 11. If (131) is split into (131) and $(1\bar{3}1)$, the feldspar is triclinic and, if both reflections are sharp, may be indexed with the aid of Tables 12 and 13. In some cases both a monoclinic and triclinic potassic phase will appear in the same sample; or the (131) reflections will be broadened and indistinct, indicating that the structural state is highly variable in the sample. In such cases the determination of significant unit-cell parameters is not possible by our methods.

Homogeneous sodic phases may be indexed as albite using the appropriate references in Table 10. Albite in perthitic intergrowth may be indexed by reference to Table 15. In many cases sodium feldspar in perthitic intergrowth will not yield enough unique reflections for a refinement.

Natural anorthoclases, including those with appreciable anorthite component, may be indexed by reference to Table 14 and the high sanidine-high albite series of Donnay and Donnay (1952) or Orville (1967).

4. For purposes of measurement, patterns should be run with an internal standard three times, from high to low values of 2θ, at a goniometer and chart speed yielding $1^\circ\ 2\theta = 1''$. Measurement of each peak should be as near the top as practicable; the CuKα_1 wavelength, $\lambda = 1.5405$ Å, is used. A list of the positions of all measurable reflections should be prepared, indexed according to Tables 10–15. The reflections should be evaluated as to quality in some manner—one such procedure developed by Wright is given in Orville (1967). This will tend to select only the most reliable measurements for the refinement.

Computation procedures. The type of refinement of unit-cell parameters depends on the type of computer program available. If the program operates solely on a 'fixed-index' cycle an accurate refinement will result only if the indices of the reflections used in the input to the computer are correct. Tables 11–15 embody a system of evaluation designed to ensure a correct input. Doubly starred (**) reflections are those which appear on the diffraction patterns of virtually every feldspar of each class and for which indexing is unambiguous. The position of such reflections should

TABLE 13. GUIDE TO INDEXING X-RAY DIFFRACTION PATTERNS OF MAXIMUM MICROCLINES

Rating[a]	Miller index[b]	Observed 2θ (range)	Approximate Intensity	Computer statistics[c]		
				Used	Not used	Not observed
	(110)	≈13.1	8	1	9	—
	$(\bar{1}10)$ (001) (020)	≈13.6	10	1	9	—
	$(\bar{1}\bar{1}1)$	≈14.9	8	1	4	5
	$(\bar{1}11)$	≈15.2	8	1	4	5
	(021) $(0\bar{2}1)$	≈19.25	5	1	—	9
**	$(\bar{2}01)$	20.96–21.04	35	10	—	—
**	(111)	22.29–22.38	20	8	1	1
**	$(1\bar{1}1)$	22.61–22.69	10	4	1	5
**	(130)	23.18–23.24	25	7	—	3
**	$(\bar{1}30)$	23.97–24.02	30	6	2	2
*	$(\bar{1}\bar{3}1)$	24.26–24.37	10	5	3	2
*	$(\bar{2}\bar{2}1)$	24.70–24.77	10	4	—	6
	$(\bar{1}31)$	≈24.9	10	1	—	9
*	$(\bar{1}\bar{1}2)$	25.53–25.56	40	4	5	1
	$(\bar{2}21)$	≈25.6	10	1	5	4
	(112)	≈25.7	<10	1	1	8
**	(220)	26.40–26.47	40	8	2	—
**	$(\bar{2}02)$	27.04–27.10	40	8	1	1
	$(\bar{2}20)$	≈27.05	10	—	1	9
**	(002)	27.44–27.52	>100	9	1	—
**	(131)	29.42–29.55	30	9	1	—
**	$(1\bar{3}1)$	30.12–30.24	30	10	—	—

TABLE 13—(*continued*)

Rating[a]	Miller index[b]	Observed 2θ (range)	Approximate Intensity	Computer statistics[c]		
				Used	Not used	Not observed
**	(041)	30.72–30.82	30	8	2	—
	$(\bar{2}22)$	≈30.75	<10	—	1	9
*	$(\bar{1}\bar{3}2)$	≈32.1	10	3	3	4
	$(\bar{3}11)$	≈32.3	10	2	—	8
*	$(\bar{1}32)$	32.44–32.47	15	5	1	4
*	$(\bar{2}\bar{4}1)$	34.19–34.27	15	6	—	4
	(221)	≈34.3	10	1	1	8
	$(\bar{3}12)$	≈34.6	15	1	—	9
*	(112)	34.88–35.03	10	4	1	5
	$(2\bar{2}1)$	35.1	10	1	2	7
*	$(\bar{2}41)$	35.48–35.57	15	5	1	4
	$(\bar{3}10)$	≈35.9	6	—	1	9
	$(\bar{2}40)$	≈36.8	10	—	2	8
*	$(\bar{1}50)$	36.98–37.00	10	3	—	7
*	$(\bar{1}13)$	≈38.6	10	3	2	5
**	(060)	41.78–41.85	30	9	1	—
	(222)	≈45.5	8	1	—	9
	$(\bar{4}22)$					
	$(\bar{4}21)$	≈45.6	8	—	3	7
	$(2\bar{2}2)$	≈46.2	8	—	1	9
	(113)	≈48.7	8	1	—	9
**	$(\bar{2}04)$	50.51–50.66	25	9	1	—
	$(0\bar{4}3)$					
	$(0\bar{6}2)$	≈50.9	10	—	1	9

[a,b,c] See footnotes for Table 11. Data of this table based on X-ray diffraction patterns of 10 maximum microclines.

TABLE 14. GUIDE TO INDEXING X-RAY DIFFRACTION PATTERNS OF ANORTHOCLASE

Rating[a]	Miller index[b]	Calculated 2θ (range)[d]	Intensity (average)	Computer statistics[c]	
				Used	Not used[e]
	(020)	13.64–13.73	10	4	4
	(001)	13.79–13.88	5	5	3
	$(\bar{1}11)$	15.3–15.6	<5	1	7
	$(0\bar{2}1)$	19.0–19.3	<5	3	5
**	$(\bar{2}01)$	21.65–21.88	65	8	0
**	$(1\bar{1}1)$	22.85	25	8	0
**	(111)	23.11–23.56	35	7	1
**	$(\bar{1}30)$	23.66	45	7	1
**	(130)	23.90–24.30	40	8	0
*	$(\bar{1}\bar{3}1)$	24.5–24.6	10	5	3
	$(\bar{1}31)$	24.85–25.3	5	4	4
**	$(\bar{1}\bar{1}2)$	25.6–25.7	15	8	0
**	$(\bar{1}12)$	25.9–26.3	20	8	0
*	(040)	27.48–27.66	>100	3	5
**	(002)	27.78–27.98	>100	8	0
	(220)	27.75–28.3	40	3	5
**	$(1\bar{3}1)$	29.64–29.91	25	8	0
**	$(0\bar{4}1)$	30.32–30.60	20	8	0
*	$(0\bar{2}2)$	30.54–30.81	25	6	2
**	(131)	30.50–31.28	25	7	1
	(041)	31.1–31.8	<5	2	6
*	$(\bar{1}\bar{3}2)$	31.80–32.16	10	6	2
*	$(\bar{1}32)$	32.75–33.48	5	6	2
	$(\bar{2}\bar{4}1)$	35.2–35.5	25	3	5
	$(\bar{2}41)$	35.25–35.6	25	3	5
	(310)	37.0–37.5	<5	1	7
	(240)	36.9–37.6	<5	1	7
	$(\bar{1}\bar{5}1)$	≈37.1	5	2	6
	$(\bar{1}51)$	37.4–38.0	5	3	5
	$(\bar{3}31)$	38.7–39.0	5	3	5
	$(\bar{3}\bar{3}1)$	38.7–39.2	<5	2	6
	$(1\bar{5}1)$	40.5–40.9	<5	1	7
**	(060)	41.74–42.03	15	8	0
	$(\bar{1}\bar{5}2)$	42.2–42.7	<5	1	7
	(151)	41.6–42.7	5	2	6
*	$(2\bar{4}1)$	42.61–42.86	10	5	3
	(061)	44.5–45.3	<5	2	6
	(222)	47.2–48.2	5	1	7
	$(\bar{4}03)$	48.6–49.0	5	1	7
	(400)	48.9–49.6	5	1	7
	(260)	48.9–49.7	<5	1	7
	$(1\bar{1}3)$	49.6–49.8	<5	1	7
	$(0\bar{6}2)$	49.7–50.4	5	2	6
*	(113)	49.92–50.62	10	4	4
	$(\bar{3}50)$	50.6	<5	1	7
**	$(\bar{2}04)$	51.02–51.31	25	8	0

[a], [b], [c] See footnotes to Table 11.

[d] Data for this table is based on 6 specimens of anorthoclase studied by the authors and the anorthoclases studied by Carmichael and Mackenzie, 1964. The ranges of 2θ values are taken from those calculated from the cell refinements of Carmichael and Mackenzie (1964, Table III, p. 956). In all cases the observed 2θ's for the 6 additional specimens fall within the range given in column 3.

[e] The computer statistics do not distinguish "not used" from "not observed" as some of the data is from the literature.

TABLE 15. GUIDE TO INDEXING X-RAY DIFFRACTION PATTERNS OF ALBITE IN PERTHITIC INTERGROWTH

1. Computer-refined albites[a]				2. Other albites[b]
Miller index	Observed 2θ (range)	Computer Statistics		Observed 2θ (range)
		Used	Not used	
(001)	13.84–13.88	6	1	
(020)	≈13.85	1	6	
$(\bar{2}01)$	22.04–22.23	7	0	21.90–22.10
$(1\bar{1}1)$	23.07–23.10	6	1	23.05–23.35
(111)	23.54–23.57	6	1	23.50–23.60
$(\bar{1}\bar{3}1)$	≈24.25	2	5	
$(\bar{1}30)$	24.26–24.31	3	4	24.05–24.35 [may conflict with K-phase $(\bar{1}\bar{3}1)$]
$(\bar{1}\bar{1}2)$	≈25.45	2	5	
$(\bar{2}\bar{2}1)$	≈25.57	3	4	
$(\bar{1}12)$	26.42–26.44	7	0	
(002)	27.92–27.95	6	1	27.90–28.10 [may conflict with (002) of highly distorted K-phases]
(040)	≈28.1	1	6	
(220)	≈28.35	1	6	
$(\bar{1}31)$	30.12–30.18	6	1	30.10–30.20 [conflicts with $(1\bar{3}1)$ and $(\bar{2}\bar{2}2)$ of triclinic K-phases]
$(0\bar{2}2)$	≈30.51	3	4	
$(0\bar{4}1)$	≈30.52	3	4	
$(\bar{1}\bar{3}1)$	31.22–31.49	7	0	31.05–31.30
$(1\bar{3}2)$	≈31.5	1	6	
(041)	≈32.2	1	6	
$(\bar{1}32)$	33.92–33.99	6	1	33.90–34.00
$(\bar{2}\bar{4}1)$	35.00–35.06	6	1	
$(\bar{3}12)$	≈36.7	1	6	
$(\bar{2}41)$	≈36.8	2	5	
$(\bar{3}\bar{3}1)$	≈38.84	3	4	
$(\bar{2}\bar{4}2)$	≈41.3	1	6	
$(1\bar{5}1$	≈41.3	1	6	
(060)	42.48–42.54	6	1	42.45–42.55
(151)	≈42.8	2	5	
$(2\bar{4}1)$	43.56–43.60	3	4	
(061)	≈45.9	1	6	
(222)	48.13–48.19	3	4	
$(0\bar{6}2)$	50.00–50.10	3	4	
(113)	50.56–50.66	6	1	
$(\bar{2}04)$	51.12–51.19	6	1	

[a] Based on refinement of 7 albites from perthites with bulk compositions more albitic than $Or_{50}Ab_{50}$.

[b] Reflections commonly observed for albite in perthites with bulk compositions more potassic than $Or_{50}Ab_{50}$.

be entered in the program, excepting rare instances where the peak quality is too poor. Singly starred (*) reflections are those which may not appear on diffraction patterns of every feldspar or those for which accurate measurement is not always possible but which are also unambiguously indexed. When such reflections can be measured their positions should also be entered in the program. Unstarred reflections should not be entered in the input for a fixed-index cycle because of possible ambiguity in indexing.

If the available computer program has a 'variable-indexing' option (Evans, Appleman, and Handwerker, 1963), it is possible to enter the positions of *all* accurately measured reflections. The indices of doubly and singly starred reflections can be entered as part of the input and the computer will use these to compute a starting unit-cell. Using these cell parameters the computer will attempt to index all other reflections, and compute a final unit cell on the basis of all reflections it can unambiguously index. A print-out of the observations against calculated 2θ values for *all* possible reflections allows the user to judge which reflections are suitable for a final refinement. A "variable-index" program is especially useful for series of related feldspars where, by a small change in unit-cell parameters, a reflection whose indexing is ambiguous on one pattern will be unambiguously indexed on another. If the particular reflection is sharp on all patterns there is no reason why it should not be entered for all with the unambiguous index indicated for the one pattern. The final refinement for many feldspars may involve a fixed-index cycle using the positions of all reflections whose indexing is unambiguous as evaluated from the variable-indexing output.

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