THE AMERICAN MINERALOGIST, VOL. 52, JANUARY-FEBRUARY, 1967

THE MICROCLINE-ORTHOCLASE TRANSFORMATION IN THE CONTACT AUREOLE OF THE ELDORA STOCK, COLORADO[1]

THOMAS L. WRIGHT, *U. S. Geological Survey, Hawaiian Volcano Observatory, Hawaii.*

ABSTRACT

Feldspars from pegmatites in Precambrian gneiss within 2770 feet of a Tertiary quartz monzonite stock near Eldora, Colorado, were transformed from maximum microcline to orthoclase by contact metamorphism. In the range 2770 to 1130 feet a monoclinic and a triclinic potassic phase coexist in perthitic intergrowth with albite of low-intermediate structural state. At greater distances perthites consisting of maximum microcline and low albite were unaffected, and at shorter distances the samples are composed of orthoclase and intermediate albite.

Data of this study combined with the work of Steiger and Hart place the upper stability limit of maximum microcline on the binary Or-Ab solvus at 375° ± 50°C. A first-order transformation is suggested by the absence of microcline of intermediate obliquity but a higher order transformation occurring over a small range of temperature is also possible.

INTRODUCTION

Hart (1964) and Steiger and Hart (1967) have described the transformation of microcline to orthoclase within the aureole of contact metamorphism surrounding the Eldora stock (Colorado). Hart kindly supplied the author with specimens from the Eldora traverse (Hart, 1964, Steiger and Hart, 1967 Fig. 2). This paper supplements the work of Steiger and Hart by providing detailed chemical, optical, and X-ray data pertinent to the microcline-orthoclase transformation in this one traverse. Previous speculation on the nature of the orthoclase-microcline transformation has been based chiefly on irreversible heating experiments (Goldsmith and Laves, 1954; Tomisaka, 1962). This paper describes the microcline-orthoclase transformation as it occurs in nature where geologic time may have favored a closer approach to equilibrium than is possible from experiments in the laboratory.

The properties of the feldspars in the Eldora traverse are plotted against distance from the contact of the Eldora stock in Figure 1 and are described in the sections following. Briefly, the transformation of microcline to orthoclase takes place over a distance of at least 1700 feet as follows (the specimens are numbered according to their distance in feet from the contact):

SH 22500 is a maximum microcline microperthite, representative of feldspar unaffected by contact metamorphism.

SH 2770, SH 2000, and SH 1130 are microperthites that contain both

---

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

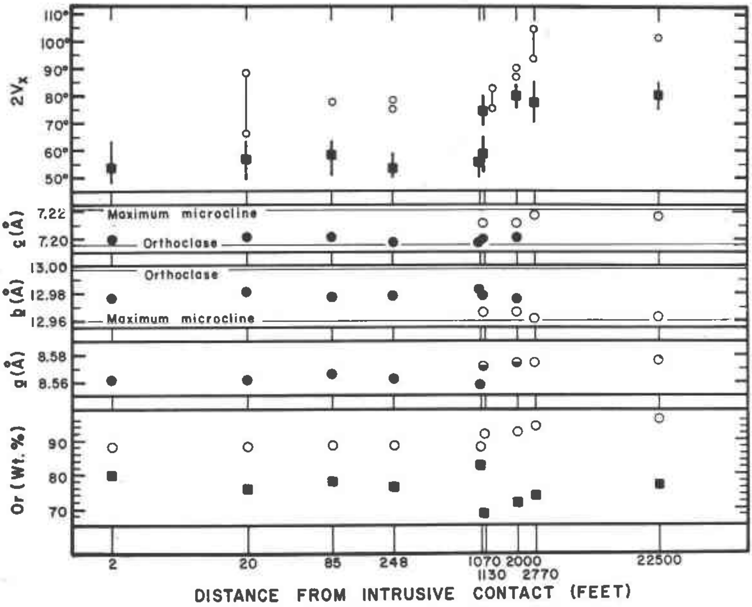

FIG. 1. Properties of perthites plotted as a function of distance from the intrusive contact.

Top figure: 2*V*. Solid squares show average and range measured on the potassic host. Open circles are the same for the sodic phase.

Middle figure: Linear cell dimensions of the potassic phase. Solid circles for orthoclase, open circles for microcline. Shaded circles represent average *a* for coexisting microcline and orthoclase. Lines labeled 'orthoclase' and 'maximum microcline' are drawn for a composition of Or_{90} in standard series obtained by alkali exchange (Orville, 1964; Wright, 1964a).

Lower figure: Chemical composition. Solid squares indicate bulk composition obtained from analysis. Open circles indicate composition of the potassic phase estimated from 2θ $(\bar{2}01)$.

microcline of high obliquity and orthoclase; the percentage of orthoclase increases toward the contact.

SH 1070, SH 248, SH 85, SH 20, and SH 2 are orthoclase microperthites.

DETERMINATIVE METHODS

Uniform sieved samples in the size range (−)100 to (+)200 mesh were separated in heavy liquids and in the magnetic separator to remove quartz, plagioclase, and any ferromagnesian inclusions. After separation, most of the samples still contained quartz; a weak quartz peak at 26.6° 2θ showed on the X-ray diffraction patterns of these samples, but the small amount of quartz did not interfere with either optical or X-ray measurements.

An optical grain mount, ground to thin-section thickness, was made for each sample. Another split of the sample was used for single crystal and X-ray diffraction work. The remainder of each sample was submitted for chemical analysis.

Optic angles were measured directly on the universal stage by the orthoscopic (extinction) method using a sodium light source. X-ray diffraction patterns were run from 57° to 20° 2θ at $\frac{1}{2}$°/min. using annealed CaF_2 ($a=5.4622$ at 25°C) as an internal standard. The position of peaks belonging to the potassic phase was measured as near the top of the peak as practicable; each final observed 2θ was the average of three traverses run from higher to lower values of 2θ. Unit-cell parameters were refined on 13 to 18 powder diffraction lines using the fixed index routine of the computer program developed by Evans, Appleman, and Handwerker (1963). Crystal fragments were also studied by the oscillation method of Smith and Mackenzie (1955).

BULK CHEMISTRY

Partial chemical analyses of the feldspars studied are given in Table 1. Silica and alumina were analyzed directly, and have also been calculated from the values of K_2O, Na_2O, and CaO assuming stoichiometric compositions for the feldspar components. In all cases the analyzed values exceed the calculated ones. Argillaceous alteration and possible minor components (e.g., celsian) account for the excess alumina. Quartz impurity accounts for the excess silica.

Bulk Or contents of the orthoclase perthites average about 6% Or higher than those of the perthites that contain microcline. Apparently this is not true for all traverses away from the Eldora stock (see discussion in Steiger and Hart, 1967). In any case chemical equilibrium away from mineral grain boundaries was not attained with increasing temperature as the bulk compositions of the feldspar samples do not vary in a regular manner with distance from the contact. This is also true for plagioclase. The composition of the plagioclase was determined from the α refractive index to be $An_{28\pm2}$ in samples collected at 2 feet, 85 feet, 1070 feet, and 2770 feet.

OPTICAL DATA

Axial angle measurements for both the sodic and potassic phases of the perthites are summarized in Table 2. The microcline-orthoclase transition is marked by an abrupt decrease in axial angle of the potassic host (see Fig. 1. and Table 2). In specimen 1130, a small amount of relic twinned microcline is present in addition to clear orthoclase. Curiously, SH 2000

TABLE 1. CHEMICAL DATA

	Orthoclase microperthites					Microperthite with orthoclase and microcline			Maximum microcline microperthite
	SH-2	SH-20	SH-85	SH-248	SH-1070	SH-1130	SH-2000	SH-2770	SH-22500
K_2O[1]	12.9	12.5	12.8	12.5	13.0	10.9	11.8	11.9	12.7
Na_2O[1]	2.1	2.5	2.3	2.5	1.7	3.2	3.1	2.8	2.6
CaO[2]	0.36	0.36	0.30	0.25	0.35	0.50	0.27	0.25	0.12
Al_2O_3[2]	18.4	19.0	19.0	18.0	19.2	19.3	19.2	19.2	19.2
SiO_2[2]	*65.3*	*64.7*	*64.8*	*65.0*	*63.8*	*65.0*	*65.0*	*64.8*	*65.2*
Sum	99.1	99.1	99.2	98.3	98.1	98.9	99.4	99.0	99.8
SiO_2[3]	+2.9	+1.4	+1.8	+2.0	+3.4	+3.6	+1.3	+2.4	+1.2
Al_2O_3[4]	+0.4	+0.8	+0.8	0.0	+1.7	+1.4	+0.8	+1.3	+1.0
Or (wt. %)	76.2	73.9	75.6	73.9	76.9	64.4	69.7	70.3	75.0
Ab (wt. %)	17.8	21.2	19.5	21.2	14.4	27.0	26.2	23.7	22.0
An (wt. %)	*1.8*	*1.8*	*1.5*	*1.2*	*1.8*	*2.5*	*1.4*	*1.3*	*0.6*
Or+Ab+An	95.8	96.9	96.6	96.3	93.1	93.9	97.3	95.3	97.6
$\frac{Or}{Or+Ab+An}$ (wt. %)	79.6	76.2	78.3	76.8	82.6	68.5	71.7	73.8	76.9
$\frac{An}{Ab+An}$	9.2	7.8	7.2	5.4	11.1	8.5	5.1	5.2	2.7

[1] Flame photometer determinations by J. I. Dinnin, U. S. Geological Survey.

[2] Analyses by method of Shapiro and Brannock (1962); analyst, Paul Elmore, U. S. Geological Survey.

[3] SiO_2 (anal.) minus SiO_2 calculated from K_2O, Na_2O, CaO, assuming stoichiometric feldspar compositions.

[4] Al_2O_3 (anal.) minus Al_2O_3 calculated from K_2O, Na_2O, CaO, assuming stoichiometric feldspar compositions.

and 2770 resemble SH 22500 in having only multiply-twinned felspar with a large axial angle even though X-ray studies (see next two sections) show conclusively that these specimens contain both a monoclinic and a triclinic potassium-rich phase. This optical anomaly (which explains why the transition appears sharp in the field—see Hart, 1964) is important in elucidating the crystallographic changes accompanying the orthoclase-microcline transition and will be discussed later.

Although axial angles were measured with difficulty on the sodic exsolution blebs they are of importance in interpreting the behavior of perthites during both the heating and cooling cycles of the metamorphism. Albite coexisting with appreciable microcline (SH 22500, SH 2770, SH 2000) is characterized by $2V=90°$ measured about X and thus is close to a low structural state. Albite coexisting with orthoclase is characterized by considerably lower values of $2V$ in the range 70–80°. An intermediate structural state is indicated for these albites by reference to the curves of J. R. Smith (1958).

TABLE 2. OPTICAL DATA

Specimen No.	$2V_X$ (K-phase)			$2V_X$ (Na phase)		Remarks
	No. of Determinations	Range	Average	No. of Determinations	Range	
SH 2	30	48°–63°	53.4°	—	–	Clear orthoclase+patchy albite
SH 20	30	49°–63°	57.0°	11	(–) 66°–88°	Clear orthoclase+patchy albite
SH 85	22	51°–63°	57.9°	1	(–) 77.5°	Clear orthoclase+patchy albite
SH 248	20	50°–59°	53.1°	2	(–) 75°, 78°	Clear orthoclzse+patchy albite
SH 1070	30	50°–60°	55.4°	4	(–) 69°–79°	Clear orthoclase+patchy albite
SH 1130	32	52°–65°	58.2°			Clear orthoclase (patchy and lamellar albite)
SH 1130	8	69°–80°	74.5°	4	(–) 75°–82.5°	Relic grid-twinned microcline
SH 2000	7	75°–84°	80°	2	(–) 87°, 90°	Grid-twinned K-phase, lamellar albite
SH 2770	8	70°–85°	77.5°	4	(+) 93°–104°	Grid-twinned K-phase, lamellar albite
SH 22500	3	75°–85°	—	1	(+) 105°	Grid-twinned K-phase, lamellar albite (measurements made on a single large crystal cut approximately normal to a).

The appearance of the exsolution is different for the orthoclase perthites and microcline perthites. Exsolution in perthite specimens containing microcline is of the lamellar or 'string' variety. With few exceptions the albite in the orthoclase perthites takes the form of patchy, commonly indistinct, blebs.[1]

---

[1] For a similar contrast see Wright, 1964b, Figs. 7 (patch perthite) and 2 (lamellar perthite).

TABLE 3. UNIT CELL PARAMETERS OF THE POTASSIUM-RICH FELDSPAR PHASE

Specimen No.		a, Å	b, Å	c, Å	α	β	γ	V, A^3	Or content[1] wt. %
SH 2		8.5618 ± .0035	12.9758 ± .0028	7.1997 ± .0013	90°	116°02.6′ ± 01.7′	90°	718.65 ± 0.30	88.0 ± 2.0
SH 20		8.5618 ± .0022	12.9807 ± .0024	7.2013 ± .0009	90°	116°00.6′ ± 01.0′	90°	719.28 ± 0.20	88.5 ± 2.0
SH 85		8.5667 ± .0035	12.9779 ± .0024	7.2010 ± .0010	90°	116°01.9′ ± 01.5′	90°	719.37 ± 0.30	89.0 ± 2.0
SH 248		8.5636 ± .0032	12.9787 ± .0033	7.1975 ± .0014	90°	116°02.4′ ± 01.5′	90°	718.76 ± 0.30	89.0 ± 2.0
SH 1070		8.5592 ± .0026	12.9835 ± .0028	7.1985 ± .0011	90°	116°00.2′ ± 0.9′	90°	718.97 ± 0.22	88.0 ± 2.0
SH 1130	(Or)		12.979[3] ± .004	7.200[4] ± .004	90°	nd	90°	nd	
		8.572 ± .01							92.0 ± 2.0
	(Mi)[2]		12.966[3] ± .004	7.212[4] ± .004	nd	nd	nd	nd	
SH 2000	(Or)		12.976[3] ± .004	7.201[4] ± .004	90°	nd	90°	nd	
		8.575 ± .01							93.0 ± 2.0
	(Mi)[2]		12.967[3] ± .004	7.212[4] ± .004	nd	nd	nd	nd	
SH 2770			nd	nd	90°	nd	90°	nd	
		8.575 ± .01							94.0 ± 2.0
	(Mi)[2]		12.962[4]	7.218[4] ± .004	nd	nd	nd	nd	
SH 22500	[2]	8.576 ± .0051	12.964 ± .0047	7.217 ± .0019	90°34.3′	115°55.6′ ± 02.4′	87°48.4′	721.10 ± 0.41	96.5 ± 2.0
					± 2.9		± 2.6′		

[1] Or content obtained by measuring $(\bar{2}01)$ using a $KBrO_3$ standard (Orville, 1960, 1963).

[2] $2\theta(131)-2\theta(1\bar{3}1)$ as follows: SH 22500 (0.737); SH 2770 (0.750); SH 2000 (0.714); SH 1130 (≈0.70).

[3] Estimated from position of (060)—see text for further explanation.

[4] Estimated from position of $(\bar{2}04)$—see text for further explanation.

X-RAY POWDER DIFFRACTION DATA

Unit-cell parameters of the potassic phases of the perthites are listed in Table 3 and are plotted in Figure 1. These were obtained on the U. S. Geological Survey computer facility using a program developed by Evans, Appleman, and Handwerker (1963). Original indexing was performed by the computer; the final dimensions were calculated on a fixed-index option using as input observed 2θ's and associated *hkl*'s.

Specimens 2, 20, 85, 248, 1070 have similar dimensions which all conform to orthoclase (rather than sanidine) as defined by the cell parameters of an isostructural series produced by base-exchange of a feldspar nearly identical to Spencer C (Spencer, 1937, Wright, 1964a). The cell dimensions of SH 22500 are those of maximum microcline as defined by the cell parameters of a series isostructural with maximum microcline (Orville, 1964, and written communication).

The cell parameters for SH 1130, SH 2000, and SH 2770 could not be refined in the usual way because of overlap of most of the peaks for the two potassic phases. Instead *c*, *b*, and *a* have been estimated by measuring $(\bar{2}04)$, (060), and $(\bar{2}01)$, respectively, and by referring to plots of *a vs* 2θ $(\bar{2}01)$, *b vs* 2θ (060), and *c vs* 2θ $(\bar{2}04)$, constructed from the computer output for a variety of base exchanged and natural feldspars. The $(\bar{2}04)$ peaks for the coexisting orthoclase and microcline were resolved at a goniometer setting of $\frac{1}{4}$°/min. and a chart speed giving $\frac{1}{2}$° 2θ/in. The (060) peaks were not well resolved but *b* of the lesser phase may be estimated from a break in slope and broadening of the peak. Peak $(\bar{2}01)$ nearly coincides for the two phases, so *a* is an average and the two compositions cannot differ by more than 10% Or and are probably within 5% Or of each other. The nature of the change in the X-ray diffraction patterns from SH 22500 to SH 1070 is shown in Figure 2. SH 22500 and SH 1070 were mixed to give approximately a 1:1 ratio of microcline to orthoclase and portions of the resulting pattern are also shown for comparison. It is evident from Figure 2 that the ratio of orthoclase to microcline increases toward the intrusive contact and that $(\bar{2}04)$ and (060) are resolved into two peaks for mixtures containing appreciable amounts of both phases.

The percentage of orthoclase in the specimens shown in Figure 2 may be estimated from the X-ray patterns of artificial mixtures of orthoclase and maximum microcline prepared by Steiger and Hart (1967, Fig. 3) as follows: SH 2770 ($\approx$5%); SH 2000 (20±10%); SH 1130 (70±10%). The microcline of SH 2770 is nearly identical, dimensionally, to that of SH 22500. Orthoclase is not detected on the powder-diffraction pattern of this sample, but is shown on oscillation photographs (see following

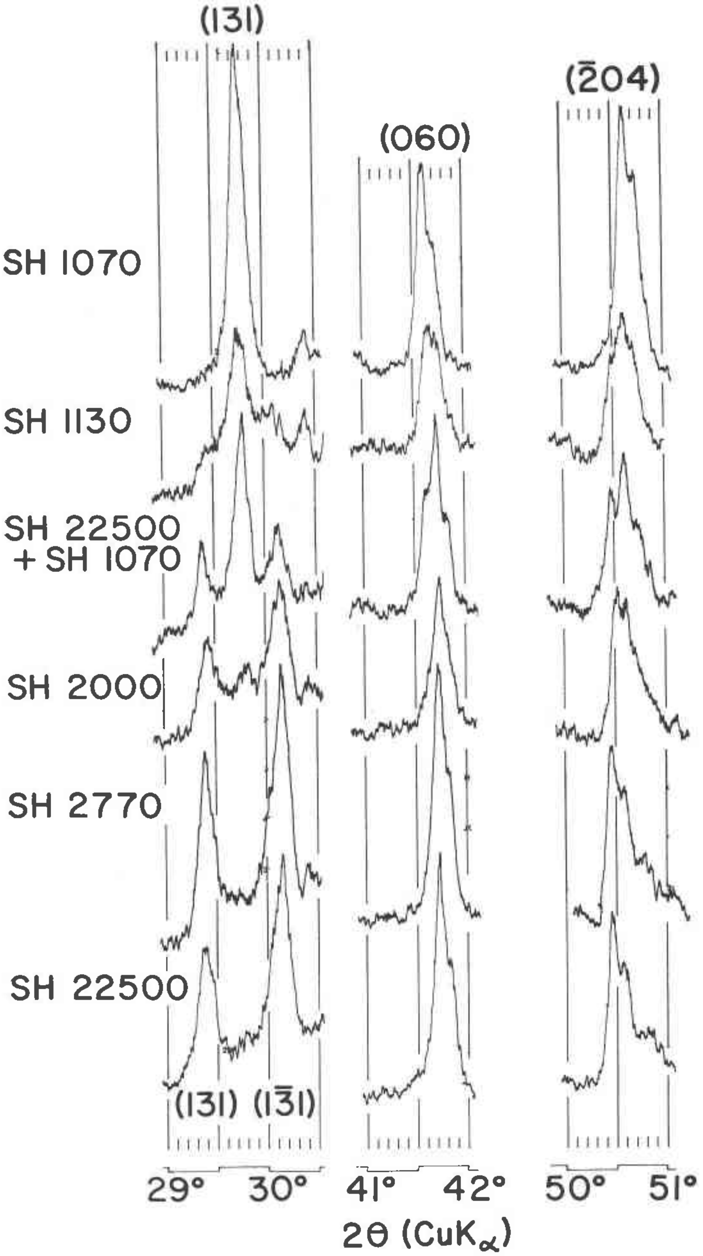

FIG. 2. Selected X-ray diffraction peaks of the potassic phases. The change from maximum microcline to orthoclase takes place from 2770 to 1130 feet without intervention of intermediate polymorphs. The pattern labeled SH 22500+SH 1070 is an artificial mixture run for comparison.

section). The microcline of SH 2000 and SH 1130 is apparently of slightly gher histructural state (close to orthoclase) indicated by a small shift in *b*, *c*, and the 131–$1\bar{3}1$ separations. The orthoclase of SH 2000 and 1130 are identical and slightly displaced toward maximum microcline (higher *c*, lower *b*), compared to the orthoclases in the interior of the aureole. Distortion, defined by low *b* and *c* relative to *a* (Wright, 1964a), is minimal.

The compositions of the potassic phases, with the exception of SH 1070 and SH 2, fall close together in the range Or_{90-95}. SH 1070 and SH 2 have compositions of Or_{88}. These specimens also have the most potassic bulk compositions and microscopic exsolution is much less visible in these perthites than in the other specimens. There is no apparent correlation between average $2V$ and *Or* content of the potassic phase as was found for microperthites from the Tatoosh pluton (Wright, 1964b).

Oscillation Photographs by the Method of Smith and Mackenzie

The α^* and γ^* for the twinned triclinic phases of the perthites were determined by the method of Smith and Mackenzie (1955); the data are given in Table 4 and plotted in Figure 3. Portions of *b*-oscillation photographs are shown in Figure 4. Another parameter, here called the 'diagonality' after the diagonal association described by Smith, 1962, p. 245, has been estimated from single crystal *b*-oscillation photographs. In the 'diagonal association' the microcline spots related by twinning fall between the correct positions for albite and for pericline twinning. The values of diagonality given in Table 4 are the angular difference between the line defined by pairs of spots for twinned microcline and the row lines along which spots related by albite twinning should lie. The diagonality is low in the microcline of specimen SH 22500 and SH 1130 and reaches a maximum in SH 2000. The possible significance of this variation will be discussed below.

Both microcline and albite components of the perthites are twinned on the albite law. Despite the appearance of 'grid' twinning no pericline twinning was observed on the oscillation photographs. This was confirmed optically. The apparent grid structure is defined by discontinuous lamellae which exhibit only two optical orientations related by the albite law. The orthoclase-microcline relations are best seen in the oscillation photographs from comparison of the $(66\bar{5})$ peak (see Smith and Mackenzie, 1955 and Fig. 4).

SH 22500 is a microcline microperthite in which spots for both albite-twinned phases are sharp and intense. The α^* and γ^* for the sodic phase are similar to those of low albite and those for the potassic phase to maximum microcline. SH 2000 and 1130 show groups of three spots for

TABLE 4. SINGLE CRYSTAL DATA

Specimen No.	K-phase				Na-phase		
	Twin Type	α*	γ*	Diagonality[1]	Twin Type	α*	γ*
SH 2a	—	90°	90°	—	Albite Twin-type superstructure		
SH 2b	—	90°	90°	—	Albite	86°27′	89°44′
SH 20	—	90°	90°	—	Albite	86°30′	90°10′
SH 20b	—	90°	90°	—	Albite	86°28′	89°45′
SH 85	—	90°	90°	—	Albite (relic superstructure?)	86°10′	88°53′
SH 85a	—	90°	90°	—	Do.	86°17′	89°14′
SH 248	—	90°	90°	—	Albite	86°25′	89°55′
SH 1070C	—	90°	90°	—	Albite (very weak spots—relic superstructure?)	86°07′	88°47′
SH 1070D	—	90°	90°	—	Do.	86°32′	89°40′
SH 1130	—	90°	90°	—	Albite	86°23′	89°54′
	Albite	90°10′	91°23′	4°± 30′			
SH 1130a	—	90°	90°	—	Albite	86°23′	89°55′
	Albite	—	91°24′	5°± 30′			
SH 2000	—	90°	90°	—	Albite	86°22′	90°06′
	Albite	90°12′	91°00′	19°± 30′			
SH 2000B	—	90°	90°	—	Albite	86°21′	90°16′
	Albite	—	—	—			
SH 2000C	—	90°	90°	—	Albite	86°24′	90°10′
	Albite	90°09′	90°54′	18°± 30′ 10°			
SH 2770	Monoclinic and triclinic phase—triclinic phase not measurable (see text)				Albite	86°35′	90°05′
SH 2770b	Do.			8°	Albite	86°29′	90°07′
SH 2770c	Do.			11°	Albite	86°20′	89°59′
SH 22500	Albite		91°30′	10°	Albite	86°31′	90°25′
SH 22500a	Albite	90°18′	91°30′	9°± 30′	Albite	86°26′	90°19′

---

[1] The angle between the line connecting two spots related by albite twinning and the closest row line Spots related by perfect albite twinning should lie on the row line with a diagonality = 0°.

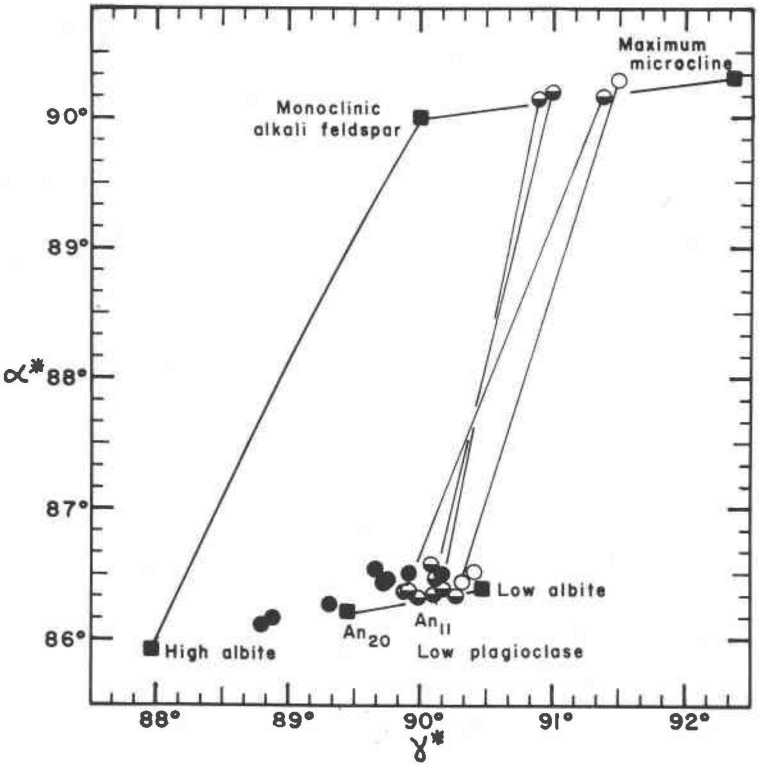

FIG. 3. Plot of the reciprocal lattice angles α^* and γ^* for perthites from the Eldora contact aureole measured by the oscillation method of Smith and Mackenzie (1955). Solid circles represent albites that coexist with orthoclase. Connected shaded circles represent albite and microcline that coexist with orthoclase. Connected open circles represent coexisting microcline and albite. The solid squares are data from Mackenzie and Smith (1955) used as reference points.

the potassic phase (Fig. 4). The middle spot belongs to orthoclase and the two on either side belong to albite-twinned microcline. The γ^* of SH 1130 is close to that of SH 22500 and the diagonality is the least of any of the specimens. SH 2000 has the highest diagonality and a γ^* lower than that for maximum microcline (even after correcting for diagonality) in agreement with the smaller $131-1\bar{3}1$ spacing, larger b, and smaller c estimated from powder data. SH 2770 is anomalous. Three separate crystals were photographed and each show three spots for $(66\bar{5})$ (Fig. 4). One of the two belonging to microcline is quite intense whereas the companion spot is barely visible and asymmetrically between the two is a weak spot corresponding to orthoclase. In addition the microcline and albite are mis-

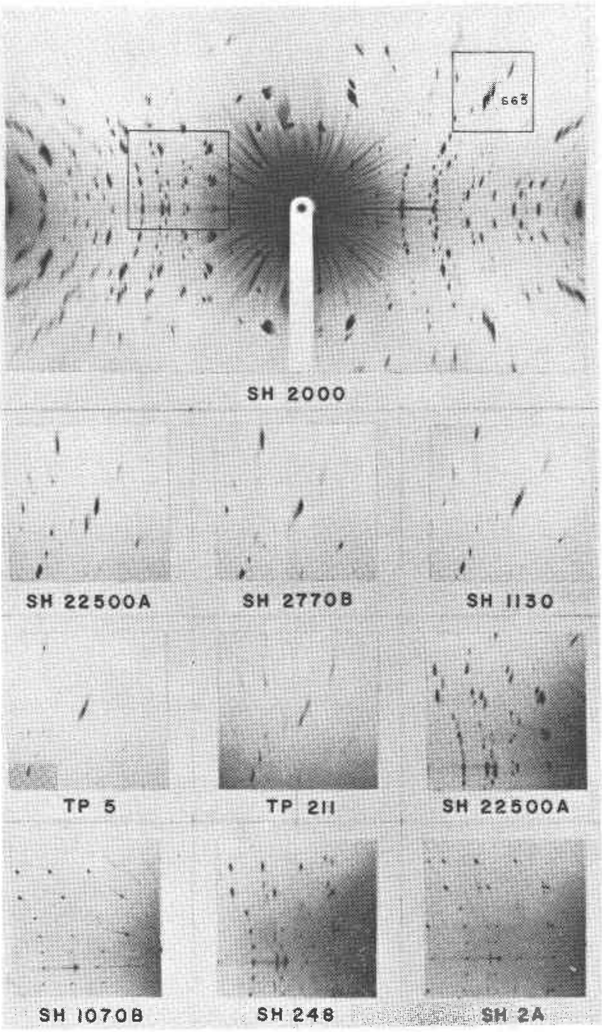

FIG. 4. Portions of *b*-oscillation photographs of perthites from the Eldora contact aureole (SH) and from the Tatoosh pluton (TP). The photos were taken following the method of Smith and Mackenzie (1955) and interpretations are made with reference to Mackenzie and Smith (1955). The top photo shows the areas covered in the insets. The first five insets show the 66$\bar{5}$ reflections. In the Eldora samples the configuration ranges from albite-twinned maximum microcline (SH 22500 A) to orthoclase coexisting with minor amount of albite-twinned maximum microcline (SH 1130). Specimens SH 1070, 248, 85, 20, and 2 all show a single spot for 66$\bar{5}$ indicative of a monoclinic potassic phase. The 66$\bar{5}$ reflections are also shown for two perthites from the Tatoosh pluton (Wright, 1964b). The potassic phase in TP 5 is dominantly monoclinic, in TP 211 is dominantly triclinic, but in both there is a complete gradation of obliquity in contrast to the Eldora samples.

The last four insets show the nature of the sodic phase. SH 22500 A has sharp spots for a oriented with respect to one another. Thus, unlike the usual case in perthites, none of the b^* axes coincide. The diagonality of SH 2770 is approximately that of SH 22500; α^* and γ^* of the microcline could not be measured accurately because of the misorientation. The $(66\bar{5})$ reflections are shown also for two perthites from the Tatoosh pluton (Wright, 1964b). The potassic phase of TP-5 and TP-211 show two stages of inversion during cooling; in both there is a broad gradation of structural state between orthoclase and a microcline of intermediate obliquity (maximum γ^* is estimated at 90° 45′) and diagonality values are close to zero. This contrasts with the Eldora specimens in which a monoclinic and triclinic phase coexist with no intermediate phase.

The α^* and γ^* measured from the b-oscillation photographs are consistently smaller than α^* and γ^* refined from powder diffraction data for the same specimens. This discrepancy is being investigated further by D. B. Stewart and the present author. Preliminary data suggest that this discrepancy is found only for microcline in perhitic intergrowth and may be related to imperfect development of albite twinning evidenced by the diagonality. At present the values of α^* and γ^* obtained by refinement of powder diffraction data are to be preferred.

The γ^* measured for albites of SH 2770, SH 2000, and SH 1130 are displaced toward high albite from that of SH 22500. This may be partly attributed to the larger An contents of these specimens but also results from a real variation of structural state. The spots for the sodic phase of these perthites are somewhat distended normal to the layer lines suggesting that the structural state covers a range of values.

SH 1070, 248, 85, 20, and 2 contain single spots of a monoclinic potassic phase. The coexisting albites are distinguished from the albites in specimens containing microcline by having a distinctly intermediate structural state (Fig. 3) and by distension of spots normal to the layer lines (Fig. 4). The distension in SH 2, 85, and 1070 is suggestive of a relic albite twin-type superstructure (Mackenzie and Smith, 1955) and one crystal of SH 2 has a fully developed superstructure of this type.

The X-ray data obtained by the two methods and the optical data agree and are consistent with a transformation of maximum microcline to orthoclase over the interval 2770 to 1100 feet. Slight variations in the cell dimensions of microcline and of orthoclase in the zone of transition can be attributed to distortion or to lack of resolution of the optical and

---

sodic phase twinned on the albite law. SH 248 has spots distended normal to the layer lines which are also indicative of an albite-twinned sodic phase. The distension may represent a variation in structural state of the sodic phase. SH 2A has a sodic phase with an albite twin-type superstructure. (See Mackenzie and Smith, 1955.) In SH 1070 the albite-twinned sodic phase is barely visible.

X-ray methods used. Potassium feldspars of structural state distinctly intermediate to maximum microcline and orthoclase are not found in the Eldora traverse.

EVIDENCE FOR HOMOGENIZATION OF THE ORTHOCLASE PERTHITES

The patchy character of the exsolution and the presence of albite of intermediate structural state in the patches commonly showing an albite-twin type superstructure are interpreted as evidence favoring exsolution produced by cooling of a homogeneous or nearly homogeneous feldspar. The patchy texture contrasts with the lamellar perthite characteristic of the microclines, and is quite similar to the exsolution texture produced in the early cooling stages of perthites from the Tatoosh pluton (Wright 1964b). The albite-twin type superstructure is probably indicative of the early stages of exsolution. According to Mackenzie and Smith (1955, p. 721), "The tendency to form a superstructure is probably highest at the beginning of the unmixing process. As the unmixing proceeds, the size of the lamellae of the soda phase should increase, thus reducing the values of strain per unit volume. It is thus reasonable to suppose that the formation of a superstructure is an intermediate step in the formation of a twinned crystal."

The intermediate structural state exhibited by perthitic albites of the Tatoosh pluton have been ascribed to metastable growth during the early stages of exsolution (Wright, 1964b) and this interpretation is favored here also. It is, however, possible that structural state of the albite phase was changed during contact heating. Mackenzie (1957) and McConnell and McKie (1960) have shown that intermediate albites are stable at least down to 400°C which is within the range of contact temperatures estimated by Steiger and Hart (1967) for the Eldora aureole.

SH 2, SH 1070, and SH 85 are interpreted as having been fully homogenized during contact heating as there is no evidence of relic exsolution lamellae; SH 20 and SH 248 show some lamellar perthite and the albites are of generally lower structural state suggesting that these orthoclases may not have been completely homogenized. The conclusions reached here regarding homogenization do not agree with those reached by Steiger and Hart (1967). Thus the argument regarding temperature of the microcline-orthoclase transformation which follows must be evaluated with respect to the evidence for and against homogenization.

TEMPERATURE OF THE MICROCLINE-ORTHOCLASE TRANSFORMATION

Gradients of maximum temperature of contact metamorphism along the Eldora traverse were derived by Hart (1964, p. 508FF) and Steiger and Hart (1967, Fig. 12; see their discussion in the section entitled *Heat* *flow*). Assuming model A, corresponding to an infinite dike,[1] approximate temperatures are as follows: 2 feet (500°C); 1070 feet (440°C); 2770 feet (350°C). Thus on the assumptions of Hart the transformation took place over a temperature range of 100°C, and 350° is a maximum temperature for stable existence of a maximum microcline having a composition of approximately Or_{95}.

An independent approach to the temperature of transformation depends on the evidence for homogenization of the orthoclase microperthites during contact heating. Figure 5 illustrates this derivation. The solvus drawn is that of Orville (1963) determined for synthetic feldspars. Each orthoclase sample is plotted at its bulk composition (Table 1). If SH 1070 is assumed to have been barely homogenized then it must have been raised to a temperature of 495°C. The temperatures reached by the other feldspars are derived using their distance from the contact and the heating model A of Steiger and Hart. Thus the maximum temperature of metamorphism is near 560°C (SH 2) and the temperature at which maximum microcline of composition Or_{95} becomes unstable is 405°C. (SH 2770).

Resolution of the discrepancy of 50°C between the two temperature estimates for the upper stability of maximum microcline depend on how closely the solvus for synthetic Or-Ab feldspars applies to natural An-bearing orthoclases and on the evidence for homogenization. Steiger and Hart (1967) have not found optical evidence favoring homogenization in the other traverses and for the Eldora traverse cite examples of rubidium and argon retention as arguments against alkali diffusion leading to homogenization. On the other hand Steiger and Hart, in deriving models of temperature gradients which obtained during contact metamorphism, assume an ambient surface temperature of 35°C. If the regional geothermal gradient were higher near the Eldora pluton in Laramide time, perhaps a general increase caused by the movement of magma to higher levels in the crust prior to intrusion, then the temperatures derived by Steiger and Hart would be raised. The many assumptions which go into deriving the temperature of metamorphism lead only to an approximate temperature for the upper limit of stability of maximum microcline (Or_{95}) of 375° ± 50°C.

NATURE OF THE MICROCLINE-ORTHOCLASE TRANSFORMATION

The data of the preceding sections show that, in the Eldora traverse, microcline of high obliquity was converted directly to orthoclase. Potassic

---

[1] Hart (1964, p. 510) states a preference for model C. This model however yields a maximum temperature of 260°C at 2800 feet which seems unreasonable for the formation of orthoclase.

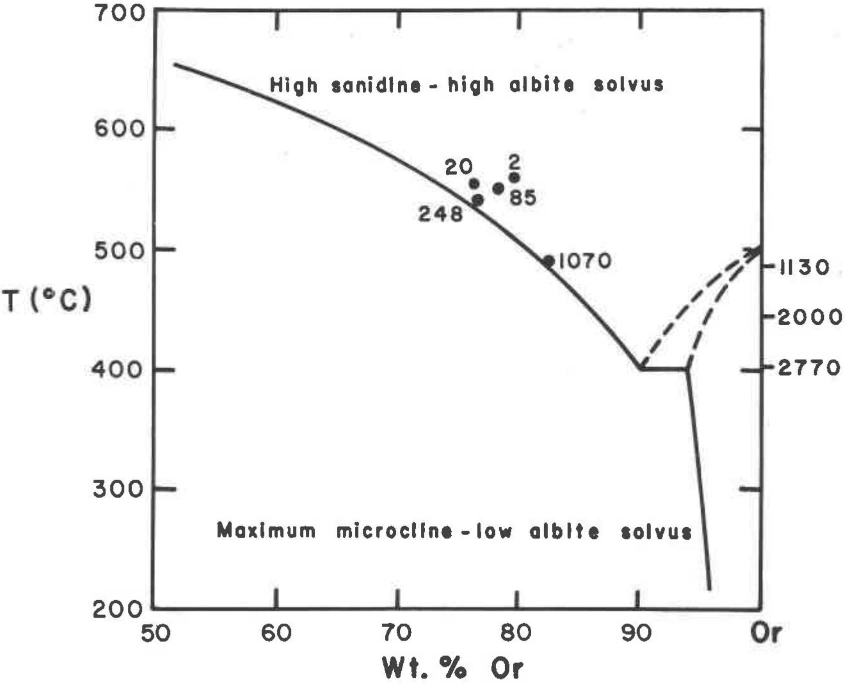

FIG. 5. Derivation of the temperature of the microcline-orthoclase transformation, and suggested phase relations of the transformation. The high albite-high sanidine solvus is from Orville (1963). The approximate position of the maximum microcline-low albite solvus is also from Orville (written communication). Numbers of plotted points correspond to Eldora (SH) specimen numbers discussed in the text. Specimens 2, 20, 85, 248, and 1070 are plotted at their respective bulk compositions according to the relative temperatures determined from model C (Hart, 1964, Fig. 5) assuming specimen 1070 was barely homogenized. The temperature of specimen 2770 is just above the inferred upper stability limit of maximum microcline more sodic than Or_{95}. In this diagram a first-order transformation on the solvus is connected to a first-order transformation on the sideline. Other possibilities are discussed in the text.

feldspars of intermediate structural state, if they were ever present, have not been preserved. It is possible to interpret this as evidence favoring a first-order transformation on the potassium-rich side of the alkali feldspar solvus. Figure 5 has been drawn to show this relation using the approximate compositions and the temperature range observed for the microcline-orthoclase transformation in the Eldora traverse. It is meant only as a model, however; it is not possible to construct a quantitative phase diagram from the data in this paper because the transformation may not have proceeded entirely at equilibrium. The diagram shown in Figure 5 is similar to that postulated by Wones and Appleman (1963, Fig. 1-B) on the basis of their determination of a reversible first-order transformation of Fe-microcline to Fe-sanidine. For microcline with a composition of Or_{90-95} the transformation would take place over a range of temperatures with microcline decreasing in amount at higher temperatures until only orthoclase is present at a temperature above that of the transition loop. The orthoclase ultimately produced would be of the same bulk composition as the starting microcline unless re-solution of albite in the potassic phase was occurring during the transformation. Re-solution of albite, in addition to changing the composition of the orthoclase would also tend to lessen the temperature interval over which the transformation took place. That is, if the bulk composition of the starting microcline was to the left of the base of the transition loop (i.e., more sodic than Or_{90} as drawn) then the transformation would take place at constant temperature.

Because of the absence of intermediate polymorphs produced during contact heating it is possible to interpret all the data from the Eldora aureole as fitting the model of a first-order transformation presented in Figure 5. However the data do not rule out the possibility of intermediate polymorphs existing stably within the narrow temperature range of the transformation. As pointed out by Steiger and Hart (1967), the conditions are unfavorable for forming and preserving intermediate polymorphs in their field of stability and the question of the exact thermodynamic nature of the transformation must remain open.

The crystallographic nature of the transformation has some puzzling features. Evidently in the earliest stages orthoclase grew misoriented with its b^* not coincident with the b^* of twinned microcline; some orthoclase may even have grown at the expense of only one of the two orientations of albite-twinned microcline to explain the widely differing intensities of the microcline spots shown in Figure 4. The transformation appears to have occurred first on a submicroscopic scale, orthoclase only becoming visible when it exceeded microcline in abundance. This may be related to growth of tiny domains as postulated by Laves and Goldsmith (1961, p. 73). There is also distortion (represented by diagonality) of the microcline lattice during inversion which is apparently relieved when the orthoclase becomes visible.

RELATIONSHIP OF THE PRESENT STUDY TO EXPERIMENTAL DETERMINATION OF THE MICROCLINE-ORTHOCLASE TRANSFORMATION

Results of the present study and that of Steiger and Hart can be interpreted compatibly with the experimental work of Goldsmith and Laves (1954) and Tomisaka (1962), on the transformation of maximum microcline to a monoclinic K-feldspar, if it is assumed that presence of 5–10% $NaAlSi_3O_8$ in solid solution lowers the stability range of maximum microcline by more than 100°C. Figure 5 shows one way of connecting a first-order transformation on the sideline to a first-order transformation on the alkali feldspar solvus. A first-order transformation on the solvus necessitates a first-order transformation on the sideline. However a high-order transformation on the solvus could connect either to a first-order transformation or to a high-order transformation on the sideline; for this latter case the tie lines for differing structural states would not converge but instead would fan out to cover a range of temperature on the sideline. (See Wones and Appleman, 1963, Fig. 1; and Wright, 1964b, Figs. 8–10 and related discussion.) The data of Goldsmith and Laves (1954) and Tomisaka (1962) favor a first-order transition on the sideline and this is also favored by analogy with the reversible first-order transformation of Fe-microcline to Fe-sanidine determined by Wones and Appleman (1963).

APPLICATIONS TO GEOTHERMOMETRY

The microcline-orthoclase relations described in the present study are believed to represent more closely the equilibrium transformation than do the orthoclase-microcline relations observed in *cooled* rocks. It is the author's experience that plutonic rocks may contain any combination of maximum microcline, orthoclase, microcline of fixed intermediate obliquity, or polymorphs of variable structural state between orthoclase and maximum microcline. The type of polymorph produced on cooling appears to be related to a number of factors other than temperature. The most important of these are bulk composition and time that the feldspar was held near the temperature of transformation. (See also Mackenzie, 1954.) Thus the potassium feldspar polymorphs yield relatively little information on the temperature of formation of plutonic rocks.

The possibility still exists that the transformation of microcline to orthoclase may be used as an isograd in regional metamorphic terrains. If maximum microcline is already present as the only polymorph of potassium feldspar in lower grade rocks then the presence of any potassium feldspar distinct from maximum microcline should indicate a temperature higher than the transformation. The absence of orthoclase is not a criterion because of possible retrograde changes. The temperature assigned to the isograd must take into account the sodium content of the potassium feldspar. Figure 5 shows the danger in trying to apply the experimental data for pure $KAlSi_3O_8$ to the microcline-orthoclase relations in rocks where the potassium feldspar polymorphs contain significant amounts of $NaAlSi_3O_8$ in solid solution. Heier (1957), for example, has used the temperature of 500°C for the microcline-orthoclase transition to define the amphibolite-granulite facies boundary. In the light of the present study if orthoclase is to be used as a facies mineral the temperature of the microcline-orthoclase isograd must be closer to 400° than to 500°C.

ACKNOWLEDGMENTS

I am indebted to S. R. Hart for introducing me to the problem and for comments which have materially improved this manuscript. D. B. Stewart read an early version of the manuscript and made many helpful suggestions. D. R. Wones and James Papike have greatly improved the final manuscript.

REFERENCES

EVANS, H. T., JR., D. E. APPLEMAN AND D. HANDWERKER (1963) The least squares refinement of crystal unit cells with powder diffraction data by an automatic computer indexing method (abs.). *Amer. Crystallogr. Assoc. Ann. Meet., Program* p. 42.

GOLDSMITH, J. R. AND F. LAVES (1954) The microcline-sanidine stability relations. *Geochim. Cosmochim. Acta* **5,** 1–19.

HART, S. R. (1964) The petrology and isotopic mineral age relations of a contact zone in the Front Range, Colorado. *J. Geol.,* **72,** 493–525.

HEIER, K. S. (1957) Phase relations of potash feldspar in metamorphism. *J. Geol.* **65,** 468–479.

LAVES, F. AND J. R. GOLDSMITH (1961) Polymorphism, order, disorder, diffusion, and confusion in the feldspars. *Cursillos Conf. Inst. Lucas Mallada,* Fasc. **8,** 71–80.

MCCONNELL, J. D. C. AND D. MCKIE (1960): The kinetics of the ordering process in triclinic $NaAlSi_3O_8$. *Mineral. Mag.,* **32,** 436–454.

MACKENZIE, W. S. (1954) The orthoclase-microcline inversion. *Mineral. Mag.* **30,** 354–366.

——— (1957) The crystalline modifications of $NaAlSi_3O_8$. *Amer. J. Sci.* **255,** 481–516.

MACKENZIE, W. M., AND J. V. SMITH (1955) The alkali feldspars. I. Orthoclase microperthites. *Amer. Mineral.* **40,** 707–732.

ORVILLE, P. M. (1960) Powder X-ray method for determination of (Ab+An) content of microcline (abs.). *Geol. Soc. Am. Bull.,* **71,** 1939–1940.

——— (1963) Alkali ion exchange between vapor and feldspar phases. *Amer. J. Sci.,* **261,** 201–237.

——— (1964) Microcline-low albite solid solution series (abs.). *Trans. Amer. Geophys. Union* **45,** p. 127.

SHAPIRO, L. AND W. W. BRANNOCK (1962) Rapid analysis of silicate, carbonate and phosphate rocks. *U. S. Geol. Surv. Bull.* **1144-A.**

SMITH, J. R. (1958) The optical properties of heated plagioclases. *Amer. Mineral.* **43,** 1179–1194.

SMITH, J. V. (1962) Genetic aspects of feldspar twinning. *Norsk Geol. Tidsskr.* **B42,** 244–263.

——— AND W. S. MACKENZIE (1955) The alkali feldspars. II. A simple X-ray technique for the study of alkali feldspars. *Amer. Mineral.* **40,** 733–747.

SPENCER, E. (1937) The potash-soda feldspars. I. Thermal stability. *Mineral. Mag.* **24,** 453–494.

STEIGER, R. H. AND S. R. HART (1967) The microcline-orthoclase transition within a contact aureole. *Amer. Mineral.* **52,** 87–116.

Tomisaka, T. (1962) On order-disorder transformation and stability range of microcline under water vapor pressure. *Mineral. J.* (*Tokyo*) **3,** 261–281.

Wones, D. R. and Appleman, D. E. (1963) Properties of synthetic triclinic $KFeSi_3O_8$, iron-microcline, with some observations on the iron-microcline⇆iron-sanidine transition. *J. Petrol.* **4,** p. 131–137.

Wright, T. L. (1964a) X-ray determination of composition and structural state of alkali feldspar (abs.). *Trans. Amer. Geophys. Union* **45,** 127.

——— (1964b) The alkali feldspars of the Tatoosh pluton in Mount Rainier National Park. *Amer. Mineral.* **49,** 715–735.

Manuscript received, February 9, 1966; accepted for publication March 8, 1966.