The orthoclase-microcline inversion.

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Introduction.

THE association of orthoclase[1] and microcline in the same rock has been commented on by many writers, and from these occurrences attempts have been made to deduce the relative stability of these two low-temperature forms of potash-felspar. Almost all investigators have concluded that microcline is the lower-temperature modification, but difficulties in explaining the relationship of adularia to orthoclase and microcline have been encountered.

The identification of the monoclinic potash-felspar in association with microcline is almost always based on optical properties, viz. straight extinction in the zone [010] or the absence of visible multiple twinning. These are necessary conditions, but are not in themselves sufficient evidence of a monoclinic felspar lattice. X-ray powder diffraction patterns are sometimes effective (MacKenzie, 1952), but detection of very slight departures from monoclinic symmetry may require single-crystal X-ray methods.

In discussing the lattice and twinning of microcline, Laves (1950) states that the relationship between the pericline and albite twinning can be explained only on the assumption that the microcline crystallized with monoclinic symmetry and subsequently acquired triclinic symmetry. Many petrologists may find difficulty in accepting this hypothesis from their experience of the occurrence of microclines, but the evidence given by Laves from the material which he investigated is very good. In one of the specimens to be described here, orthoclase is actually present along with microcline, and the relationship between pericline and albite twinning in the microcline appears to be identical with that described by Laves (1950). There seems no firm reason, however, to extend the hypothesis to untwinned microclines.

[1] The term orthoclase is used throughout this paper to indicate low-temperature monoclinic potash-felspar.

Variations in the microcline lattice.

In 1950 Laves considered that microcline and triclinic adularia should be regarded as separate modifications of potash-rich felspar, and he gives lattice angles 'characteristic' of each form even in a more recent paper (1952), in which he suggests that there may be a continuous gradation from a truly monoclinic lattice to a triclinic lattice with angles α 90° 39′ and γ 87° 47′. These values are, however, very common in microclines. They represent the largest departure from monoclinic symmetry so far found, and following a suggestion by Dr. Laves (personal communication), the term 'maximum' microcline is used here to denote a potash-felspar having approximately these lattice angles.

Fig. 1 shows the X-ray spectrometer patterns of five samples of low-temperature, potash-rich felspar. Pattern A is of a truly monoclinic felspar, and the remaining patterns are produced by triclinic felspars. The peaks joined by broken lines represent reflections from the (130) and ($1\bar{3}0$) planes between 2θ values of 23° and 25° (Cu-$K\alpha$), and from the (131) and ($1\bar{3}1$) planes between 2θ values of 29° and 31°. The patterns are arranged in order of increasing departure from monoclinic symmetry.

The lattice parameters of specimens C, D, and E, measured from these patterns by the method of Donnay and Donnay (1952), are set down in table I. The relation between the separation of the 130 and $1\bar{3}0$ peaks and the angle γ^* is given by the following expression:

$$Q_{1\bar{3}0}-Q_{130} = 12a^*b^* \cos\gamma^*, \text{ where } Q_{hkl} = \frac{1}{d^2_{hkl}}.$$

The value of $2\theta_{1\bar{3}0}-2\theta_{130}$ is thus directly dependent on variations in γ^*, since variations in a^* and b^* are very small. The angles α and γ calculated from specimen E correspond fairly closely to the angles of a 'maximum' microcline. The value of $2\theta_{1\bar{3}0}-2\theta_{130}$ (Cu-$K\alpha$) for this mineral is 0·84°.

The compositions of these five minerals, calculated from the chemical analyses, are given in fig. 1. In samples B, D, and E the peak at about $2\theta = 28°$ (Cu-$K\alpha$) indicates the presence of albite as a separate phase. This is the strongest peak in the powder diffraction pattern of low-temperature albite[1] and is made up of reflections from 040, 002, and 220. Thus the compositions do not represent the potash phase alone and cannot be used in a study of the microcline lattice without correcting for the amount of albite present as a distinct phase. If a large amount of low-temperature albite is present, the 111 reflection of the albite may

[1] From this peak alone it is impossible to distinguish between high- and low-temperature albite.

obscure the 130 reflection of orthoclase, but in these patterns this difficulty does not arise.

The lattice parameters of sample B have not been determined, because

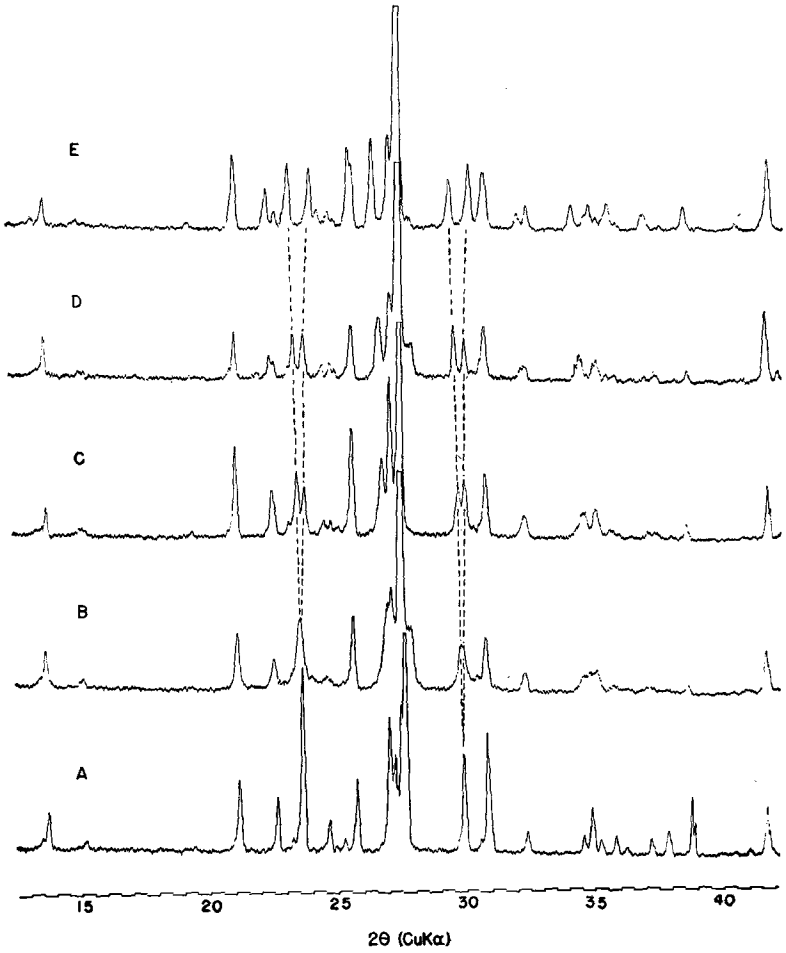

FIG. 1. Powder X-ray diffraction patterns of low-temperature alkali-felspars. Pattern A is of a monoclinic felspar and patterns B, C, D, and E are of microclines with varying departure from monoclinic symmetry. The peak at about 28° (Cu-$K\alpha$) in patterns B, D, and E is due to the presence of albite as a separate phase.

The compositions of these minerals from chemical analyses are: (A–D, Spencer, 1937) A, $Or_{84\cdot5}Ab_{13\cdot8}An_{1\cdot7}$; B, $Or_{81\cdot5}Ab_{18\cdot1}An_{0\cdot4}$; C, $Or_{85\cdot9}Ab_{12\cdot7}An_{1\cdot4}$; D, $Or_{83\cdot3}Ab_{14\cdot9}An_{1\cdot8}$; E (Blue Mt. microcline, table II), $Or_{90\cdot5}Ab_{9\cdot2}An_{0\cdot3}$. (See p. 366, *Note.*)

the reflections which show the triclinic character of the lattice are not clearly resolved from one another. It is probable that the lattice angles of this mineral are close to those given by Laves (1952) as characteristic

TABLE I. Cell parameters of microclines.

	Specimen C.	Specimen D.	Specimen E.
a	$8{\cdot}56_6$	$8{\cdot}55_9$	$8{\cdot}57_4$
b	$12{\cdot}96_4$	$12{\cdot}97_6$	$12{\cdot}98_1$
c	$7{\cdot}21_1$	$7{\cdot}20_2$	$7{\cdot}22_2$
α	90° 17′	90° 23′	90° 41′
β	115 58	115 54	115 59
γ	89 11	88 47	87 30
α^*	90 05	90 09	90 18
γ^*	90 46	91 09	92 22

The revised orientation suggested by Laves (1951) has been adopted. Dr. S. W. Bailey, of the University of Wisconsin, has determined cell parameters of a specimen of the same material as sample C by single-crystal X-ray methods. These are given for comparison with the above values (Bailey, personal communication): a 8·5784, b 12·9600, c 7·2112, α 90° 18′, β 116° 02′, γ 89° 08′, α^* 90° 05′, β^* 63° 58′, γ^* 90° 50′.

TABLE II. Analyses of 'maximum' microclines. (Analyst, J. H. Scoon.)

	1.	2.	3.
SiO_2	64·46	64·58	64·40
Al_2O_3	18·55	18·68	19·09
Fe_2O_3	0·14	0·12	0·31
MgO	nil	nil	0·04
CaO	0·17	0·20	0·05
Na_2O	0·49	0·63	1·09
K_2O	16·07	15·68	15·26
H_2O-	0·06	0·07	nil
MnO	nil	nil	0·01
	99·94	99·96	100·25
Or (wt. %)	95·0	93·6	90·5
Ab	4·2	5·4	9·2
An	0·8	1·0	0·3

1. Microcline from a pegmatite in grennaite, Norra Kärr, Sweden. $Or_{95\cdot0}Ab_{4\cdot2}An_{0\cdot8}$.
2. Amazonstone from Pikes Peak, Colorado. The analysed sample was estimated optically to contain 2 % of albite as a separate phase; thus the composition of the potash phase is $Or_{95\cdot6}Ab_{3\cdot4}An_{1\cdot0}$.
3. Microcline from the nepheline-syenite of Blue Mountain, Ontario. The analysed sample was estimated optically and by X-rays to contain 2 % of albite. The corrected composition of the potash phase is $Or_{92\cdot5}Ab_{7\cdot2}An_{0\cdot3}$.

of triclinic adularia, but few petrologists, on seeing the uniform cross-hatch twinning covering the entire area of the crystals, would call this mineral adularia.

Specimens A, B, C, and D are from Dr. E. Spencer's collection of orthoclase- and microcline-microperthites (Spencer, 1937), and the

writer is indebted to Drs. N. L. Bowen and O. F. Tuttle for permission to use them. Specimen E is from the nepheline-syenite of Blue Mountain, Ontario, and its composition was calculated from a chemical analysis by Mr. J. H. Scoon (table II).

Felspar from the Bearpaw Mountains, Montana.

The felspars from the nepheline-syenite pegmatites of Rocky Boy stock in the Bearpaw Mountains, Montana, have been described by Pecora (1942). He suggested that the felspars in many of the pegmatites had been hydrothermally altered and noted that, in some cases, grains which appear homogeneous in plane polarized light have a 'splotchy' texture under crossed nicols. Professor C. E. Tilley noted a considerable variation in the size of the optic axial angle of what appeared, in plane polarized light, to be a homogeneous felspar crystal from one of these pegmatites. The specimen described here is not identical with any of the materials described by Pecora, but is of the same general type and under crossed nicols it shows the 'splotchy' texture mentioned by him.

Fig. 2 shows a photomicrograph of part of one of these felspar crystals under crossed nicols; a suggestion of multiple twinning can be seen in this photograph. The small included crystals are aegirine. The section is approximately normal to the acute bisectrix. The optic axial angle of the dark areas is moderate (30–40°); in the lighter areas it is much larger (70–75°). The optic plane is common to the whole crystal, but the position of the acute bisectrix differs with the size of the optic axial angle. It was not possible to make optical determinations of the symmetry of the various parts of the crystal, since the cleavages are not well enough defined in thin section to obtain measurements more accurate than $\pm 1°$. The (001) and (010) cleavages appear to be continuous throughout the whole crystal, thus emphasizing its apparent optical homogeneity in plane polarized light. An X-ray spectrometer powder pattern of this mineral shows that it is rich in potash and consists of microcline and orthoclase with no soda-felspar phase. Fig. 5*a* (p. 362) shows part of the X-ray spectrometer pattern.

Zero layer-line *a*- and *c*-axis Weissenberg photographs were made of crystal fragments of both the material of moderate optic axial angle and that of larger optic axial angle. The patterns of the former show only one set of reflections and are consistent with monoclinic symmetry. The pattern obtained from the fragment of larger optic axial angle (fig. 3) shows groups of three and five reflections instead of single reflections. The centre spot in every case corresponds with the appropriate spot on

the photographs of the monoclinic crystal, while the additional spots represent four triclinic components.

The stereogram in fig. 4 shows the relations between these five units as deduced from the X-ray photographs by Dr. J. V. Smith. The axes of the monoclinic component are denoted by the subscript M and those of

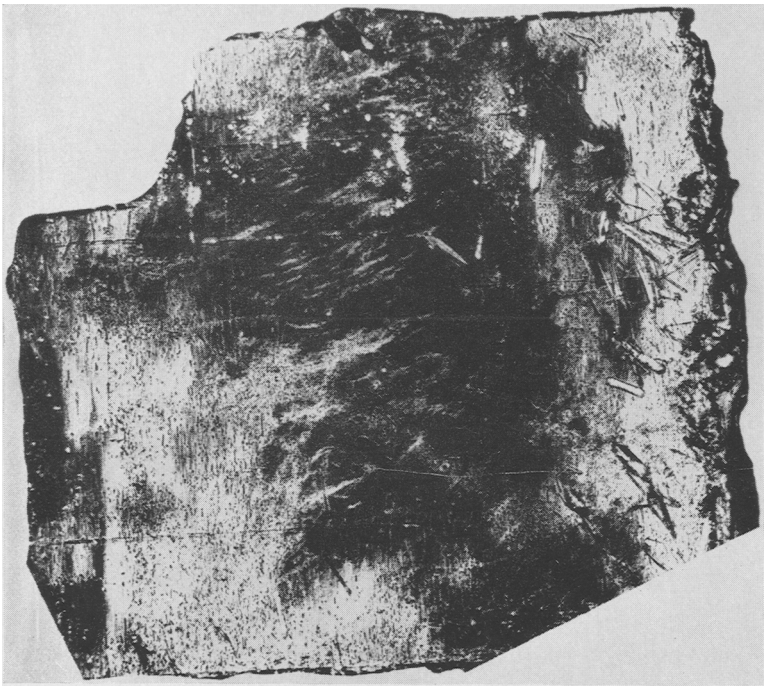

FIG. 2. Photomicrograph of a felspar from a nepheline-syenite pegmatite of Rocky Boy stock, Bearpaw Mts., Montana. The crystal is cut approximately normal to the a crystallographic axis. The dark areas are monoclinic and the lighter areas are triclinic. Crossed nicols: ×96.

the triclinic components by the subscripts 1, 2, 3, and 4. The c^*-axis appears to be common to both monoclinic and triclinic parts. Equally inclined to the a^*-axis of the monoclinic component are two additional a^*-axes which lie in the a^*b^* plane of the monoclinic material. Two additional b^*-axes are equally inclined to the b^*-axis of the monoclinic material, and lie in the plane at 90° to the common c^*-axis. There are thus five separate orientations, of which one is monoclinic and four are triclinic with a common c^*-axis. Study of the stereogram reveals that it

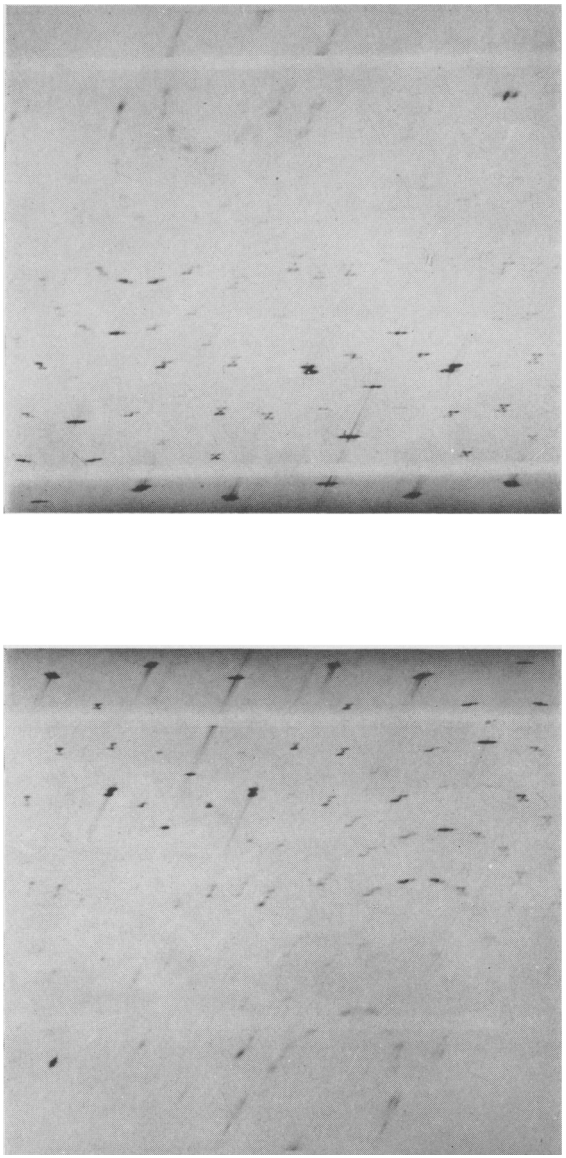

FIG. 3. Zero layer-line Weissenberg photograph taken about the c-axis of a fragment of the felspar from the Bearpaw Mts., Montana, using Cu-$K\alpha$ radiation. The reflections from the lattice planes of the five differently oriented units in this crystal are clearly shown and form small crosses in the photograph.

must be only an approximation, as two of the triclinic components evidently have b^* in common with the monoclinic material and therefore cannot have a common c^*-axis with it unless the 'triclinic' α^* is exactly 90°. The maximum departure from 90° of the angle α^* in a microcline, about 25′ according to Laves (1950), cannot be reliably detected in these Weissenberg photographs.

Laves (1950) has described the relationship between the separate

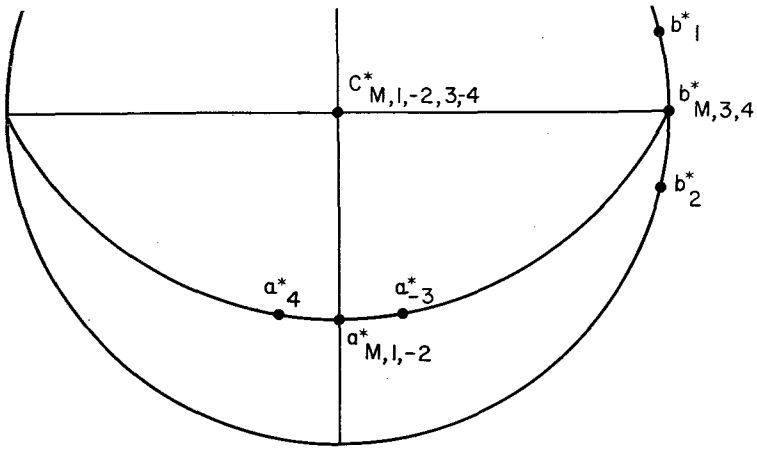

FIG. 4. Stereogram showing the approximate relation between the axes of the reciprocal lattices of the five different units of the felspar from the Bearpaw Mts., Montana. The subscript *M* refers to the monoclinic part and the subscripts 1, 2, 3, and 4 refer to the four triclinic parts. The angular relations in the stereogram are very much exaggerated for clarity.

triclinic units of a twinned microcline as due to albite and pericline twinning, the albite-twinned parts retaining the plane of symmetry of the original monoclinic material and the pericline-twinned parts retaining the axis of symmetry. From the stereogram in fig. 4 it can be seen that the triclinic parts 1 and 2 are in pericline twin relation and parts 3 and 4 are in albite twin relation. There is no evidence to suggest that the twinning arrangement differs from that proposed by Laves (1950), with the exception that the original monoclinic material is still preserved, and the close relationship between the orientations of the triclinic material and the monoclinic parent material can be seen in the X-ray photographs.

The lattice angles α and γ of this triclinic material, measured from the X-ray spectrometer pattern, do not show as large a departure from 90°

as in 'maximum' microcline, the value of $2\theta_{1\bar{3}0}-2\theta_{130}$ being 0·71° (Cu-$K\alpha$).

Felspar from paragneiss, Glen Urquhart, Scotland

This felspar occurs in an area of paragneisses which, according to Francis (1952), have been subjected to potash metasomatism. Almost all the grains show very uneven extinction, parts of individual crystals show cross-hatch twinning typical of microcline, and other parts are untwinned. This is quite a common feature of microcline, and, on the basis of extinction-angle measurements, many authors have attributed this to the association of orthoclase and microcline. A small amount of microperthitic albite is irregularly distributed in many of the crystals.

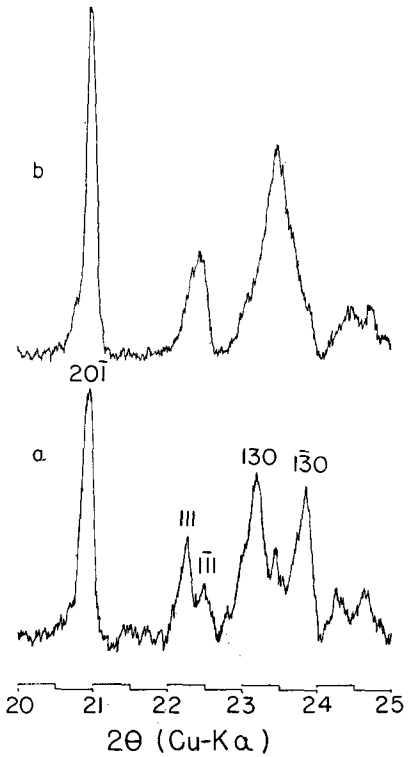

Fig. 5. Parts of the X-ray spectrometer patterns of the felspars from (*a*) the Bearpaw Mts., Montana, and (*b*) Glen Urquhart, Scotland. In pattern (*a*) the presence of orthoclase is indicated by the reflection between the 130 and 1$\bar{3}$0 reflections of microcline. In pattern (*b*) the variable lattice of microcline is shown by the broad peaks representing the 130 and 1$\bar{3}$0 reflections and the 111 and 1$\bar{1}$1 reflections. By contrast the 20$\bar{1}$ peak is sharp and well defined.

Laves (1950, p. 553) has discussed this question of uneven extinction and optically monoclinic areas in a microcline from Madagascar, and has presented two possible explanations; viz. optical deviation from monoclinic symmetry is a function of either (*a*) the lattice angles α and γ, or (*b*) the ratio of left-hand to right-hand albite twin positions if the material is submicroscopically twinned. Since he found differences in the intensities of the X-ray reflections from the two parts of the twin, he adopted the

latter explanation as the correct one for the Madagascar microcline.

Part of an X-ray spectrometer pattern of the Glen Urquhart felspar is reproduced in fig. 5*b*. The single broad peak shown by this mineral for the 130 and $1\bar{3}0$ reflections indicates that, although monoclinic or very nearly monoclinic material is predominant, microcline is present and there is considerable variation in its lattice. In this particular case, then, the optical deviation from monoclinic symmetry may well be a measure of the structural deviation. Although it seems quite likely, it cannot be established from this pattern that a truly monoclinic felspar is present, since a very slight departure from monoclinic symmetry will not cause sufficient separation between the $1\bar{3}0$ and 130 peaks in the powder pattern for these to be clearly resolved from each other.

Discussion.

From these two examples it would appear that there are two different ways in which triclinic and monoclinic potash-felspar may coexist: (*a*) the monoclinic material is associated with triclinic material having a fixed and fairly large departure from monoclinic symmetry, or (*b*) the monoclinic material is associated with triclinic material which shows all gradations in its deviation from monoclinic symmetry.

Barth (1934) first suggested that the differences between orthoclase and microcline are the result of disordering and ordering of the Si and Al atoms, microcline being the form in which ordering is more nearly complete. Laves (1950, 1952) elaborated on Barth's hypothesis and suggested that below 700° C. the values of the axial angles α and γ in potash-felspar increasingly deviate from 90°, the deviation being a function of the degree of ordering of the Si and Al atoms. Felspars showing intermediate structural states between a monoclinic lattice and that of a 'maximum' microcline might be described by Laves as adularia (1952, p. 445). In an attempt to explain the relationship of adularia to orthoclase and microcline, he suggested that, although adularia is generally considered to have been formed at very low temperatures, it might be a partially disordered metastable form resulting from the rate of growth being sufficiently high 'that the ordering forces are overwhelmed during crystallization'. Laves himself states, however, that 'no natural albites have been reported that display a behaviour that could be considered to be due to an intermediate state between albite and analbite'[1] (1952,

[1] Although petrologists may not have reported intermediate states between high- and low-temperature albite, these probably do exist in volcanic and hypabyssal

p. 446). Albites from low-temperature environments characteristically show very sharp extinction. The presence of any high-temperature albite would be easy to detect optically because of the considerable differences in the extinction angles and optic angles of the two forms.

Although Laves (1952) has inserted a footnote to the effect that the cell angles which he gives for microcline may be somewhat variable depending on the soda content, none of the discussions of the relationship between monoclinic and triclinic potash-felspar appear to have taken full account of the possibility that the symmetry may be controlled by the chemical composition. This omission can probably be explained by the difficulty of obtaining accurately the composition of the potash phase in microperthites.[1] It seems possible that variations in the lattice of microclines might be directly related to their chemical composition, as has been shown to be the case in the anorthoclase series (Donnay and Donnay, 1952). Since microclines are almost always microperthitic, it is difficult to find material from which the soda phase can be completely separated and the composition of the potash phase determined chemically. A solution to this problem might be found in an estimate, from the X-ray spectrometer pattern, of the amount of albite present as a separate phase in each analysed specimen.

Mixtures containing 10, 5, 4, and 2 % of albite were prepared from natural samples of a rather pure homogeneous orthoclase and a low-temperature albite, previously sieved to the same grain-size. X-ray spectrometer patterns of these mixtures showed that the height of the peak representing the 002, 040, and 200 reflections of albite is a function of the concentration of albite. This peak was easily detected in the mixture containing only 2 % of albite. Because of the uncertainty regarding the minimum size of the units of albite in microcline-perthites, the accuracy of this method for determining the amount of albite in a perthite has not been investigated in detail.

In three new analyses of 'maximum' microclines from which most of the albite was separated (table II), the amount of soda-felspar in solid solution does not exceed 7·5 % after correcting for albite visible under the microscope. Felspars like those described by Laves (1950) as triclinic adularia having only a small departure from monoclinic symmetry

rocks. Optical inhomogeneity generally would be attributed to chemical zoning, which, of course, may also be present.

[1] Vogt (1926), Andersen (1928), and Spencer (1937) have remarked on the limited range of composition of microcline-microperthites, but Spencer states that more extreme compositions could possibly have been found in material which was discarded as not suitable for his accurate optical investigations.

are frequently non-perthitic. In the literature, chemical analyses of adularias show that these have between 10 and 20 % of soda-felspar in solid solution. Specimen C (fig. 1) probably has less than 1 % of albite as a separate phase, so it will have 13 % of soda-felspar in solid solution.

Returning to a consideration of the two specimens described in this communication, it appears that the felspar from the Bearpaw Mountains has changed from a monoclinic lattice directly to a triclinic lattice of fixed lattice parameters with very little material of intermediate structural states. There is no evidence of a soda phase either under the microscope or in the X-ray diffraction patterns. According to the argument proposed here, this type of change is possible only because the original monoclinic felspar has a very low soda content. The Glen Urquhart felspar, on the other hand, shows gradational lattice parameters, and the presence of small blebs of albite indicates that some exsolution has taken place. It is conceivable that these two factors are related and that only by exsolution of albite to reduce the amount held in the potash phase can the lattice angles approach those of a 'maximum' microcline.

One piece of evidence which may conflict with the hypothesis of chemical control of the lattice of microclines was given to me recently by Dr. O. F. Tuttle (personal communication). An X-ray spectrometer pattern was made of a microcline-microperthite and the distance between the (130) and ($1\bar{3}0$) peaks was measured on the chart; the presence of albite lines in the pattern was noted. The specimen was heated for different periods of time until albite lines could no longer be detected in the X-ray pattern, and it was found that the separation of the (130) and ($1\bar{3}0$) peaks had not altered within the limits of error in measurement. The albite had been taken into solid solution in the potash phase. Dr. Tuttle has remarked, however, that the homogeneous phase produced may be metastable, so this cannot be considered as evidence against the hypothesis proposed above.

The writer believes that both the character of the lattice and the very existence of the lattice of microcline are controlled chiefly by the chemical composition of the potash phase, which, in most cases, is controlled by the extent to which the exsolution of soda-felspar has proceeded. If metamorphism is capable of promoting exsolution, and many petrologists have expressed the view that it is, a possible reason for the occurrence of microcline as the stable form of potash-felspar in rocks which have been subjected to regional metamorphism is that the mineral is almost pure $KAlSi_3O_8$.

The hypothesis of chemical control of the lattice angles of microclines

may not be completely at variance with the idea that the change from monoclinic to triclinic symmetry is connected with the ordering of the Si and Al atoms. Perhaps the Si and Al atoms cannot order beyond a certain limit until the soda and potash phases have unmixed to the extent that each is almost a pure end-member of the solid solution series. This limit of the ordering of Si and Al may be represented by orthoclase occurring as a discrete phase or by the monoclinic potash phase in orthoclase-microperthites.

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Note.—Fig. 1, B and D: lattice parameters and amount of exsolved albite are variable in different fragments. A, B, C, D are Spencer's D, W, U, E; his analyses are recalculated to 100%.