

## Composition and Structural State of K-Feldspars From K-Feldspar + Sillimanite Grade Rocks in Northwestern Maine

CHARLES V. GUIDOTTI

*Department of Geology and Geophysics, University of Wisconsin,  
Madison, Wisconsin 53705*

H. H. HERD

*Lawrence Radiation Laboratory, Livermore, California*

C. L. TUTTLE

*Department of Geology and Geophysics, University of Wisconsin,  
Madison, Wisconsin 53705*

### Abstract

Study of K-feldspars from high-grade migmatitic rocks in northwest Maine reveals distinct interrelations among paragenesis, composition, and structural state of the K-feldspars. Structural state has been characterized in the manner suggested by Wright and Stewart (1968) and using the  $\Delta bc$  plot of Crosby (1971).

Petrographically the rocks have been subdivided into eight groups. These are:

Group	Rock Type	Ab% in K-feldspar	$\Delta bc$
I	Coarse mica schist with groundmass K-feldspar and sillimanite	14	.765
II	Biotite granulite with groundmass K-feldspar	9.5	.86
III	Calc-silicate granulite with groundmass K-feldspar	6.5	.86
IV	K-feldspar from sillimanite-bearing, coarse, leucocratic bands and megacrysts	14.5	.80
IV'	K-feldspar from sillimanite-free, coarse, leucocratic bands and megacrysts	10	.83
V	Retrograded specimens	8.5	.88
VI	Specimens with resorbed sillimanite	9	.85
VII	Specimens with retrograding concentrated along well defined veinlets	2	.70
VIII	K-feldspar from adamellite	—	.912
	K-feldspar from diorite	—	.827

K-feldspar compositions for specimens from Groups I, II, and III are believed to represent the original, high temperature, homogeneous feldspars. Several models explain the observed differences in structural state and their obvious relation to Ab content. The favored model involves disequilibrium ordering interrelated with the  $Al/(K + Na)$  ratio in the surrounding pore fluid.

### Introduction

Wright (1968) and Wright and Stewart (1968) have provided field petrologists with incentives to measure cell parameters of alkali feldspars in order to relate feldspar structural states to the petrogenesis of igneous and metamorphic rocks. These parameters enable quite accurate assessment of alkali feldspar structure states (Stewart and Ribbe, 1969). Thus far, only a few papers have appeared which make use of these procedures. These include Ragland

(1970), Tilling (1968), Crosby (1971), and Hipple (1971).

The objectives of this paper are to try to interrelate K-feldspar structure states, compositions, and petrogenesis in a suite of closely related metamorphic rocks. Parameters correlated with the K-feldspar properties are metamorphic grade, metamorphic history, and mineral assemblage. Study of K-feldspars from metamorphic terranes such as the one considered here seems desirable because the minerals may

have had a relatively simple history compared to many igneous parageneses, and at least some approach to chemical equilibrium can be demonstrated. Many earlier works have tried to interrelate feldspar compositions and structure states with metamorphism (*e.g.*, Heier, 1961) but they have been hampered by inadequate X-ray parameters to measure and lack of the abundant compositional data now available by means of electron probe analyses.

**Geologic Setting**

The area covered in this report lies in the Buckfield and Bryant Pond quadrangles in N. W. Maine (Fig. 1). Details on the stratigraphy, structure, and petrography of these rocks are given in Guidotti (1965), Evans and Guidotti (1966), and Warner (1967). Geologic description presented here involves only features pertinent to this study.

Stratified and layered rocks have steep dips and NE to NW trends. Most are highly deformed and

consist of interbedded coarse-grained micaceous and migmatitic gneisses, biotite granulites, and a few thin calc-silicate units. The leucocratic layers of the migmatites are interlayered with coarse mica schist and/or biotite granulite and range from diffuse stringers to distinct lit-par-lit pegmatitic layers having highly variable thickness from band to band. Irregular crystals of subhedral feldspars up to 5 cm in diameter occur in some of the mica schist layers.

Figure 1 shows the location of the K-feldspar + sillimanite isograd. Most specimens were subjected to metamorphic temperatures higher than that of the isograd. It is likely that rocks to the S. and S.W. of this isograd crystallized at progressively higher temperatures but as developed in Evans and Guidotti (1966) temperatures never exceeded the upper stability limit of pure K-muscovite. Using the experimental curve of Evans (1965) for the breakdown of muscovite, it is evident that the *maximum* temperatures attained, (at 3–4 kbar) would be 650–

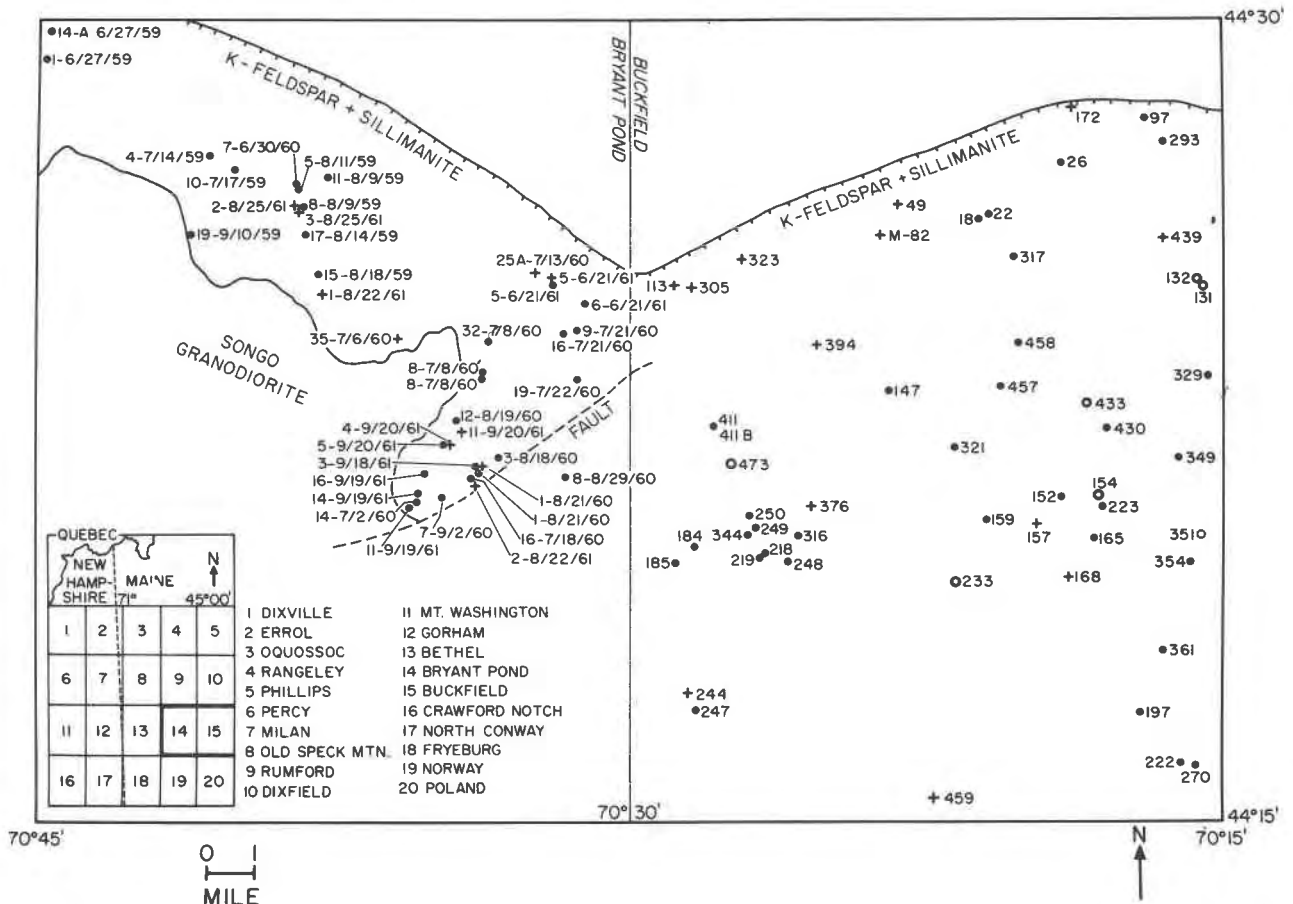


FIG. 1. Locations of specimens from Groups I, IV, V, VI. These specimens define the K-feldspar + sillimanite zone. ● = Group I; + = Group IV; ○ = Groups V and VI.

685°C. It is estimated that the metamorphic rocks at the isograd and above crystallized between 635°C and 685°C with rocks at the isograd forming at the lower end of this temperature range.

Many small to large bodies of adamellite and pegmatite intrude the metamorphic rocks. One large body of diorite ("Songo Granodiorite") is present in the western portion of the Bryant Pond quadrangle (see maps in Warner, 1967, and Guidotti, 1965).

### Descriptive petrography and mineralogy

All specimens considered in this study were stained to ascertain the presence and distribution of K-feldspar and virtually all were studied in thin section. Descriptive categories which can be distinguished are:

#### *I. Coarse mica schist with groundmass K-feldspar and sillimanite*

In these rocks K-feldspar and sillimanite are in intimate association and well distributed throughout the groundmass. The usual assemblage is Qtz + Plag + Musc + Ksp + Sill + Bio ± Garn, but muscovite is usually present in only small amounts (<5%). Plagioclase compositions are near An<sub>20</sub> to An<sub>25</sub> and the data of Evans and Guidotti (1966) suggests that the An content increases with metamorphic grade.

In terms of the system Al<sub>2</sub>O<sub>3</sub>-K<sub>2</sub>O-Na<sub>2</sub>O-CaO with quartz present, it is apparent that these rocks plot within the 4 phase volume Sill-Musc-Ksp-Plag shown in Figure 9C of Evans and Guidotti (1966).

Although clear exsolution of Ab is present in a few specimens of K-feldspar, in general it is not a prominent feature. Only about 1/2 of the specimens display some minor development of exsolution, and it is usually restricted to just a small fraction of the K-feldspar grains in a given thin section.

A few K-feldspar samples show undulatory extinction and rarely a weakly developed grid twinning.

#### *II. Biotite granulites with groundmass K-feldspar*

These rocks are medium grained and only weakly schistose. They contain Qtz + Plag + Bio + Ksp ± Musc ± Garn. Plagioclase compositions, as determined by refractive indices, optical measurements on twinned crystals, and some X-ray data, range from An<sub>30</sub> to An<sub>45</sub>. K-feldspar grains have little exsolution (only one specimen) but undulatory extinction and grid twinning are seen in many specimens.

In terms of the components Al<sub>2</sub>O<sub>3</sub>, K<sub>2</sub>O, Na<sub>2</sub>O,

and CaO, these specimens plot on the CaO side of the four-phase volume mentioned above. Those with muscovite plot on the three-phase tie planes, Mus + Ksp + Plag; those without muscovite plot on the feldspar plane of this system.

#### *III. Calc-silicate granulites with groundmass K-feldspar*

Most of these specimens are medium grained diopside granulites that commonly contain diopside, quartz, plagioclase, calcite, biotite, hornblende, sphene, and groundmass K-feldspar. K-feldspar usually shows strong grid twinning but only very minor exsolution. Plagioclase compositions range from An<sub>50</sub> to An<sub>70</sub> based upon optical data and some probe analyses (Evans and Guidotti, 1966).

These rocks plot on the feldspar plane of Figure 9C in Evans and Guidotti (1966). Moreover they lie closer to the CaO corner than do specimens from the two preceding groups.

#### *IV. K-feldspar from coarse grained, leucocratic bands and megacrysts*

K-feldspar in these specimens usually occurs as translucent to transparent grains, whereas associated plagioclase has a milky white color. Many specimens have sillimanite intimately associated with the K-feldspar, others do not. Table 1 Part D<sup>1</sup> distinguishes these two cases. Exsolution is better developed than in K-feldspar from Group I. In some cases albite twins are developed in the exsolution lamellae. Well developed undulose extinction is common, and small patches of good grid twinning are present, especially near exsolution patches.

#### *V. Specimens showing evidence of retrogression*

These rocks are characterized by the typical evidence of retrogression such as biotite altering to chlorite, and sericite replacing plagioclase and sillimanite. K-feldspar occurs in the groundmass and in a few cases as sheaves in chlorite after biotite. Due to the retrogression it is difficult to discern the textural and optical appearance of the K-feldspar. Some

<sup>1</sup>Table 1, Parts A-I, is available from ASIS/NAPS. To obtain a copy, order NAPS Document Number 02117 by remitting \$1.50 for microfiche or \$5.00 for photocopies, payable to Microfiche Publications, 305 East 46th Street, New York, N.Y. 10017. Please check the most recent issue of this journal for the current address and prices.

Table 1, Part J is representative of the information given in Table 1, Parts A-I.

TABLE 1, PART J. Examples of K-feldspar data for Group I-VIII Specimens

Spec. #	Ab %	Dev Ab Cnts	Dev K Cnts	Peak Struc.	3	Refnd. Struc.	Qual	$\Delta bc$ Value	a	b	c	$\alpha$	$\beta$	$\gamma$	Vol. %	$\Delta^{\dagger}$ 201	$\Delta^{\dagger}$ a	Pk. Acc. Pk. Ent.	Std. Error 20	Remarks
(I) 15-8/18/59	13.9	10.5	1.4	SH*	Ben.	Sharp	Qual 131	8.5612 ±.0022	12.9880 ±.0028	7.1969 ±.0016	90°	116° 0.998† ±0.127	90°	71.9 ±.215	.19	.0262	29/30	.01862	No Ab 201 Peak † No Exsolution Seen	
(II) 5-8/9/59	9.0	10	0.9	$\mu$	$\mu$ +1/3	Mod. Broad		8.5374 ±.0080	12.9671 ±.0085	7.2016 ±.0033	90°	115° 53.291† ±0.325	89° 42.314† ±0.190	71.8 ±.748	.13	.0774	18/22	.03751	No Ab 201 Peak No Exsolution Seen	
(III) 6-6/25/60	5.6	9	1	$\mu$ *	$\mu$	Broad to Split		8.5704 ±.0011	12.9539 ±.0012	7.2011 ±.0047	90°	115° 58.706† ±0.200	89° 39.804† ±0.186	71.8 ±.104	.245	.1304	20/23	.05395	No Ab 201 Peak No Exsolution Seen	
(IV) 25A-7/13/60	16.4	17	3.3	SH-1/4	SH	Sharp		8.5637 ±.0020	12.9767 ±.0026	7.1950 ±.0014	90°	116° 1.070† ±0.955	90°	71.8 ±.5429	.19	.0987	26/28	.01614	Good Ab 201 Peak, I ~ 1/2* Abundant Exsolution Sill. Mig.	
(V) 5-6/23/60	11.8	10	1.2	$\mu$ -1/3	Mic.	Three Peaks		8.5628 ±.0010	12.9612 ±.0010	7.2114 ±.0042	90°	116° 13.704† ±0.469	89° 6.263† ±0.559	71.9 ±.837	.102	.0128	20/23	.04698	Weak Ab 201 Peak No Exsolution Seen $\Delta$ 131 = .6	
(VI) BK-473	7.8	29	2	$\mu$	$\mu$	Mod. Broad		8.5706 ±.0055	12.9640 ±.0058	7.2041 ±.0019	90°	115° 2.218† ±0.039	89° 58.305† ±0.345	71.9 ±.552	.187	.0906	16/19	.0210	Fair Ab 201 Peak, I ~ 1/2 Possible Tr. Exsolution.	
(VII) BK-241A	1.8	13	1.7	Ben +1/2	Ben +2/3	Sharp		8.5887 ±.0021	13.0009 ±.0025	7.1901 ±.0014	90°	116° 2.010† ±0.960	90°	72.1 ±.3955	.16	.0487	26/31	.0164	Good Ab 201 Peak, I > 1.	
(VIII) 7-8/3/59	--	--	--	Mic.	Mic.	Much Irreg. Splitting		8.5490 ±.0010	12.9452 ±.0014	7.2122 ±.0070	90°	116° 47.026† ±0.324	88° 3.215† ±0.286	71.6 ±.7039	.081	.0790	24/25	.07630	Good Ab 201 Peak, I ~ 1/2 Minor Exsolution	

(I)-(VIII), Column One, Petrographic Group (See text) of Specimen.

\*I = Intensity of Ab 201 Peak based on scale of 1-10. †Ab 201 Peak gives a rough measure of the development of Plagioclase peaks on X-Ray Patterns. ‡ Difference between observed value and that predicted from Fig. 3 of Wright (1968). † = Difference calculated value and that predicted from Fig. 2b of Wright and Stewart (1968).

do have well developed grid twinning. It is clear that many of these rocks are retrograde products of Group I rocks.

#### VI. Specimens with resorbed sillimanite

These specimens are quite similar to those of Group I with the exception that they have considerably more muscovite. Sillimanite is present but in rather peculiar textural arrangements. (1) It is not in contact with biotite. (2) Sillimanite needles do not cross grain boundaries. (3) Sillimanite occurs as sharply bounded patches of prisms in the cores of quartz and feldspar grains and in some cases also in the cores of large muscovite tablets. Guidotti (1966) found that muscovite in such rocks is K-enriched. The unusual sillimanite textures indicate that the rocks have undergone processes differing from simple retrogression; perhaps they are products of local K-metasomatism or late re-equilibration. There seems little doubt, from the above described sillimanite textures, that these rocks once passed through a stage equivalent to those of rocks in Group I. Guidotti (1966, p. 1783) presented arguments suggesting that these rocks formed at about the same time and in approximate equilibrium with the rocks containing abundant sillimanite within the micas. Grid twinning is well developed in the K-feldspar of most (but not all) specimens. Most of these K-feldspars contain only faint exsolution lamellae.

#### VII. Specimens showing retrogression along well defined veinlets

Retrogression in these specimens seems concentrated along and emanating out from well defined "alteration" veinlets. In this respect they differ from Group V rocks in which retrogression seems to be randomly distributed throughout the specimen. Staining of rock slabs shows that the K-feldspar is located near the central part of the vein and in some cases occurs as a thin seam along the core of the veinlet. In outcrop these veinlets look like fine jointing along which alteration has occurred. Spacing of these "joints" is on the order of 0.1 to 3 meters and the alteration band on either side of the joint is only 1 to 2 cms thick.

#### VIII. Intrusive granitic rocks

These specimens include Fisher's (1962) "Songo Granodiorite" and Evans Notch quartz monzonite (adamellite). The Songo pluton consists of coarse grained plagioclase ( $\sim An_{45}$ ), biotite, quartz, horn-

blende, sphene, and in a few specimens K-feldspar in amounts ranging up to 5 modal percent. Only weak twinning is evident in this K-feldspar.

The adamellite has sharp to gradational contacts. Specimens from the gradational contacts commonly contain large muscovite megacrysts and schistose schlieren which appear to be "undigested" remnants of inclusions of the country rock. Muscovite is present in most specimens of the adamellite and that occurring as coarse megacrysts commonly has sillimanite associated with it. Sillimanite is relatively abundant in specimens from gradational contacts and may occur as "resorbed" remnants included in other minerals or in some cases as a groundmass mineral crossing grain boundaries. In specimens with abundant sillimanite, K-feldspar is only weakly twinned whereas it is strongly twinned in the sillimanite-free specimens.

#### Analytical Procedures

*X-ray procedures.* The procedures for running and measuring X-ray diffraction patterns recommended by Wright and Stewart (1968) were followed as closely as possible in this study. The structural state has been estimated both by the 3 peak method (Wright, 1968) and from cell dimensions obtained from the Evans, Appleman, and Handwerker (1963) variable indexing program.

Patterns were run on purified mineral separates or, in the case of megacrysts, on crushed fragments. Based upon the absence of quartz peaks, absence or weakness of plagioclase peaks, and the fact that other phases were rarely encountered in probe traverses, the mineral separates appear to have been quite pure. (See below for specific details regarding the various petrographic groups)

Separation work and X-ray diffraction work was largely done by H. H. H. Measurement of the patterns and computer processing was largely done by C. L. T. Measurement of  $2\theta$  for  $\bar{2}01$ ,  $\bar{2}04$ , and  $060$  was carried out by both H. H. H. and C. L. T. All peaks were corrected with reference to three peaks of fluorite ( $28.280^\circ$ ,  $47.015^\circ$ , and  $55.771^\circ$ ).

The vast majority of patterns were quite good, enabling the use of about twenty  $2\theta$  values for each refinement calculation. Table 1, Parts A-J, give the ratio of the number of peaks entered and accepted by the computer for each K-feldspar specimen.

X-ray running conditions on a General Electric unit include: Cu  $K\alpha_1$  radiation with a Ni filter, M.A. 16, K.V. 50, slit detector  $.04^\circ$ , and beam slit  $3^\circ$ .

Each pattern was refined on the basis of the structural state suggested by the three peak method taking into account whether 131 and 130 are single peaks (monoclinic) or split (triclinic). This procedure seemed to work well, and the structural state estimated from the refined cell parameters usually agreed with that estimated by the 3-peak method. However, problems occur for some samples which are actually mixtures of structural states as indicated by broadened or irregularly split 131 and 130 peaks (in some cases showing three distinct peaks). Strictly speaking such specimens are not amenable to the Wright and Stewart method unless the peaks are sufficiently distinct to permit a monoclinic and then triclinic refinement using the appropriate 131, 131̄, 130 and 130 peaks. Nonetheless, refinements based upon our patterns were carried out using average values for 130 and 131 even if they were only broadened or just slightly split. If strongly and irregularly split, 130 and 131 were omitted from the refinement. The majority of patterns show only varying degrees of broadening of 131 and 130. The results of this procedure are discussed below for the appropriate groups of specimens.

**Electron probe procedures.** Probe analyses were run on grain mounts of a portion from the same mineral separates used for the X-ray diffraction patterns. K, Na, and Ca were determined simultaneously on the ARL microprobe at Wisconsin. Machine conditions include: beam Current 2 $\mu$ , beam width 10 $\mu$ , K.V. 15. Counting time was based upon the time required for 100,000 counts of sample current to accumulate—usually near 30 seconds. Standards used include: (1) Albite from Tiburon; (2) sodic plagioclase from Emmons (1953) collections; (3) Labradorite; (4) Or 5-168; (5) Microcline. Standards 1, 3, and 4 were kindly provided by Dr. B. W. Evans, and Standards 2 and 5 were provided by E. D. Glover of the University of Wisconsin Probe Lab. All of the standards appear to be quite homogeneous.

Two separate counts on each of 5 to 7 randomly chosen grains were made for each specimen. The results were then averaged. Table 1, Parts A–I give information on the counting variability and hence sample variability. The compositional homogeneity of individual samples is discussed later for each of Groups I to VII. Na loss was not observed in repeated counts made on the same spot.

Table 2 gives the results of several duplicate runs of samples from this study. Table 3 compares probe results from this study with results from Evans and

TABLE 2. Duplicate Analyses (in wt percent) of Selected Specimens

	Na <sub>2</sub> O	CaO	K <sub>2</sub> O
(A) Separate analyses of groundmass and megacryst K-feldspar for two Group I specimens			
5-6/21/61 (Groundmass)	1.58	.03	14.46
(Megacryst)	1.41	.04	14.75
1-8/21/60 (Groundmass)	1.68	.05	14.26
(Megacryst)	1.54	.04	14.44
(B) Analyses on two separate mounts of same Group I specimen			
16-9/19/61	1.66	.05	14.22
	1.69	.04	14.21
(C) Duplicate runs (on separate days) of the same mount			
BK-9 Group IV	.93	.06	15.28
	.96	.05	15.14
BK-113 Group IV	1.40	.04	14.49
	1.42	.06	14.34
BK-264 Group III	.84	.08	15.31
	.99	.05	15.16
BK-329 Group I	1.36	.04	14.58
	1.44	.06	14.40

Guidotti on the same sample (but not the same K-feldspar separate). Most of the results compare quite well. Any significant differences may well result from the analyses being carried out on different portions of the same hand specimen. Such local compositional variation within a hand specimen is now being recognized in studies of metamorphic rocks, e.g. Blackburn

TABLE 3. Comparison of K-feldspar Analyses in Evans and Guidotti (1966) and This Study

# in Evans & Guidotti	Field Number	Evans and Guidotti			This Study			Difference	
		Na <sub>2</sub> O	K <sub>2</sub> O	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	CaO	Na <sub>2</sub> O	K <sub>2</sub> O
37	17-8/14/59	1.74	14.1	.02	1.53	14.04	.03	-.21	-.06
38	5-9/20/61	1.58	14.2	.03	1.43	14.49	.04	-.15	+.29
41	14A-6/27/59	1.56	14.5	.02	1.56	14.56	.02	.00	+.06
42	10-7/17/59	1.62	14.2	.02	1.75	14.19	.02	+.13	-.01
43	14-7/2/60	1.60	14.2	.02	1.52	14.34	.05	-.08	+.14
51	14-6/20/60	.86	15.2	.03	1.39	14.48	.03	+.53	-.72**
52	5-8/11/59	1.79	14.1	.01	1.48	14.42	.04	-.31	+.32
53	8-7/8/60	1.60	14.2	.02	1.65	14.20	.04	+.05	.00
55	6-9/17/59	1.14	15.0	.05	1.43	14.72	.03	+.29	-.28
60	7-9/2/60	1.70	14.3	.03	1.66	14.28	.03	-.04	-.02
63	9-7/21/60	1.47	14.1	.01	1.49	14.41	.03	+.02	+.31
65	19-7/22/60	1.72	13.8	.01	---	---	---	---	---
68	15-8/18/59	1.82	13.8	.02	1.53	14.41	.03	-.29	+.61
70	8-8/29/60	1.69	14.1	.04	1.63	14.36	.03	-.06	+.26
71	5-6/23/60	.87	15.1	.03	1.32	14.84	.04	+.45	-.26†

† Thin Section show patchy and in some places strong retrograding.

\*\* Resorbed Specimen

\* = Specimens showing largest variation in Na<sub>2</sub>O and K<sub>2</sub>O from Analyses in Evans and Guidotti (1966)

(1968). The five specimens showing the largest (+) or (-) discrepancy in the  $\text{Na}_2\text{O}$  values (indicated by \* on Table 3) always have similar discrepancies in  $\text{K}_2\text{O}$  but with the opposite sign. This strongly suggests that the two analyses of each specimen do vary in composition and the differences are not due to analytical error.

### Analytical Results

Table 1, Parts A-J present the details of the X-ray and electron microprobe analyses grouped according to the eight descriptive categories discussed previously. The most important data on these tables are the Ab percents and structural states as indicated by  $\Delta bc$  value (see Figure 1 of Crosby, 1971). These data are summarized by histograms in Figures 2A and 2B.

Before considering the details of Groups I-VIII it is necessary to consider the meaning of the Ab percent given, especially for Groups I-IV. In Group I the Ab content given is for the bulk phase. This is evident from the following:

- (1) Probe points rarely hit Ab-rich points within K-feldspar grains.<sup>2</sup>
- (2) Optically, very little exsolution is evident in these specimens.
- (3) X-ray patterns show variable and, not uncommonly, only weak development of the  $\bar{2}01$  peak of albite (See Table 1). Many specimens show no development of the  $\bar{2}01$  peak (or any other recognizable plagioclase peaks). Nonetheless, these as well as the few specimens showing a distinct  $\bar{2}01$  albite peak, have essentially the same Ab percent as determined by probe analysis. Moreover, there is also no correlation between those few specimens showing "relatively" well developed exsolution and the degree of development of the Ab  $\bar{2}01$  peak.

Points 1-3 strongly suggest that the compositions given for Group I K-feldspars are very close to that of the homogeneous phase produced during the peak of metamorphism. Any plagioclase peaks present on the X-ray patterns are likely due to incomplete heavy liquid separation of plagioclase and quartz from K-feldspar.

<sup>2</sup> A few specimens do show a substantial range in Na counts (see Table 1A) but the vast majority do not. Moreover, the percent standard deviation of Na counts given in Table 1, Parts A-G, must take into account the fact that Na counts are only in the range of 100 to 500. Hence the seemingly large percents.

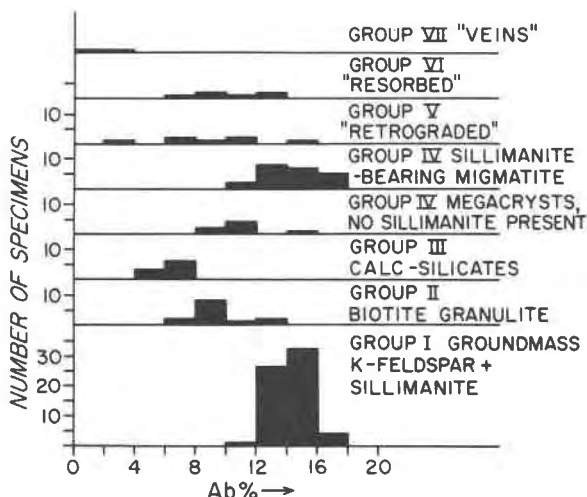


FIG. 2A. K-feldspar compositions.

In Groups II and III, the Ab percent given is again for the homogeneous K-feldspar produced during the peak of metamorphism. Thin section study shows virtually no exsolution in these specimens, and the X-ray patterns usually lack albite peaks. Moreover, probe points never hit Na-rich points within K-feldspar grains. The lack of plagioclase impurity to give any Ab  $\bar{2}01$  peak is probably due to cleaner separation for these specimens because the plagioclase is more calcic and hence more dense.

For the megacrysts (Group IV), exsolution is much more evident in thin section examination, even

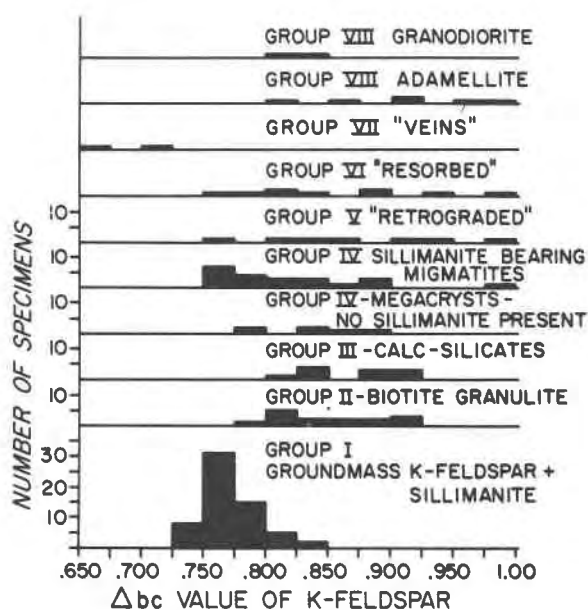


FIG. 2B. K-feldspar structural states.

showing development of Ab-twinning within lamellae. Commonly, points probed hit Na-rich areas within K-feldspar grains. The Ab  $\bar{2}01$  peak is usually fairly well developed in the X-ray patterns of these specimens. Moreover, the plagioclase peaks necessarily represent exsolved albite because the patterns were run on fragments from large, clean K-feldspar megacrysts. Because the counts from probe points on highly sodic areas were deleted from the final data reduction, the compositions for Group IV specimens give some approximation to the K-enriched phase produced by exsolution. It is noteworthy that these compositions are still somewhat more sodic than the compositions of specimens from Group I.

*Group I: Coarse mica schist with groundmass K-feldspar and sillimanite*

From Figure 2 (and Table 1A) it is quite apparent that in these specimens the K-feldspar is fairly uniform in composition ( $\sim$ Ab<sub>14</sub>) and structural state. Structural states range from Spencer B to Benson on Figure 2b of Wright and Stewart (1968) ( $\Delta bc = .850$  to  $.735$  on Figure 1 of Crosby, 1971), but most are near SH 1070 to Benson ( $\Delta bc = .78$  to  $.75$ ). All have monoclinic symmetry and can be called orthoclase. A large fraction of these feldspars are equivalent to the orthoclase (SH 1070) described by Wright (1967) from a metamorphic environment. However, many of the feldspars listed in Table 1A are anomalous in the sense that the *a*-cell dimension calculated exceeds by  $>.05\text{\AA}$  the *a*-cell dimension predicted from Figure 2b of Wright and Stewart.

*Group II: Biotite granulite with groundmass K-feldspar*

The average Ab content of K-feldspar in this group is  $\sim 9.5$  percent but the range among the different specimens is from Ab<sub>7.56</sub> to Ab<sub>13.65</sub> (see Table 1B and Fig. 2A). This range is certainly to be expected considering that the assemblage is not one which fixes (at a given *PT*) the mineral compositions (*i.e.*, the number of phases  $\neq$  number of components). With minor exception these feldspars are less sodic than those in Group I. Individual specimens show little compositional variation as indicated by the low Na-count variability shown in Table 1B for specimens in this Group. The low percent deviation in Na counts for specimens in biotite granulites is especially notable considering

the low mean values of count totals for Na in this group.

Structure state determination poses a problem in this group because broadening to partial splitting of (131) and (130) clearly suggests mixtures of different structural states, as have been observed also by Steiger and Hart (1967) and Wright (1967). The previously mentioned grid twinning in these specimens is consistent with the presence of at least some more highly ordered structure states.

Despite some question on the meaning of the cell refinement of these specimens, one can state that these feldspars are more ordered than those in Group I as indicated by (1) the broadening and splitting of 131 and 130; (2) the occurrence of some microcline twinning; (3) the 3 peak and  $\Delta bc$  designation (see Fig. 2B).

Of particular note, despite the range in structure states, the low values of percent deviation Na counts suggests that the various structural states present all have the same composition.

*Group III: Calc-Silicate granulites with groundmass K-feldspar*

In this group the K-feldspars are more K-rich than those of Group II (Fig. 2A)—most being near Ab<sub>6.5</sub>. Variability in their Na count is low. The structural states recorded (Fig. 2B) suggest greater ordering than for the K-feldspars of Group II, this greater ordering coinciding with the rather common occurrence of grid twinning. Again, however, broadening and irregular splitting of 131 and 130 indicate ranges or mixtures of structural states, the splitting being more pronounced than that observed in Group II.

*Group IV: K-feldspar from coarse leucocratic bands and megacrysts*

Ab percent in this group of specimens is similar or slightly greater than that in Group I. (See Figure 2A and Table 1D). However, the range of Ab percentages is somewhat more variable and for individual specimens the percent deviation Na counts is generally greater. This latter point seems to relate to the obviously better developed exsolution in this group. The above comments exclude these specimens (Group IV' in abstract) showing evidence of retrogression, resorption, or absence of sillimanite inasmuch as they clearly have lower Ab contents (note especially some of the megacrysts from the Buckfield quadrangle).



Specimens in Group IV showing evidence of retrogression or resorption, as well as those lacking sillimanite, clearly have more ordered structure states, as seen in Figure 2B (and Table 1D). However, those designated as "Sillimanite migmatites" also appear to have somewhat more ordered structures, when compared with Group I, despite the fact that Ab contents are similar in both groups. Generally the structural states in this group tend to lie between those in Group I and II. However, a few have well ordered structure states, usually with broadened-to-split 130 and 131 peaks.

#### Groups V and VI

As seen in Figure 2A (and Tables 1E and 1F), these specimens show a wide range of Ab contents and individual specimens commonly have rather large values of percent deviation Na counts.

The structure states (Fig. 2B) are generally somewhat more ordered than the other groups, but specimens range from maximum microcline to orthoclase. Many individual specimens exhibit a range of structure states.

The presence of remnant sillimanite and the general textural appearance clearly show that most of these specimens are derived from rocks initially in Group I. Hence the obvious changes of composition and structure state are clearly the result of the retrogression and resorption processes.

#### Group VII

These K-feldspars are interesting in that they appear related to retrogressive effects but nonetheless have the most disordered structures observed in the study. As seen in Figure 2B (and Table 1G), they have structure significantly more disordered than the "orthoclases" of Group I. Also particularly notable is their very low Ab contents (Fig. 2A).

The occurrence of these K-feldspars along "alteration veins" suggests a metastable development of feldspars with disordered structural states. Interestingly, these specimens plot in the same position as some of the authigenic K-feldspars of Woodard (1972, Fig. 2).

#### Group VIII

No chemical data is available for these specimens. Figure 2B (and Table 1, Part I) shows that K-feldspar from the Songo granodiorite is moderately disordered. However, no splitting of (131) or

(130) is present—at most there is only very slight broadening of these peaks.

Of the specimens from the Evans Notch adamellite, the two with "relatively abundant" sillimanite have the most disordered K-feldspars (and no splitting of 131 or 130 peaks) but these are still significantly more ordered than specimens from Group I. The four specimens without sillimanite (or sillimanite only as trace inclusions) have significantly ordered structural states and strong (commonly multiple) splitting of the 131 and 130 peaks.

### Discussion of Analytical and Observational Data

#### *Petrologic considerations*

(1) In Groups I, II, III, and IV, the close relation between the K-feldspar's Ab content and the mineral assemblage (and hence bulk composition) reinforces the suggestion of Evans and Guidotti (1966) that these rocks have approached chemical equilibrium. (See earlier discussion relating K-feldspar composition and assemblages to the system  $\text{CaO-Na}_2\text{O-K}_2\text{O-Al}_2\text{O}_3$  shown in Figure 9C of Evans and Guidotti, 1966).

(2) The rather uniform Ab contents in Group I are consistent with the assemblage being one where phase compositions are dependent upon  $P$ ,  $T$ , and  $a\text{H}_2\text{O}$  and independent of bulk composition, (*i.e.*, the number of phases equals the number of components).

(3) No systematic regional variation of Ab percent or structure state was observed although such variation as a function of metamorphic grade was sought for specimens in Group I. According to Evans and Guidotti (1966, p. 53), one might readily expect a continuous *decrease* of the Ab content in orthoclase in Group I rocks as grade rises. (See Thompson, 1957 and 1961, for theory and details of "continuous reactions"). Two possible explanations for this apparent lack of Ab decrease are (a) variation of the plagioclase An content effects a shift of the plagioclase-orthoclase tie lines; (b) the fixed composition of muscovite at  $\text{Pg}_8$  by a buffer reaction, Evans and Guidotti (1966), may also serve to fix the Ab content in the co-existing orthoclase.

(4) The obvious contrast of Ab-content and structure state of K-feldspars in Groups V and VI compared to Group I seems clearly related to the retrograding and resorption effects. Both processes

have affected rocks formerly in Group I and caused distinct changes in the mineralogy of the rocks and compositions of the minerals. The resorption process is not understood but probably occurred at temperatures similar to these producing Group I rocks (see earlier discussion). If such is the case, a question arises as to when the increased ordering took place in these K-feldspars. For the retrograded specimens it seems likely that the ordering resulted from low temperature effects.

#### *Mineralogic considerations*

Data in Figures 2A and 2B (and Table 1, Parts A–D) show an obvious relation *between structural state and K/Na ratio* for K-feldspars of Groups I–IV. Attempts to understand this relation in terms of hypothetical equilibrium phase diagrams have been unsuccessful. Indeed, two groups of observations suggest that many if not all K-feldspars of Groups II and III presently have neither high nor low temperature equilibrium structural states.

(1) The similarity of these K-feldspars with those from Group V, in terms of composition, structural states, and especially mixture of structural states in individual specimens, is suggestive of non-equilibrium. There is little doubt that Group V specimens are not at equilibrium and so by analogy the same can be implied for Groups II and III.

(2) Because specimens from Groups II, III, and V contain plagioclase, there is little doubt that the initial K-feldspar would plot on the solvus. The X-ray patterns from the present mixture of structural states in such specimens commonly include a single "monoclinic" 131 and 130 peak among split or broadened 131 and 130 peaks. This clearly suggests that the initial K-feldspars (which plotted on the solvus and so had to have a single structural state) had monoclinic symmetry. On cooling, all of these K-feldspars must have followed paths within the solvus. If equilibrium ordering had been maintained, each specimen would have achieved a new, uniform structural state. Individual specimens presently have mixtures of structural states and hence must not represent equilibrium ordering. The fact that K-feldspars from Groups II and III have quite uniform composition and virtually no exsolution indicates, however, that the initial high temperature compositions have been retained despite the varying degrees of readjustment of the structural state.

Martin (1967) suggests that rates of ordering upon recrystallization of an alkali feldspar depend

upon the  $Al/(K + Na)$  ratio of the fluid phase surrounding the feldspar. High Al inhibits ordering and high  $(K + Na)$  facilitates ordering. It is apparent (considering Groups I–IV) that K-feldspars coexisting with groundmass sillimanite are the most disordered. Feldspars from megacrysts, usually with associated sillimanite, are almost as disordered. Feldspars from sillimanite-free rocks (*i.e.*, not Al-saturated) are consistently the most ordered. Hence, a relation exists between the inferable degree of Al-saturation in the rocks and the structural state observed.

It is tentatively suggested here that a control on ordering such as that proposed by Martin (1967) was operative during cooling of the K-feldspars considered in this study. That is, in specimens from Groups II, III, and some from IV, lower structural states and the mixtures of structural states may have resulted from recrystallization during cooling, which produced variable degrees of ordering; however, uniform equilibrium structural states were not attained. In specimens from Group I and many from IV, recrystallization to more ordered structural states was inhibited due to relatively high alumina in the fluid phase.

Further information bearing on the above suggestion is found in the fact that K-feldspar from adamellite is more ordered than that in Group I metamorphic rocks which are intruded by the adamellite. Surely the adamellite formed initially at temperatures at least somewhat greater than those of the Group I rocks. The observation that the most disordered K-feldspar in the adamellites comes from sillimanite-bearing specimens lends additional support to the model. The mixture of structural states present in K-feldspars from the other specimens of adamellite suggests a cooling history similar to that for Group II and III specimens, *i.e.*, from an initially monoclinic form on the alkali feldspar solvus.

The specimens from the Songo granodiorite present some problem inasmuch as they are Al-undersaturated rocks (*e.g.*, hornblende present and no muscovite), yet the K-feldspar present is more disordered than that in the adamellite and many Group II and III specimens (but not Group I specimens). In this respect they fit into the pattern described by Parsons and Boyd (1971) who note that K-feldspar tends to be more disordered in early members than in later members of an intrusive sequence. The model of Parsons and Boyd, like that employed in this study, relates alkali feldspar

structural states to compositional factors in the environment (e.g., alumina vs alkali content). However, their model suggests that these factors operate during the early crystallization of the feldspars and influence the susceptibility of initially monoclinic forms to order during later cooling. This differs from the view preferred in this study in that composition factors in the environment *during cooling* are presumed to influence the approach to ordering.

### Conclusions

(1) The K-feldspar-bearing rocks considered in this study are readily divisible into distinct petrographic groups (I-VIII). The observed structure states and compositions of the K-feldspars are closely tied to the petrographic groupings.

(2) Excluding the retrograded and resorbed rocks, the data suggest some approach to chemical equilibrium.

(3) A model appealing to Al/(K + Na) ratio in the pore fluid as the control on rates of ordering during cooling seems most appropriate to explain the greater ordering and mixture of K-feldspar structural states in the biotite granulites and calc-silicates than in Group I rocks. The observational data suggest that the initial K-feldspar in all of these rocks was near orthoclase.

(4) The absence of any relation of Group I structural states to metamorphic grade probably results from partial readjustment (i.e., ordering) of the structural state during cooling. However, high Al/(K + Na) in the pore fluid of these rocks may have prevented the significant ordering attained during cooling of the K-feldspars in the biotite granulites and calc-silicates.

(5) The results of this paper would tend to suggest that much microcline now observed in granitic rocks originally crystallized as orthoclase but inverted because of a low Al/(K + Na) ratio in the environment. Moreover, for *regional metamorphic rocks*, the data of this paper suggest that, with the possible exception of Al-silicate bearing rocks, the K-feldspar structure states (but not composition) will usually reflect cooling history rather than the conditions of formation. It should be noted, however, that some Al-silicate bearing rocks have microcline (e.g., Barker, 1962). Conceivably, low  $\text{PH}_2\text{O}$  in such environments may permit compatibility of Al-silicate + K-feldspar at temperatures sufficiently low to stabilize microcline. However, the possibility

of polymetamorphism producing the microcline must also be considered.

### Acknowledgments

Particular thanks is extended to Dr. D. B. Stewart, who initially suggested this study (to C. V. G.) and provided advice and suggestions on many aspects of the problem as work proceeded. Dr. J. Fink Warner helped by providing rock samples from the Buckfield quadrangle. E. D. Glover provided valuable aid with the electron probe analyses. Support for this work by NSF Grants GA-1496 and GA-13415 is greatly appreciated. An early draft of the manuscript was criticized by Drs. S. W. Bailey, L. G. Medaris, and D. B. Stewart, and by Mr. J. T. Cheney; a final draft was read by Dr. T. L. Wright. Their comments and suggestions have proven very useful. However, any inadequacies or errors are the responsibility of the senior author.

### References

- BARKER, F. (1962) Cordierite-garnet gneiss and associated microcline-rich pegmatite at Sturbridge, Massachusetts, and Union, Connecticut. *Amer. Mineral.* **47**, 907-918.
- BLACKBURN, W. H. (1968) The spatial extent of chemical equilibrium in some highgrade metamorphic rocks from the Grenville of southeastern Ontario. *Contrib. Mineral. Petrology*, **19**, 72-92.
- CROSBY, P. (1971) Composition and structure state of alkali feldspars from charnockitic rocks on Whiteface Mountain, New York. *Amer. Mineral.* **56**, 1788-1811.
- EMMONS, R. C. (1953) Selected petrogenic relationships of plagioclase. *Geol. Soc. Amer. Mem.* **52**, 142 pp.
- EVANS, B. W. (1965) Application of a reaction-rate method to the breakdown equilibria of muscovite and muscovite plus quartz. *Amer. J. Sci.* **263**, 647-667.
- , AND C. V. GUIDOTTI (1966) The sillimanite-potash feldspar isograd in western Maine, U.S.A. *Beitr. Mineral. Petrogr.* **12**, 25-62.
- EVANS, H. T. JR., D. E. APPLEMAN, AND D. S. HANDWERKER (1963) The least squares refinement of crystal unit cells with powder diffraction data by an automatic computer indexing method. (abstr.) *Annu. Meet. Amer. Crystallogr. Soc., Cambridge, Mass. Program*, pp. 42-43.
- FISHER, I. S. (1962) Petrology and structure of the Bethel area, Maine. *Geol. Soc. Amer. Bull.* **73**, 1395-1420.
- GUIDOTTI, C. V. (1965) Geology of the Bryant Pond Quadrangle, Maine. *Maine Dept. Econ. Develop. Quad., Map Ser. No. 3*, 116 pp.
- (1966) Variations of the basal spacings of muscovite in sillimanite-bearing pelitic schists of northwestern Maine. *Amer. Mineral.* **51**, 1778-1786.
- HEIER, K. S. (1961) The amphibolite-granulite facies transition reflected in the mineralogy of potassium feldspars. *Instituto Lucas Mallada (Madrid), Curs. Y. Conf.* **8**, 131-137.
- HIPPLE, D. L. (1971) Study of the structure state and composition of feldspars of the Bedford Augen Gneiss, New York. *Geo. Soc. Amer. Bull.* **82**, 3212-3220.

- MARTIN, R. F. (1967) The synthesis of low albite. (abstr.) *Amer. Geophys. Union Trans.* **48**, 225-226.
- PARSONS, I., AND R. BOYD (1971) Distribution of potassium feldspar polymorphs in intrusive sequences. *Mineral. Mag.* **38**, 295-311.
- RAGLAND, P. C. (1970) Composition and structural state of the potassic phase in perthites as related to petrogenesis of a granite pluton. *Lithos*, **3**, 167-189.
- STEIGER, R. H., AND S. E. HART (1967) The microcline-orthoclase transition within a contact aureole. *Amer. Mineral.* **52**, 87-116.
- STEWART, D. B., AND P. H. RIBBE (1969) Structural explanation for variations in all parameters of alkali feldspars with Al/Si ordering. *Amer. J. Sci.* **267-A**, 444-462.
- THOMPSON, J. B., JR. (1957) The graphical analysis of mineral assemblages in pelitic schists. *Amer. Mineral.* **42**, 842-858.
- (1961) Mineral facies in pelitic schists. In, G. A. Sokolov, Ed., *Physico-chemical problems of formation of rocks and ores*. Akad. Nauk. SSSR (in Russian, English summary).
- TILLING, R. I. (1968) Zonal distribution of variations in structural state of alkali feldspar within the Rader Creek Pluton, Boulder Batholith, Montana. *J. Petrology*, **9**, 331-57.
- WARNER, J. F. L. (1967) *Geology of the Bugfield quadrangle, Maine*. Ph.D. thesis, Harvard University.
- WOODARD, H. H. (1972) Syngenetic sanadine beds from middle Ordovician Saint Peter Sandstone, Wisconsin. *J. Geol.* **80**, 323-332.
- WRIGHT, T. L. (1967) The microcline-orthoclase transformation in the contact aureole of the Eldora stock. *Amer. Mineral.* **52**, 117-136.
- (1968) X-ray and optical study of alkali feldspar: II. An X-ray method of determining the composition and structure state from measurement of 2 $\theta$  values for three reflections. *Amer. Mineral.* **53**, 88-104.
- , AND D. B. STEWART (1968) X-ray and optical study of alkali feldspar: I. Determination of composition and structural state from refined unit-cell parameters. *Amer. Mineral.* **53**, 38-87.

*Manuscript received, June 8, 1972;  
accepted for publication, February 26, 1973.*