THERMAL STUDY OF POTASH-SODA FELDSPARS*

MILTON T. HEALD, *West Virginia University, Morgantown, West Virginia.*

ABSTRACT

The temperatures required to homogenize lamellar feldspars from various types of rock have been determined. The results obtained indicate that the temperatures which are necessary to effect homogenization of the specimens do not in all cases represent the minimum temperature at which the feldspars crystallized. Many of the finely lamellar feldspars may have formed by simultaneous crystallization of soda feldspar and potash feldspar rather than by the exsolution of an initially homogeneous feldspar.

INTRODUCTION

In the course of investigating the origin of a number of plutonic rocks, the writer undertook a thermal study of several lamellar feldspars[1] from metamorphic and igneous rocks in the hope of obtaining information on the temperature of formation of different rock-types. It has generally been accepted (8) that finely lamellar feldspar of the "string" type is of exsolution origin and that the temperature of crystallization of the original homogeneous feldspar is equal to, or is above, the temperature at which the heated lamellar feldspar becomes homogeneous. However, the results of the present study indicate that these assumptions are not valid for all finely lamellar feldspars. Attempts to explain the thermal behavior of the treated specimens have been only partially successful because of insufficient data, especially on the structure of the feldspars.

EXPERIMENTAL METHOD

The amount of solution of the soda feldspar lamellae at a given temperature was determined by noting the decrease in the size of the lamellae after the specimens had been heated. In the schillerized specimens the decrease in the intensity of the schiller was noted. Spencer's (8) method of determining the amount of solution by the decrease in refractive indices proved to be unreliable.

The specimens were crushed to minus 60 mesh to facilitate ready examination under the microscope by the immersion method. All of the optical properties given for the microperthites refer to the aggregate effect of the two feldspar components. The refractive indices were measured to $\pm .0005$ by the dispersion method. In order to observe the changes in

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[1] The term lamellar feldspar as used in this paper refers to "submicroscopic" perthite as well as ordinary microperthite.

color in the schillerized feldspars, fragments one centimeter in length were treated. The samples were heated in a platinum furnace and temperatures were measured with platinum-platinum 10% rhodium thermocouples. The temperatures were maintained at $\pm 5°$ C. After each run the specimens were chilled in air and examined microscopically.

Description of Specimens

The composition and optical data for the specimens studied are given in Table 1.

Table 1. Potash-Soda Feldspars

Specimen	K_2O	Na_2O	CaO	Or (weight, per cent)	Ab+An (weight, per cent)	α	β	γ	2V
1. Orthoclase-microperthite,[1] New Hampshire	12.61	2.38	0.16	78	22	1.5206	1.5246	1.5267	70°
2. Orthoclase-microperthite,[2] California (El 38–265)†	12.10	2.47	n.d.	77	23	1.5205	1.5245	—	65°
3. Orthoclase-microperthite,[2] California (El 38–167)	10.62	3.48	n.d.	68	32	1.5210	1.5250	—	65°
4. White moonstone, Ceylon	—	—	—	65	35*	1.5220	1.5260	—	70°
5. Blue moonstone, Ceylon	—	—	—	65	35*	1.5217	1.5257	—	70°
6. Blue moonstone, New Mexico	—	—	—	50	50*	1.5210	—	1.5270	37°
7. Blue moonstone,[3] New Mexico (JL7)	6.56	6.55	0.40	40	60	1.5220	—	1.5280	42°
8. Homogeneous sanidine,[3] Colorado (U3027)	10.35	4.26	n.d.	63	37	1.5200	—	1.5255	34°

* Composition estimated from optical properties.
† Numbers in parentheses refer to the numbers used in Larsen's collections
[1] F. A. Gonyer, analyst.
[2] Analyses from Larsen (personal communication).
Analyses from Larsen and others (6).

Specimen No. 1 is an orthoclase-microperthite which occurs as porphyroblasts in paragneisses of the Littleton formation in the Lovewell Mountain quadrangle, New Hampshire. The microperthitic structure is very uniform and the soda feldspar lamellae, as observed on (010), average about 0.04 millimeter in length.

Specimen No. 2 is an orthoclase-microperthite from the Rubideaux granite of the southern California batholith. The lengths of the soda feldspar lamellae as observed on (010) are variable, ranging from 0.05 millimeter to 0.25 millimeter.

Specimen No. 3 is an orthoclase-microperthite from the Rubideaux granite of the southern California batholith. The lamellae are irregular on (010) and range in length from 0.05 millimeter to 0.5 millimeter.

Specimen No. 4 is a white schillerized moonstone from Ceylon. It occurs in a sheared quartz-orthoclase rock which is "an acid phase of a pegmatite" according to Coates (4). The specimen shows conspicuous white schiller and a fine uniform microperthitic structure. The individual lamellae are fairly sharp and rarely exceed a few hundredths of a millimeter in length.

Specimen No. 5 is a blue schillerized moonstone from Ceylon and has the same mode of

occurrence as specimen No. 4. It exhibits an intense sky-blue schiller but appears homogeneous under the microscope.

Specimen No. 6 is a blue schillerized moonstone which occurs as phenocrysts in rhyolites of the Valles Grande Mountains, New Mexico. No definite microperthitic structure was seen under the microscope.

Specimen No. 7 is a blue schillerized moonstone which occurs as phenocrysts in rhyolites in the same area as specimen No. 6. The moonstone has a vague microperthitic structure.

Specimen No. 8 is a sanidine which occurs as phenocrysts in rhyolites in the Uncompahgre quadrangle, Colorado. The specimen exhibits no schiller or microperthitic structure.

Results of Heat-Treatment

The more significant results of the thermal experiments on the orthoclase-microperthites are given in Table 2. In specimen No. 1 no change in the microperthitic structure was observed after prolonged heating at 700° C., but the refractive indices decreased about 0.001. A special set of experiments were run at 700° C. to determine the length of time necessary for the refractive indices to establish equilibrium. As shown in Fig. 1, the indices decreased appreciably in 13 hours at 700° C., but no further changes were noted after prolonged heating. At temperatures above

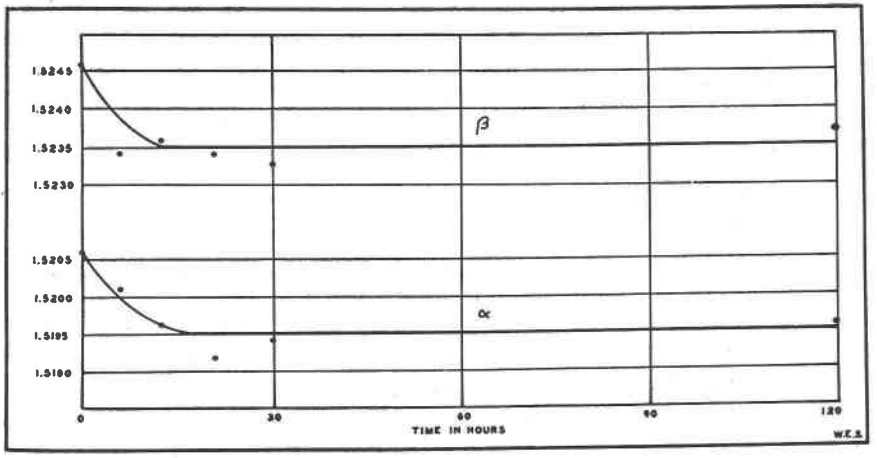

Fig. 1. Rate of change of the α and β indices of specimen No. 1 at 700° C.

850° C., numerous cracks developed in the specimen so that the refractive indices could not be accurately measured. After prolonged heating at 1000° C., the boundaries of the lamellae were found to be less sharp. On heating to 1075° C., the smaller lamellae disappeared and the larger lamellae became indistinct.

In specimens No. 2 and No. 3 of orthoclase-microperthite, no significant change in the microperthitic structure was observed on heating to

950° C. although the refractive indices decreased appreciably. These specimens were not studied at temperatures above 950° C.

TABLE 2. RESULTS OF HEAT-TREATMENT

Specimen No. 1, orthoclase-microperthite (22% Ab+An), New Hampshire
Specimen No. 2, orthoclase-microperthite (23% Ab), California
Specimen, No. 3, orthoclase-microperthite (32% Ab), California

Specimen	Temp. ° C.	Time in hrs.	α	β	2V	Microperthitic structure
No. 1	22	—	1.5206	1.5246	70°	Lamellae 0.04×0.005 mm.
	700	192	1.5195	1.5237	70°	No apparent change
	900	100	*	*	70°	Boundaries slightly less distinct
	1000	300	*	*	40°	Slightly less distinct
	1040	370	*	*	35°	Lamellae smaller
	1075	330	*	*	20°	Only larger lamellae visible. Trace of glass
No. 2	22	—	1.5205	1.5245	65°	Fine and coarse lamellae
	950	19	1.5185	1.5223	65°	No significant change
No. 3	22	—	1.5210	1.5250	65°	Fine and coarse lamellae
	950	19	1.5184	1.5228	65°	No significant change

* Accurate index determinations not possible because of cracks in the heated material.

The results of the thermal studies of the moonstones which had large axial angles (specimens No. 4 and No. 5) are given in Table 3. In specimen No. 4, the microperthitic structure was found to be less pronounced after heating to 800° C. Under ordinary light, the boundaries of the lamellae were indistinct and differences in relief were slight. Under crossed nicols, however, the lamellae were readily seen on favorably oriented grains. The fact that the white schiller was plainly visible after 145 hours, although somewhat fainter, indicated that the soda feldspar was only partially dissolved at 800° C.

The refractive indices decreased about 0.003 between 500° C. and 800° C. and showed little further decrease at higher temperatures. The decrease in index was as great after one hour at 600° C. as after 100 hours at the same temperature; therefore equilibrium was probably attained. As shown in Fig. 2, the total drop in indices does not occur at one definite temperature, but over a range of temperatures. On heating above 800° C., no further decrease in indices was observed although the microperthitic structure and intensity of the schiller were appreciably reduced.

The study of blue Ceylon moonstone (specimen No. 5) also indicates

TABLE 3. RESULTS OF HEAT-TREATMENT
Specimen No. 4, white moonstone (35% Ab), Ceylon

Temp. ° C.	Time in hrs.	α	β	2V	Microperthitic structure	Schiller
22	—	1.5220	1.5260	70°	Fine lamellae	White schiller
400	42	1.5220	1.5260	70°	No apparent change	n.d.
500	90	1.5220	1.5260	70°	No apparent change	n.d.
600	116	1.5202	1.5247	70°	Lamellae slightly reduced	n.d.
800	6	1.5190	1.5232	70°	Lamellae indistinct under ordinary light. Fairly conspicuous under crossed nicols	n.d.
800	145	1.5190	1.5232	70°	No further change apparent	Less intense
900	138	1.5190	1.5230	70°	Faint	n.d.
990	18	1.5190	1.5230	70°	Faint	Very faint

Specimen No. 5, blue moonstone (35% Ab), Ceylon
(no microperthitic structure visible)

Temp. ° C.	Time in hrs.	α	β	2V	Schiller
22	—	1.5217	1.5257	70°	Intense blue
800	1	1.5190	1.5227	70°	Less intense
800	90	1.5190	1.5227	70°	Same as after one hour
1000	22	1.5190	1.5232	n.d.	Very faint
1000	700	1.5190	1.5232	40°	Same as after 22 hours

that the drop in refractive indices is completed before the final solution of the soda feldspar lamellae. Although the specimen appeared to be homogeneous under the microscope, the intense sky-blue schiller showed that a submicroscopic lamellar structure existed. After heating to 800° C., the refractive indices were found to be about 0.003 lower, and although the intensity of the schiller was reduced, a violet-blue color was still conspicuous. The schiller became very faint on heating to 1000° C. for 22 hours. No further change in the intensity of the schiller was observed after heating for 700 hours at 1000° C. and the mean refractive index was the same as after the run at 800° C.

The results of the heat-treatment of the moonstones which had small axial angles (specimens No. 6 and No. 7) are given in Table 4. In specimen No. 6, no definite microperthitic structure could be seen under the microscope. However, many of the lines in the x-ray powder photographs of the moonstone were diffuse and broad. These lines were doublets linked

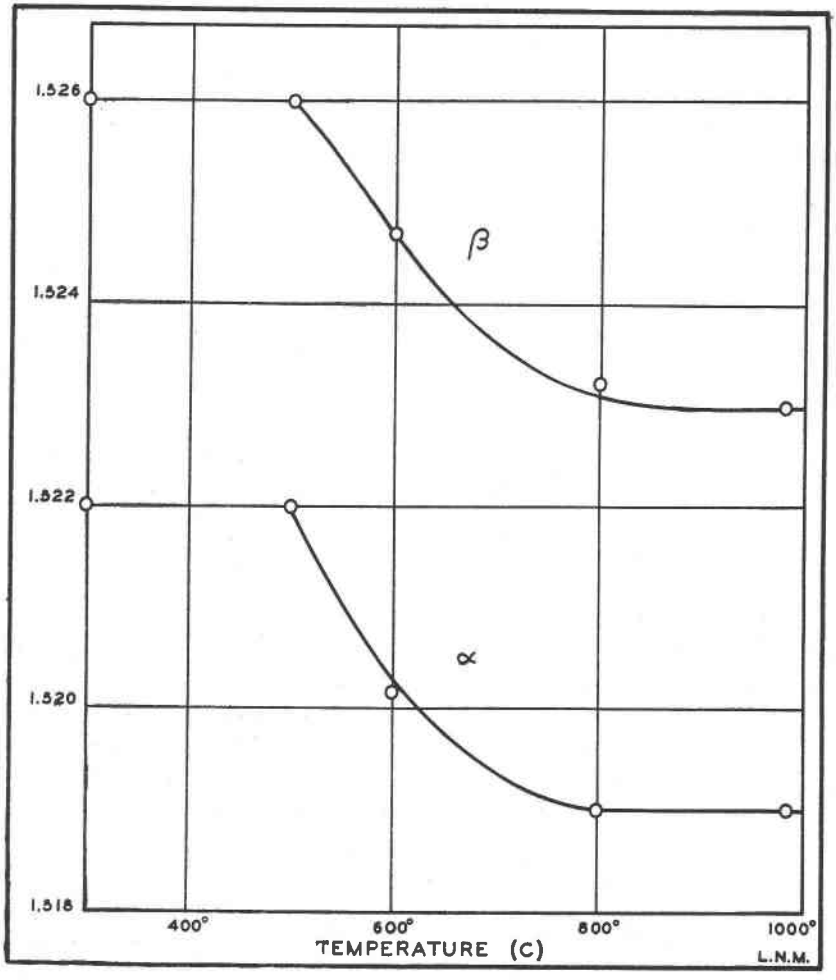

FIG. 2. Changes in the α and β indices of specimen No. 4 with changes in temperature.

by a band of blackening and were presumably due to the presence of two phases. On heating to 800° C. the blue schiller disappeared and the refractive indices decreased 0.0018. No further changes in indices were observed at temperatures up to 1000° C. In the x-ray powder photographs of the material that had been heated to 990° C., a single sharp line occurred in place of each doublet in the initial photographs. This indicated that homogenization had been completed.

In specimen No. 7 changes in the microperthitic structure were difficult to observe because the lamellae in the initial material were indistinct. On heating to 900° C., the lamellae apparently dissolved completely and

TABLE 4. RESULTS OF HEAT-TREATMENT

Specimen No. 6, blue moonstone (50% Ab), New Mexico
Specimen No. 7, blue moonstone (60% Ab+An), New Mexico
Specimen No. 8, homogeneous sanidine (37% Ab), Colorado

Specimen	Temp. ° C.	Time in hrs.	α	γ	2V	Remarks
No. 6	22	—	1.5210	1.5270	37°	Blue schiller. No visible microperthite
	700	48	1.5192	1.5252	37°	Very faint schiller
	800	96	1.5192	1.5252	37°	No schiller
	1000	80	1.5192	1.5252	—	No schiller
No. 7	22	—	1.5220	1.5280	42°	Vague microperthitic structure
	900	24	1.5200	1.5258	42°	No definite lamellae visible
No. 8	22	—	1.5200	1.5255	34°	Homogeneous
	800	24	1.5200	1.5255	34°	Homogeneous

the refractive indices decreased 0.0021. No attempt was made to determine the effects on the schiller in this specimen because the fragments available were so small that significant changes could not be observed.

Homogeneous sanidine (specimen No. 8) showed no decrease in refractive indices on heating to 800° C. for 24 hours (Table 4). Under similar treatment the microperthitic white moonstone (specimen No. 4) of approximately the same composition showed a 0.003 decrease in indices.

COMPARISON OF RESULTS WITH THOSE OF PREVIOUS WORKERS

Barth (1) found that orthoclase-microperthite of his "guttate" type, which contained 25% soda feldspar, became homogeneous by heating to 1000° C. for 700 hours. Kôzu and Endô (5) reported that Ceylon moonstone containing 26% soda feldspar became homogeneous between 1060° C. and 1115° C. Spencer (8), on the other hand, concluded that in orthoclase-microperthites containing less than 30% soda feldspar, homogenization was essentially completed at temperatures below 800° C.

The results of the present study indicating that temperatures of over 1000° C. are required to homogenize the low-soda perthites (specimens No. 1 and No. 2) are in better agreement with the earlier studies than with the more recent data of Spencer. Although the microperthitic structure in Spencer's specimens was finer than in the writer's, the duration of the runs in the present study appears to have been sufficient for the attainment of equilibrium. A possible explanation for the difference in be-

havior of Spencer's low-soda specimens is given in a later section.

The writer's determinations of the temperatures required to homogenize the high-soda lamellar feldspars (>30% Ab) are in good agreement with the results of Spencer and earlier workers.

Factors Which Influence the Temperature at Which Lamellar Feldspars Become Homogeneous

The results of the thermal studies of feldspars which have been conducted up to the present time indicate that the lamellar feldspars which have axial angles less than about 60° become homogeneous at temperatures below 850° C. In the lamellar feldspars that have axial angles greater than about 60°, temperatures above 1000° C. are required to effect homogenization.

The difference in behavior of these lamellar feldspars is probably due to differences in structure. Although the structural data on feldspars are meager, they do suggest that the lamellar feldspars which have large axial angles are structurally different from those with small axial angles. In Fig. 3, it is seen that in the lamellar feldspars studied by *x*-ray methods those with axial angles larger than about 60° correspond to the "M" structural type of Chao and Taylor (3), whereas those with smaller axial angles correspond to the "F" structural type.

This difference in structure may account for the apparent disagreement between the writer's results and those of Spencer in the specimens which contain less than 30% soda feldspar. Spencer's low-soda microperthites had axial angles less than 60° and became homogeneous at temperatures below 800° C. In the writer's specimens the axial angles were greater than 60° and temperatures above 1000° C. were required to effect homogenization. Kôzu and Endô (5) also found that a temperature of over 1000° C. was necessary to homogenize their specimen of low-soda (Ceylon) moonstone which had an axial angle of 66°.

The change in axial angle which occurs before homogenization is completed is apparently unrelated to a change in structure which facilitates solution of the lamellae. Although the axial angle of specimen No. 5 was reduced from 70° to 40° at 1000° C., homogenization was not completed even after 700 hours at this temperature (Table 3).

Relation Between Axial Angle and Degree of Solution in Lamellar Feldspars

It is generally accepted that in unheated lamellar feldspars which have relatively large axial angles no more than about 10% soda feldspar is held in solid solution. On the other hand, in the lamellar feldspars which have relatively small axial angles, Spencer (8) and Chao and Taylor (3) concluded that a large part of the soda feldspar was held in solid solution.

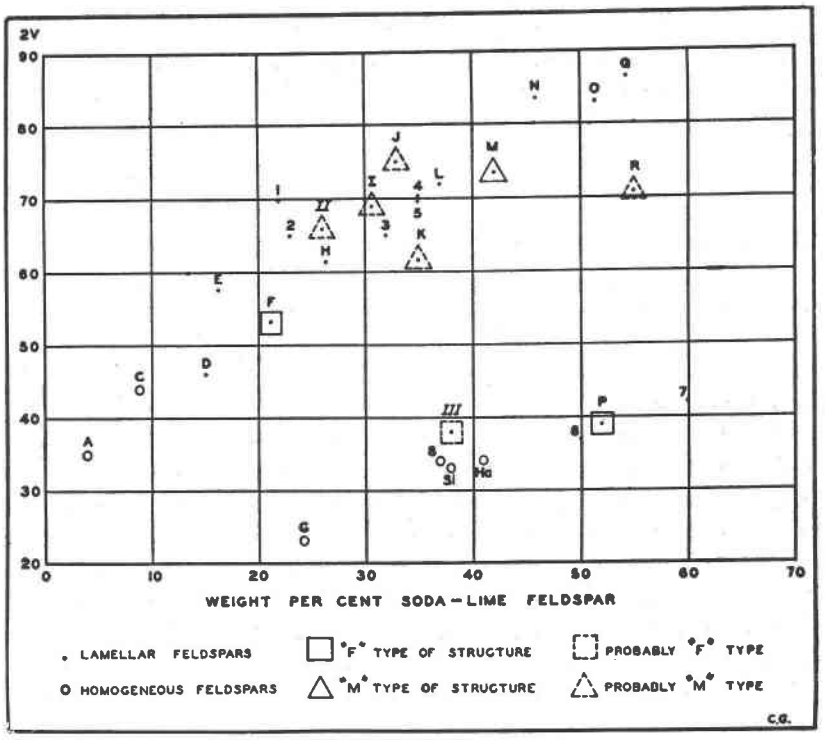

FIG. 3. Axial angles of potash-soda feldspars plotted against composition. Numbers correspond to specimens in Table 1. Letters refer to the specimens studied by Spencer (8). II and III refer to specimens studied by Kôzu and Endô (5). The structures of specimens F, M, and P were determined by Chao and Taylor (3). Structures of specimens I, J, K, and R based on preliminary x-ray studies by Chao and Taylor (3).

However, x-ray powder photographs of specimen No. 6, which has an axial angle of only 37°, did not indicate that an abnormal amount of soda feldspar was held in solid solution. The spacings of the potash feldspar lines in specimen No. 6 were found to be essentially the same as in the lamellar feldspars of corresponding composition which had large axial angles.

From the Laue photographs of the lamellar feldspars studied by Kôzu and Endô (5), there is no indication that the proportion of soda feldspar held in solid solution in lamellar feldspars is related to the size of the axial angles.

CAUSES OF THE DECREASE IN REFRACTIVE INDICES

The results of the present study do not support Spencer's contention that the decrease in refractive indices which occurs during the heating of

lamellar feldspars is related solely to solution of the soda feldspar lamellae. In the orthoclase-microperthites (specimens Nos. 1, 2, and 3), no significant decrease in the size of the lamellae was observed during the drop in indices. In the Ceylon moonstone (specimen No. 4), the microperthitic structure became less distinct in the same temperature interval during which the indices decreased, but the persistence of the schiller at still higher temperatures indicated that the solution was only partially completed. During the solution of the lamellae at higher temperatures, no further decrease in indices was observed. In Fig. 4, it is seen that

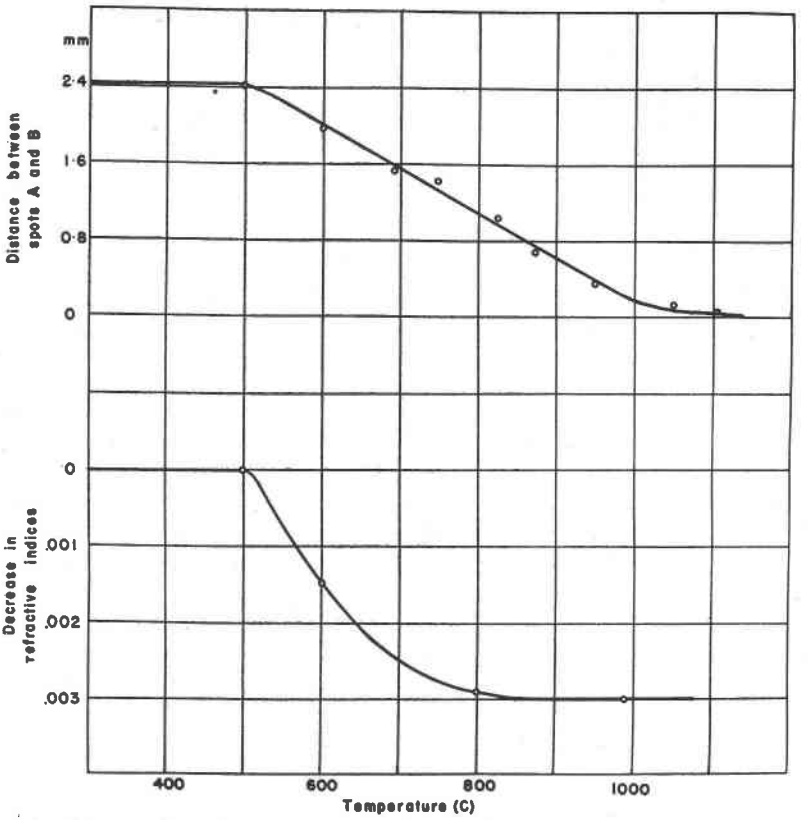

FIG. 4. Comparison of the rate of convergence of the two Laue spot systems in moonstone with the rate of decrease of the refractive indices on heating. The measurements were not made on the same sample of moonstone but the specimens compared were similar in the size of the axial angle, composition, and mode of occurrence.

Upper curve: Decrease in the distance between the two Laue spot systems of Ceylon moonstone as determined by Kôzu and Endô (5). Distance was measured between the two spots designated by Kôzu and Endô as *A* and *B* (p. 13).

Lower curve: Rate of decrease of the refractive indices of Ceylon moonstone, specimen No. 4.

the rate of solution of the soda feldspar lamellae in Ceylon moonstone as determined by the *x*-ray studies of Kôzu and Endô (5) is not the same as the rate of change of index as determined in the present study of Ceylon moonstone. The drop in refractive indices in the writer's specimen was completed well below the temperature at which the less sodic moonstone of Kôzu and Endô became homogeneous. For these reasons, it is doubtful whether the decrease in indices on heating is related only to solution of the lamellae.

An inversion of the soda feldspar component to a form with lower indices does not satisfactorily account for the observed facts. In the series of microperthites which Spencer (8) studied, the drop in indices on heating to 850° C. was proportional to the soda content between 8 per cent and 30 per cent soda feldspar. With greater soda content the drop in indices was less. Therefore, an inversion of the soda feldspar component does not appear to be the sole cause of the decrease in indices.

As Buerger (2) has pointed out, the homogenization of perthite may be regarded as a transformation of two ordered crystals to one disordered crystal. He states that at the onset of disorder there is commonly a tendency for open spaces to develop. This increase in volume might account for part of the decrease in indices.

Until more is known about the structure of lamellar feldspars, it may not be possible to give a complete explanation of the changes in indices. Chao and Taylor (3) state that the structure of the soda feldspar component in lamellar feldspars may be different from that of ordinary albite. Furthermore, the structure of the soda feldspar component in the "F" type of lamellar feldspar may not be the same as that in the "M" type. With so many variables it is difficult to say what changes in volume take place on heating. The decrease in refractive indices may be due partly to solution of the lamellae and partly to inversions in one or both of the components of the lamellar feldspars. The amount of decrease may depend as much upon the structure of the feldspar as upon its bulk composition.

Origin of the Lamellar Feldspars

The lamellar feldspars that have small axial angles become homogeneous at temperatures (below 850° C.) which are probably lower than the crystallization temperatures of many homogeneous feldspars. These lamellar feldspars, therefore, may be of exsolution origin.

The fact that high temperatures (above 1000° C.) are required to homogenize the lamellar feldspars which have large axial angles raises the question as to whether the soda feldspar lamellae in these specimens are entirely of exsolution origin. The writer has found that mixtures of quartz and sodic potash feldspar become largely liquid at 1000° C. under

atmospheric conditions. The lamellar feldspars which have large axial angles may be examples of anomalous mixed crystals (7). These intergrowths are formed by simultaneous intercrystallization of two phases, one being disseminated in oriented fashion in the host crystal as a sort of buried overgrowth.

Summary

In many of the finely lamellar feldspars which have axial angles greater than 60°, the temperatures required to effect homogenization probably do not represent the minimum temperatures at which the feldspars could have crystallized. The lamellar feldspars with large axial angles may have formed largely by the simultaneous crystallization of potash feldspar and soda feldspar rather than by the exsolution of an initially homogeneous feldspar. The lamellar feldspars which have axial angles less than about 60° are probably of exsolution origin. The changes in refractive indices which accompany heating may be due partly to solution of the lamellae and partly to inversions of one or both of the components of the lamellar feldspar. The temperature at which the indices cease to decrease cannot be relied upon to give the temperature at which homogenization is completed. Some of the relatively fine lamellar feldspars in the low-soda group were found to be very resistant to heat-treatment compared to Spencer's specimens. The writer proposes that the specimens in the two cases may be structurally different and therefore do not respond similarly to thermal treatment. Data from *x*-ray investigations indicate that there is no significant difference between the degree of solution in the unheated lamellar feldspars which have small axial angles and those which have large axial angles.

Acknowledgments

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References

1. Barth, T. F. W., Permanent changes in the optical orientation of feldspars exposed to heat: *Norsk Geol. Tidsskr.*, **12,** 57 (1931).
2. Buerger, M. J., The rôle of temperature in mineralogy: *Am. Mineral.*, **33,** 101 (1948).

3. CHAO, S. H., AND TAYLOR, W. H., The lamellar structure of potash-soda feldspars: *Royal Soc. London, Pr.*, A, **174**, 57 (1940).
4. COATES, J. S., The geology of Ceylon: *Ceylon J. Sci., Sect.* B, **19**, 101 (1935).
5. KÔZU, S., AND ENDÔ, Y., *X*-ray analysis of adularia and moonstone and the influence of temperature on the atomic arrangement of these minerals: *Tohoku Imp. Univ., Sci. Repts.* (3), **1**, 1 (1921).
6. LARSEN, E. S., IRVING, JOHN, GONYER, F. A., AND LARSEN, E. S. 3rd, Petrologic results of a study of the minerals from the Tertiary volcanic rocks of the San Juan Mountains, Colorado: *Am. Mineral.*, **23**, 417 (1938).
7. SEIFERT, H., Die anomalen Mischkristalle: *Forts. Min.*, **19**, 103 (1935); **20**, 324 (1936).
8. SPENCER, E., The potash-soda feldspars, I thermal stability: *Mineral. Mag.*, **24**, 453 (1937).