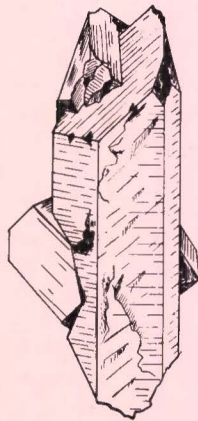


CIRCULAR 62

ALKALI FELDSPARS FROM SOME INTRUSIVE PORPHYRIES OF
SOUTHWESTERN UNITED STATES

by Frederick J. Kuellmer

Reprinted from the Feldspar Symposium at
the Second General Meeting and Congress of
the International Mineralogical Association,
August 22-25, 1960, Copenhagen, Denmark



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Alkali feldspars from some intrusive porphyries of Southwestern United States

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ABSTRACT

Powder X-ray diffraction analysis of the (201) reflections of many perthitic alkali feldspars at room temperature, 750°C., and 1050°C. shows considerable differences which appear to be a function of the relative temperature-structural states of the feldspars. Sanidines remix more rapidly and completely than microclines, whereas orthoclases show all intermediate stages. Variation in rate and completeness of remixing appears to be independent of bulk composition, although the ultimate cause may well be affected by impurity elements and/or lattice defects.

The average bulk composition of the feldspars studied (225) is about $Or_{60}(Ab + An)_{40}$ weight percent, and the compositional range for any porphyry is 20 to 40 + weight percent. Perthitic remixing is accomplished faster and more completely in feldspar specimens from those parts of an igneous sequence which are more porphyritic (Globe-Miami, Arizona; Rabb Canyon, and Hillsboro, New Mexico), more pegmatitic (Rabb Canyon), more eruptive (La Sal Mountains, Utah), and/or more orebearing (Ajo, and Globe-Miami, Arizona; Questa, New Mexico). Thus the perthitic alkali feldspars showing the relatively highest temperature-structural states appear to be found in those parts of an igneous sequence which show the most hydrothermal features.

Such a method of comparing alkali feldspars from an intrusion appears to have value for igneous petrogenesis, as well as ore distribution. The results provide additional evidence of a genetic association between igneous crystallization and ore deposition.

INTRODUCTION

Many studies of mineral variation within homogeneous rock units have been and are being made in order to obtain a better understanding of the conditions of origin of the rock mass. For hypabyssal igneous rocks one may likewise expect rock properties to vary systematically throughout the rock mass according to the conditions of origin, unless all parts of the intrusive have approached identical equilibrium states to the same degree. The present paper, which has been assisted by a research grant from the National Science Foundation, is an attempt to apply some of the newer data on alkali feldspars (LAVES, 1950, 1952; GOLDSMITH and LAVES, 1954 a, b; MACKENZIE and SMITH, 1955, 1956; TUTTLE and BOWEN, 1958) and newer X-ray techniques (BIRKS and FRIEDMAN, 1947; WEISS and ROWLAND, 1956; BASSETT and LAPHAM, 1957) to a study of some Tertiary porphyries of the United States.

Porphyries common throughout the western mountains of both North and South America show a full range in composition from andesite to granite and appear to be hypabyssal (shallow to intermediate depth). Many of the more granitic varieties, of which quartz monzonite may be most common, are about middle Tertiary in age and contain numerous alkali feldspars. Such alkali feldspars are, for the most part, perthitic on an X-ray or microscopic scale, and exhibit the optical properties of sanidine or orthoclase.

In an igneous rock such as a porphyry, the first alkali feldspars would be a homogeneous sanidine which upon cooling should separate into two phases, forming a perthite (LAVES, 1952). This unmixing reaction, which might be written, Homogeneous feldspar \longleftrightarrow cryptoperthite \longleftrightarrow macropertthite, is readily reversible under laboratory conditions (TUTTLE and BOWEN, 1958), although no optically-visible exsolution has been produced. Under simple cooling conditions of an igneous mass, without dynamic metamorphism, the above reaction should proceed to the right, but in most Tertiary porphyries is far from complete. The basic idea of this study was to take a natural alkali feldspar, subject it to various heat-treatments, and compare the extent to which these heat-treatments displaced the unmixing reaction (above) toward the homogeneous feldspar state. The more readily and completely this remixing occurred for any set of laboratory conditions, presumably, the closer the natural feldspar was to its original high-temperature state. One should remember that a high-temperature form may arise through low-temperature inequilibrium crystallization.

However, numerous data are available suggesting that the foregoing hypothesis is subject to considerable limitation and has value primarily in providing geologic-petrographic comparisons. First, GOLDSMITH and LAVES (1954 b) have shown that numerous crystals of similar unmixing status are composed of a range of monoclinic to triclinic states. Such variations occur even within single morphological units.

In using alkali feldspars as a petrographic guide, therefore, it is desirable to study as many morphological units per hand specimen as possible. This in turn almost precludes using single-crystal X-ray diffraction techniques because of the tremendous difficulty involved in adequately summarizing the structural features of all the alkali feldspars in a hand specimen. Second, recent studies of crystal-growth and phase relations demonstrate that even many of the most important crystallographic and solid-state system properties are dependent on impurity elements and lattice defects. Differing concentrations of trace elements such as Li, Rb, and Sr may reflect such differences in pressure-temperature-crystallization rate that variation in perthitic unmixing should not be surprising. These limitations exist in most crystallographic studies of materials from widely separated geological environments.

METHOD OF MEASUREMENT

In order to compare alkali feldspars from an igneous rock or several igneous rocks, many of which may be rather fine-grained, it is necessary to obtain adequately precise compositional and structural data from numerous small-size samples. Bulk compositions of the alkali feldspars are based on (1) spectrographic analysis of Na, K, Ca, Ba, etc. ($\pm 5-10\%$ of the element present), and (2) position of the (201) reflection of heated alkali feldspars (heated more than 48 hours at 1050°C). Each group of spectrographically-analyzed samples included four repeatedly-analyzed feldspar standards. The maximum measured range of the analyses of the feldspar standard compositions was 5.6 wt. % orthoclase (see KUELLMER, 1960 a) and for this reason the spectrographically-analyzed compositions are believed accurate to ± 5 wt. % orthoclase. Measurement of the (201) reflection of heated alkali feldspars, according to BOWEN and TUTTLE, provides only a measure of the orthoclase percent of the total Or + Ab + An. Although the heat-treatment was not sufficient to sanidinize the alkali feldspars, the orthoclase weight percent of the X-ray determined compositions is believed accurate to within a minus 7 % and plus 3 wt. % (see ORVILLE, 1958; KUELLMER, 1960 b).

In using the compositional determinations the alkali feldspars are regarded as a two-component mixture, namely an orthoclase-rich phase and an albitic plagioclase, ignoring the calcic plagioclase component. In an analogous manner plagioclase optical properties are commonly used as a measure of the bulk composition, ignoring the potassium component. An additional justification for this is that the material here studied, with the exception of specimens from the La Sal Mountains, Utah, had morphological and optical properties of a potash-rich feldspar, namely sanidine, or-

thoclase, or microcline. The calcic plagioclase component is most likely to be important in those alkali feldspars which are sodium-rich. Furthermore every attempt was made to correlate the X-ray properties herein described with the calcium content of the alkali feldspar, where known, with little success.

The 2 θ position of the (201) reflection from both phases of the perthite, or one phase of the heated homogeneous-appearing perthite was measured on a Norelco Phillips X-ray goniometer using an internal standard, and are believed accurate to within 0.02°2 θ .

X-ray measurements were made of the variation of the (201) spacings with time and temperature of heating by means of a furnace built onto a Phillips X-ray goniometer diffractometer. This furnace was a modification of one built by G. L. DAVIS of the Geophysical Laboratory who generously furnished the author with complete plans and photographs of his apparatus. This furnace was calibrated by (1) melting various compounds and noting the temperature at which characteristic X-ray reflections disappeared, (2) measuring the thermal expansion of lattice spacings of extremely pure Pt and Ag powders, and by (3) auxiliary thermocouples placed at various points on the upper surface of the powdered sample. The recorded temperature is believed accurate to $\pm 20^\circ\text{C}$, and the (201) spacings at higher temperatures accurate to $\pm 0.05^\circ 2\theta$.

Feldspar powders, prepared, mounted and heated in exactly the same way, were X-rayed during heat-treatment by means of this furnace. Samples were heated from room temperature to 750°C in a uniform manner, and maintained at this temperature in general for periods of more than 10 hours, and as much as 30 hours, during which time the position of the (201) reflection was recorded. During this heat-treatment the (201) spacing of the potassium-rich phase of a perthitic alkali feldspar increases as a consequence of the temperature-increase, or if any remixing of the perthite phases occurs, decreases (or increases less than the normal amount). The reason for the decrease in the (201) spacing during heat-treatment is that the potassium-rich phase of the perthitic alkali feldspar accepts more sodium (see BOWEN and TUTTLE, 1950). For a homogeneous sanidine the (201) spacing is proportional to the sodium-potassium composition (see TUTTLE and BOWEN, 1958). The more readily and completely the (201) spacing of a perthitic feldspar, during and after heat-treatment, corresponds to that expected from the bulk composition, the less the natural perthitic feldspar has unmixed from its original homogeneous high-temperature state.

COMPOSITIONAL VARIATION

Table I presents the bulk composition of a large number of perthitic alkali feldspars from intrusive

Table I

APPROXIMATE BULK COMPOSITION OF THE EXAMINED PERTHITIC ALKALI FELDSPARS

Locality in U. S. A.	Rock Unit	No. of Samples in Each Compositional Range *								Total No.
		21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100	
Mt. Pennell Utah ^b	Qz. Monz. Por.				4	1				5
	Rhyolite Tuff			2		7	3			12
Grant Co., New Mex.	Sanidine Por.				2	14	4			20
	Sanidine Pegmatite					1				1
Idaho ^c	Tert. Por.			1	2	2				5
Hillsboro, New Mex.	Qz. Monz. Por.			1	18	10	2			31
Questa, New Mex. ^d	Soda Granite		1	1	3	6	3	2		16
	Diorite Por.		1	1						2
La Sal Mts., Utah ^b	Monz. Por.	2		1						3
	Syenite		1			1				2
	Feld. Sy. & Gr.	1	2	1				1		5
California-Idaho- Washington	Nevadan Intrus. ^e			2			6	1		9
Miami, Arizona	Lost Gulch Qz. Monz.					3	11	14	4	32
	Gr. Por.					3	7	3		13
	Schultze Granite				1	8	6			15
Ajo, Arizona	Cornelia Qz. Monz.	1				3	9	1		14
	Porphyry					1	7	1		9
Twin Buttes Quad. Ariz. ^f	Tertiary						12	2		14
	Mig.					2	3			5
	pre Cambr.					2	4			6
	Vein Peg.					1	2	1		4

a. Composition range given in Orthoclase weight percent of the total Or + Ab + An content.

b. Samples from C. B. HUNT.

c. Samples from W. B. HAMILTON.

d. Samples from J. H. SCHILLING.

e. Samples from W. B. HAMILTON, C. A. HOPSON, and A. C. WATERS.

f. Samples collected with J. COOPER. Rock unit names are field terms, representing different textures.

rocks of the western United States, expressed in terms of Or weight percent of the total Or + Ab (+ An) content. The compositions summarized in Table I are believed accurate to within about 10 weight percent. This includes both spectrographically and X-ray determined compositions.

The table demonstrates that even a small homogeneous hypabyssal porphyry may exhibit a considerable range of alkali feldspar bulk composition. The average bulk composition of all alkali feldspars in Table I is 69 weight percent orthoclase. It may be significant that all the Arizona samples (Ajo, Miami, and Twin Buttes) are richer in orthoclase content than the New Mexico samples (Questa, Hillsboro, and Grant County). All of the sample groups, with the exception of the La Sal specimens and one Ajo specimen, contain more orthoclase than albite (and anorthite) and do not extend across the compositions of the minimum-temperature trough of the system- $\text{NaAlSi}_3\text{O}_8$ - KAlSi_3O_8 (TUTTLE and BOWEN, 1958).

THERMAL EXPANSION OF (201) SPACINGS OF HOMOGENEOUS ALKALI FELDSPARS

In order to compare remixing rates of the perthitic alkali feldspars during heat-treatment, information concerning the expansion properties of homogeneous alkali feldspar phases is necessary. Such data are presented in Figure 1. Note that the figure shows the measured 2θ positions (for $\text{CuK}\alpha$ radiation) plotted against the temperature, instead of the actual lattice spacing. All the feldspars here depicted show about the same decrease in 2θ , namely 0.20 degrees, between room temperature and 740°C. For this reason the (201) thermal expansion is believed to be the same magnitude for all homogeneous alkali feldspars regardless of temperature state or composition.

Both the high and low albite (Fig. 1) samples are from the same material, one part of which was heat-treated (KUELLMER, 1959, p. 656) and the other not. The composition of this albite from a pegmatite near Ribera, New Mexico is $\text{Or}_{0.3}\text{Ab}_{94}\text{An}_5$ (± 5) wt. % (KUELLMER, 1960 a). The difference between the high and low-form curves may well be due to a slight compositional difference in the high-form, as a result of the heat-treatment which would remix all Na, Ca, and K to a more homogeneous phase.

The homogeneous moonstone (Fig. 1) refers to a moonstone sanidine specimen from a high-temperature pegmatite in Rabb Canyon, Grant County, New Mexico which was heated to 900°C for several days to remix the perthitic phases. A bulk composition of $\text{Or}_{63}\text{Ab}_{34}\text{An}_3$ (± 5) wt. %, was determined by spectrographic analysis (see KUELLMER, 1960 a). A part of the moonstone specimen was quenched; i.e. cooled to room temperature in less than one minute;

whereas a second part was annealed, i.e. cooled to less than 100°C in about 10 hours. Samples from both quenched and annealed parts of this moonstone specimen show no pronounced differences in thermal behavior.

Linear thermal expansion of three microcline specimens from pegmatites in northern New Mexico is shown by the squares, triangles, and black dots adjacent to the word "Microclines" in Figure 1. The specimen indicated by the black dot has an approximate composition of $\text{Or}_{78}\text{Ab}_{22}$ (± 5) wt. %, based on spectrographic analysis, and therefore may contain some albite; whereas the composition of the other specimens is unknown.

The sanidine expansion (Fig. 1) is based on a synthetic sanidine (KAlSi_3O_8), crystallized at 800°C and 1000 bars water pressure for a period of six days, and generously loaned to the author by PHILIP M. ORVILLE of the Geophysical Laboratory. The difference between the microcline and sanidine variations is probably due to the sodium content of the natural microclines.

For comparison (Fig. 1), the thermal expansion of the $(10\bar{1}0)$ spacing of part of a large oscillator-grade quartz crystal is shown. The quartz determinations were made because many of the natural perthite feldspars were so poikilitically intergrown with quartz that complete quartz removal during sample preparation appeared impossible. Each set of symbols (circles, squares, black dots, etc.) in Figure 1 for quartz refers to replicate determinations on the same powdered quartz, and thus furnishes some idea of the reproducibility of the measurements. The measurements in the vicinity of the low-high quartz transition are less accurate than the remaining points, for the reflections were changing more rapidly than they could be recorded by the Geiger counter. The change in 2θ from room temperature to 750°C for the quartz here studied is about 0.30°, and that illustrated by BASSETT and LAPHAM (1957) for a similar temperature range is about 0.36°.

COMPARATIVE REMIXING OF PERTHITIC FELDSPARS

Sanidine and Microcline Perthites.

Figure 2 shows the variation of the (201) reflections for the potash-rich phase of various sanidine and microcline perthites as a function of the time of heat-treatment at 750°C. The vertical scale for this figure and all similar subsequent figures is the 2θ value (for $\text{CuK}\alpha$ radiation) of the potash-rich (201) reflection. The horizontal scale is the duration of the heating cycle at 750°C in hours. During the first hour and a half, the sample temperature was being raised from room temperature to 750°C. This is indicated

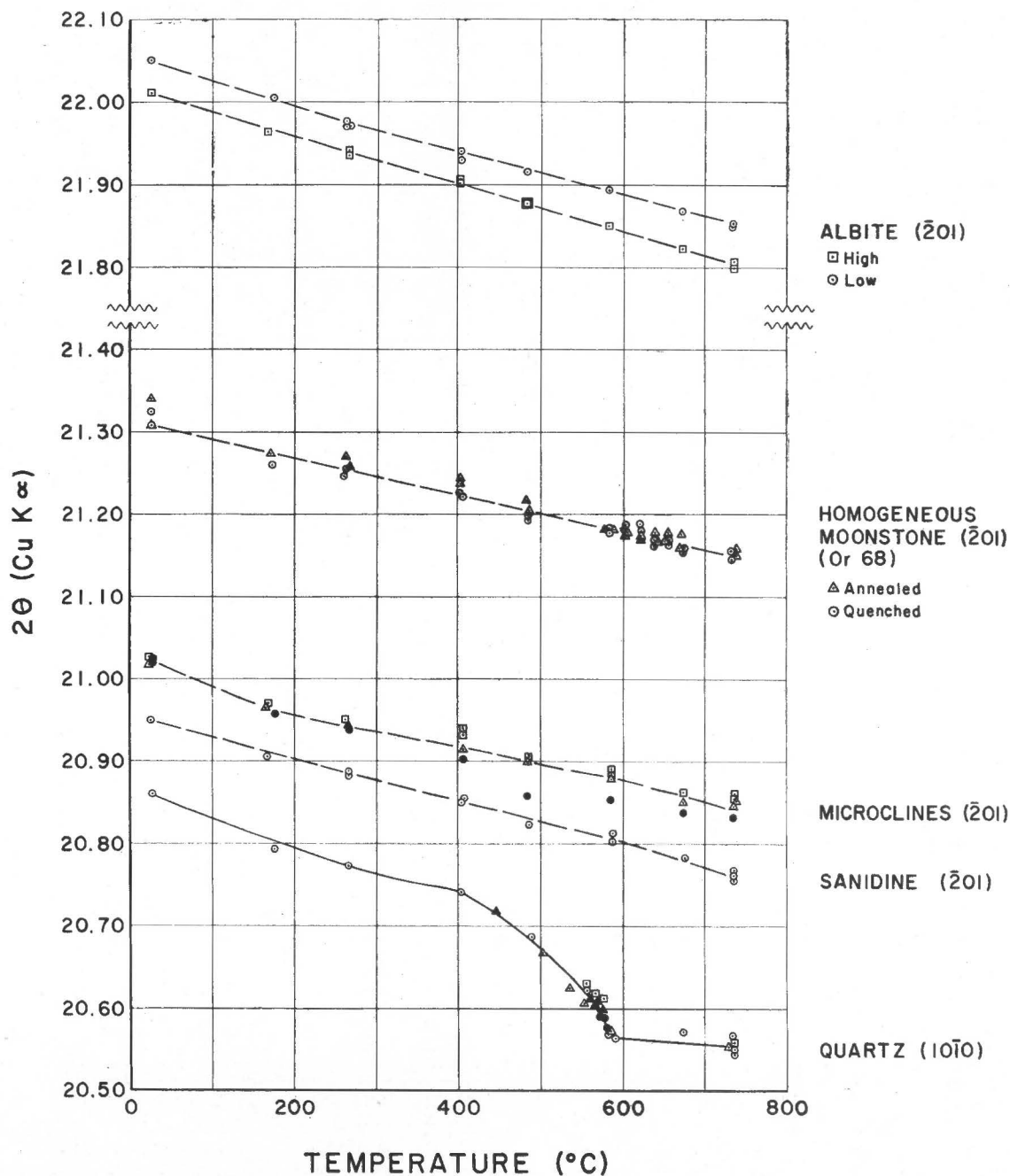


Fig. 1.—Thermal expansion of the $(\bar{2}01)$ reflections of some homogeneous alkali feldspars, and for comparison the thermal variation of a $(10\bar{1}0)$ quartz reflection.

along the abscissa and is reflected in the continual decrease in 2θ during the time from 0 to $1\frac{1}{2}$ hours. The horizontal line labeled Exp Or₁₀₀, which is added as a reference, indicates the 2θ position for a pure potassium sanidine (KAISi₃O₈) at 750°C. Such a potassium feldspar would undergo no remixing. The (201) reflection of an extremely pure potassium phase which undergoes no remixing during heat-treatment, when plotted should remain close to the sanidine-750°C line. An arrow joins the last 2θ measurement at 750°C to the final 2θ measurement at room tempera-

From this, it is concluded that, in a general way, the more readily and completely remixing takes place, the closer the natural perthite is to its original homogeneous or high temperature-structural state if the bulk composition of the perthite lies within the unmixing range of the orthoclase-albite system. However, the original homogeneous state may have occurred at a variety of temperatures depending on the variation of exsolution with composition (see Fig. 12, p. 561, LAVES, 1952). Furthermore, this does not imply that all sanidine perthites from a wide variety of geologic

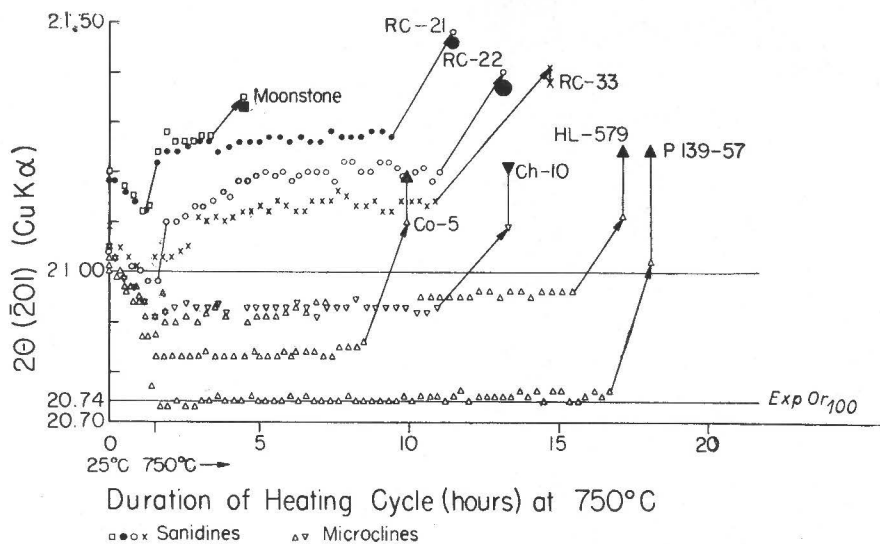


Fig. 2.—Variation of the $(\bar{2}01)$ reflection of the potash-rich phase of several sanidine and microcline perthites during heat-treatment. See text.

ture after the sample was cooled. Sanidines, which are all from the Rabb Canyon sanidine pegmatite area, Grant County, New Mexico, are indicated by the circles and squares. Microclines from various Nevada intrusives are indicated by the triangles. The filled or solid circles, square, and triangles indicate the final room-temperature 2θ position which the sample should have attained if it were a homogeneous sanidine (based on the relationship between composition and lattice spacings given by TUTTLE and BOWEN, 1958). Note that all the sanidine specimens attain or overshoot this 2θ position whereas none of the microclines do. There is no correlation between the estimated bulk composition, which is proportional to the position of the filled or black symbols, and the nature or extent of remixing. Even identical bulk compositions for sanidines (RC-22 and RC-33) and microclines (HL579 and P139-57) show considerable variation in the behavior of the (201) reflection with uniform heat-treatment.

All the sanidine perthites in Figure 2 remix more completely and readily than the microcline perthites.

environments must remix more readily than all microcline perthites. The entire unmixing process, which may occur stably or metastably, will be dependent on a wide variety of factors, such as hydrothermal pressure, crystallization rate, impurity ions, and the mosaic nature of the crystal. Indeed, this dependence on rate and impurity factors appears to affect many natural and artificial silicate systems (FLÖRKE, 1955; YODER, 1959).

Orthoclase Perthites With Similar Bulk Composition.

Figures 3, 4, and 5 present the variation of the $(\bar{2}01)$ reflections for the potash-rich phase of various orthoclase perthites as a function of the time of heat-treatment at 750°C. The composition of all these orthoclase perthites, based on spectrographic analysis, falls within the range Or₅₈ to Or₆₅. All these perthite specimens are from Tertiary (or late Cretaceous) intrusives and the numbering scheme is identical to that previously used (see KUELLMER, 1960 a). Fi-

figures 3 to 5 are similar to Figure 2, with the addition of four horizontal reference lines indicating the expected 2θ position of homogeneous sanidines with the bulk compositions ($Or_{58}Ab_{62}$) and ($Or_{65}Ab_{35}$), at room temperature (indicated by "Or₅₈" and "Or₆₅") and at 750°C (indicated by "Exp. Or₅₈" and "Exp. Or₆₅"). The 2θ position of the potash-rich ($\bar{2}01$) reflection within this field gives some idea of the composition and extent of remixing.

Comparison of Figures 3 to 5 with Figure 2 shows

that the twelve orthoclase perthite specimens, both in their 2θ positions at 750°C and in their remixing pattern, show all intermediate states between sanidine and microcline. If no remixing occurred, and if the potash-rich phase were nearly pure $KAlSi_3O_8$ the reflection would occur at $20.74^\circ 2\theta$. If complete remixing occurred the ($\bar{2}01$) reflection should lie between 21.14 and $21.21^\circ 2\theta$ for compositions Or₅₈ to Or₆₅. A specimen (H126-52) from the quartz monzonite porphyry of the HENRY MOUNTAINS, Utah

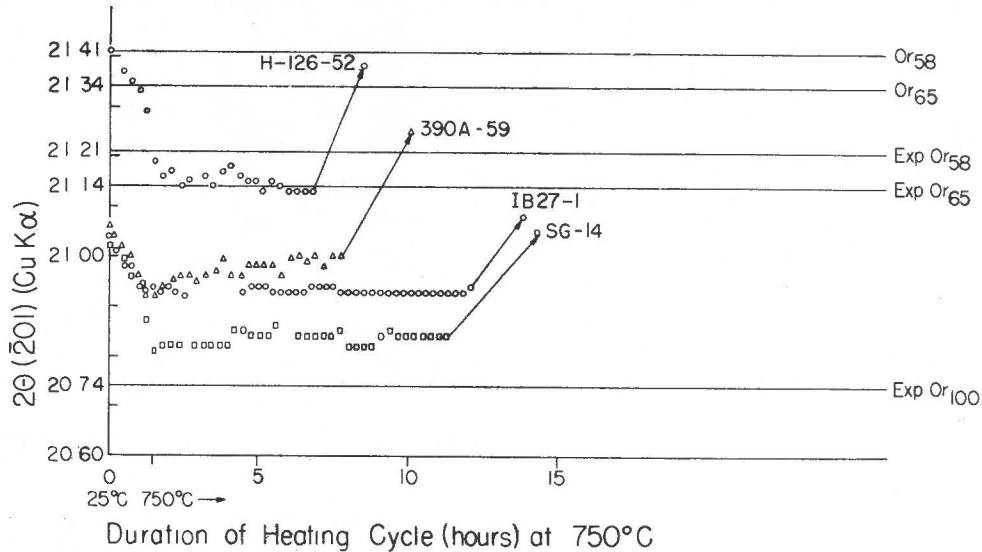


Fig. 3.—Variation of the ($\bar{2}01$) reflection of the potash-rich phase of several orthoclase perthites during heat-treatment. See text.

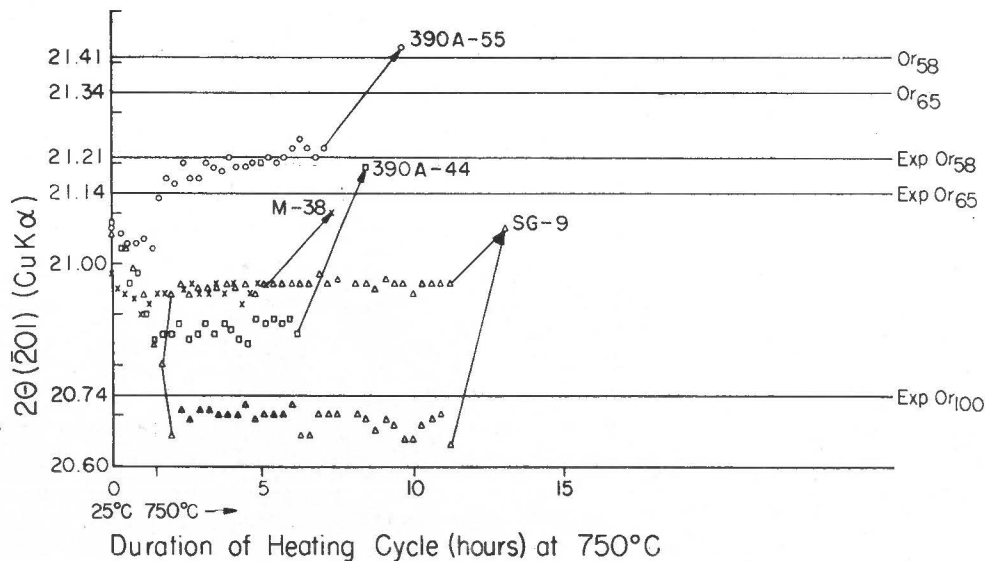


Fig. 4.—Variation of the ($\bar{2}01$) reflection of the potash-rich phase of several orthoclase perthites during heat-treatment. See text.

shows (Fig. 3) a potash-rich $(\bar{2}01)$ reflection indicating even less unmixing than the sanidines (Fig. 2). A specimen (SG-9) from the Schultze granite near Miami, Arizona during heat-treatment shows (Fig. 4) two potash-rich $(\bar{2}01)$ reflections, one at about pure KAlSi_3O_8 , and a second at a position corresponding

should decrease in 2θ about 0.20° ($\text{CuK}\alpha$) for a temperature increase from 25°C to 750°C . If one then adds the value 0.20 to all the 2θ positions at 750°C (points B and C above), all the $(\bar{2}01)$ reflection positions may be compared on a room-temperature basis. The shift in 2θ as a result of heat-treatment at 750°C

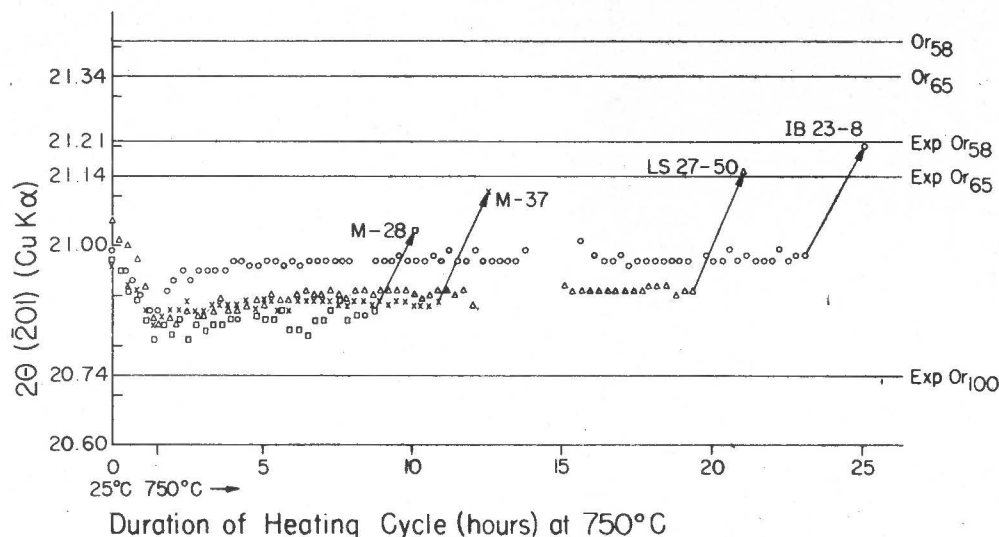


Fig. 5.—Variation of the $(\bar{2}01)$ reflection of the potash-rich phase of several orthoclase perthites during heat-treatment. See text.

to about Or_{80} . Thus, the nature and extent of the remixing shown by these orthoclase specimens, which are optically monoclinic and all of approximately the same bulk composition, covers the entire range from sanidine to microcline.

PERTHITES FROM A SINGLE INTRUSIVE OR INTRUSIVE SEQUENCE

Although the previous figures (2, 3, 4, and 5) illustrate the $(\bar{2}01)$ variation during heat-treatment, such a method of illustration when used for a wide range of compositions is extremely difficult to comprehend. Accordingly another type of illustration will be used in the hope of subtracting at least a part of the compositional and temperature effect. Figure 6 presents a generalized version of the previous figures. Five points appear to be sufficient to evaluate such a diagram (Fig. 6), namely (A) the room temperature 2θ position at the start of the run; (B) the 2θ position at 750°C at the start of heat-treatment; (C) the 2θ position at 750°C at the end of the heat-treatment; (D) the room temperature 2θ position at the end of the determination; and (E) the 2θ position which a homogeneous sanidine of this bulk composition would have (see TUTTLE and BOWEN, 1958) at room temperature. On the basis of the $(\bar{2}01)$ linear expansion measured on homogeneous alkali feldspars, the $(\bar{2}01)$ reflection

is plotted as if it occurred at room temperature, i.e. at a 2θ position which is 0.20 degrees higher than measured. Errors due to adifferent thermal change in 2θ than the 0.20 degrees here assumed for all alkali

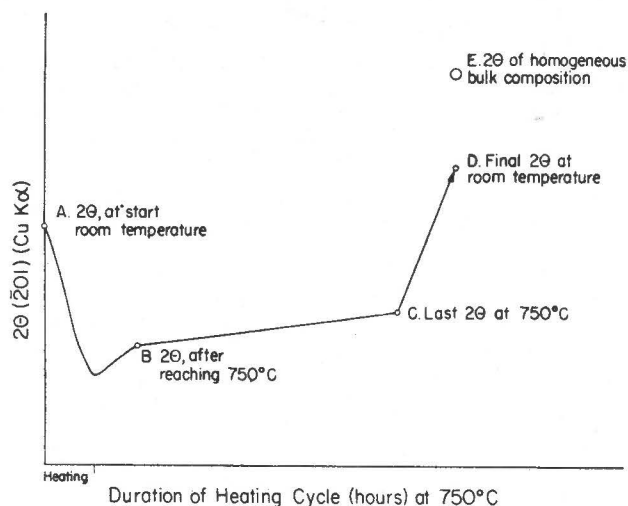
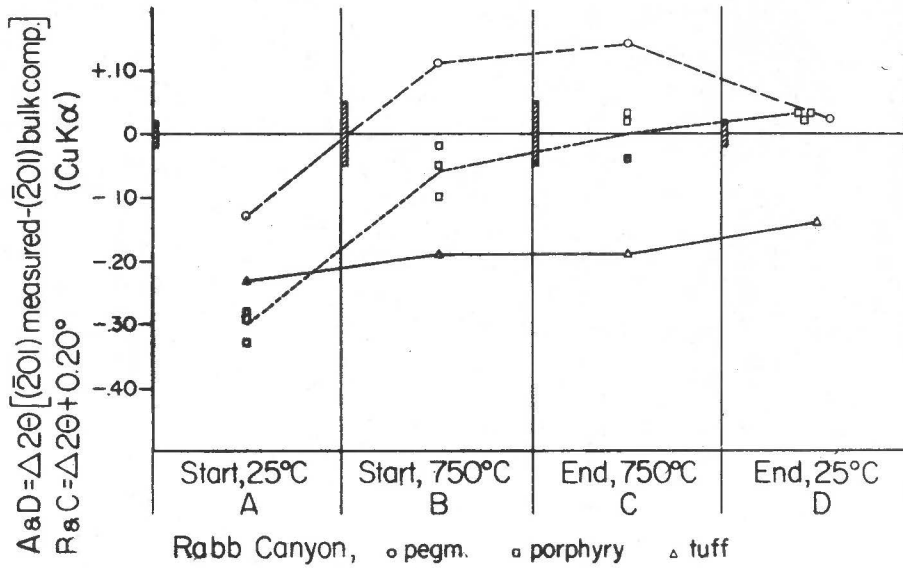


Fig. 6.—Generalized diagram showing the variation of the $(\bar{2}01)$ reflection of the potash-rich phase of a perthite during heat-treatment. The letters, A through E, indicate various 2θ positions during the heat-treatment which are used in the following diagrams (Fig. 7-14) for comparing the remixing rates of various perthitic specimens. See text.

feldspars, and other errors will affect the diagrams regardless of the method of illustration.

Figures 7 through 14 show the 2θ variation of the potash-rich $(\bar{2}01)$ phase before, during, and after

$(\bar{2}01)$ reflection of the potash-rich phase. The manner in which the $(\bar{2}01)$ reflection approaches or fails to approach the bulk composition position (item E of the foregoing paragraph is the zero or bulk-



Figs. 7 through 14.—Diagrams comparing the remixing rates of alkali feldspar perthite specimens from the same intrusive or the same intrusive sequence. See text.

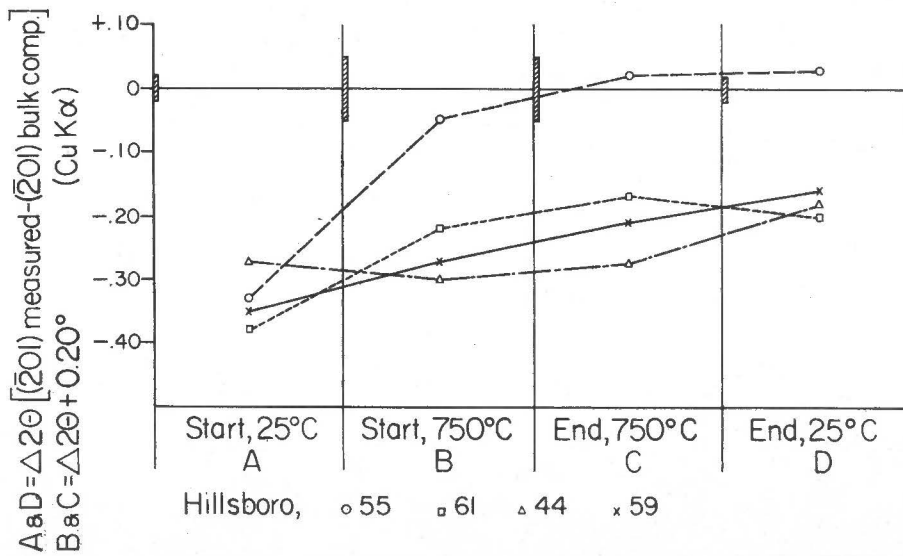


Fig. 8.

heat-treatment at 750°C, plotted as if the heating took place at room-temperature, i.e. a 2θ value of 0.20 is added to all readings at 750°C. The vertical scale is the 2θ difference between the $(\bar{2}01)$ reflection of a homogeneous sanidine of this bulk composition (based on data of TUTTLE and BOWEN, 1958) and the actual

composition position) may be seen. Along the horizontal scale each column refers to a part of the heating cycle, namely A, B, C, or D, as described in the preceding paragraph. The short heavy line on the left of each column at the zero line indicates the estimated maximum range of error in measuring the 2θ position.

The heavy line to the right of column D indicates the estimated range of error in fixing the zero 2θ position, because of the errors in compositional determination.

Remixing data for perthite samples from the Rabb Canyon sanidine pegmatite area, Grant County, New

sequence (see KELLEY and BRANSON, 1947; KUELLMER, 1960 a, p. 317) is (1) rhyolite tuff, intruded by (2) sanidine porphyry, in which (3) sanidine pegmatite lenses formed. Here the last-formed, more hydrothermal (i.e. pegmatitic and porphyritic phases)

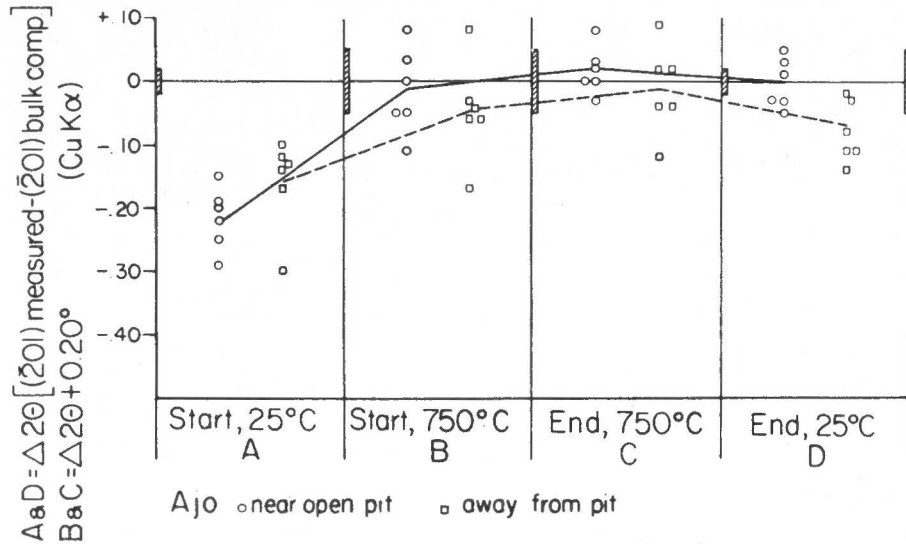


Fig. 9.

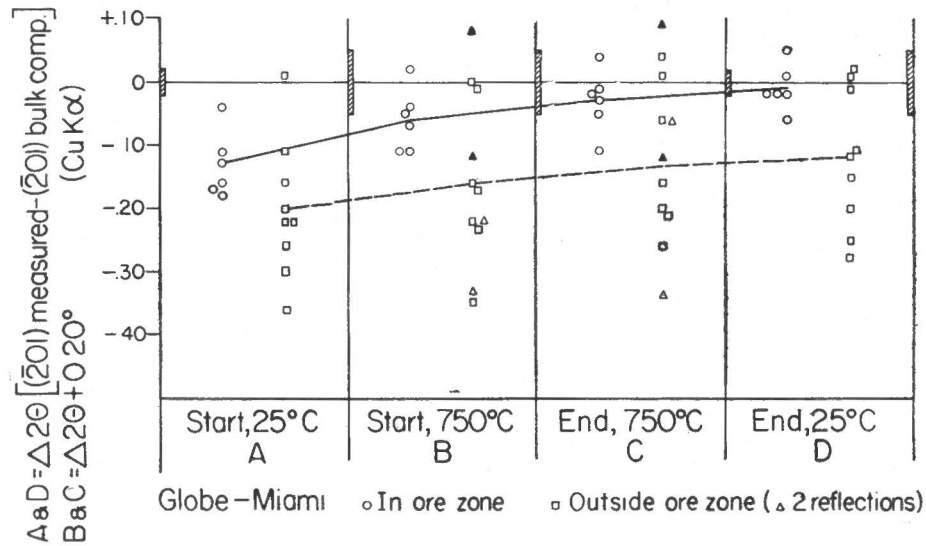


Fig. 10.

Mexico are presented in Figure 7. The moonstone sanidine from a high-temperature pegmatite remixes faster than the sanidine specimens from the sanidine porphyry, and both of these materials remix faster and more completely than a perthite specimen from the surrounding rhyolite tuff. The estimated rock

perthites, which presumably formed at lower temperatures, show the most rapid high-temperature type of remixing. Clearly, the foregoing data demonstrate that remixing is affected by additional factors other than the temperature-structural state.

Figure 8 illustrates the variation in remixing rates

for four orthoclase specimens from the quartz monzonite porphyry near Hillsboro, New Mexico. One specimen (number 55) remixes considerably more ra-

pidly and completely than the others, and indeed as readily as most sanidines. Specimen 55 differs from the others in that it comes from a higher intrusive horizon, and contains conspicuously larger and more

ovoid-shaped orthoclase phenocrysts (see KUELLMER, 1958). Differences in the remixing behavior of specimens

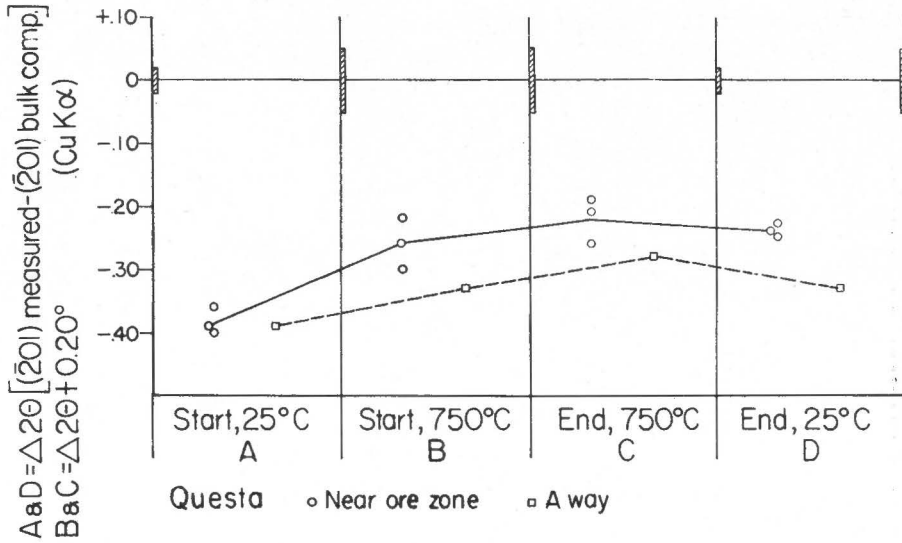


Fig. 11.

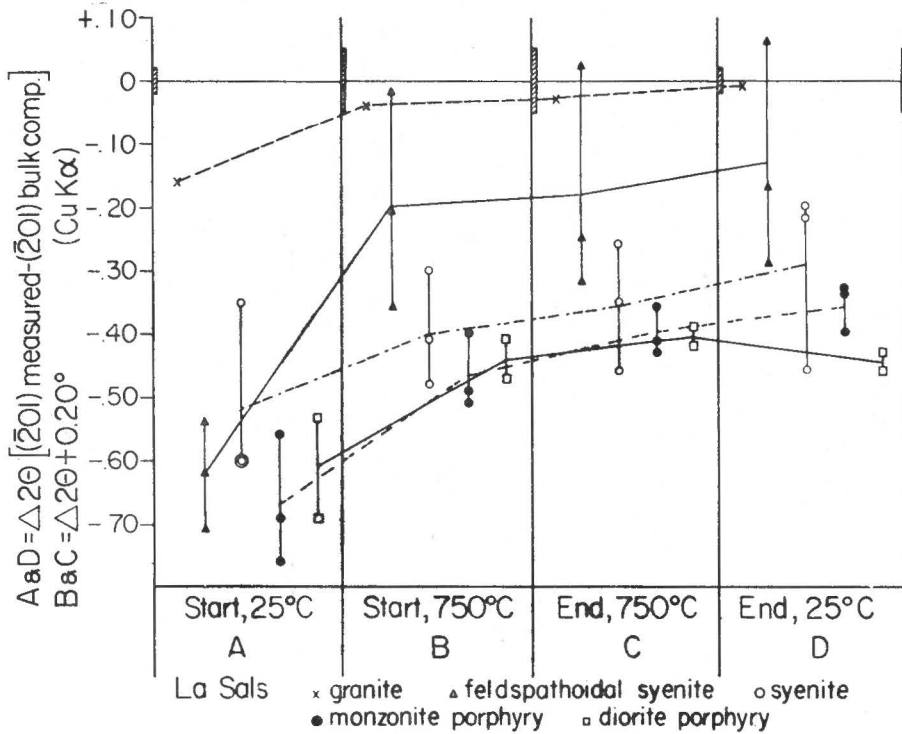


Fig. 12.

pidly and completely than the others, and indeed as readily as most sanidines. Specimen 55 differs from the others in that it comes from a higher intrusive horizon, and contains conspicuously larger and more

from the Cornelia quartz monzonite (GILLULY, 1946) near Ajo, Arizona are shown in Figure 9. Specimens are divided into two groups, those from in or on the edge of the open-pit mine, and those farther away.

The open-pit specimens, from the more orebearing part of the intrusive, remix more readily and completely

Figure 10 shows the remixing behavior of orthoclase perthite specimens from the Globe-Miami area, Arizona, which are divided into ore (from areas of moderate

ted in Figure 10 by the two sets of triangles. Two of the three non-ore specimens which show complete remixing are from the Castle Dome area (near Globe-Miami, Arizona) where the differences in completeness of mixing are negligible, and the third is from

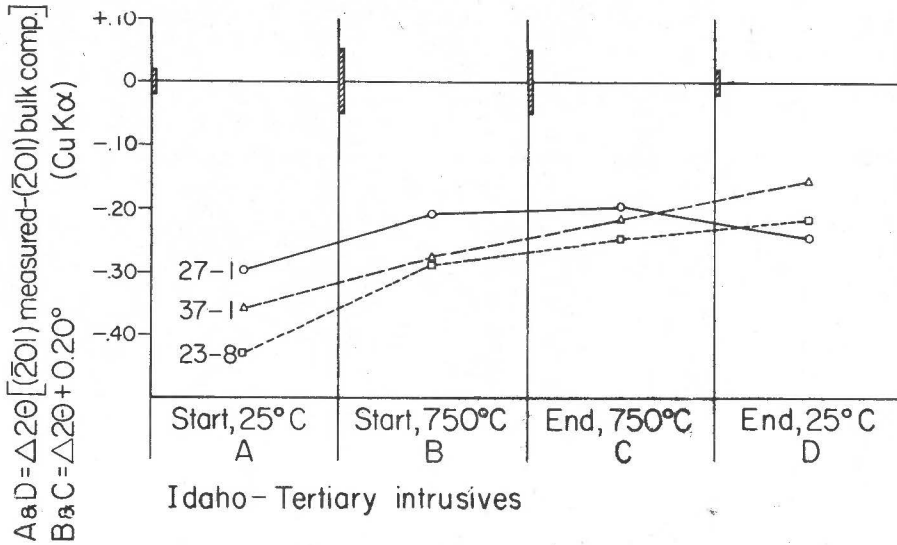


Fig. 13.

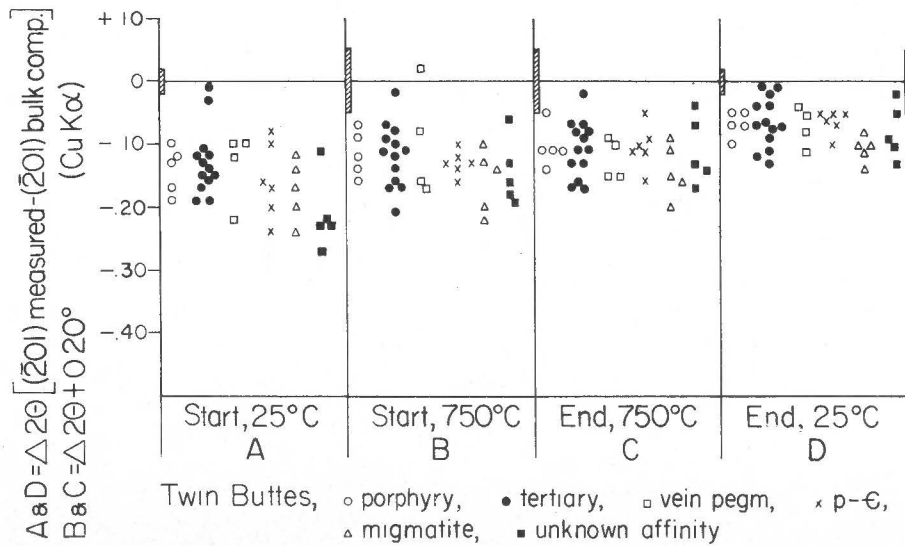


Fig. 14.

hydrothermal alteration) and non-ore specimens, based on data from PETERSON (1952). The ore specimens from this igneous sequence which includes Lost Gulch quartz monzonite, granite porphyry and Schultze granite remix more completely than most specimens from the non-ore areas. Two of the specimens from this group show two potash-rich phases which are indica-

the Inspiration mining area where the geographic separation of ore and non-ore specimens is very small. Other figures could be drawn, such as one for the Castle Dome area, which would show that the northernmost sample remixes like a sanidine, the southernmost has two potash-rich phases, and the two ore-area specimens lie somewhere inbetween, so that

the variation appears systematic with geographic position. A similar general variation with geographic position holds for the Copper Cities intrusive area. Another illustration which might be prepared is to compare the remixing rates of the more porphyritic (Lost Gulch quartz monzonite and granite porphyry) rocks and the less porphyritic Schultze granite (note that both groups contain equally large perthite phenocrysts, but the Schultze granite has a coarser matrix, in general, and therefore appears less porphyritic). Here too the general amount of remixing of the Lost Gulch and granite porphyry specimens is greater than that of the Schultze granite.

Data on the relative remixing of four perthite specimens from the Tertiary soda granite near Questa, New Mexico (SCHILLING, 1956) are presented in Figure 11. Here too, the three ore-area specimens remix more readily and more completely than the specimen from a non-ore area.

Variation of perthitic remixing of twelve specimens from the La Sal Mountains, Utah, shown in Figure 12, conforms closely with the intrusive sequence and temperature deductions as worked out by HUNT and WATERS (HUNT, 1958; WATERS, 1955). The intrusive sequence is: diorite porphyry; monzonite porphyry; syenite; and feldspathoidal syenite, aegirine granites, and soda rhyolites. The latter stages of intrusion, on the basis of HUNT's and WATERS' studies, are thought to have occurred at a higher temperature than the early stages. Examination of figure 12 shows a systematic variation of remixing with the various rock types. Furthermore, those perthites from rocks occurring late in the intrusive sequence at a higher temperature and more eruptive stage show a faster and more complete remixing.

Figure 13 shows the relative remixing of three perthite specimens from Tertiary intrusives into the Idaho batholith. The relative remixing of a large number of perthite samples from the Twin Buttes quadrangle, Pima County, Arizona is presented in Figure 14. The five rock names shown in Figure 14 are tentative field names used by J. COOPER for slightly different textural varieties. It appears that all the Twin Buttes samples are rather homogeneous in bulk composition and that there are no significant differences in rate or completeness of remixing. Such uniformity in remixing relations may result from (1) a real primary homogeneity, (2) inadequate sampling spread over 153 square kilometers of the quadrangle, (3) selecting a temperature of heat-treatment either too high or too low to cause differences in remixing rate, or (4) a complete recrystallization of the perthites.

CONCLUSIONS

Perthitic alkali feldspars from a single intrusion show a considerable compositional range (Table I). The fact that most of the orthoclases are optically

homogeneous and have bulk compositional ranges which do not extend across the minimum temperature trough of the system- $\text{NaAlSi}_3\text{O}_8$ - KAlSi_3O_8 (TUTTLE and BOWEN, 1958) suggests that these compositions are the result of a primary magmatic (including hydrothermal) crystallization.

All homogeneous alkali feldspars here measured, regardless of structural state, have about the same (201) linear thermal expansion in the range 20 to 750°C, which involves a change in 2θ ($\text{CuK}\alpha$) of about $0.20 \pm .05^\circ$. In a general way, the closer a perthite is to its original homogeneous or high-temperature state, the more readily and completely it will remix upon proper heat-treatment, on the basis of the study of the microcline and sanidine perthites. The foregoing statement must be modified to exclude bulk compositions outside the unmixing range, and metasomatic and other perthites which may have crystallized under conditions deviating considerably from the idealized orthoclase-albite system. Orthoclase perthites show every intermediate variety of remixing.

Perthites from a single intrusive or intrusive sequence show such variation in their remixing rates, that unmixing is probably considerably affected by other factors, such as impurity ions and lattice defects. In spite of this, the comparative remixing rates appear to be of petrographic value. For mosts igneous rocks here studied, the more pegmatitic, the more ore-bearing, and/or the more eruptive or high-temperature stage, the more readily and completely the perthite will remix. Most of the rocks studied here are porphyries, so that when the term "more porphyritic" is used, it means that the perthitic feldspar phenocrysts are larger, more abundant, more conspicuous and/or fresher in appearance. The fact that more-porphyritic specimens remix more readily and completely than other perthite specimens can only be reconciled with the greater ease of remixing of specimens from a more hydrothermal facies, if these occurrences have something in common. One explanation might be that the phenocrysts of the more-porphyritic facies crystallized or recrystallized late in the magmatic cycle rather than intratellurically. Therefore two types of phenocrysts may occur in many hypabyssal porphyries, one intratelluric and another formed or re-formed at a late hydrothermal stage. An alternate explanation is that crystal growth and unmixing occurred so rapidly during the hydrothermal stage that a more high-temperature type of unmixing was preserved. Experimental studies by JAHNS and BURNHAM (1958) suggest that a late hydrothermal and rapid growth of larger crystals may readily occur. Crystals grown rapidly in a hydrothermal stage might contain more impurities and lattice defects which would affect remixing rates. The foregoing analytical procedure may thus provide an important tool for differentiating perthitic alkali feldspars formed during various stages of magmatic crystallization.

ACKNOWLEDGMENTS

This work was supported by a research grant (G2277) from the National Science Foundation. Special acknowledgment is made to E. J. WORKMAN and A. J. THOMPSON for their encouragement, and to F. LAVES for reading the manuscript. Specimens, and advice and assistance pertinent to sampling were obtained from J. COOPER, W. B. HAMILTON, C. B. HUNT, P. M. ORVILLE, N. P. PETERSON, E. F. REED, J. H. SCHILLING, E. M. SHOEMAKER, W. W. SIMMONS, and A. C. WATERS. The Inspiration-Consolidated Copper Company, the Miami Copper Company, and the Phelps-Dodge Corporation were most helpful in obtaining samples from within their mining properties. G. L. DAVIS of the Geophysical Laboratory made all plans of his diffractometer furnace available. J. RENAULT and J. CARMAN provided careful assistance.

REFERENCES

- BASSETT, W. A., and LAPHAM, D. M.
1957. A thermal increment diffractometer. *Am. Mineralogist*, **42**, 548-555.
- BIRKS, L. S., and FRIEDMAN, H. A.
1947. A high-temperature diffraction apparatus. *Rev. Sci. Instruments*, **18**, 578-580.
- BOWEN, N. L., and TUTTLE, O. F.
1950. The system $\text{NaAlSi}_3\text{O}_8\text{-KAlSi}_3\text{O}_8\text{-H}_2\text{O}$. *Jour. Geology*, **58**, 489-511.
- FLÖRKE, O. W.
1955. Struktur-anomalien bei Tridymit und Cristobalit. *Bericht. Deutschen Keram. Gesellschaft*, **32**, 369-381.
- GILLULY, J.
1946. The Ajo mining district, Arizona. *U. S. Geol. Survey Prof. Paper*, **209**.
- GOLDSMITH, J. R., and LAVES, F.
1954 a. The microcline-sanidine stability relations. *Geochim. et Cosmochim. Acta*, **5**, 1-19.
1954 b. Potassium feldspars structurally intermediate between microcline and sanidine. *ibid.*, **6**, 100-118.
- HUNT, C. B.
1958. Structural and igneous geology of the La Sal Mountains, Utah. *U. S. Geol. Survey Prof. Paper*, **294-I**.
- JAHNS, R. H., and BURNHAM, C. W.
1958. Experimental studies of pegmatite genesis: melting and crystallization of granite and pegmatite: (Abst.), *Bull. Geol. Soc. America*, **69**, 1592-1593.
- KELLEY, V. C., and BRANSON, O. T.
1947. Shallow, high-temperature pegmatites, Grant County, New Mexico. *Econ. Geology*, **42**, 699-712.
- KUELLMER, F. J.
1958. Alkali feldspars in a Tertiary porphyry near Hillsboro, New Mexico. *Jour. Geology*, **66**, 151-162.
1959. X-ray intensity measurements on perthitic materials. I. Theoretical considerations. *ibid.*, **67**, 648-660.
1960 a. *ibid.* II. Data from natural alkali feldspars. *ibid.*, **68**, 307-323.
1960 b. Compositional variation of alkali feldspars in some intrusive rocks near Globe-Miami, Arizona. *Econ. Geology*, **55**, 557-562.
- LAVES, F.
1950. The lattice and twinning of microcline and other potash feldspars. *Jour. Geology*, **58**, 548-571.
1952. Phase relations of the alkali feldspars. *ibid.*, **60**, 436-450, 549-574.
- MACKENZIE, W. S., and SMITH, J. V.
1955. The alkali feldspars. I. *Am. Mineralogist*, **40**, 707-732.
1956. The alkali feldspars. III. *ibid.*, **41**, 405-427.
- ORVILLE, P. M.
1958. Feldspar investigations. in *Annual Report, Carnegie Inst. of Washington Year Book*, **57**, 206-209.
- PETERSON, N. P.
1952. Structural history of the Globe-Miami district. Guidebook for field trip excursions in southern Arizona. *Arizona Geol. Soc.*, p. 123-127.
- SCHILLING, J. H.
1956. Geology of the Questa molybdenum (Moly) mine area, Taos County, New Mexico. *New Mexico Bur. Mines & Min. Res. Bull.* **51**.
- TUTTLE, O. F., and BOWEN, N. L.
1958. Origin of granite in the light of experimental studies in the system $\text{NaAlSi}_3\text{O}_8\text{-KAlSi}_3\text{O}_8\text{-H}_2\text{O}$. *Geol. Soc. Am., Mem.*, **74**.
- WATERS, A. C.
1955. Volcanic rocks and the tectonic cycle. *Geol. Soc. Am. Special Paper*, **62**, 703-722.
- WEISS, E. J., and ROWLAND, R.
1956. Oscillating-heating x-ray diffractometer studies of clay mineral dehydroxylation. *Am. Mineralogist*, **41**, 117-126.
- YODER, H. S., Jr.
1959. Experimental studies on micas: a synthesis. *Proc. 6th. Natl. Conf. on Clays and Clay Minerals*, 42-60, Pergamon Press, New York.

DISCUSSION

KAMB (Pasadena):

Have you remixed data on microclines of various triclinicities?

KUELLMER (Socorro). Answer:

Todate I have no data on the remixing of microcline

perthites, in which the potassium phase has less than the maximum triclinicity. A few preliminary studies of some microcline perthites suggest that the deeper and «more plutonic» (using these terms in a very general way) specimens contain perthites which remix more slowly and reluctantly than those microcline perthites from «less plutonic», or younger rocks. However, there are conspicuous exceptions to this generalization, and the number of specimens studied to date is small.

KUELLMER (Socorro). Answer to Mr. MEIER (The question was not received):

No I have not compared the matrix alkali feldspar with alkali feldspar phenocrysts from the same specimen. Some

of the specimens from the Ajo, Arizona area contain no phenocrysts of alkali feldspar and matrix alkali feldspars were used. In most cases the phenocrysts, because of included impurities, required considerable microscopic sorting so that separation of alkali feldspars from a very fine-grained matrix was not attempted at this time.