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The ordering path for igneous K-feldspar megacrysts

RICHARD A. EGGLETON

Department of Geology, Australian National University
Canberra, A.C.T. 2600, Australia

Abstract

Of 61 K-feldspar megacrysts examined from one granodiorite pluton, local shearing has rendered nine triclinic with $\gamma < 88.2°$ and twelve triclinic with $\gamma > 89.3°$. On a Δbc *vs.* $\Delta\alpha^*\gamma^*$ plot, both triclinic groups show an ordering trend parallel to the 'one-step' trend of albite; there is a discontinuity between these groups across which it is postulated that γ changes by about 1° with no change in order.

Introduction

In southeastern Australia, Devonian meridionally-trending batholiths intrude Ordovician sedimentary rocks. The Bega Batholith (Brown, 1933) is the easternmost, and is a composite body comprising at least 35 plutons (Beams *et al.*, in preparation), of which one, the Kameruka Granodiorite, bears abundant K-feldspar megacrysts (Lesh, 1975). A study of the structural states of these megacrysts was undertaken for its possible application to understanding the petrology and geochemistry of the pluton. As data accumulated, it became apparent that there was sufficient information to add to the discussion of Al/Si ordering in K-feldspar.

In their 1974 study of alkali feldspars from different geological environments, Stewart and Wright noted that intermediate microclines followed many ordering paths. The K-feldspars from the Kameruka Granodiorite exhibit a range of order, as indicated by the Δbc indicator. As they all come from a single pluton, these K-feldspars might be expected to define a single ordering path.

Methods

Cell dimensions for 61 megacrysts have been determined from Guinier camera and diffractometer data collected by J. H. Pennington, using crystal-monochromatized Co$K\alpha$ radiation. Refinement of parameters was done on a Hewlett-Packard 9825 calculator, and the indexing checked by inspection. Chemical analyses of nine megacrysts were obtained by energy-dispersive electron-microprobe analysis, N. Ware, analyst.

The megacrysts were first sampled on four E–W traverses across the pluton; later sampling concentrated on marginal samples and along postulated faults, for initial examination suggested a relation between shearing intensity in the rock and degree of order of the K-feldspar. The frequency distribution of structural states is probably weighted toward high degrees of order as a result of sampling bias. Several megacrysts were sampled from core to rim; the difference in Δbc is not significant (samples 17 and 18, 39 and 45, 42 and 43, 15 and 32). Megacrysts taken from the same outcrop also show no variation (6 and 54, 37 and 57). All samples listed in Table 1 have sharp X-ray diffraction peaks, except that 130 and 131 are broadened in samples 29 and 45, indicating they are probably triclinic. Four additional samples with high values of Δbc estimated from 060 and $\bar{2}04$ show multiple reflections in the 131 region and have not been included in the data list.

The reported values of Δbc and $\Delta\alpha^*\gamma^*$ have been computed from the refined cell dimensions, based on the relation of Luth quoted in Stewart and Wright (1974). From the standard deviations of a, b, and γ^*, standard deviations in Δbc and $\Delta\alpha^*\gamma^*$ can be estimated. For the best data, Δbc and $\Delta\alpha^*\gamma^*$ can be estimated to within 0.02 at the 95 percent confidence level (2σ) and to within 0.08 at the same confidence for the worst data. The symbols in Figure 1 extend one standard deviation on either side of the mean.

Description of the megacrysts

The largest of the megacrysts reaches 7 × 7 × 5 cm, tabular on {010}. Carlsbad twinning has been

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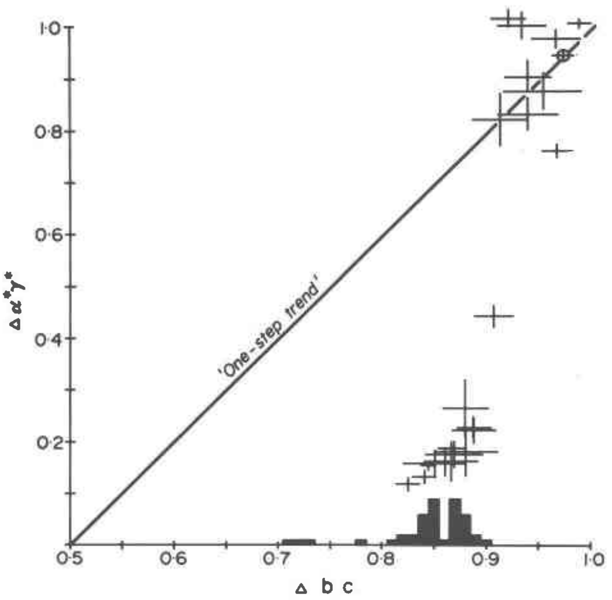

Fig. 1. Δbc *vs.* $\Delta\alpha^*\gamma^*$ for 65 K-feldspars and one albite in perthitic intergrowth (circled, sample 66). Symbols for triclinic samples extend one standard deviation from the mean. Distribution of monoclinic samples is shown by the histogram; the smallest step represents one sample.

found in every crystal examined, and is presumably ubiquitous. The twin 'plane' is very irregular, stepping back and forth, and in some instances crossing the crystal for a millimeter or so at angles of up to 45° to (010) in optically-unresolved steps. Quartz strings and veins may follow the twin boundary for short distances, as well as being present in irregular patches throughout the megacrysts. Many large megacrysts are prominently zoned, the zone boundaries being marked by the alignment of intermittent biotite and plagioclase crystals ($Ab_{73}An_{25}Or_2$ in sample 10). Some megacrysts have a core 2–3 cm long with a 1 mm mantle of plagioclase between the core and the rest of the crystal. Others have an outer mantle of plagioclase; no detailed study of rapakivi and unmantled megacrysts has been attempted. Myrmekitic intergrowths of quartz and feldspar occur at many of the K-feldspar–plagioclase boundaries. No significant variation in composition as estimated from cell volume has been detected in core and edge samples from the same megacryst (17 and 18, 39 and 45, 42 and 43, 15 and 32).

The megacrysts are coarsely perthitic, with irregular veins of albite (Ab 97) and parallel laminae of micro-albite. Most show a domain structure with patchy and uneven extinction, and variation in $2V$ of up to 5°. The triclinic crystals show albite–pericline cross-hatch twinning, and are generally pinker than the orthoclase megacrysts. The Kameruka megacrysts are very similar in appearance to those from the Cathedral Peak pluton (Kerrick, 1969).

At a locality near the northern edge of the Kameruka pluton, a dyke composed of fine-grained granodiorite with K-feldspar megacrysts up to 4 cm long intrudes an earlier pluton (sample 50). In nearby marginal areas the megacrysts are on average smaller than those in the main body of the pluton. The existence of smaller megacrysts in some marginal areas, the existence of similar sized cores to larger megacrysts, and the mantling of successive zones by groundmass minerals suggest crystallization of the megacrysts from a melt.

The distribution of structural states of K-feldspar over the Kameruka pluton is similar to that found by Bordet and Chauris (1965) and Caillère and Kraut (1960): marginal samples are microcline, samples from the pluton centre are orthoclase (Fig. 2). The Kameruka pluton is cut by two major faults (Beams *et al.*, in preparation). Along both, the K-feldspar megacrysts are maximum microcline, and the rocks containing them are noticeably sheared. Away from these faults Δbc decreases, and in unfaulted areas is constant at 0.86. High values of Δbc at the pluton margin are presumed to result from shearing as the solidified skin of the intruding pluton experienced stress from the still-mobile center. The importance of shearing stress in the formation of microcline is summarized by Smith (1974, p. 384), and the field evidence shows clearly that for the Kameruka feldspars the transition to microcline is caused by shearing.

Near the southern limit of the pluton, a Mesozoic syenite (Beams, 1975) has intruded the Kameruka pluton. Megacrysts adjacent to this intrusion (1, 2, 3) have the lowest value for Δbc of all those examined, and are presumed to have been reheated. Samples 15, 16, 19, and 42 are close to a diorite body. Although geological relations between diorite and the granites are not yet clear, the low values of Δbc found for the four samples (0.77, 0.82, 0.84) suggest that they may have been heated by the diorite intrusion. With the exception of the seven reheated samples, the K-feldspar megacrysts of the Kameruka pluton provide a constant-temperature suite exhibiting a range of Al/Si order in crystals of common origin and restricted composition.

Ordering path

A plot of Δbc *vs.* $\Delta\alpha^*\gamma^*$ (Fig. 1) separates the Kameruka K-feldspars into three groups. Thirty-six

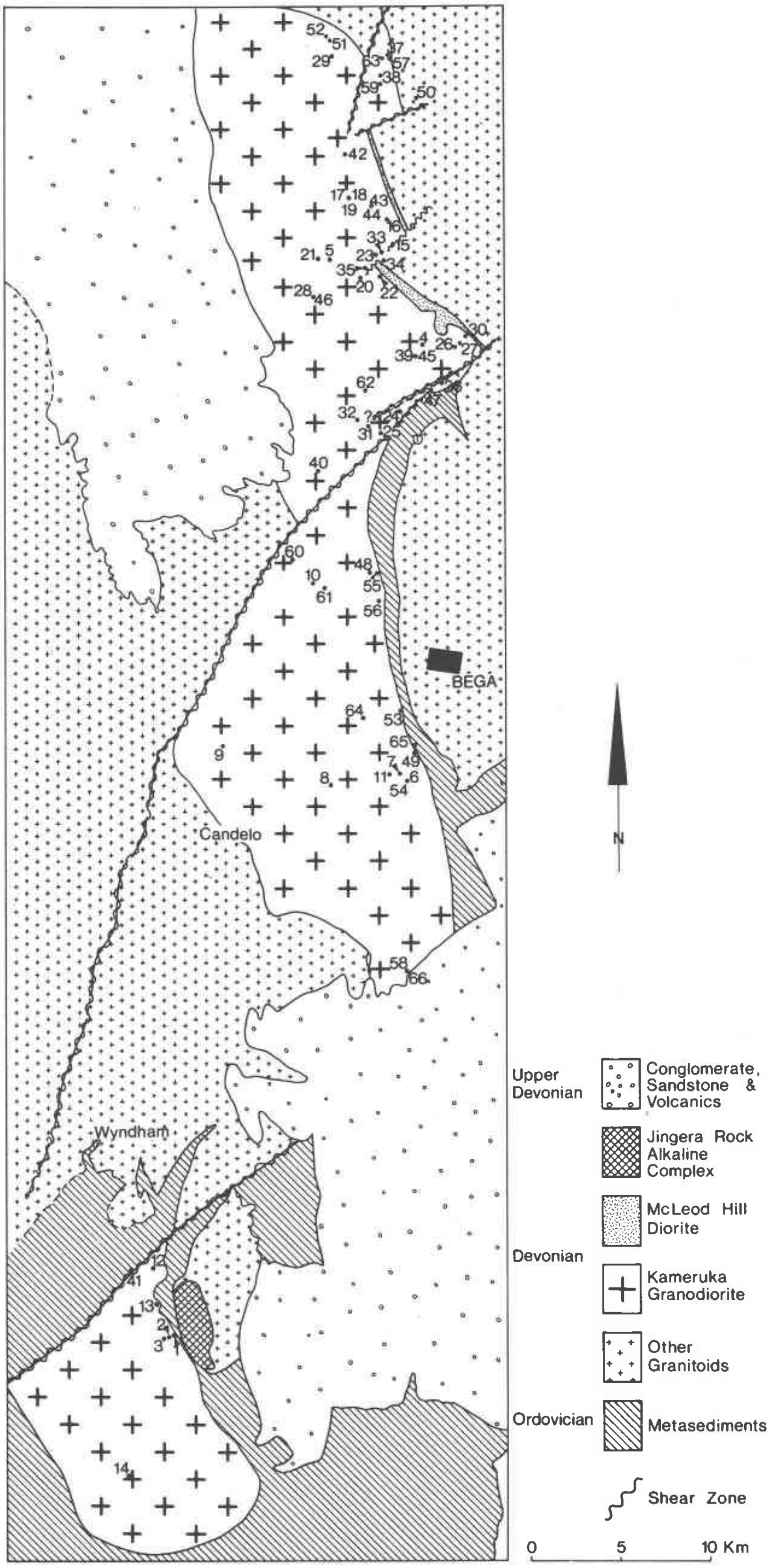

Fig. 2. Sample location map.

Table 1. Alkali feldspar data

Sample	Mole % Or anal	vol	a(Å)	b(Å)	c(Å)	α	β	γ	Δa	Δbc	Δα*γ*
01	-	90	8.579(1)	12.983(2)	7.188(1)	90	116.03(2)	90	0.107	0.73	
02	-	89	8.567(1)	12.996(1)	7.189(1)	90	116.03(2)	90	0.025	0.70	
03	-	89	8.576(1)	12.985(1)	7.187(1)	90	116.03(1)	90	0.100	0.72	
04	-	96	8.584(1)	12.982(1)	7.205(1)	90.08(3)	116.01(1)	89.60(2)	0.011	0.85	0.15
05	89	88	8.564(5)	12.961(3)	7.202(1)	90	115.99(4)	90	0.106	0.87	
06	-	96	8.585(1)	12.975(2)	7.209(1)	90	116.03(1)	90	0.021	0.89	
07	-	88	8.560(6)	12.973(7)	7.198(4)	90	115.97(11)	90	0.074	0.82	
08	-	96	8.583(1)	12.977(2)	7.206(1)	90	115.98(2)	90	0.027	0.86	
09	-	93	8.574(3)	12.977(3)	7.206(1)	90	115.98(5)	90	0.019	0.86	
10	95	95	8.585(2)	12.972(2)	7.213(2)	90.92(9)	116.04(4)	87.65(4)	0.011	0.92	1.02
11	89	91	8.573(1)	12.971(3)	7.200(1)	90	115.95(3)	90	0.082	0.84	
12	-	93	8.560(3)	12.968(2)	7.218(2)	90.64(3)	115.87(4)	87.73(4)	-0.031	0.97	0.98
13	-	89	8.557(5)	12.954(4)	7.211(2)	90.65(8)	115.84(6)	87.94(8)	0.077	0.95	0.88
14	-	95	8.582(4)	12.976(3)	7.205(1)	90	115.99(4)	90	0.035	0.86	
15	91	95	8.581(1)	12.981(1)	7.204(1)	90	116.01(1)	90	0.016	0.84	
16	-	93	8.587(3)	12.981(4)	7.194(1)	90	116.02(4)	90	0.087	0.77	
17	-	96	8.585(1)	12.982(2)	7.205(1)	90	116.00(2)	90	0.016	0.84	
18	-	97	8.585(4)	12.980(3)	7.208(2)	90	116.01(5)	90	0.002	0.87	
19	91	91	8.574(3)	12.975(3)	7.197(1)	90	115.96(4)	90	0.083	0.81	
20	94	96	8.582(1)	12.989(2)	7.205(1)	90.02(4)	116.02(2)	89.69(3)	-0.020	0.83	0.12
21	-	90	8.573(5)	12.962(6)	7.202(3)	90	116.01(8)	90	0.110	0.87	
22	-	88	8.566(3)	12.967(4)	7.200(2)	90	115.98(7)	90	0.097	0.85	
23	-	96	8.584(1)	12.978(1)	7.208(1)	90	116.03(1)	90	0.014	0.87	
24	95	98	8.586(2)	12.979(2)	7.210(1)	90.21(6)	115.99(4)	89.42(5)	-0.009	0.89	0.23
25	-	92	8.574(5)	12.978(4)	7.202(1)	90	115.99(5)	90	0.040	0.83	
26	-	97	8.584(5)	12.983(3)	7.206(2)	90	115.96(7)	90	-0.003	0.85	
27	94	96	8.580(1)	12.984(2)	7.205(1)	90.13(4)	115.99(2)	89.66(3)	-0.005	0.84	0.13
28	-	94	8.579(2)	12.973(4)	7.205(2)	90.08(10)	115.99(4)	89.58(9)	0.051	0.87	0.16
29	-	96	8.584(1)	12.979(2)	7.207(1)	90	116.01(1)	90	0.016	0.86	
30	-	96	8.581(1)	12.984(2)	7.209(1)	90.17(5)	116.02(3)	89.52(3)	-0.024	0.87	0.19
31	-	97	8.584(1)	12.983(2)	7.209(1)	90	116.02(3)	90	-0.022	0.87	
32	-	96	8.582(1)	12.985(1)	7.206(1)	90	116.03(1)	90	-0.016	0.85	
33	-	98	8.595(3)	12.972(4)	7.207(1)	90.06(8)	115.96(4)	89.53(11)	0.056	0.88	0.18
34	-	95	8.591(2)	12.975(2)	7.201(1)	90	116.02(2)	90	0.076	0.83	
35	-	95	8.586(3)	12.980(3)	7.202(1)	90	116.02(4)	90	0.041	0.83	
36	93	95	8.581(2)	12.973(3)	7.208(1)	90.15(6)	115.99(3)	89.43(6)	0.029	0.89	0.22
37	-	88	8.575(5)	12.964(7)	7.199(3)	90	116.06(7)	90	0.127	0.85	
38	-	94	8.582(1)	12.982(1)	7.202(1)	90	116.03(1)	90	0.029	0.82	
39	-	95	8.581(4)	12.982(2)	7.204(2)	90	116.01(6)	90	0.015	0.84	
40	-	99	8.593(2)	12.966(2)	7.218(2)	90.49(5)	115.94(5)	88.18(3)	0.017	0.97	0.76
41	-	97	8.579(1)	12.967(2)	7.221(1)	90.64(3)	115.93(2)	87.67(2)	-0.026	0.99	1.01
42	-	95	8.578(3)	12.982(4)	7.202(2)	90	115.95(5)	90	0.024	0.82	
43	-	97	8.582(1)	12.987(3)	7.208(1)	90	116.03(3)	90	-0.038	0.86	
44	-	91	8.584(3)	12.965(4)	7.199(1)	90	116.03(4)	90	0.126	0.84	
45	-	95	8.580(1)	12.977(1)	7.207(1)	90	116.03(2)	90	0.017	0.87	
46	-	91	8.572(1)	12.967(1)	7.204(1)	90	115.97(3)	90	0.081	0.87	
47	-	94	8.583(1)	12.969(3)	7.208(1)	90	116.02(2)	90	0.052	0.89	
48	-	93	8.580(2)	12.966(3)	7.213(3)	90.96(13)	115.99(7)	87.68(6)	0.035	0.93	1.00
49	-	96	8.582(1)	12.982(3)	7.207(1)	90.14(6)	116.02(2)	89.59(6)	-0.006	0.86	0.16
50	-	90	8.571(5)	12.975(5)	7.198(2)	90	115.98(7)	90	0.078	0.81	
51	-	93	8.585(2)	12.968(3)	7.201(1)	90	115.97(4)	90	0.107	0.85	
52	-	93	8.580(2)	12.974(4)	7.206(2)	89.99(12)	116.03(4)	89.54(6)	0.039	0.87	0.18
53	-	94	8.580(5)	12.970(3)	7.206(2)	90	116.01(4)	90	0.052	0.88	
54	-	93	8.578(2)	12.972(2)	7.204(1)	90	115.99(2)	90	0.058	0.86	
55	-	100	8.597(3)	12.979(3)	7.209(2)	90	116.02(5)	90	0.014	0.87	
56	-	95	8.579(1)	12.974(3)	7.211(1)	90.35(6)	116.01(3)	88.90(5)	0.004	0.91	0.44
57	-	95	8.587(3)	12.976(3)	7.203(1)	90	116.00(3)	90	0.056	0.84	
58	-	96	8.595(3)	12.976(4)	7.213(2)	90.60(9)	116.13(7)	88.05(12)	0.001	0.91	0.82
59	-	91	8.580(3)	12.965(4)	7.202(1)	90	116.02(4)	90	0.102	0.87	
60	-	95	8.582(4)	12.977(6)	7.207(2)	90	116.00(4)	90	0.019	0.87	
61	-	94	8.577(3)	12.968(4)	7.214(2)	90.50(8)	115.97(5)	88.03(7)	0.008	0.94	0.83
62	-	95	8.581(1)	12.983(2)	7.205(1)	90	116.02(2)	90	0.001	0.84	
63	-	93	8.584(3)	12.969(4)	7.201(2)	90.25(8)	115.99(4)	89.60(6)	0.097	0.85	0.16
64	-	93	8.578(1)	12.971(4)	7.206(1)	90.24(7)	116.02(2)	89.33(13)	0.048	0.88	0.27
65	-	96	8.582(2)	12.972(3)	7.216(1)	90.65(8)	115.98(3)	87.88(7)	-0.012	0.94	0.90
66	-	-2	8.137(1)	12.788(1)	7.158(1)	94.26(2)	116.62(2)	87.79(2)	0.779	0.97	0.95

are monoclinic, with mean $\Delta bc = 0.85$, S.D. = 0.02, and mode = 0.86. Twelve are triclinic with $\Delta bc = 0.87$ (0.02), $\Delta\alpha^*\gamma^* = 0.16$ (0.05), $\gamma = 89.6$ (0.1). Nine are triclinic with $\Delta bc = 0.95$ (0.03), $\Delta\alpha^*\gamma^* = 0.91$ (0.10), $\gamma = 87.9$ (0.2). Only sample 56 falls clearly outside these groups. The distinction between low γ and high γ K-feldspars is noted by Stewart and Wright (1974) as a gap in their $\Delta\alpha^*\gamma^*$ values between 0.4 and 0.65, and is apparent as a narrower gap in data of Guidotti *et al.* (1973) as summarized by Stewart and Wright, in that only three of their 33 triclinic samples have Al in T_1m between 0.1 and 0.25. Rhodes (1966), in a study of triclinicity from Australian granites, found only six out of 71 samples with triclinicities between 0.3 and 0.6. Ever since Dietrich's 1962 compilation of obliquity data from 500 K-feldspars, the dearth of specimens with intermediate triclinicities has remained.

Prominent within the two triclinic groups is the alignment of points parallel to the ordering path of albite. Albite in perthitic intergrowth from sample 58 is plotted as a circle in Figure 1, and the trend of the high $\Delta\alpha^*\gamma^*$ group is indistinguishable from albite's one-step ordering path. The 12 samples with $\Delta\alpha^*\gamma^* \sim 0.15$ lie on a second trend, also parallel to the one-step trend.

If Stewart and Wright's interpretation of $\Delta\alpha^*\gamma^*$ as a measure of the difference in Al content between T_1m and T_1o is accepted, the Kameruka data imply a discontinuity in the ordering process at $\Delta bc = 0.9$, when Al in $T_1m = 0.33$. Migration of Al to T_1o must then take place with no change in Δbc, and over such a narrow stability field that few specimens occur naturally. Continuous ordering resumes at $\Delta bc > 0.9$, only when Al in T_1m has dropped to 0.05. Such a sharp discontinuity can be readily understood for a displacive transformation, but is much harder to explain for a reconstructive transformation such as Al/Si ordering.

A simpler explanation for the ordering path shown in Figure 1 is that, for K-feldspars, $\Delta\alpha^*\gamma^*$ is not a smooth function of Al–Si order. Stewart and Wright spread the migration of Al into T_1o uniformly over the range of $\Delta\alpha^*\gamma^*$. If, however, the segment of $\Delta\alpha^*\gamma^*$ from 0.45 to 0.8 represents a change in γ with no change in order, triclinic K-feldspar orders in much the same way as albite, starting at a value of Δbc appropriate to the monoclinic–triclinic inversion of that particular feldspar. For example, if a K-feldspar inverts at $\Delta bc = 0.8$ with 0.4 Al equally in T_1o and T_1m, and 0.1 Al in T_2o and T_2m, a steady migration of Al from T_1m and T_2 sites to T_1o would reduce Al in these sites by about half at $\Delta\alpha^*\gamma^* = 0.35$ (since $\Delta\alpha^*\gamma^*$ is an indicator of order over only 0.75 of its range), leaving 0.2 Al in T_1m and 0.05 Al in T_2o and T_2m, close to the occupancy of Spencer U. At this degree of order, the lattice changes shape, largely by change in γ, leading to a value of $\Delta\alpha^*\gamma^*$ of about 0.8, and further ordering takes place as in albite.

a-axis and composition

According to Stewart and Wright, the *bc* plot can be contoured to predict *a*. When predicted and observed values of *a* differ by more than 0.05A, the feldspar is said to be anomalous. Such anomalies have generally been regarded as the result of lattice strain associated with the presence of albite in perthitic intergrowth. The Kameruka megacrysts are all obviously perthitic at low magnifications, and show a second generation of fine lamellar albite at higher magnification. It is not surprising then that 25 of the 61 samples are anomalous by the Stewart and Wright criteria (Δa in Table 1). Half the monoclinic samples are anomalous, compared to less than one-fifth of the triclinic, suggesting that shearing promotes coarsening of the albite lamellae with a consequent reduction in strain.

Cell volume provides a good estimator of composition for these megacrysts, using the Waldbaum and Thompson (1968) relation as recast by Stewart and Wright. Table 1 lists microprobe analyses of the most K-rich regions of nine megacrysts; the Or percent estimated from cell volume is slightly greater than the measured quantity, presumably because of included albite lamellae.

Summary

K-feldspar megacrysts of the Kameruka granodiorite have ordered from $\Delta bc = 0.8$ to 1.0 as the result of shearing. After the crystals become triclinic, the ordering path is discontinuous with respect to γ, producing a gap in $\Delta\alpha^*\gamma^*$ between 0.45 and 0.8. Lattice strain resulting from included albite lamellae is less pronounced in triclinic samples. Cell volume can be used to estimate Or content to within 4 percent.

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