THE DISORDERING OF ALKALI FELDSPARS
I. DRY HEATING OF A MICROCLINE PERTHITE

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ABSTRACT

It was possible to follow the disordering path of a microcline microperthite, with bulk grain composition OrurAbas, by calculating the Al-Si distribution from refined unit-cell parameters (obtained from X-ray powder diffraction patterns) for samples that were dry-heated at 1025°C for times ranging from 4 to 2200 hours. Dry-heating results in: (a) Na–K homogenization in less than 4 hours; (b) Al–Si disordering with retention of a triclinic cell for annealing times of 12 to 128 hours; (c) transformation from triclinic to monoclinic for annealing times of 128 to 222 hours; (d) Al–Si disordering in a monoclinic cell for annealing times greater than 270 hours. The Al–Si disordering is much more rapid in a triclinic cell (b) than in a monoclinic cell (d). The product of the triclinic-to-monoclinic transformation (c) is an ordered monoclinic feldspar, not a sanidine.

SOMMAIRE

On a pu suivre l’évolution du désordre dans un microcline microperthitique, de composition globale OrurAbas, en calculant la distribution Al–Si à partir des dimensions affinées de la maille (obtenues par diffraction X de poudres) pour des échantillons qui furent chauffés à sec à 1025°C pendant des laps de temps variant de 4 à 2200 heures. On observe: (a) en moins de 4 heures, homogénéisation Na–K; (b) après recuit de 12 à 128 heures, désordre Al–Si dans une maille qui reste triclinique; (c) après recuit de 128 à 222 heures, transformation de triclinique en monoclinique; (d) pour tout recuit excédant 270 heures, désordre Al–Si dans une maille monoclinique. Le désordre Al–Si se produit beaucoup plus rapidement dans une maille triclinique (b) que dans une maille monoclinique (d). Le produit de la transformation (c) est un feldspar monoclinique ordonné, et non pas une sanidine.

EXPERIMENTAL MATERIALS AND METHODS

The feldspar used in the study is from the coarse-grained, hypidiomorphic-granular granite in the near-surface Devonian Charlotte pluton in southwestern New Brunswick. The granites in the pluton have essentially ternary-minimum-melt compositions (e.g., sample 73–170A has 33.1% quartz, 28.9% orthoclase, 31.6% albite
Fig. 1. Trapezoidal plot of Al occupancies (Stewart & Wright 1974) illustrating ideal one- and two-step disordering paths for alkali feldspars.

and 1.9% anorthite in its norm) and are composed of quartz, albic plagioclase, microperthitic potassium feldspar and minor biotite (Cherry 1976, Cherry & Trembath 1973). The potassium feldspar grains contain 20% to 50% exsolved albic lamellae. Most grains contain (1) coarse lamellae 1 mm long and 0.1 mm wide in widely spaced parallel bands and (2) fine lamellae 0.5 to 1.0 mm long and 0.01 to 0.02 mm wide in areas between the coarse lamellae. The potassium feldspar in sample 73-170A was selected for the study of disordering because of its relatively well-ordered \( t_0 = 0.87 \) Al–Si distribution (Cherry 1976). It has a bulk grain composition, determined from refined unit-cell volume, of Or10Ab80. The perthite grains in sample 73–170A average 1.5 cm in size and are readily separated by hand-picking from a coarsely broken hand specimen. The sample material was estimated to be >95% perthite; sodic plagioclase from the granite not removed from the sample would change its composition and, hence, its cell parameters but probably does not affect the results reported for the disordering process.

The disordering process was followed by observing the changes in X-ray powder diffraction patterns of, and calculating the Al–Si distribution in, portions of the sample heated for different times at 1025°C. Al–Si distributions in the experimental products were calculated from refined unit-cell parameters obtained from the X-ray powder-diffraction data using the methods of Stewart & Ribbe (1969). The sample was crushed (grain size <25μ), thoroughly mixed, and portions placed in gold capsules for heat treatment. The majority of the experiments were made in crimped capsules; one was made in a sealed capsule with powder dried at 110°C to check for loss of alkalis. The annealed samples were air-quenched to room temperature in less than five minutes and the products then used in smear mounts for X-ray diffraction, with heat-treated CaF₂ (a 5.4626Å) as an internal standard. Three scans were made of each product from 60° to 10° 2θ at a rate of 0.25° 2θ per minute, using Cu radiation (Kα, λ = 1.54178Å

Fig. 2. Segments of X-ray powder diffraction patterns (Cu Kα) of feldspar 73–170A: (a) natural microperthite; (b) heated for 72 hours; (c) heated for 135.4 hours; (d) heated for 336 hours, and (e) heated for 672 hours. All samples were annealed at 1025°C.
for all reflections with $2\theta < 47^\circ$, $K\alpha_1$, $\lambda = 1.54051$ Å for all reflections with $2\theta > 47^\circ$; 40 kV, 30 mA). Mean $2\theta$ values from the three scans were then used as input data in a cell-refinement program (Appleman & Evans 1973). The patterns were indexed using data in Wright & Stewart (1968) and in Borg & Smith (1969). Fixed indexing was used in all final refinements and unit value was assigned to all reflections.

RESULTS AND DISCUSSION

X-ray diffraction patterns

The changes in the diffraction patterns that occur with heat treatment are illustrated in Figure 2. The pattern of the natural perthitic feldspar (Fig. 2a) has separate peaks for the sodic and potassic phases; the 130, 130, 131 and 131 reflections of the potassic phase are sharp and the reflections in each pair are well separated. The reflections of the sodic phase are absent from the diffraction patterns of all the products heated longer than four hours, indicating rapid Na-K homogenization. The patterns of products held at 1025°C for successively longer times show a steady decrease in the separation of the 130–130 and 131–131 reflections. The 130–130 pair becomes ragged and broadened at its peak; the 131–131 pair is broadened at its peak. In addition to these changes, the diffraction patterns for products 10 (Fig. 2c), 11, 12 and 13 have an additional reflection between the 130 and 130 peaks and between the 131 and 131 peaks. We interpret these reflections to indicate the presence of both monoclinic and triclinic cell geometries in the products of these four experiments. Both a monoclinic and a triclinic unit-cell can be refined for the products of only these four experiments. Careful examination of all diffraction patterns after initial refinements resulted in the assignment of minor reflections on the diffraction patterns of these products to either the monoclinic or the triclinic crystal system. The diffraction patterns of experimental products 2 to 10 have reflections that can be assigned only to the triclinic crystal system and those of experiments 14 to 22 have reflections that can be assigned to the monoclinic crystal system. Each pair of refined unit-cells in products 10 to 13 has similar parameters; this is largely dictated by the use of the same strong reflections (201, 111, 041, 060, 204) in the refinements of both unit-cells. Peak height-to-width ratios for these major reflections remain relatively constant on the diffraction patterns of the experimental products with triclinic unit-cell geometries and the reflections do not exhibit splitting or broadening (Fig. 2). The 201 reflection shifts markedly from $\sim 21^\circ 2\theta$ in the perthite to $\sim 21.4^\circ 2\theta$ in the homogenized feldspar; other reflections have smaller shifts in their positions. The diffraction patterns of products of experiments 14 to 22 (Figs. 2d and 2e) show only minor changes in peak positions and are consistent with a monoclinic unit-cell. However, the reflections in these patterns become sharper with increased duration of annealing. The 201, 060 and 204 reflections on these patterns have relatively constant peak height-to-width ratios but the 111, 130, 112 and 131 reflections have increased height-to-width ratios with longer annealing times. These changes in the diffraction patterns of the annealed feldspars with monoclinic geometry probably reflect increasing domain size and homogeneity within the feldspar as annealing time is increased.

Refined unit-cell parameters

The refined unit-cell parameters of the experimental products are given in Table 1. The accuracy and precision of refined unit-cell data have been discussed by Stewart (1975), who cautioned against overinterpretation of data obtained from X-ray powder diffraction methods which undoubtedly give results for an 'average' structure composed of a number of domains with different degrees of Al-Si order. We acknowledge the limits to interpretation imposed by the techniques but consider the systematic changes we have observed to be interpretable.

The refined unit-cell data are plotted on $b - c$ and $\alpha^* - \gamma^*$ diagrams (Stewart & Wright 1974) in Figures 3 and 4, respectively. Alkali homogenization, which occurs in less than four hours, results in a shift from the cell dimensions of the potassic phase of the perthite (experiment 1). There is, however, little if any Al-Si migration for annealing times less than 48 hours (experiments 2 to 5). The products of these experiments have larger $\Delta a$ values ($\Delta a = a_{obs} - a_{obs}$; Stewart & Wright 1974) than does the perthite; these $\Delta a$ values probably represent 'strain' brought about by the alkali homogenization. Appreciable Al-Si migration occurs during experiments of 72 to 128 hours duration (experiments 6 to 9) and satisfactory refinements based on a triclinic unit-cell can be obtained. The decrease in degree of order during these experiments is accompanied by a decrease in the 'strain' in the feldspar as indicated by $\Delta a$.
Expt. Time  α  β  γ  α°  β°  γ°  Volume  Z  Or  t₁0  t₁₅  t₂₀Δn n
1  0  8.590(6)  12.977(6)  7.211(3)  90.63(6)  116.03(4)  87.99(6)  90.28(5)  91.93(4)  721.9(6)  97.0  0.87  0.02  0.04  0.00  28
12  12  8.419(12)  12.966(8)  7.206(4)  91.07(6)  116.07(6)  88.05(7)  89.76(6)  91.65(7)  707.1(6)  60.1  0.86  0.03  0.06  0.08  18
16  6  8.481(16)  12.963(10)  7.209(6)  91.01(12)  116.07(6)  88.09(11)  89.81(11)  91.63(10)  707.0(12)  61.9  0.86  0.05  0.04  0.08  15
24  4  8.438(15)  12.963(9)  7.204(4)  90.85(10)  116.06(7)  88.23(10)  89.91(10)  91.59(9)  707.5(11)  62.8  0.81  0.07  0.06  0.04  15
48  8  8.410(16)  12.962(11)  7.208(6)  90.96(11)  116.10(9)  88.18(12)  89.62(13)  91.56(13)  705.6(14)  59.2  0.83  0.06  0.05  0.06  16
72  72  8.420(16)  12.963(10)  7.198(5)  90.87(9)  116.00(8)  88.43(11)  89.80(9)  91.32(11)  706.4(13)  60.7  0.75  0.09  0.08  0.02  18
96  96  8.426(14)  12.961(8)  7.197(4)  90.76(7)  116.01(7)  88.48(6)  89.86(7)  91.31(8)  708.0(10)  59.9  0.74  0.10  0.08  0.00  18
120  120  8.426(17)  12.965(10)  7.200(5)  90.84(8)  116.08(6)  88.49(10)  89.81(8)  91.27(10)  706.3(12)  60.5  0.73  0.11  0.08  0.06  18
152  152  8.426(19)  12.966(11)  7.203(5)  90.80(9)  116.09(9)  88.54(11)  89.81(9)  91.23(9)  706.2(14)  60.3  0.73  0.12  0.08  0.04  17

TABLE I. REFINED UNIT-CELL PARAMETERS OBTAINED FROM X-RAY DIFFRACTION DATA FOR HEAT-TREATED SAMPLES OF FELDSPAR 73-170A

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<th>β°</th>
<th>γ°</th>
<th>Volume</th>
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Disordering path and Al occupancy

The multistep character of the disordering path is best illustrated on a trapezoidal plot (Fig. 5) of calculated Al occupancies of the tetrahedral sites (Stewart & Wright 1974). The alkali homogenization obvious on the b - c and α° - γ° plots (Figs. 3 and 4) is not evident on the Al occupancy plot because it occurs without a change in Al-Si order. The step in which Al moves from the TₐO site into all three of Tₐₐ, Tₐ₀ and Tₐ₃m is shown on Figure 5 by experimental products 5 to 13. A least-squares linear-regression fit for experiments 1 to 9 and the triclinic refinements of experiments 10 to 13 is drawn on Figure 5; this line is parallel to, although offset to higher Al occupancies than, the band of microclines from a suite of metamorphic rocks plotted by Stewart & Wright (1974). This suggests similar relative rates of Al-Si migration during the ordering of the potassium feldspars in the metamorphic rocks discussed by Stewart & Wright (1974) and the disordering of the perthite from granite sample 73-170A; Al migrated from Tₐ₀
Fig. 3. Refined $b - c$ unit-cell dimension diagram (Stewart & Wright 1974) for heat-treated samples of feldspar 73-170A. Experiment numbers are as in Table 1. Circles are experimental products with triclinic refined unit-cells; squares are experimental products with monoclinic refined unit-cells. Filled symbols indicate the experiments for which both a monoclinic and a triclinic refined unit-cell were obtained. Error bar lengths are twice the standard error calculated by the cell-refinement program.

Fig. 4. Refined $a^* - \gamma^*$ dimension diagram (Stewart & Wright 1974) for experimental products with triclinic refined unit-cells. The symbols are as for Figure 3.

into $T_{1m}$ approximately four times as rapidly as into the $T_2$ sites. A gap is present on the Al occupancy plot (Fig. 5) and on the $a^* - \gamma^*$ plot (Fig. 4) between the most disordered triclinic feldspar and the most ordered monoclinic feldspar. Attempts to fill this gap resulted in experimental products with both monoclinic and triclinic cell geometries. The products of these experiments, as shown on Figure 5, have approximately the same Al content in the $T_2$ sites of
Fig. 5. Trapezoidal plot of calculated Al occupancies of the tetrahedral sites in the experimental products. The symbols are as for Figure 3. The light solid lines join monoclinic and triclinic refined unit-cells for experiments 10 to 13. The heavy solid line is a least-squares linear regression fit for experiments 1 to 9 and the triclinic refined unit-cells of experiments 10 to 13. The dashed line is the trend of intermediate microclines plotted by Stewart & Wright (1974) for a suite of metamorphic feldspars (Guidotti et al. 1973).

Fig. 6. Rate of movement of Al from the T₁₀ site in the experiments. The symbols are as for Figure 3. Light solid lines join monoclinic and triclinic refined unit-cells for experiments 10 to 13. The heavy solid lines are least-squares linear regression fits for experiments 1 to 9 and the triclinic refined unit-cells of experiments 10 to 13, and for experiments 18 to 22. The dashed line is a visually estimated fit for experiments 14 to 18 and the monoclinic refined unit-cells of experiments 10 to 13.

Both the monoclinic and the triclinic refined unit-cells; this Al distribution (\(2t_1 \approx 0.20\)) may be an upper limit for the existence of a triclinic structure. The final stage of the disordering process involves a slower movement of Al into the \(T_2\) sites from the \(T_1\) sites, illustrated on Figure 5 by experiments 14 to 22.

Rate of Al–Si migration

The rate of change in Al occupancy of the \(T_10\) site is shown on Figure 6. An ‘incubation’ period of approximately 24 hours is apparently needed before Al and Si can sensibly migrate through the feldspar structure. This contrasts
with the initial rapid change in order parameters reported by Sipling & Yund (1974) for <44µ samples of Hugo microcline (Or_{ab}) and its K-exchanged equivalent annealed at 1070°C. Disordering occurs rapidly after the incubation period (experiments 4 to 9) until monoclinic cell geometries appear when t_{0} + t_{m} ≈ 0.80. There follows a period during which both monoclinic and triclinic cell geometries are present (experiments 10 to 13) and apparently an interval of intermediate rate of Al-Si migration in experiments with only monoclinic geometry (experiments 14 to 18) until 2t_{1} ≈ 0.60. These are followed by a slower migration of Al and Si at a constant rate (experiments 18 to 22) until disordering is complete.

Nature of ‘strain’ in the feldspar

As would be anticipated, the microperthitic natural potassium feldspar exhibits no evidence of ‘strain’ as indicated by Δα. A significant degree of ‘strain’ becomes apparent following alkali homogenization in experimental products retaining a triclinic cell geometry and a high degree of Al-Si order. This ‘strain’ decreases as the Al-Si order decreases and the products of experiments resulting in both monoclinic and triclinic cell geometries are ‘unstrained’. Experiments resulting in monoclinic cell geometries are initially ‘unstrained’ but become increasingly ‘strained’ as annealing times are increased. In itself, the ‘strain’ may not be an important part of the disordering process, but it may have an appreciable effect on the rates of Al-Si migration among the tetrahedral sites or on the nature of a subsequent transformation. With increased duration of heat treatment, the Al-Si disordering occurring within a triclinic cell geometry coincides with an apparent decrease in ‘strain’, suggesting that the Al-Si order is adjusting to the Na–K distribution.

Nature of the triclinic–monoclinic transformation in alkali feldspars

Most studies of order–disorder relationships in the alkali feldspars have been concerned with following the process for end-member compositions. We have used a feldspar with a grain composition of Or_{ab}Ab. Although the appreciable sodium content of the feldspar introduces an extra complication into order–disorder considerations, we think that this grain composition is representative of conditions of formation of microclines in many igneous environments. As the microperthitic microcline is homogenized in the first few hours, the subsequent dry-heating disordering experiments would be characteristic of a highly ordered triclinic feldspar with a grain composition of about 60 mole % Or.

Experiments 2 to 9 (Fig. 5) represent a continuous disordering process with only a triclinic unit-cell geometry evident. The Al content of the T_{0} + T_{m} sites in the feldspar is initially approximately 0.89 and remains at approximately 0.88 during alkali homogenization. It then decreases to approximately 0.84 while triclinic geometry is retained. The disordering path of Figure 5 indicates a more rapid transfer of Al from T_{0} to T_{m} than to the T_{1} sites, consistent with an intermediate two-step disordering path, as distinct from the one-step path proposed by Sipling & Yund (1974) for the Hugo microcline. As only one triclinic cell geometry is apparent, we consider this early stage of the disordering process to be a homogeneous transformation.

Stewart & Wright (1974) noted a minimum t_{0} + t_{m} occupancy of 0.70 and a gap in t_{0} - t_{m} values from 0.40 to 0.65, implying that certain degrees of order are not achieved or, at least, are not retained. In our annealed material, the minimum t_{0} + t_{m} occupancy attained while retaining triclinic unit-cell geometry was 0.84. Attempts to extend the t_{0} + t_{m} occupancy (Fig. 3) to lower values and to fill the gap in t_{0} - t_{m} values (Fig. 4) resulted in experimental products (numbers 10 to 13) with both monoclinic and triclinic unit-cell geometries rather than a single intermediate geometry. We interpret this second stage as a discontinuous transformation with both monoclinic and triclinic geometries present. The transformation requires time to initiate but once started the change in geometry takes place rapidly and is not accompanied by an appreciable transfer of Al out of the T_{1} sites. This break in geometry would be consistent with a discontinuous transformation requiring nucleation and coarsening of domains.

The product of the discontinuous transformation has a monoclinic geometry and retains a high degree of Al-Si order with 2t_{1} = 0.78. We could not establish the presence of intermediate triclinic geometries but we could establish that the resulting monoclinic material is highly ordered. It is quite possible that a triclinic Al-Si distribution is also retained although X-ray powder-diffraction techniques could not establish this. It should be observed that this T_{0} occupancy approximates the most commonly observed degree of monoclinic order for natural specimens (Stewart & Wright 1974). This degree of order is also similar to values determined
from structural analyses of orthoclase (Spencer C) and adularia (Spencer B) suggested by Colville & Ribbe (1968) to have "as low a structural state as is observed in 'monoclinic' potassium feldspars." In experiments of longer duration (numbers 14 to 22) the monoclinic feldspar goes through a second continuous disordering stage involving a transfer of Al from the $T_1$ to the $T_2$ site. This is a comparatively slow process approaching completion for annealing times greater than 2000 hours. We regard this as a second homogeneous reaction.

In summary, the sequence of events observed with dry-heating of a triclinic alkali feldspar ($Or_0A_b$) at 1025°C is: (1) Sodium – potassium homogenization. (2) Al–Si disordering with triclinic unit-cell geometry. Al migrates from $T_0$ to $T_m$ and, to a lesser extent, to $T_0$ and $T_{zm}$. (3) Transformation from triclinic to monoclinic unit-cell geometry. The result of this transformation is a highly ordered monoclinic feldspar, not a sanidine. (4) Al–Si disordering with monoclinic unit-cell geometry. Al migrates from $T_1$ to $T_2$ at a much slower rate than during the triclinic disordering.

The disordering process is at least a two-step process and differs from that of the albite end-member, which has been shown (Müller 1969) to be a continuous one-step process.

Applications to natural alkali feldspars

Interpretations of order–disorder processes and of the monoclinic–triclinic transformation in alkali feldspars based upon the structural states of naturally occurring potassium feldspars are hindered by the complexities of the host-rock petrogenesis, including such commonly accepted controls of the structural state as the crystallization and cooling rates of igneous rocks, the heating and cooling rates of metamorphism, the temperatures of igneous intrusion and extrusion and of metamorphism, the presence or absence of fluid phases and the composition of fluid phases. We suggest that the common structural states in the potassium feldspars reflect, in part at least, the multistep order–disorder process outlined in the previous section.

The most rapid step in this process is the change from maximum microcline to intermediate microcline during disordering (or, conversely, the change from intermediate microcline to maximum microcline during ordering). The slowest step is the change from ordered monoclinic feldspar to sanidine. The discontinuous character of the triclinic–monoclinic transformation is indicated by a lack of intermediate triclinic structural states with $t_0 + t_m < 0.80$, which is reflected in gaps on $\alpha^* - \gamma^*$ plots (Fig. 4; Stewart & Wright 1974, p. 370) and on Al occupancy plots (Fig. 5; Stewart & Wright 1974, Fig. 8).

A paucity of intermediate microclines in comparison to the abundance of maximum microcline and monoclinic potassium feldspars was indicated by Dietrich's studies (1961, 1962) of the triclinicity (Goldsmith & Laves 1954) of potassium feldspars from different geological environments and, more recently, has been noted by Stewart & Wright (1974) in their extensive compilation of refined unit-cell parameters of potassium feldspars. The presence of both monoclinic and triclinic phases within single potassium feldspar grains is common (MacKenzie 1954, Emeleus & Smith 1959, Smith & MacKenzie 1959, Wright 1964, 1967, Crosby 1971). The triclinic phase in these occurrences has been described, with one exception (Wright 1967), as intermediate microcline, commonly with a variable structural state; the monoclinic phase has been described as orthoclase. Refined unit-cell parameters for these intermediate microclines reveal, however, that with few exceptions they have $t_0 + t_m > 0.80$ and do not fill the gaps on the $\alpha^* - \gamma^*$ and Al occupancy plots. In fact, the only suite of potassium feldspars known to us to have such intermediate Al occupancies is the suite of metamorphic feldspars described by Guidotti et al. (1973) and included in Stewart & Wright (1974, Fig. 7). The lack of intermediate microclines with $t_0 + t_m < 0.80$ and the occurrence of monoclinic and triclinic unit-cell geometries within single grains of potassium feldspar would be consistent with a discontinuous transformation.

The rates of movement of Al from the $T_0$ site during the disordering process indicated on Figure 6 are also compatible with the relative abundances of potassium feldspar polymorphs (Dietrich 1961, 1962, Stewart & Wright 1974). The most abundant polymorphs should be a monoclinic feldspar with $2t_0 \approx 0.60 - 0.80$ in rocks that cooled relatively rapidly in volcanic or contact metamorphic environments, and a microcline with $t_0 > 0.80$ in more slowly cooled rocks such as plutonic igneous or regional metamorphic environments.

Application of the order–disorder process that we have described is limited by the anhydrous character of our experiments. Similar experiments must be done in $H_2O$-undersaturated and saturated conditions to determine the effects of $H_2O$ upon the process.
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REFERENCES


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