

Angular relations of alkali feldspar series and the triclinic-monoclinic displacive transformation

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Abstract

One measure of monoclinic geometry in alkali feldspars is the angle ϕ between b and b^* . Monoclinic geometry is possessed if ϕ is zero, likewise if the function $(1 - \cos \phi)$ is zero. This function has been found to behave linearly with composition for triclinic members of various alkali feldspar series and is a parameter which can be used to calculate triclinic-monoclinic transformation compositions, temperatures, and pressures. During the present investigation, linear least-squares fits of $(1 - \cos \phi)$ as a function of mole fraction KAlSi_3O_8 were used to calculate transformation compositions for various ion-exchange and synthesis series based on data collected at room temperature and pressure. Transformation compositions using this method are significantly less potassic than those estimated previously by others from observations of peak broadening and splitting on X-ray powder diffraction charts. Furthermore, transformation composition becomes less potassic with increased Al-Si order of the feldspar series. This implies for an individual topochemically monoclinic alkali feldspar that transformation temperature decreases as Al-Si order increases. The critical parameter associated with the transformation seems to be unit-cell volume, as opposed to particular values of individual unit-cell dimensions. Structural changes related to the triclinic-monoclinic transformation in relatively disordered series are apparently paralleled in microcline-low albite series, even though the latter cannot attain monoclinic symmetry.

Introduction

It is known that certain alkali feldspars or alkali feldspar series undergo a displacive transformation from triclinic to monoclinic symmetry (or *vice versa*) and that key variables which cause the transformation to take place are composition (K/Na ratio), temperature, and pressure. A question addressed in the past has been whether the Al-Si distribution is also a factor in the transformation. Though an alkali feldspar must possess a topochemically monoclinic Al-Si distribution in order to transform to monoclinic geometry, various distributions of Al and Si between T_1 and T_2 sites (*i.e.*, different Z-values; Thompson, 1969, 1970) in such a feldspar are possible. These in turn may affect the composition, temperature, and pressure at which the transformation takes place. Generally, systematic single-crystal studies on individual feldspars of different Al-Si distributions as a function of temperature or pressure or composition had not been made before the work of Kroll *et al.* (1980), whose investigation, independent of this one, will be reported in a future issue of *The American Mineral-*

ogist. For the most part the problem has been studied not by investigation of individual feldspars, but rather by an attempt to see if alkali feldspar series of different Al-Si distributions have different transformation compositions at room temperature and pressure. Though such work shows that triclinic-monoclinic transformation compositions are not grossly dependent on Al-Si distribution, the studies have been inconclusive as to whether or not some dependence might exist. The question is a significant one, because if the Al-Si distribution of a feldspar series does affect its triclinic-monoclinic transformation composition, even to a small degree, the implication is that transformation temperatures and pressures of individual feldspars (*e.g.*, analbite-monalbite) would be affected by Al-Si distribution as well. That is, there would be different transformation temperatures and pressures for a given composition, depending on the Z-value of the feldspar.

In attempting to detect transformation compositions based on X-ray powder diffraction data, the principal method employed has been to look for

broadened or split peaks for feldspars whose compositions are near the suspected transformation composition (e.g., Orville, 1967; Wright and Stewart, 1968). This method suffers from the requirement that one must be able to recognize very small changes in peak widths for feldspars whose compositions are near the transformation composition. Even for one using the most objective criteria, the precision obtainable with this method is less than desirable. Furthermore, this method may lead to inaccurate results. For example, if a feldspar near the transformation composition is not perfectly homogeneous but possesses a small compositional range, the relatively sodic parts of the crystals will cause peak broadening or splitting, even if the bulk composition is on the potassic side of the transformation composition.

Other methods for determination of transformation compositions have also been employed. Orville (1967) and Kroll (1971) have plotted the difference in 2θ for "split" peaks [e.g., (131)–($\bar{1}\bar{3}1$) or (111)–($\bar{1}\bar{1}1$)] against composition and extrapolated to the transformation composition, where the difference is zero. Such relationships do not behave linearly, and extrapolation here also leads to precision which is less than desirable.

Waldbaum (1974) [also Thompson *et al.* (1974, p. 241)] used functions of the interaxial angle α to determine transformation compositions, though the details of his work were never published and it is not known what specific functions he used. The results for the three feldspar series he studied agree well with mine. Kroll (personal communication) more recently has used the function $\cos^2\alpha$ to determine transformation compositions, independent of Waldbaum's results. Results on his feldspars agree well with those presented here.

The object of the current investigation (Hovis, 1977a) was to find a parameter that behaved linearly with composition, and which could be used to determine triclinic–monoclinic transformation compositions based on room temperature X-ray data which now exist for a number of alkali feldspar series. The methods employed here are equally applicable in finding inversion temperatures and pressures for individual topochemically monoclinic alkali feldspars with fixed K/Na ratios.

Alkali feldspar series

It is important to recognize in what follows that at least three different types of feldspar series have been studied to date (Table 1).

Table 1. Feldspar series synthesized by various investigators

<u>Ion-exchange series</u>	
Sanidine-analbite:	Hovis, 1977b
Orthoclase-analbite:	Wright and Stewart, 1968 Hovis, in preparation
Adularia-analbite:	Hovis, Waldbaum, and Thompson, 1976
Microcline-low albite:	Orville, 1967 Waldbaum, 1966; Waldbaum and Robie, 1971
<u>Short-term crystallization series</u>	
Sanidine-high albite:	Donnay and Donnay, 1952 Orville, 1967 Luth and Querol-Suñé, 1970
<u>Long-term crystallization series</u>	
Sanidine-high albite:	Kroll, 1971, five series; 950°, 900°, 850°, 800°, 750° C (also Kroll <i>et al.</i> , 1980)

Ion-exchange series

An ion-exchange series is made by starting with a single natural feldspar and changing its composition by ion-exchange techniques, either hydrothermal (e.g., the microcline–low albite series of Orville, 1967), molten salt (e.g., the feldspar end members of Waldbaum and Robie, 1971), or dry powder (e.g., intermediate members of the microcline–low albite series of Waldbaum and Robie, 1971). Since the ion exchange is generally short-term relative to times needed for Al–Si ordering/disordering, all members of such series are most likely to have a constant, or very nearly constant, Al–Si distribution inherited from the parent feldspar. Thus, on a plot of $\cos \gamma - \cot \alpha^*$ (Thompson and Hovis, 1978), triclinic members of such a series produce a line nearly parallel (with a slightly negative slope) to the $\cot \alpha^*$ axis (Fig. 1a).

Short-term crystallization series

Short-term crystallization series have been made by starting with glasses (e.g., Donnay and Donnay, 1952) or dehydrated gels (Luth and Querol-Suñé, 1970) of different alkali feldspar compositions and hydrothermally crystallizing such materials to produce the desired feldspars. Synthesis times generally have been on the order of 5 to 14 days for such series, owing to the relatively short time needed for crystallization at elevated temperatures. The calculations of Thompson *et al.* (1974) indicate that hydrothermally crystallized series in general tend first to crystallize

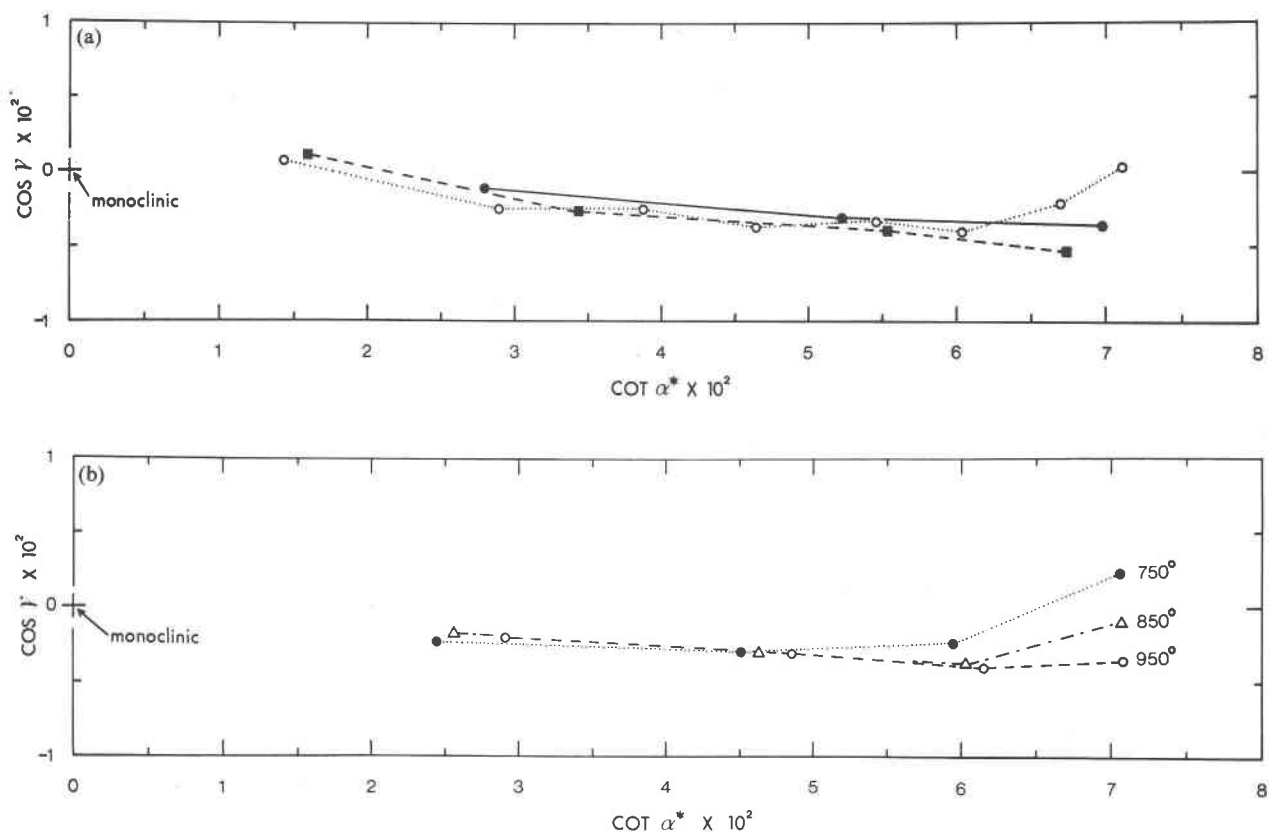


Fig. 1. $\cos \gamma$ vs. $\cot \alpha^*$ for triclinic members of various alkali feldspar series. Na/K of series members increases from left to right. (a) Solid symbols are for sanidine (circles; Hovis, 1977b) and orthoclase (squares; Hovis, in preparation) ion-exchange series. Open circles are for the sanidine short-term crystallization series of Orville (1967). Note that for ion-exchange series $\cos \gamma$ increases slightly with increased potassium content. For the short-term synthesis series, however, $\cos \gamma$ also increases toward the sodium end of the series, indicating a more ordered (topochemically triclinic) Al-Si distribution for the most sodic series members. (b) Three of five long-term crystallization series of Kroll. The 800° and 900°C series were omitted for simplicity but indicate the same relationships as the three series shown. Compositions of the feldspars in each series from left to right are $N_{Or} = 0.3, 0.2, 0.1,$ and 0. Note the increase in $\cos \gamma$ toward the sodium end of the series, which is different from the behavior of ion-exchange series shown in part (a). Al-Si distribution changes along all series. For feldspars synthesized at 950°C, all series members are probably topochemically monoclinic, with the possible exception of the sodic end member. The most sodic members of other series are topochemically triclinic, with ordering increasing as equilibration temperature decreases.

with a very disordered Al-Si distribution, then proceed toward a more ordered equilibrium distribution consistent with the synthesis conditions. Since Al-Si ordering is a relatively longer-term process, short-term crystallization series probably tend to possess more disordered Al-Si distributions than would otherwise be indicated by their synthesis conditions. It is also well known that K/Na ratio affects the kinetics of order/disorder (as well as the Al-Si distribution itself) in alkali feldspars, with more potassic feldspars needing longer times for equilibration. Even in short-term crystallization series, Al-Si distribution may be relatively more ordered as one proceeds from the potassic to the sodic end of the series, assuming all series members were synthesized under similar condi-

tions. Thus, on the $\cos \gamma$ - $\cot \alpha^*$ plot (Fig. 1a) the more sodic members of Orville's sanidine-analbite series tail upward to higher values of $\cos \gamma$ and are topochemically triclinic, even though more potassic series members are topochemically monoclinic (Thompson and Hovis, 1979).

Long-term crystallization series

A long-term crystallization series differs from those just discussed in that synthesis times are long enough to produce equilibrium, or at least steady-state, Al-Si distributions (e.g., series of Kroll, 1971; also Kroll *et al.*, 1980). Even for relatively sodic members of such series, this may take weeks or months, depending on the particular composition,

temperature, and pressure of synthesis (Kroll, 1971). In such a series the Al-Si distribution definitely changes across the series, as evidenced by the curvature of $\cos \gamma$ values with $\cot \alpha^*$ (Fig. 1b) as composition changes. These series also have the potential to yield important thermodynamic information, especially when studied at the conditions of equilibration.

Obliquity

One measure of monoclinic geometry in an alkali feldspar is the angle ϕ (referred to as *obliquity* by Donnay, 1940) between b and b^* . The cosine of this angle is related to the unit-cell interaxial angles as

$$\cos \phi = \sin \alpha^* \sin \gamma \quad (1)$$

(Thompson and Hovis, 1978; see also Donnay, 1940; Gay, 1956). In a dimensionally monoclinic feldspar ϕ is zero, $\cos \phi$ is 1, and the quantity $(1 - \cos \phi)$ is 0. Thompson and Hovis (unpublished data) have used the latter quantity to determine a monalbite-analbite transition temperature. It may be used equally well to determine transformation compositions in alkali feldspar series at room temperature and pressure.

Methods

Linear least-squares fits of $(1 - \cos \phi)$ were performed for triclinic members of all alkali feldspar series listed in Table 1, except for low albite-microcline. Generally, data for feldspars whose chemical compositions were within a few mole percent of the transformation compositions were not used in the calculations, unless they were clearly triclinic. For each feldspar series the transformation composition was determined simply by extrapolating the calculated line to a $(1 - \cos \phi)$ value of zero.

Since it was known that transformation composition would not be grossly dependent on Al-Si distribution, it was necessary to insure that any apparent dependence of transformation composition on Al-Si distribution was not due simply to inconsistent chemical analyses of the feldspars. Therefore, feldspars of the three ion-exchange series (sanidine, orthoclase, and adularia) from our laboratory (see Table 1) were reanalyzed by Mr. Norman Suhr at the Pennsylvania State University so that comparisons could be based on an internally consistent set of chemical data. This is also the reason why transformation compositions reported here for these series differ slightly from previously reported values (Hovis *et al.*, 1976; Thompson and Hovis, 1979).

Values of $(1 - \cos \phi)$ also were calculated for members of two topochemically triclinic microcline-

low albite series (Orville, 1967; Waldbaum, 1966; Waldbaum and Robie, 1971; see also Hovis and Peckins, 1978). While it is not possible for either of the series to attain true monoclinic symmetry, it is interesting to compare the behavior of $(1 - \cos \phi)$ in these series to that in other feldspars.

Results

Linearity

Plots of $(1 - \cos \phi)$ vs. composition for the various feldspar series (Figs. 2 to 4) exhibit strikingly linear relationships (Hovis, 1977a). This is true both of feldspar series with large numbers of data points, for example the sanidine series of Orville (1967; Fig. 3), and of series with only three or four data points, where one might expect any one data point to be badly out of line with the others. Linearity is evident, especially for the sanidine series of Donnay and Donnay (1952, as reinvestigated by Wright and Stewart, 1968; Fig. 3), several of Kroll's (1971) sanidine series (Fig. 4), and the sanidine and orthoclase series of Hovis (Fig. 2; 1977b and in preparation).

Transformation compositions

Transformation compositions calculated by this method are significantly lower in N_{Or} (mole fraction $KAlSi_3O_8$), generally by 0.05 to 0.08, than those estimated by others from visual detection of peak broadening on X-ray powder diffraction charts (see Table 2). It is noteworthy that our results agree well with those of Waldbaum (1974 and personal communication), who estimated inversion compositions for three of the sanidine series using functions of the interaxial angle α . Also Kroll's calculations (personal communication) using the function $\cos^2 \alpha$ on his feldspars agree with the present results for his series.

Dependence of transformation composition on Al-Si distribution

This investigation indicates that transformation composition at room temperature is dependent on Al-Si distribution. This is seen in two bodies of data (Table 2), those of the ion-exchange series and those of the five long-term crystallization series of Kroll (1971).

The sanidine (Hovis, 1977b), orthoclase (Wright and Stewart, 1968; Hovis, in preparation), and adularia (Hovis *et al.*, 1976; Hovis, in preparation) ion-exchange series indicate that transformation composition decreases in the mole fraction of $KAlSi_3O_8$ from 0.353 to 0.309 with an increase in ordering cor-

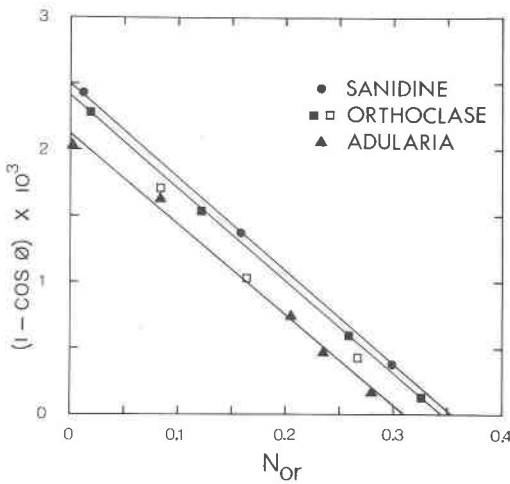


Fig. 2. $(1 - \cos \phi)$ vs. N_{Or} for alkali feldspar ion-exchange series. Lines are least-squares fits to data for sanidine (circles; Hovis, 1977), orthoclase (closed squares; Hovis, in preparation), and adularia (triangles; Hovis *et al.*, 1976 and Hovis, in preparation) ion-exchange series. Open squares are data for a second orthoclase series (Wright and Stewart, 1968). Note that triclinic-monoclinic displacive transformation compositions, where the lines extrapolate to a $(1 - \cos \phi)$ value of 0, decrease in N_{Or} with increased ordering. This is a revised version of Fig. 5b in Thompson and Hovis (1979) based on (1) the new chemical data referred to in the text and (2) additional members of the sanidine and adularia series.

responding to a change in Z of at least 0.5. This cannot be ascribed to inconsistent chemical data, since feldspars from the three series were reanalyzed to assure internal consistency. Transformation composi-

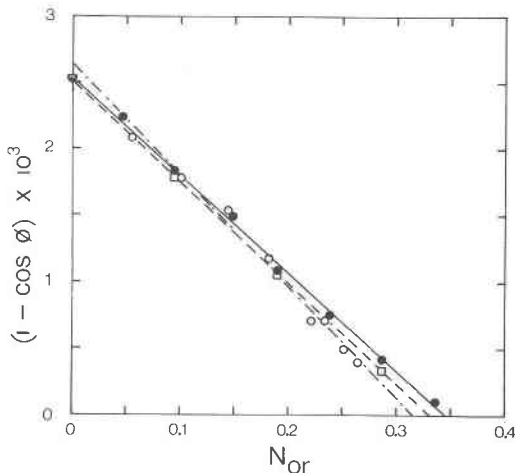


Fig. 3. $(1 - \cos \phi)$ vs. N_{Or} for alkali feldspar short-term crystallization series. Lines are least-squares fits to the sanidine series of Donnay and Donnay (dashed line, open squares, 1952; data presented are the revised data for the series as given by Wright and Stewart, 1968), Orville (solid line and solid circles; 1967), and Luth and Querol-Suñé (dash-dot line, open circles; 1970).

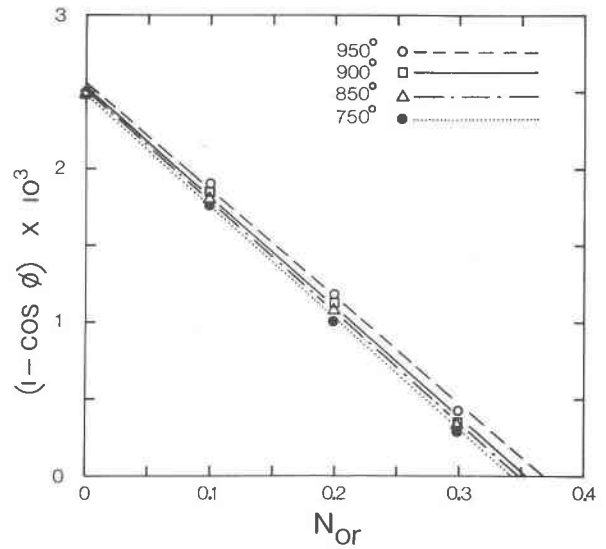


Fig. 4. $(1 - \cos \phi)$ vs. N_{Or} for alkali feldspar long-term crystallization series. Lines are least-squares fits to the data of Kroll (1971) for feldspar series synthesized at the indicated temperatures for periods long enough to produce equilibrium, or at least steady-state Al-Si distributions. Al-Si distribution changes with composition. Displacive transformation compositions systematically decrease in N_{Or} with increased ordering. (To improve clarity, data for the 800°C series were omitted. This series behaves similarly to the other series and has a displacive transformation composition between those of the 750° and 850°C series.)

tions calculated prior to the new analyses, based on chemical data collected by Geochron, Inc. and at Princeton University, were 0.017 lower in N_{Or} (*i.e.*, from 0.336 for sanidine to 0.292 for adularia) than those reported in Table 2, but nevertheless gave the same relative results. Thus, the new set of chemical data confirms our original findings. If the latter values are used, rather than those in Table 2, better agreement between the transformation compositions for our orthoclase series and that of Wright and Stewart (1968) is attained.

Further suggestion that transformation composition is dependent on Al-Si distribution (or Z) is found in analyzing calculations based on Kroll's (1971) data (Fig. 4). Kroll synthesized five feldspar series, each at a different temperature in 50° intervals from 950° to 750°C, and for times long enough to reach equilibrium, or at least steady-state, Al-Si distributions, the lower-temperature series being more ordered at any particular composition. The significance of calculated transformation compositions of these series is somewhat different than for other series because Al-Si distribution changes across the series. Even though some series members are topo-

Table 2. Triclinic-monoclinic transformation compositions for various alkali feldspar series

	Transformation composition estimated by original investigator(s), N_{Or}	Transformation composition calculated during present investigation, N_{Or}^{**}	Value of ($1 - \cos \phi$) $\times 10^3$ at $N_{Or} = 0$
ION-EXCHANGE SERIES			
<u>Sanidine-analbite</u>			
Hovis, 1977b	- - -	0.353 \pm .001	2.50 \pm .01
<u>Orthoclase-analbite</u>			
Wright and Stewart, 1968	0.386 \pm .028	0.324 \pm .037	2.24 \pm .14
Hovis, in preparation	- - -	0.344 \pm .001	2.40 \pm .01
<u>Adularia-analbite</u>			
Hovis, Waldbaum, and Thompson, 1976	- - -	0.309 \pm .005	2.12 \pm .04
SHORT-TERM CRYSTALLIZATION SERIES			
<u>Sanidine-high albite</u>			
Donnay and Donnay, 1952	0.332 \pm .005*	0.324 \pm .013	2.63 \pm .05
Wright and Stewart, 1968 (Donnay and Donnay series)	0.386 \pm .028	0.331 \pm .002	2.52 \pm .01
Orville, 1967	0.420 \pm .020	0.341 \pm .003	2.54 \pm .01
Luth and Querol-Suñé, 1970	0.375 \pm .035*	0.314 \pm .005	2.64 \pm .03
LONG-TERM CRYSTALLIZATION SERIES			
<u>Sanidine-high albite (or analbite)</u>			
Kroll, 1971:			
950°C, 0.2 kbar, 5 days	0.400	0.366 \pm .012	2.54 \pm .03
900°C, 0.4 kbar, 10.8 days	- - -	0.353 \pm .011	2.52 \pm .03
850°C, 0.7 kbar, 21 days	- - -	0.347 \pm .005	2.51 \pm .02
800°C, 1 kbar, 28 days	- - -	0.344 \pm .007	2.51 \pm .03
750°C, 1 kbar, 70 days	- - -	0.341 \pm .001	2.48 \pm .01

* Inversion composition taken as mid-point between most potassic triclinic feldspar and least potassic monoclinic feldspar of the series. Uncertainty is half the difference between these two compositions.

**Stated uncertainties are one standard error for the inversion compositions determined from linear least-squares fits of ($1 - \cos \phi$) vs. N_{Or} .

chemically triclinic, however, the series do transform to monoclinic symmetry at some composition, and it is valid to use data for all geometrically triclinic series members, whether topochemically triclinic or monoclinic, to calculate these compositions. Note that calculated inversion compositions decrease systematically for all series from 0.366 for the 950°C series to 0.341 for the 750°C series. While the changes from one series to the next are small and generally not outside the combined uncertainties of the calculated transformation compositions, it seems very fortuitous that so systematic a change with synthesis temperature is exhibited. Furthermore, the differences between the calculated transformation compositions of the higher temperature vs. the lower temperature series are outside the combined uncertainties of the calculations.

Intercepts at $N_{Or} = 0$

An interesting feature of the linear least-squares fits is the calculated intercept of ($1 - \cos \phi$) for each series at $N_{Or} = 0$ (Table 2). Intercepts of the ten sanidine series range from 2.48×10^{-3} to 2.64×10^{-3} , averaging 2.54×10^{-3} , but for the orthoclase and adularia series are significantly lower at $2.32(\pm 0.08) \times 10^{-3}$ and 2.12×10^{-3} , respectively. Therefore, values of the intercepts decrease with increased Al-Si order and are themselves indicators of the specific Z-values of the series. It is obvious from Figures 2 and 4 that in general at any one K/Na ratio ($1 - \cos \phi$) increases as Z decreases.

Equilibrium temperatures

From Kroll's (1971) data it is possible to calculate equilibrium temperature as a function of composi-

tion and $(1 - \cos \phi)$ as measured at room temperature. The simplest least-squares fit to his data yields:

$$T(^{\circ}\text{C}) = -1.96(15) \times 10^3 + 8.03(41) \times 10^3 N_{\text{Or}} + 1.12(6) \times 10^6 (1 - \cos \phi) \quad (2)$$

which corresponds to a standard deviation of fit of $\pm 50^{\circ}\text{C}$. If one tries various second-order relations, the best fit to the data is:

$$T(^{\circ}\text{C}) = -2.45(15) \times 10^3 + 8.74(20) \times 10^3 N_{\text{Or}} + 2.47(28) \times 10^3 N_{\text{Or}}^2 + 1.32(6) \times 10^6 (1 - \cos \phi) \quad (3)$$

with a standard deviation of $\pm 45^{\circ}\text{C}$.

Technically it is not valid to apply these equations to the ion-exchange series, where Al-Si distribution is constant across each series, but slopes of N_{Or} vs. $(1 - \cos \phi)$ for ion-exchange and long-term crystallization series are quite similar (Figs. 2 and 4, Table 2), so it is acceptable to test these equations on the adularia, orthoclase, and sanidine series to see if calculated temperatures are reasonable. Average temperatures of equilibration for members of these three series based on equation (2) are 469° , 769° , and 852°C , respectively; based on equation (3) they are 386° , 752° , and 846°C . The most interesting test of Kroll's data is the result from the adularia series, because it represents a lower temperature of equilibration than any of Kroll's series and is therefore an extrapolation considerably outside his data range. The temperatures calculated seem quite reasonable for this specimen of adularia (#7007; see Hovis, 1974, and Phillips and Ribbe, 1973), which crystallized as a potassic ($N_{\text{Or}} = 0.88$) monoclinic feldspar in an alpine vein deposit (St. Gotthard, Switzerland). Such a deposit crystallized at relatively low temperatures, but nevertheless above the microcline-orthoclase (adularia) transition temperature, which has been estimated to occur between $450^{\circ} \pm 50^{\circ}\text{C}$ (Hovis, 1974) and 525°C (Goldsmith and Laves, 1954) in the pure KAlSi_3O_8 system.

The temperatures for the orthoclase series also seem reasonable, the specimen (#B18938, Smithsonian Institution) coming from a Madagascar pegmatite. The sanidine series is based on a specimen of Amelia albite (Hovis, 1977b) disordered at 1052°C (1 atm) for 710 hours under dry conditions, thus the calculated temperatures seem a bit low. However, we have no way of knowing whether the specimen reached an equilibrium Al-Si distribution under these conditions. In fact, on a b - c plot (Hovis, 1977b)

sodic members of this series cross the 950° , 900° , and 850°C series of Kroll and closely parallel the short-term synthesis series of Orville (1967), so the calculated temperatures may be reasonable.

Based on these calculations it is likely that Kroll's feldspars not only reached steady-state Al-Si distributions, but that these are equilibrium distributions for the synthesis temperatures.

Values of unit-cell dimensions at transformation compositions

Hazen (1976) has pointed out that disordered alkali feldspars of various compositions have similar unit-cell dimensions at their transformation pressures and temperatures. Based on the present investigation, unit-cell volume is probably the critical parameter associated with the triclinic-monoclinic transformation, rather than individual unit-cell dimensions. Least-squares fits of unit-cell dimensions and volumes as functions of composition for the three ion-exchange series produced by our laboratory (Table 3) indicate that triclinic-monoclinic transformation values of these parameters at room temperature and pressure change with Al-Si order. While the transformation value of the a unit-cell dimension decreases slightly, b decreases and c and β increase markedly with increasing Z . The changes in b and c from the sanidine to the adularia series are equivalent to about 40% of those from the K- to Na-end of an ion-exchange series. Though the transformation value for volume also appears to decrease with increasing Z , the change from the sanidine to the adularia series reported in Table 3 is equivalent to only about 8% of that from the K- to the Na-end of an ion-exchange series and thus represents a small range of values.

Microcline-low albite series

Behavior of the topochemically triclinic microcline-low albite series (Fig. 5) of Orville (1967) and Waldbaum and Robie (1971; also Hovis and Peckins, 1978) parallels that of those series in which monoclinic symmetry actually can be achieved. At the sodium-rich end of these series values of $(1 - \cos \phi)$ decrease rapidly with the substitution of K for Na, though not quite so rapidly as in the other feldspar series. Although no members of these series attain $(1 - \cos \phi)$ values of zero, both series reach limiting values of about 0.0008 at an N_{Or} of approximately 0.6 and maintain this value to the potassium end.

The behavior of $(1 - \cos \phi)$ in microcline-low albite series relative to that in other alkali feldspar se-

Table 3. Values of unit-cell dimensions and volumes at triclinic-monoclinic transformation compositions, pressures, and temperatures

	N_{Or}	P(kbar)	T(°C)	a(Å)	b(Å)	c(Å)	β (deg)	V(Å ³)
<u>This investigation</u>								
Sanidine	0.353	.001	25	8.31	12.97	7.15	116.21	691.5
Orthoclase	0.344	.001	25	8.29	12.93	7.17	116.29	689.0
Adularia	0.309	.001	25	8.28	12.91	7.18	116.31	687.0
<u>Hazen, 1976</u>								
Sanidine	0.82	18	25	8.30	12.97	7.14	116.2	689.7
	0.67	12	25					
<u>Okamura and Ghose, 1975</u>								
Monalbite (disordered)	0.01	.001	930	8.26	12.97	7.14	116.10	686.9

ries supports the suggestion by a number of investigators that structural changes accompanying the substitution of K for Na in alkali feldspars are similar in all feldspar series, regardless of Al-Si distribution.

Summary

The quantity $(1 - \cos \phi)$ appears to be a linear function of composition for various alkali feldspar series and is a useful parameter that can be used to calculate triclinic-monoclinic transformation compositions, temperatures, and pressures. Triclinic-mono-

clinic transformation compositions calculated from this function at room temperature and pressure are generally less potassic than those estimated from peak broadening on X-ray powder diffraction charts.

Transformation composition at room temperature and pressure depends on the Al-Si distribution of the feldspar, as indicated by the systematic decrease of transformation composition with increased Al-Si order for the four ion-exchange series and also by the systematic change of transformation composition with synthesis temperature for the five series of Kroll (1971). This suggests that the transformation temperature and pressure for an individual topochemically monoclinic alkali feldspar is dependent on its Z-value, as has been suggested by some for the monalbite/analbite transition. Based on the present investigation, as well as on the transformation temperature for disordered analbite (Kroll, 1971; Thompson *et al.*, 1974; Okamura and Ghose, 1974; Kroll *et al.*, 1980), the transformation temperature for a relatively ordered analbite (corresponding to adularia) would be about 140°C below that of its disordered analogue.

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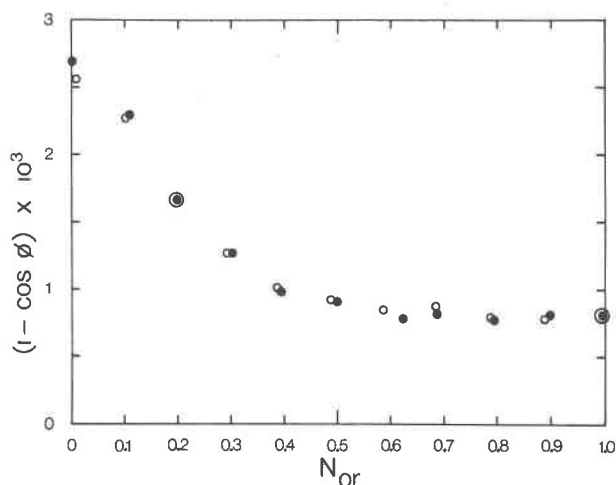


Fig. 5. $(1 - \cos \phi)$ vs. N_{Or} for microcline-low albite crystalline solutions. Data are for the series of Orville (open circles, 1967) and Waldbaum and Robie (closed circles, 1971). Actual data presented for the latter series are the revised data of Hovis and Peckins, 1978. Note the similar behavior of $(1 - \cos \phi)$ for these series to that in the other alkali feldspar series, even though monoclinic geometry cannot be attained.

References

- Donnay, G. and J. D. H. Donnay (1952) The symmetry change in the high-temperature alkali feldspar series. *Am. J. Sci.*, 250A, 115–132.
- Donnay, J. D. H. (1940) Width of albite-twinning lamellae. *Am. Mineral.*, 25, 578–586.
- Gay, P. (1956) A note on albite twinning in plagioclase feldspars. *Mineral. Mag.*, 31, 301–305.
- Goldsmith, J. R. and F. Laves (1954) The microcline–sanidine stability relations. *Geochim. Cosmochim. Acta*, 5, 1–19.
- Hazen, R. M. (1976) Sanidine: predicted and observed monoclinic to triclinic reversible transformations at high pressure. *Science*, 194, 105–107.
- Hovis, G. L. (1974) A solution calorimetric and X-ray investigation of Al–Si distribution in monoclinic potassium feldspars. In W. S. MacKenzie and J. Zussman, Eds., *The Feldspars*, p. 114–144. University of Manchester Press, Manchester, England.
- (1977a) Reevaluation of triclinic/monoclinic inversion compositions at room temperature in alkali feldspars (abstr.). *Geol. Soc. Am. Abstracts with Programs*, 9, 1027.
- (1977b) Unit-cell dimensions and molar volumes for a sanidine–analbite ion-exchange series. *Am. Mineral.*, 62, 672–679.
- and E. Peckins (1978) A new X-ray investigation of maximum microcline crystalline solutions. *Contrib. Mineral. Petrol.*, 66, 345–349.
- , D. R. Waldbaum and J. B. Thompson, Jr. (1976) Molar enthalpy and volume of K–Na mixing for an alkali feldspar ion-exchange series based on monoclinic adularia (abstr.). *Geol. Soc. Am. Abstracts with Programs*, 6, 927–928.
- Kroll, H. (1971) *Feldspäte im System K(AlSi₃O₈)-Na(AlSi₃O₈)-Ca(Al₂Si₂O₈): Al,Si-Verteilung und Gitterparameter, Phasen-Transformationen und Chemismus*. Inaug.-Diss. der Westfälischen Wilhelms-Universität in Münster, Münster, Germany.
- , H.-U. Bambauer and U. Schirmer (1980) The high albite–monalbite and analbite–monalbite transitions. *Am. Mineral.*, 65, in press.
- Luth, W. C. and F. Querol-Suñé (1970) An alkali feldspar series. *Contrib. Mineral. Petrol.*, 25, 25–40.
- MacKenzie, W. S. (1952) The effect of temperature on the symmetry of high-temperature soda-rich feldspars. *Am. J. Sci.*, 252A, 319–342.
- Okamura, F. P. and S. Ghose (1975) Analbite → monalbite transition in a heat treated twinned Amelia albite. *Contrib. Mineral. Petrol.*, 50, 211–216.
- Orville, P. M. (1967) Unit cell parameters of the microcline–low albite and sanidine–high albite solid solution series. *Am. Mineral.*, 52, 55–86.
- Phillips, M. W. and P. Ribbe (1973) The structures of monoclinic potassium-rich feldspars. *Am. Mineral.*, 58, 263–270.
- Thompson, J. B., Jr. (1969) Chemical reactions in crystals. *Am. Mineral.*, 54, 341–375.
- (1970) Chemical reactions in crystals: corrections and clarification. *Am. Mineral.*, 55, 528–532.
- and G. L. Hovis (1978) Triclinic feldspars: angular relations and the representation of feldspar series. *Am. Mineral.*, 63, 981–996.
- and ——— (1979) Structural–thermodynamic relations of the alkali feldspars. *Trans. Am. Crystallogr. Assoc.*, 15, 1–26.
- , D. R. Waldbaum and G. L. Hovis (1974) Thermodynamic properties related to ordering in end-member alkali feldspars. In W. S. MacKenzie and J. Zussman, Eds., *The Feldspars*, p. 218–248. University of Manchester Press, Manchester, England.
- Waldbaum, D. R. (1966) *Calorimetric Investigation of the Alkali Feldspars*. Ph.D. Dissertation, Harvard University, Cambridge, Massachusetts.
- (1974) Critical behavior of the displacive monoclinic–triclinic symmetry change in NaAlSi₃O₈–KAlSi₃O₈ crystalline solutions (abstr.). *Bull. Soc. fr. Mineral. Cristallogr.*, 97, 345.
- and R. A. Robie (1971) Calorimetric investigation of Na–K mixing and polymorphism in the alkali feldspars. *Z. Kristallogr.*, 134, 381–420.
- Wright, T. L. 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 and 2V. *Am. Mineral.*, 53, 38–87.

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