

## Composition and structural state of alkali feldspars from high-grade metamorphic rocks, central Australia

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### Abstract

A wide range of structural states is displayed by alkali feldspars in Precambrian high-grade metamorphic rocks from central Australia. Orthoclase is present in granulite facies and transitional granulite to amphibolite facies rocks, and microcline occurs in amphibolite facies gneisses. The inversion of monoclinic to triclinic symmetry occurred during amphibolite facies metamorphic conditions. The minimum exsolution temperature in the alkali feldspars from the transitional and granulite facies is approximately 560°C.

### Introduction

Estimates of maximum *P-T* conditions attained during metamorphism can be made relatively easily by comparing observed equilibrium relationships in certain critical mineral assemblages with experimentally derived phase relationships (obtained where physical conditions have been closely controlled). However, the determination of the temperatures at which minerals reequilibrate, following cooling, is more difficult to make. Studies of the composition, phase relationships, and structural states of alkali feldspars have been shown by Wright (1967) and Crosby (1971) to give feasible estimates of these temperatures.

The purpose of this study is to investigate the composition and structural state of alkali feldspars in three discrete groups of high-grade metamorphic rocks from the Musgrave Orogenic Belt of central Australia. These rocks differ significantly in grade of metamorphism, from granulite facies to amphibolite facies (Collerson *et al.*, 1972). It was anticipated that estimates of the temperatures at which the alkali feldspars in the three groups of rocks equilibrated could be made as a result of this study.

### Geological setting

This study was undertaken in the Amata area of the Musgrave Ranges (Fig. 1), where Precambrian

basement lithologies may be divided into three structural and metamorphic units. The ranges consists of a central core of granulite facies lithologies, bounded on the north by amphibolite facies lithologies and on the south by lithologies transitional between granulite and amphibolite facies. Extensive east-west trending faults of regional significance separate the granulite facies terrane from the "lower grade" terranes. A detailed account of the structural and metamorphic relationships in this area is given by Collerson *et al.* (1972) and Collerson (1972).

### Petrography

Alkali feldspar occurs predominantly in the quartzofeldspathic lithologies in the Amata area, and in the rocks investigated in this study it ranges in modal abundance from 10.4 percent to 72.4 percent (Table 1).

The quartzofeldspathic granulites consist of varying assemblages of the following primary phases: quartz, alkali feldspar, plagioclase, orthopyroxene, clinopyroxene, garnet, opaque oxides, and accessories. Secondary biotite, garnet, cummingtonite, and clinopyroxene occur as coronal growths on opaque oxides or ferromagnesian phases. Microstructures are either porphyroblastic inequigranular, or equigranular, with grain aggregates ranging from granoblastic to platy granoblastic. Alkali feldspar occurs as irregular xenoblastic grains with straight, curved, sutured, or embayed interfaces. Grains range in size from  $0.1 \times 0.05$  mm to  $4.5 \times 1.0$  mm. They invariably contain albite lamellae that form either

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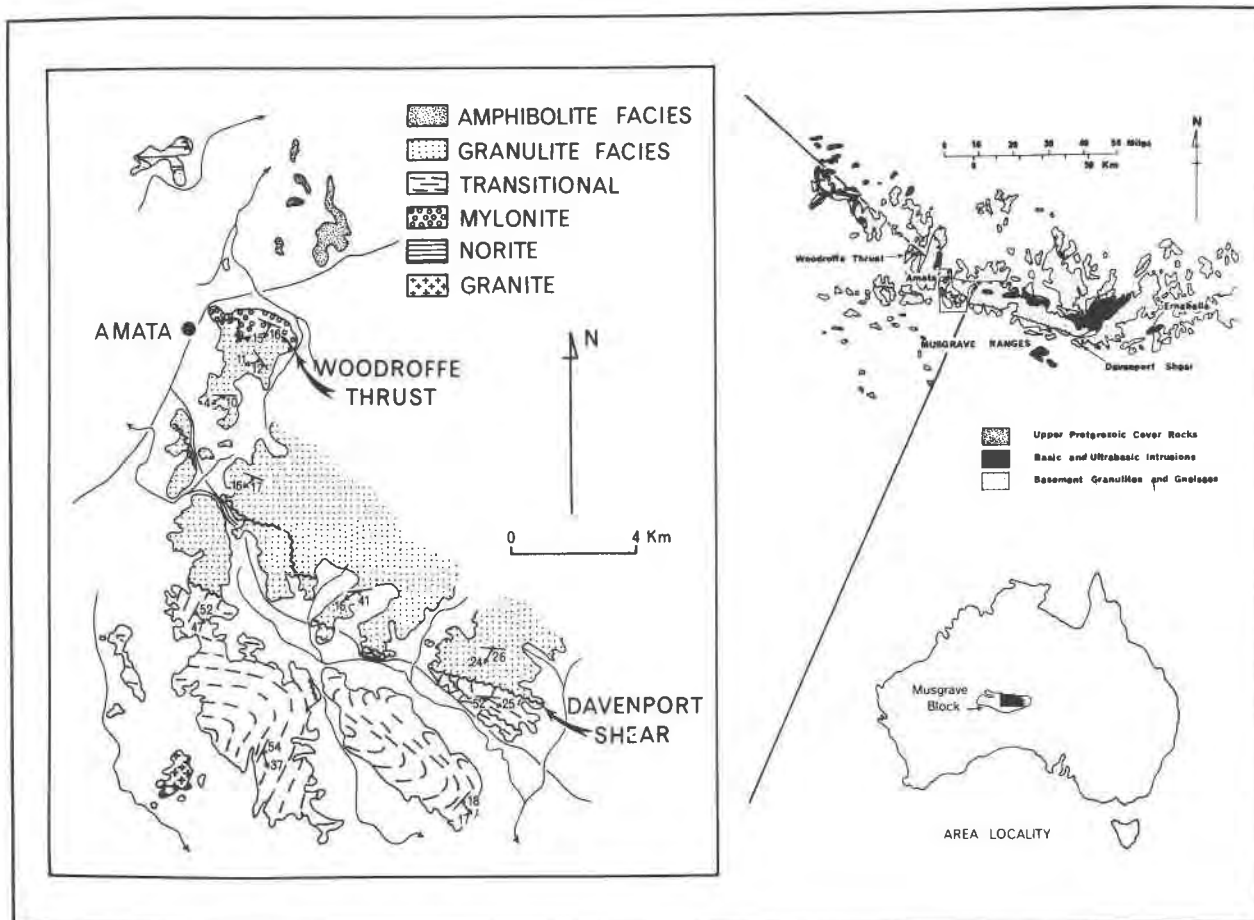


FIG. 1. Simplified geological map of the Musgrave Ranges showing geological relationships in the Amata area.

delicate micropertthitic intergrowths in some grains or ribbon-like mesoperthitic intergrowths in others (Fig. 2). Grains are rarely twinned.

ditional terrain consist of the following primary minerals: quartz, alkali feldspar, plagioclase, orthopyroxene, clinopyroxene, hornblende, biotite, garnet, sillimanite, opaque oxides, and accessories.

The quartzo-feldspathic gneisses from the tran-

TABLE 1. Modal analyses of quartzo-feldspathic granulites and gneisses from the Musgrave Ranges

Reference No.	1	2	3	4	5	6	7	8	9	10	11	12	13
Specimen No. A325/-	138	1165a	77	1121	783	323	396	400	531	474	18	1659	1744
Quartz	29.81	24.72	31.72	28.87	33.68	21.58	18.63	25.66	19.32	26.63	27.29	28.50	22.58
Alkali Feldspar	39.63#	10.36#	43.80	18.48*	63.45*	31.98*	72.44*	56.60*	23.64	54.53*	40.03*	34.16*	44.39*
Plagioclase	24.54 <sup>x</sup>	61.43 <sup>x</sup>	12.49 <sup>x</sup>	42.57	-	19.52	-	8.63	39.97	14.54	27.75	31.66	25.27
Clinopyroxene	-	-	-	-	0.45	-	1.50	0.22	-	-	-	-	-
Orthopyroxene	3.30	2.17	-	0.78	0.69	-	-	-	-	-	-	-	-
Biotite	-	tr	-	-	-	7.90	0.98	1.02	0.58	3.43	3.24	3.85	3.43
Hornblende	-	-	-	-	-	2.31	2.91	5.00	-	-	-	-	-
Z <sup>o</sup> Amphibole	0.48	0.25	-	0.98	-	-	-	-	-*	0.18	-	-	-
Opaque Oxides	2.21	1.07	1.27	2.24	1.46	5.74	1.56	1.51	2.70	0.44	1.46	1.43	0.95
Garnet	-	-	10.63	5.90	0.16 <sup>+</sup>	10.64 <sup>+</sup>	0.93 <sup>+</sup>	0.09 <sup>+</sup>	13.71 <sup>+</sup>	0.18 <sup>+</sup>	0.05 <sup>+</sup>	0.15 <sup>+</sup>	3.01
Others	0.03	tr	0.08	0.18	0.11	0.34	1.03	1.28	0.09	0.08	0.09	0.25	0.35

\* = Micropertthite  
<sup>x</sup> = Includes antiperthite  
<sup>+</sup> = Secondary garnet  
# = Mesoperthite

1 to 4 Quartzo-feldspathic granulites  
5 to 11 Quartzo-feldspathic gneisses from the transitional terrain  
12 to 13 Quartzo-feldspathic gneiss from the amphibolite facies terrain

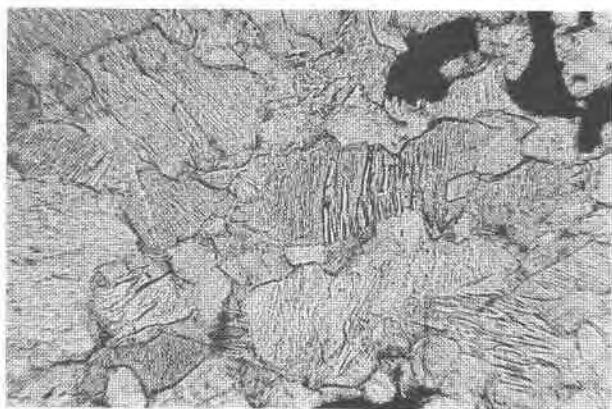


FIG. 2. Ribbon-type exsolution in mesoperthite from quartzofeldspathic granulite. Plane polarized light. Width of field 0.9 mm.

Secondary (coronal) phases include garnet, biotite, clinopyroxene, quartz, alkali feldspar, and hornblende. The gneisses are either homogeneous or banded, and grain sizes range from fine to coarse. Microstructural arrays are dominated by xenoblastic and, to a lesser extent, lepidoblastic and nematoblastic grains, which generally form granoblastic to granoblastic-elongate aggregates. Grain boundaries are generally curved or sutured. Alkali feldspar occurs as sub-idioblastic to xenoblastic grains with irregularly sutured or gently curved grain boundaries. Grain sizes range from less than  $0.5 \times 0.3$  mm to greater than  $4.0 \times 4.0$  mm. Most grains are untwinned; however, some show Carlsbad twinning or shadowy cross-hatched twinning. Micro- and mesoperthitic segregation of albite is commonly well developed. Some of the larger xenoblasts are poikiloblastic with round inclusions of quartz and plagioclase.

Minerals observed in thin sections of quartzofeldspathic gneiss from the amphibolite facies terrane include: quartz, alkali feldspar, plagioclase, biotite, muscovite, hornblende, garnet, opaque oxides, and accessories. Microstructures are dominated by the presence of xenoblastic grains which form granoblastic arrays and by compositional banding and anastomosing layering. Perthitic alkali feldspar occurs as large tabular to lozenge-shaped xenoblasts and sub-idioblastic porphyroblasts up to  $3.0 \times 1.5$  cm in size. Shadowy to distinct cross-hatched twinning and Carlsbad twinning are commonly developed.

#### Analytical methods

Except for FeO and Na<sub>2</sub>O, which were determined by classical and flame photometric methods respec-

tively, all other major and trace elements were measured by X-ray fluorescence methods. Mass-absorption coefficients were calculated from the major element data (Norrish and Chappell, 1967).

#### Host rock chemistry

Chemical analyses and c.i.p.w. norms (Table 2) of the host rocks from which the alkali feldspars of this study were separated show that potash is greater than soda in all but one of the rocks. This is reflected in a higher content of modal plagioclase and normative albite in this sample than in other samples studied. No strong correlation could be found between host rock chemistry and the structural state of the alkali feldspars.

#### Separation of alkali feldspars

Alkali feldspar separations for both chemical and X-ray determinations were carried out using standard techniques on finely crushed (<120>180 mesh fraction), dust-free samples. Highly magnetic minerals were removed by hand magnet, and samples were then passed through a Frantz Isodynamic Separator to obtain relatively pure concentrates of alkali feldspar, plagioclase, and quartz. Alkali feldspar was then separated from the plagioclase and quartz by gravity settling using tetrabromoethane adjusted to the correct density with acetone. Separates of alkali feldspar were washed in acetone and dried. Samples were then hand picked to obtain a separate of greater than 99 percent purity for analysis.

#### Composition of the alkali feldspars

The analyses and structural formulae (based on  $O=32$  atoms) presented in Table 3 show that the feldspars are relatively low in lime, with two exceptions. The lime enrichment shown by numbers 1 and 2 (1.89 and 2.12% respectively) is compensated by a concomitant depletion in potash in these specimens. The slightly anomalous composition of these two feldspars from the granulite facies terrane is interpreted to be due to their mesoperthitic character; the other feldspars are micropertthitic or perthitic.

The feldspars range in composition from 51.2 to 81.2 percent orthoclase, 14.1 to 41.0 percent albite, 1.3 to 11.6 percent anorthite, and 0.3 to 1.2 percent celsian. Small quantities of rubidium and strontium feldspar components are also present. A standard ternary plot of the molecular end member compo-

TABLE 2. Chemical analyses and CIPW norms of quartzo-feldspathic granulites and gneisses from the Musgrave Ranges

Reference No.	1	2	3	4	5	6	7	8	9	10	11	12	13
Specimen No. A325/-	138	1165a	77	1121	783	323	396	400	531	474	18	1659	1744
SiO <sub>2</sub>	71.82	70.02	71.78	69.10	74.44	62.68	68.75	69.73	63.50	71.44	71.85	71.81	67.40
Al <sub>2</sub> O <sub>3</sub>	13.51	16.37	14.72	15.25	12.90	14.68	14.46	13.70	17.57	14.74	14.75	14.22	15.80
Fe <sub>2</sub> O <sub>3</sub>	1.28	0.64	0.99	1.53	1.15	3.35	1.43	1.62	1.59	0.83	0.99	1.07	1.00
FeO	1.45	0.92	2.75	2.68	1.17	3.85	1.43	2.31	3.87	1.24	1.05	1.38	1.93
MgO	0.71	0.57	0.90	1.19	0.15	1.45	0.70	1.26	2.27	0.32	0.30	0.51	1.00
CaO	1.98	3.30	1.37	2.65	0.90	3.39	1.82	2.60	2.65	1.27	1.62	2.54	2.00
Na <sub>2</sub> O	3.58	4.90	3.03	2.93	3.02	3.20	4.21	3.42	3.16	2.93	3.83	3.14	2.60
K <sub>2</sub> O	3.92	1.94	3.99	3.33	5.74	4.63	5.57	4.58	3.59	6.78	5.01	4.45	6.80
TiO <sub>2</sub>	0.48	0.21	0.50	0.54	0.38	1.22	0.47	0.55	0.77	0.35	0.29	0.50	0.70
P <sub>2</sub> O <sub>5</sub>	0.02	0.04	0.04	0.07	0.04	0.55	0.16	0.11	0.04	0.10	0.09	0.09	0.20
MnO	0.11	0.06	0.14	0.15	0.07	0.16	0.10	0.10	0.15	0.05	0.07	0.09	0.10
L.O.I.	0.30	0.55	0.10	0.28	0.09	0.54	0.64	0.47	0.40	0.27	n.m.	0.38	0.49
Total	99.66	99.52	100.31	99.70	100.05	99.70	99.74	100.45	99.56	100.32	99.86	100.18	100.08
<u>Trace Elements in ppm</u>													
Sr	196.0	615.3	215.6	327.3	65.6	243.6	284.0	128.4	339.1	216.1	157.9	189.8	250.7
Rb	84.9	24.3	83.6	76.2	217.0	166.5	154.2	188.0	121.0	217.0	275.0	159.0	298.2
<u>C.I.P.W. Norms</u>													
q	29.97	25.86	33.05	30.67	32.77	17.55	18.90	24.97	20.24	25.03	26.38	30.21	20.26
c	-	0.31	3.02	2.18	0.18	-	-	-	3.76	0.51	0.30	-	1.01
or	23.17	11.47	23.58	19.68	33.92	27.36	32.92	27.07	21.22	40.07	29.61	26.30	40.19
ab	30.29	41.46	25.64	24.79	25.55	27.08	35.62	28.94	26.74	24.79	32.41	26.57	22.00
an	9.22	16.11	6.54	12.69	4.20	12.02	4.11	8.50	12.89	5.65	7.45	11.56	8.61
di	0.39	-	-	-	-	0.98	3.14	3.00	-	-	-	0.37	-
hy	3.50	2.35	5.91	6.01	0.07	5.71	1.08	3.85	10.45	1.91	1.53	2.08	4.19
il	0.91	0.40	0.95	1.03	0.72	2.32	0.89	1.04	1.46	0.66	0.55	0.95	1.33
ap	0.05	0.09	0.95	0.16	0.09	1.28	0.37	0.26	0.09	0.23	0.21	0.21	0.46
mt	1.86	0.93	1.44	0.22	1.67	4.86	2.07	2.35	2.31	1.20	1.44	1.55	1.54

Analyst: K.D. Collinson

nents of the feldspars (Fig. 3) shows that the two anomalous feldspars have higher contents of anorthite than the other feldspars.

### Determination of structural state

The separated feldspars were finely ground and mixed with a small amount of silicon as an internal standard. Smear mounts were prepared and irradiated with filtered  $\text{CuK}\alpha$  radiation.<sup>2</sup>

The feldspar reflections were indexed following the method of Wright and Stewart (1968).  $2\theta$  values were calculated for the indexed peaks by a Diehl Combitron S Calculator program that corrected for

<sup>2</sup> Operating conditions of the Philips X-ray diffractometer were as follows:

Radiation	: $\text{CuK}\alpha$
Generator	: 40 kV/24 mA
Slit Width	: $1^\circ-1^\circ$
Counting rate	: 300 c.p.s.
Mean Probable Error	: 5%
Goniometer	: $1/2^\circ/\text{min}$ .

chart drive variation. Cell dimensions were refined from the corrected diffractometer powder data by use of a FORTRAN IV program adapted from a program written by Appleman and Evans (1973). The direct cell parameter data of the alkali feldspars are listed in Table 4.

Petrological observations concerning the crystal symmetry and degree of homogeneity of the feldspars were verified by the diffractometer data. For example, an estimate of the degree of order was obtained from the nature of the  $(131)-(1\bar{3}1)$  doublet, following the method of Goldsmith and Laves (1954). Likewise, the presence of a peak at  $27.94^\circ 2\theta$  (the (002) albite peak) indicated that many of the potassium feldspars contained albite and were thus not compositionally homogeneous.

In the majority of the charts the  $(131)$  and  $(1\bar{3}1)$  positions could not be revealed clearly. It was therefore not possible to use the relationship  $12.5[d(131)-d(1\bar{3}1)]$  of Goldsmith and Laves (1954) to accurately estimate the degree of ordering the feld-

TABLE 3. Chemical analyses of alkali feldspars from the Musgrave Ranges

Reference No.	1	2	3	4	5	6	7	8	9	10	11	12
Specimen No. A325/-	138*	1165a*	77	1121	783	323	396	400	531	474	18	1659
SiO <sub>2</sub>	65.87	65.05	65.78	64.24	64.04	64.32	64.20	64.72	63.76	63.79	66.76	64.65
Al <sub>2</sub> O <sub>3</sub>	19.15	19.00	19.33	18.50	19.12	18.69	19.41	19.03	19.13	18.87	18.71	18.59
Fe <sub>2</sub> O <sub>3</sub>	0.17	0.25	0.13	0.12	0.14	0.16	0.14	0.13	0.10	0.11	0.25	0.10
MgO	n.d.	0.09	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.02	0.10
CaO	1.89	2.12	0.41	0.60	0.99	0.49	0.78	0.42	0.54	0.26	1.10	0.48
Na <sub>2</sub> O	3.94	3.71	2.07	1.44	3.70	2.73	4.71	3.85	2.17	2.23	4.61	2.23
K <sub>2</sub> O	8.11	7.94	12.44	12.57	9.70	11.30	9.48	11.66	12.66	12.72	9.07	13.02
TiO <sub>2</sub>	0.07	0.07	0.08	0.07	0.07	0.08	0.06	0.07	0.09	0.06	0.06	0.05
MnO	0.04	0.03	0.02	0.03	0.03	0.03	0.04	0.04	0.02	0.03	0.03	0.03
P <sub>2</sub> O <sub>3</sub>	n.d.	0.05	0.01	0.08	0.03	0.02	0.01	n.d.	0.10	n.d.	n.d.	0.05
Rb <sub>2</sub> O	0.02	n.m.	n.m.	0.03	0.03	0.03	0.03	0.04	0.03	0.04	0.04	0.03
SrO	0.04	n.m.	n.m.	0.07	0.01	0.05	0.05	0.02	0.06	0.04	0.02	0.02
BaO	0.45	n.m.	n.m.	0.52	0.23	0.59	0.30	0.17	0.64	0.38	0.22	0.45
L.O.I.	0.57	0.29	0.05	0.82	0.61	0.79	n.d.	n.d.	n.d.	0.64	0.10	0.57
Total	100.32	98.60	100.28	99.09	98.70	99.28	99.21	100.15	99.30	99.17	100.90	100.37
Rb ppm	189	n.m.	n.m.	275	335	316	272	399	307	376	438	344
Sr ppm	339	n.m.	n.m.	618	109	389	411	175	543	299	206	226
Ba ppm	3991	n.m.	n.m.	4739	2078	5256	2670	1536	5729	3413	1995	4033
STRUCTURAL FORMULAE (BASED ON 32 OXYGEN ATOMS)												
Si	11.898	11.883	11.935	11.968	11.838	11.921	11.766	11.829	11.817	11.873	11.959	11.910
Al <sup>IV</sup>	4.077	4.091	4.132	4.062	4.166	4.083	4.193	4.100	4.179	4.140	3.956	4.037
Fe <sup>3+</sup>	0.023	0.034	0.016	0.017	0.019	0.022	0.019	0.018	0.014	0.015	0.034	0.014
Mn	0.006	0.005	0.003	0.005	0.005	0.005	0.006	0.006	0.003	0.005	0.005	0.005
Mg	-	0.025	-	-	-	-	-	-	-	-	0.005	0.027
Ca	0.366	0.415	0.080	0.120	0.196	0.097	0.153	0.082	0.107	0.052	0.211	0.095
Na	1.380	1.314	0.728	0.520	1.326	0.981	1.674	1.364	0.780	0.805	1.603	0.797
K	1.869	1.850	2.879	2.988	2.288	2.672	2.217	2.719	2.993	3.021	2.076	3.060
Ti	0.010	0.010	0.011	0.010	0.010	0.011	0.008	0.010	0.013	0.008	0.008	0.007
Ba	0.032	-	-	0.038	0.017	0.043	0.022	0.012	0.046	0.028	0.015	0.032
Sr	0.004	-	-	0.008	0.001	0.005	0.005	0.002	0.006	0.004	0.002	0.002
Rb	0.002	-	-	0.004	0.004	0.004	0.004	0.005	0.004	0.005	0.005	0.004
Z	15.976	15.974	16.067	16.030	16.004	16.004	15.959	15.929	15.996	16.013	15.915	15.946
X	3.692	3.653	3.717	3.708	3.865	3.840	4.108	4.218	3.967	3.943	3.964	4.042
Mol % Feldspar End Members												
Or	51.2	51.7	78.1	81.2	59.7	70.3	54.4	64.9	76.0	77.2	53.1	76.7
Ab	37.8	36.7	19.7	14.1	34.6	25.8	41.1	32.6	19.8	20.6	41.0	19.9
An	10.0	11.6	2.2	3.3	5.1	2.6	3.8	2.0	2.7	1.3	5.4	2.4
Ba Feld.	0.9	-	-	1.0	0.4	1.1	0.5	0.3	1.2	0.7	0.4	0.8
Sr Feld.	0.1	-	-	0.2	0.0	0.1	0.1	0.0	0.2	0.1	0.0	0.0
Rb Feld.	0.0	-	-	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

n.d. = Not detected

n.m. = Not measured

\* = Mesoperthite

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spars. The structural state of the feldspars was, however, estimated from two relationships: (1) the  $c^*/b^*$  method of Jones (1966); and (2) the function  $\Delta(bc) = t_1O + t_1M$ , of Stewart and Ribbe (1969) and Stewart and Wright (1974).

The values of  $c^*/b^*$  were calculated from the cell

refinement data (Table 4) and not from the ratio of  $2d_{040}/d_{002}$  as was suggested initially by Jones (1966). The  $c^*/b^*$  ratios were plotted on Figure 4 to determine the degree of ordering. The values obtained are listed in Table 5. The most ordered phases are those from the amphibolite facies gneisses, and the least

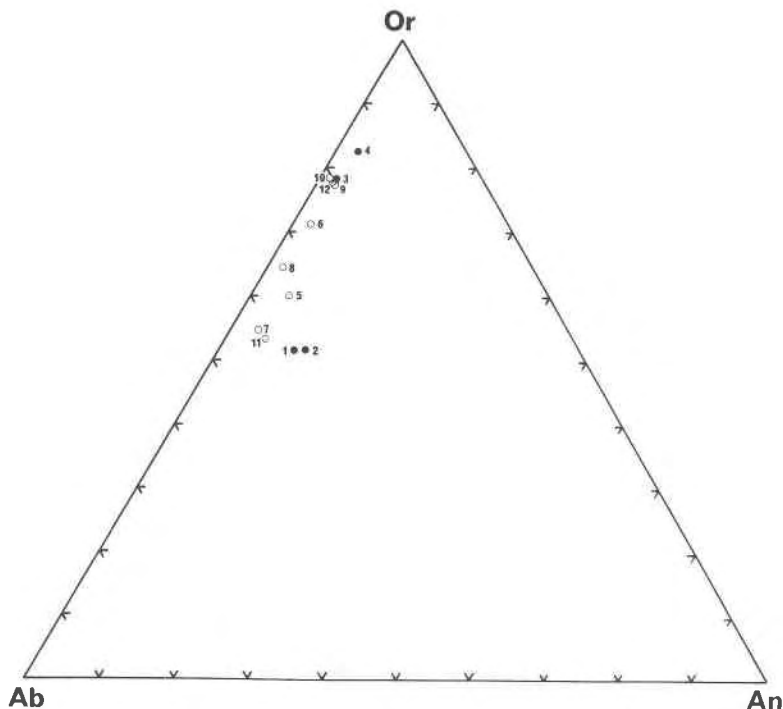


FIG. 3. Ternary plot of Or-Ab-An showing the compositions of the Amata alkali feldspars. Closed circles refer to feldspars from the granulite facies terrane. Open circles refer to feldspars from the transitional terrane. Open circles with spots refer to feldspars from the amphibolite facies terrane.

ordered are from the transitional and granulite facies rocks. The  $c$ - $b$  cell parameters (Table 4) were plotted in Figure 5 (from Stewart and Wright, 1974)<sup>3</sup> and the structural states of the alkali feldspars deduced. The structural states of the feldspars represented by means of the  $b$ - $c$  plot and the  $\Delta(bc)$  (or  $t_1O + t_1M$ ) value (Stewart and Ribbe, 1969) compare favourably with the variation in order-disorder obtained by means of the  $c^*/b^*$  method (*cf.* Lehtinen, 1974).

The presence of mixtures of alkali feldspars with different degrees of ordering within individual grains is suggested by the partial development of cross-hatched twinning, the broadening and partial splitting of the (131) peak, and the necessity to reject a number of peaks from the cell refinement calculation. Therefore reported degrees of order are to be considered approximations of an average value.

In the refinement of the power diffraction data, both monoclinic and triclinic solutions were attempted for alkali feldspars with intermediate structural states. The monoclinic cell invariably gave lower unit weight standard errors for  $2\theta$  values than

did the triclinic solution (*cf.* Crosby, 1971). This is not surprising as the transition between ordered and disordered structural states has been shown to overlap (Stewart and Ribbe, 1969), and therefore no unique position on plots of cell angles, corresponding to the symmetry change, can be delineated.

#### Composition of alkali feldspars from direct cell data

The alkali feldspar compositions, deduced from the direct cell data using the determinative graphs of Wright and Stewart (1968), are presented in Table 6. There is a close correspondence between the compositions of the potassic phases determined from  $a$  and those determined from cell volume. However, with the exception of Number 10, there is a general discrepancy with the composition of the alkali feldspars determined by analysis. This is probably because the analysed feldspars are heterogeneous fine-grained intergrowths of two phases. The values of percent Or obtained from the direct cell data probably approximate the compositions of the potassic phases (*cf.* Smith, 1961; Wright and Stewart, 1968; Crosby, 1971) despite indications of anomalous unit cells resulting from strain (see below).

<sup>3</sup> This figure is a modification based on new cell dimensions for high sanidine and low albite of their earlier  $c$ - $b$  plot (Wright and Stewart, 1968).

TABLE 4. Direct cell parameters of potassium feldspars

Reference Number	Specimen No. A325/-	$\overset{\circ}{a}$ (Å)	$\overset{\circ}{b}$ (Å)	$\overset{\circ}{c}$ (Å)	Interaxial Angle	Cell volume (Å <sup>3</sup> )	S.E.	Ref.
2	1165a	8.5772 ± 0.0043	12.9894 ± 0.0045	7.1916 ± 0.0020	$\beta$ 115° 58.79' ± 02.10'	720.26 ± 0.40	0.018	21/25
3	77	8.5843 ± 0.0044	12.9621 ± 0.0035	7.2074 ± 0.0015	$\beta$ 115° 59.26' ± 01.87'	720.88 ± 0.39	0.014	18/20
4	1121	8.5663 ± 0.0036	12.9878 ± 0.0034	7.1920 ± 0.0016	$\beta$ 115° 59.98' ± 01.84'	719.18 ± 0.32	0.016	24/29
5	783	8.5902 ± 0.0035	12.9838 ± 0.0036	7.1940 ± 0.0016	$\beta$ 116° 02.44' ± 01.73'	720.92 ± 0.32	0.015	24/29
6	323	8.5815 ± 0.0044	12.9873 ± 0.0035	7.1991 ± 0.0018	$\beta$ 115° 59.94' ± 01.87'	721.14 ± 0.37	0.013	19/25
8	400	8.5821 ± 0.0048	12.9649 ± 0.0044	7.2070 ± 0.0020	$\beta$ 115° 59.44' ± 02.08'	720.80 ± 0.44	0.015	14/14
9	531	8.5906 ± 0.0028	12.9829 ± 0.0030	7.2059 ± 0.0021	$\beta$ 116° 01.86' ± 02.21'	722.16 ± 0.32	0.016	21/22
10	474 <sup>+</sup>	8.5297 ± 0.0042	12.9760 ± 0.0044	7.2021 ± 0.0019	$\beta$ 115° 57.58' ± 02.01'	716.71 ± 0.39	0.019	18/19
11	18*	8.5728 ± 0.0028	12.9648 ± 0.0032	7.2148 ± 0.0016	$\alpha$ 90° 26.39' ± 05.16' $\beta$ 116° 05.09' ± 02.37' $\gamma$ 88° 04.38' ± 05.03'	719.78 ± 0.49	0.016	19/24
12	1659*	8.5626 ± 0.0045	12.9617 ± 0.0037	7.2197 ± 0.0017	$\alpha$ 90° 38.02' ± 03.68' $\beta$ 115° 58.04' ± 01.81' $\gamma$ 87° 46.17' ± 03.31'	719.83 ± 0.36	0.015	18/26
12	1659* <sup>+</sup>	8.5360 ± 0.0058	12.9625 ± 0.0051	7.2103 ± 0.0022	$\alpha$ 90° 35.97' ± 04.21' $\beta$ 115° 53.90' ± 02.38' $\gamma$ 87° 54.79' ± 03.85'	717.19 ± 0.47	0.020	19/23
13	1744*	8.5671 ± 0.0025	12.9680 ± 0.0038	7.2258 ± 0.0018	$\alpha$ 90° 09.29' ± 06.09' $\beta$ 116° 06.10' ± 04.03' $\gamma$ 86° 44.52' ± 05.14'	719.51 ± 0.42	0.016	16/28

\* = Triclinic

+ = Homogenized

S.E. = Standard error of observation of unit weight

Ref. = Number of lines used in the refinement/ number of input diffraction lines

### Degree of strain in the alkali feldspars

Alkali feldspar structures are commonly strained; the observed  $a$  being significantly larger than the value of  $a$  estimated from the  $b$ - $c$  plot (Wright and Stewart, 1968; Willaime and Gandais, 1972; Brown *et*

*al.*, 1972; Tullis, 1975). An estimate of the amount of strain in any particular feldspar structure is given by the expression:

$$\Delta a = a \text{ (observed)} - a \text{ (estimated from } b\text{-}c \text{ plot).}$$

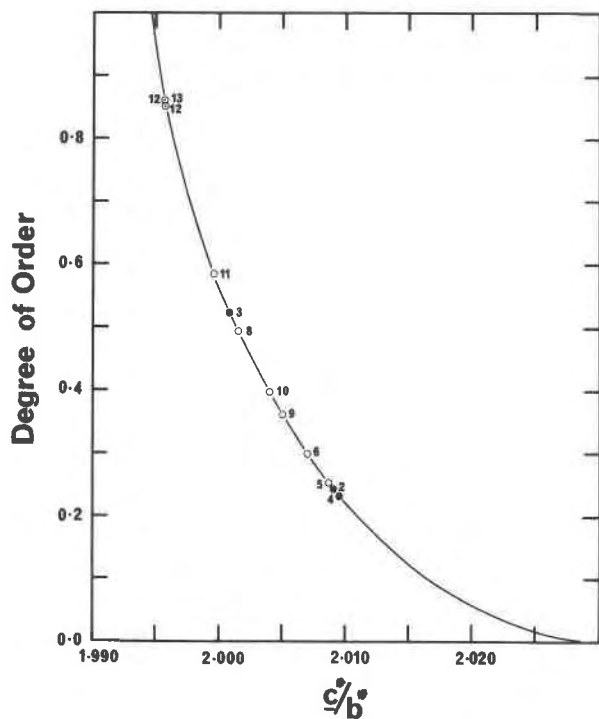


FIG. 4. Degree of order of the alkali feldspars shown by plotting on the degree of order vs.  $c^*/b^*$  graph of Jones (1966). Symbols as in Figure 3.

(Wright and Stewart, 1968; Brown and Willaime, 1974) where  $\Delta a$  is the index of strain and  $a$  is derived from the  $b$ - $c$  plot (Figure 5). Stewart and Wright (1974) consider strained feldspars to be those with  $\Delta a$  greater than 0.05Å.

Values of  $\Delta a$  calculated for the Amata alkali feldspars are given in Table 6. It can be seen that the alkali feldspars from the granulite facies rocks (Nos. 2, 3, 4) are strained. Those from the transitional granulite to amphibolite facies rocks are in part strained (Nos. 5, 8) and in part unstrained (Nos. 6, 9, 10), and those from amphibolite facies rocks are all unstrained (Nos. 11, 12).

The amount of strain in alkali feldspars is regarded as being nearly independent of the degree of Al/Si ordering (Stewart and Wright, 1974) and therefore of metamorphic grade. The variation in  $\Delta a$  in the Amata alkali feldspars is probably due to the sizes of the domains of the sodic and potassic phases (*cf.* Stewart and Wright, 1974). Micro- and mesoperthitic intergrowths are typical of the granulite facies and transitional granulite to amphibolite facies rocks, whereas more coarse-grained perthitic intergrowths are common in rocks from the amphibolite facies area.

## Discussion

The principal features which emerge from this study of the Amata alkali feldspars are:

- (1) highly ordered microcline perthites occur in the amphibolite facies gneisses, whereas the alkali feldspars from the higher-grade rocks are predominantly orthoclase microperthites and mesoperthites which are not fully ordered;

TABLE 5. Determination of triclinicity by  $c^*/b^*$  method

Reference Number	Specimen Number A325/-	$c^*$	$b^*$	$c^*/b^*$	Degree of Order
2	1165a	0.15468	0.07699	2.0091	0.242
3	77	0.15435	0.07715	2.0007	0.522
4	1121	0.15470	0.07699	2.0094	0.232
5	783	0.15471	0.07702	2.0087	0.254
6	323	0.15455	0.07700	2.0071	0.299
8	400	0.15437	0.07713	2.0014	0.493
9	531	0.15444	0.07703	2.0050	0.360
10	474 <sup>+</sup>	0.15443	0.07706	2.0040	0.395
11	18*	0.15433	0.07718	1.9996	0.583
12	1659*	0.15407	0.07721	1.9955	0.860
12	1659 <sup>+</sup> *	0.15417	0.07720	1.9970	0.850
13	1744*	0.15416	0.07726	1.9953	0.860

<sup>+</sup> Homogenized  
\* Triclinic



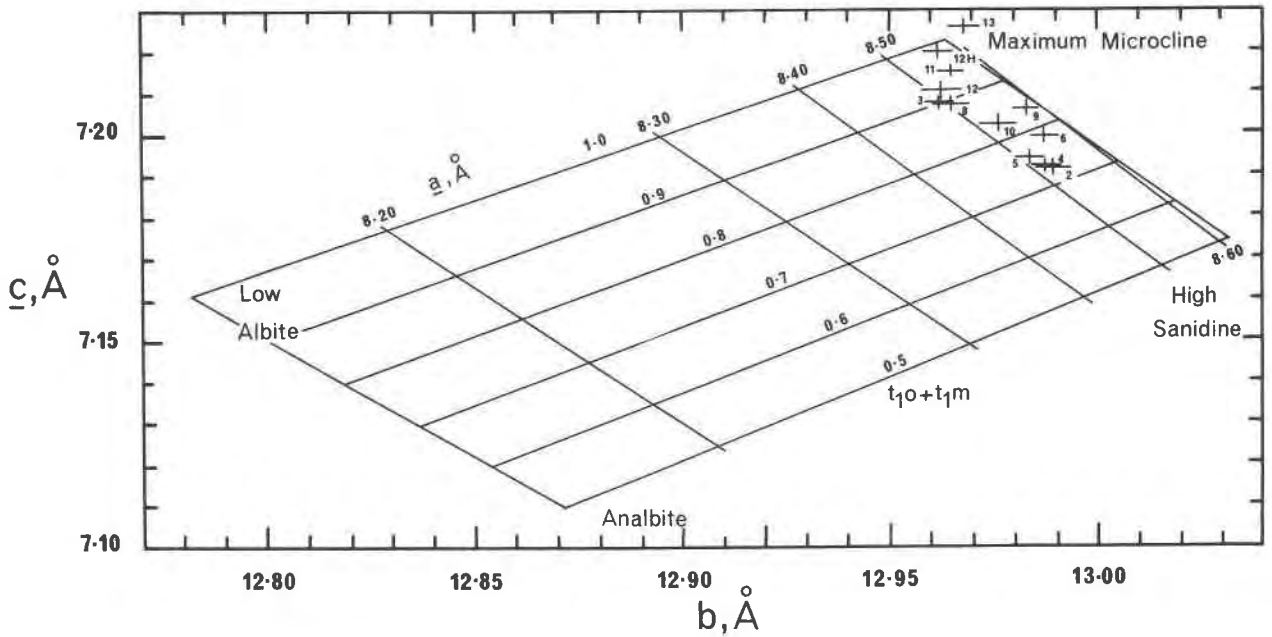


FIG. 5. Potassium feldspars from Table 4 on  $c$ - $b$  plot (after Stewart and Wright, 1974). The lengths of the bars represent the  $b$  and  $c$  standard errors for each sample. The letter  $H$  following the specimen number indicates the feldspar has been homogenized.

- (2) there is evidence to suggest a range of degrees of order in some of the feldspars; and
- (3) micro- and mesoperthitic feldspars from the granulite facies rocks are strained, perthitic feldspars from the amphibolite facies gneisses are unstrained, and feldspars from the transitional terrane display varying degrees of strain.

These features are typical of the alkali feldspars from high-grade metamorphic rocks (Eskola, 1952; Heier, 1957; 1961; Binns, 1964; Leelanandam, 1967; Ohta and Kizaki, 1966; Suwa, 1968; Crosby, 1971; Hipple, 1971; Guidotti *et al.*, 1973).

The structural state of alkali feldspars reflects the degree of ordering of aluminum in the tetrahedral sites of the structure (Stewart and Ribbe, 1969). Dis-

TABLE 6. Comparison of compositions and indices of strain of alkali feldspars

Reference Number	Specimen Number A325/-	% K from feldspar analysis	% Or Analysis	% Or from $\bar{a}$	% Or from Volume	$\Delta \bar{a}$ $\bar{a}$ $\bar{a}$
1	138	8.11	51.2	**	**	**
2	1165a	7.94	51.7	91.0	89.0	0.052
3	77	12.44	78.1	93.5	90.0	0.084
4	1121	12.57	81.3	89.0	86.0	0.048
5	783	9.70	59.7	95.0	90.0	0.076
6	323	11.30	70.3	91.5	90.0	0.020
7	396	9.48	54.4	**	**	**
8	400	11.66	65.0	92.0	90.0	0.075
9	531	12.66	76.0	95.0	91.0	0.010
10	474+	12.72	77.2	80.0	80.0	0.001
11	18*	9.07	53.0	90.0	89.0	0.023
12	1659*	13.02	76.7	89.0	88.0	0.002
12	1659**	**	**	83.0	81.0	0.018
13	1744*	**	**	88.5	89.0	**

ordered monoclinic alkali feldspar is believed to change into a more ordered triclinic form in response to a number of physical and chemical variables. There is little general agreement, however, concerning the mechanics of this process and the effects of specific variables (Laves and Goldsmith, 1961).

MacKenzie and Smith (1961) have argued that a solution of sodium and possibly calcium in alkali feldspars promotes Al/Si disorder, stabilizing the more disordered form at lower temperatures. However, this is disputed by Laves (1960). According to Heier (1961) the high temperatures which accompany metamorphism under granulite facies conditions favor the entry of greater amounts of sodium into the feldspar structure. This facilitates Al/Si disorder in the monoclinic orthoclase structure. Other factors which are considered to influence the degree of Al/Si order in alkali feldspars include:

- (1) temperature (Hafner and Laves, 1957);
- (2) the activity of water (Heier, 1961; Martin, 1969);
- (3) the role of  $P_{H_2O}$  (Tomisaka, 1962);
- (4) the activity of peralkaline fluids (Martin, 1969);
- (5) the effect of volatiles (Emeleus and Smith, 1959);
- (6) the influence of bulk composition and shearing stress (Parsons and Boyd, 1971); and
- (7) the cooling history of the feldspars (Guidotti *et al.*, 1973).

Goldsmith and Laves (1954) established an approximate temperature of 500°C for the inversion of triclinic feldspar to its monoclinic polymorph. However, they emphasized that this value was not to be construed as an equilibrium transition temperature as it was obtained by disordering microcline to sanidine. Heier (1957, 1961) considered that the transformation takes place at pressures and temperatures slightly below the upper boundary of the amphibolite facies. As a result of a recent study of heat flow data from the contact aureole of a Tertiary quartz monzonite stock, Steiger and Hart (1967) placed the temperature of the microcline to orthoclase transition at between 350 and 400°C. Wright (1967) independently concluded that  $375 \pm 50^\circ\text{C}$  was the upper stability limit of microcline in the same group of rocks. However, according to Waldbaum and Thompson (1968), if ordering of potassium feldspar structures is by a displacive rather than a diffusive mechanism, precise temperatures of the transformation cannot be deduced, as symmetry

changes are metastable if they are the result of displacement.

Guidotti *et al.* (1973), in a study of the composition and structural states of potassium feldspars from sillimanite-bearing gneisses, have shown that microcline is unstable above the sillimanite isograd. They favour Martin's (1969) contention that a close relationship exists between the Al/(K+Na) ratio of the fluid phase and the degree of ordering shown by the feldspars. Ordering is facilitated in alkali feldspars where the Al/(K+Na) ratio of the fluid phase in the rock is low, and it is inhibited where the Al/(K+Na) ratio is high. These factors are considered to influence the degree of ordering of the feldspar during cooling rather than during initial crystallization.

Results from Amata suggest that both thermal and compositional effects are important in governing the degree of order of the alkali feldspars. The most ordered phases (Figs. 4, 5; Nos. 11, 12, 13) from the amphibolite facies terrane are believed to have resulted from equilibrium ordering during cooling because the range of ordering is limited. Petrogenetic studies on the Amata amphibolite facies gneisses (Collerson, 1972) indicate that load and water pressures were approximately 4 kbars. It is probable that the inversion occurred at a higher temperature than the 350–440°C of Steiger and Hart (1967) and may have been well within the amphibolite facies range between 400 and 700°C (Turner, 1968). Based on the presence of muscovite and the absence of sillimanite in pelitic schists from the amphibolite facies terrane and using the experimental muscovite stability curve of Evans (1965), the maximum temperature attained at 4 kbars would have been 685°C. The temperature suggested for the orthoclase to microcline inversion in the amphibolite facies grade metamorphic rocks at Amata may be regarded as the minimum temperature attained during equilibration of alkali feldspar in the gneisses from the transitional terrane.

Alkali feldspars from the transitional terrane exhibit a wide range of structural states (Figs. 4, 5) which is suggestive of non-uniform Al/Si ordering. In some of the feldspars (Nos. 5, 6, 8, 10) ordering probably occurred during cooling under the influence of variable (K+Na) concentrations in the fluid phase. In more aluminous host rock (those with a significant amount of normative corundum, *i.e.* No. 9, Table 2) a higher content of Al in the fluid phase may have influenced the degree of ordering of the potassium feldspars (*cf.* Martin, 1969; Guidotti *et al.*, 1973).

The alkali feldspars from rocks metamorphosed under granulite facies conditions initially crystallized

in a disordered state under the influence of high pressure, 8 to 9 kbars, and temperatures, 950 to 1000°C (Collerson, 1972). On cooling they equilibrated with varying degrees of Al/Si ordering. Feldspars 3 and 4 have remarkably similar compositions (Table 3, Fig. 3), yet they exhibit widely differing structural states. The reason for this is unclear in view of the fact that both rocks in which the feldspar occurred are corundum normative and therefore presumably contained a moderately high Al concentration in the fluid phase (*cf.* Martin, 1969; Guidotti *et al.*, 1973). Stewart and Wright (1974) believe that strain in the feldspar lattice could influence Al/Si order-disorder and the symmetry. The feldspar with the highest degree of strain (No. 3) is the most ordered (compare Nos. 2 and 4; Table 6). Strain may therefore account for the differing structural states of the alkali feldspars from the granulite facies terrane.

The wide range of degrees of Al/Si order displayed by the feldspars in the transitional and granulite facies rocks (Figs. 4 and 5, and Tables 4 and 5) is regarded as reflecting the effects of variable physico-chemical conditions during deformation, recrystallization, and equilibration within the two metamorphic terranes.

Assuming a mean structural state of  $\Delta(bc) = 0.82$  for the disordered feldspars, an estimate of the minimum exsolution temperature of the alkali feldspars can be determined from Crosby, 1971 (Fig. 2). In this figure is plotted the partial binodal curve for the Or-Ab system at 7 kbar with a structural state of

TABLE 7. Estimated approximate minimum temperatures of equilibration for peralkaline conditions at 7 kbar\*

Reference Number	Specimen Number A325/-	% Or	T°C
2	1165a	91.0	563
3	77	93.5	525
4	1121	89.0	590
	Mean Temperature 559°C (Granulite Facies)		
5	783	95.0	490
6	323	91.5	550
8	400	92.0	555
9	531	95.0	490
11	18	90.0	575
	Mean Temperature 555°C (Transitional Terrain)		

\* Assuming a mean structural state for the disordered feldspars of  $\Delta(bc) = 0.82$

$\Delta(bc)$  0.82 for peralkaline conditions, following the method of Waldbaum and Thompson (1969) and Thompson and Waldbaum (1969). The results for the Amata feldspars are given in Table 7. Although these must only be regarded as approximate temperature estimates, the means for the granulite facies and transitional terranes compare favourably with the estimated minimum exsolution temperature of the Whiteface Mountain charnockite, 588°C (Crosby, 1971). The values are also in close agreement with the temperature range, deduced from oxygen isotopes by Wilson *et al.*, (1970), *viz.* 510–575°C for the equilibration of the plagioclase-magnetite pair in granulites from Ernabella in the Musgrave Ranges.

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