# MONOCLINIC K-FELDSPAR WITH TRICLINIC MORPHOLOGY

By

JULIAN R. GOLDSMITH [1] and FRITZ LAVES [2]

[1] Department of Geophysical Sciences, University of Chicago.
[2] Institut für Kristallographie und Petrograpie.
Eidg. Techn. Hochschule. Zürich.

## Abstract

Many of the altered phenocrysts of K-feldspar in the Lincoln Porphyry near Leadville, Colorado, show small but real external deviations from monoclinic geometry. All of the evidence indicates that distortion of normal monoclinic feldspar rather than initial triclinic crystallization is responsible.

## Introduction

Essentially all ideomorphic microcline crystals are morphologically monoclinic. Exceptions are very rare and the only good example known to the writers is a microcline from Ivigtut, measured and described by Böggild (1911, 1953). This material occurs as tiny overgrowths on larger masses of cross-hatched microcline. A somewhat similar but less clear-cut case is the microcline from Hundholmen, Norway, described by Laves (1950), and Goldsmith and Laves (1954). The morphology of the Hundholmen material was not investigated. It is likely that these represent rare occurrences of primary microcline, the only other known examples being some of the authigenic K-feldspars. The authigenic microclines however have an atypical and unique morphology produced by an unusual fourling twinning (Baskin (1956)).

It appears that all of the known primary microclines were formed at low temperatures, and the Ivigtut and Hundholmen microclines may well have crystallized at temperatures not much above those of the authigenic examples. The typically well-formed crystals of microcline from pegmatites and other occurrences show monoclinic morphology. In addition, essentially all microclines show the typical albite-pericline cross-hatch twinning combination. Laves (1950) has shown that the geometric relations of these twins can be accounted for by inversion but not by growth. It has therefore been concluded that the great majority of what we now see as microcline originally crystallized with monoclinic symmetry.

In the Spring of 1952, Mr. Gerald Wasserburg, then a graduate student at the University of Chicago and aware of our interest in feldspars, presented the writers with a well-formed single-crystal of K-feldspar that he had earlier found in the Leadville, Colorado, area. It was almost immediately noted that the crystal, which in all other respects appeared to be a rather typical orthoclase, did not seem to be truly monoclinic. The angle (001) $\wedge$ (010) ($\alpha^*$) which is 90° in the monoclinic case showed a small but visually observable deviation from a right angle.

Morphologically triclinic alkali feldspars could be accounted for in several ways:

a) By the primary crystallization of microcline with little or no growth twinning, or, if growth twinning is of either the albite or pericline type, it could be sufficiently unbalanced or gross enough that the triclinic morphology is expressed.
b) The crystallization of a high-temperature alkali feldspar with a large enough Na-content to develop triclinic symmetry (anorthoclase). The extreme case in terms of composition, is of course essentially pure albite, and here, it is not necessary that the high-temperature modification be formed; low-temperature albite is also triclinic.
c) The direct crystallization of a member of the metastable microcline—albite series. The production of this series in the laboratory by alkali interdiffusion has been described by Goldsmith and Laves (1961). In these experiments however, as in the case of the production of microcline from albite by Laves (1951), natural starting materials were used. No examples of direct crystallization of these low-temperature series are known, and it is rather unlikely that these metastable triclinic alkali feldspars have ever been primarily crystallized in nature.

Although all three of the above possibilities appeared unlikely to the authors, the triclinic morphology of the one crystal on hand could not be ignored, and it was decided that an investigation of additional material from the Leadville region should be carried out. In the summer of 1952 Mr. Wasserburg kindly guided us to the location near Leadville from which he had obtained the sample, and approximately one week was spent in collecting crystals in the area.

## The Porphyries

The geology of the Leadville district, Colorado, is treated in detail by Emmons, Irving, and Laughlin (1927). There is a widespread group of intrusive porphyries considered by Emmons, *et al*, to be of late Cretaceous or early Tertiary age. The porphyries occur mainly as sills, but also form dikes. The above authors state that the sills attained a minimum aggregate thickness of 2,500 feet, and in some parts of the region were much thicker. Two general types of porphyry have been recognized since the early days of the mining activity, and have been called the "White" porphyry and the "Gray" porphyry. The White porphyry is older, but in places it is difficult to distinguish between the two. The White porphyry is said to correspond to a muscovite granite or salic granodiorite, and the younger Gray pophyry includes varieties ranging from granodiorite to quartz monzonite. However, both types are in general so much altered that it is difficult to define them with assurance. The phenocrysts of the White porphyry are andesine (Emmons, Irving, and Laughlin (1927)), and usually less than several millimeters in size. All of the samples collected for this study were from the Gray porphyry.

The so-called Gray porphyry is actually a group of intrusive rocks, with four varieties represented in the Leadville district—the Lincoln porphyry, the Johnson Gulch porphyry, the Evans Gulch porphyry, and the Mount Zion porphyry. It is believed that essentially all of the phenocrysts were collected from the Lincoln porphyry, which according to Emmons, Irving, and Laughlin (1927) is the only type with a significant number of large orthoclase phenocrysts.

The sills of the White porphyry tend to be conformable to the bedding. There are numerous cross-cutting contacts, however, and the Gray porphyry bodies are much more commonly crosscutting, in places terminate abruptly, and are accompanied by short, "stumpy", and transgressing offshoots. Emmons, Irving, and Laughlin (1927) ascribe this behavior to the difference in viscosity of the two magmas, and state:

> "The white porphyry, which is very finely porphyritic was evidently intruded at a temperature above the crystallization points of feldspar and quartz, but after intrusion it was quickly chilled, so that even in the thickest sill these minerals had little time to crystallize. The Gray porphyry, on the other hand, had already begun to crystallize and contained feldspar, quartz, and biotite crystals of considerable size when it reached the sedimentary rocks. It was therefore, intruded at a lower temperature and must have been more viscous and more likely to deform the strata locally rather than to follow bedding planes."

The above discussion is included because of the relation that may exist between structure, rock movement, and physical deformation of the phenocrysts, a point to be later touched upon.

Folding is present although not pronounced in the Leadville district, but it is conspicuous in parts of the surrounding region. According to Emmons, Irving, and Laughlin (1927) the faulting, which is prominent in the area, took place during at least three periods. It is of interest to note, however, that all porphyry sheets were intruded before any appreciable folding or faulting took place. After the intrusion of the sills, the sequence of events can be generalized as follows:

1. Reverse faults accompanying regional folding.
2. Normal faults subsequent to folding, but prior to ore-deposition.
3. Normal faults subsequent to ore-deposition. These are the major faults of the region.

## The Phenocrysts

Well over 500 phenocrysts ranging in size from 1/4″ to over 2″ long were collected from a variety of sites in the Lincoln porphyry. Many of the samples were taken from the Evans Gulch area. The phenocrysts make up less than 10% of the rock. Almost all of the crystals were obtained by breaking up large segments of the outcrops with 16 pound sledges ("doublejacks" in the miners' parlance). The rock shows somewhat varying degrees of alteration from place to place, but at best it is far from fresh; alteration and weathering was in all cases far enough advanced that the K-feldspar phenocrysts tended to separate rather cleanly from the matrix rock. Collection was greatly aided by this behavior, and when large fragments of rock were broken with the sledge any crystals exposed tended to remain intact rather than part along the break. They could often then be popped-out unbroken by further fragmentation of the rock, although considerable care was used in chipping around the sample when a well-formed, sharply defined crystal was exposed.

The longest dimension of the untwinned phenocrysts is in the direction of the $a$-axis. There are, however, numerous Carlsbad twins, and in some localities one even gets the impression that the twinned crystals are much more abundant than the single crystals. Mannebach twins are also present, but are relatively uncommon. There is a curious relation between morphological axial ratios and twinning in these crystals. Five untwinned crystals were measured as typical of the phenocrysts collected, and the $a:b:c$ ratios are 1.61 : 1 : 1.17, 1.61 : 1 : 1.23, 1.62 : 1 : 1.19, 1.60 : 1 : 1.25, and 1.61 : 1 : 1.16. The Carlsbad twinned crystals, however, are elongated along the $c$-direction to the extent that this dimension is very close to twice its relative length in the untwinned crystals. The same is true of the Manebach twins, but they are elongated in the $a$-direction.Only a single exception was noted among the hundreds of crystals examined; one small Carlsbad twin showed essentially the same dimensional configuration as the untwinned crystals.

The phenocrysts are also altered in varying degrees from place to place, and rarely is anything approaching a fresh K-feldspar found. Less than half of any of the original feldspar substance is generally observed, and normal cleavage behavior is destroyed as a consequence. Much of the alteration product is now calcite, and various other inclusions are common. A number of the crystals were thin-sectioned, and zoning also appears common, although in the badly altered crystals it is apparent chiefly by the arrangement of the alteration products rather than by direct observation of the K-feldspar itself.

## The apparent triclinic geometry

Many, but by no means all, of the crystals that were collected appeared to the eye to deviate from monoclinic symmetry. No measurements were made in the field, however, but all of the reasonably intact crystals were brought back to Chicago. The faces of some of the phenocrysts were rather rough, but many were quite smooth and plane, even in those crystals that were highly altered. Nevertheless, measurements were made only on selected samples with sharply defined faces, and it is most unlikely that observed angular deviations can be ascribed to sloughing-off of material or roughness of the faces. All measurements were made on single crystals, and none on the Carlsbad twins.

The angular measurements were made on the rotating stage of a petrographic microscope. The optical system was removed, and cross-hairs mounted in the tube; the crystal was placed in the appropriate position on the stage so that faces or edges could be lined-up against the cross-hairs. Parallax was easily avoided, and it was felt that measurements made in this way were superior to those obtained with a contact goniometer.

The best crystals from several localities that appeared to deviate from monoclinic geometry were numbered and measured. Multiple measurements were normally made on each angle, and in addition as many combinations as possible on each crystal were also measured, i.e., $(001) \wedge (010)$, $(001) \wedge (0\bar{1}0)$, $(00\bar{1}) \wedge (010)$, $(00\bar{1}) \wedge (0\bar{1}0)$.

In Plate I five crystals are shown, resting on $(00\bar{1})$, and photographed in the general direction of the $a$-axis. In this position the deviations from monoclinic symmetry are easily seen.

It was soon observed that the measured and computed triclinic

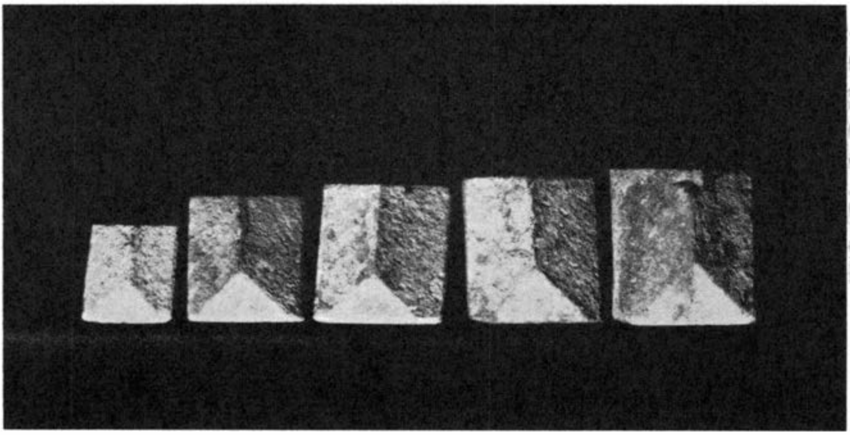

**Plate 1. Five of the phenocrysts from the Lincoln porphyry, placed with $(00\bar{1})$ on a flat surface, and with parallel alignment of the $a$-axes. The photograph is taken in the general direction of the $a$-axes, and the crystals were ordered in a way to most clearly show the deviations from monoclinic geometry.**

angles showed no crystallographic regularity. This fact was not completely unexpected, for even during the collection of the phenocrysts differences were apparent, and as mentioned, many if not most of the crystals did not appear to deviate significantly from monoclinic symmetry. The value of $\alpha^*$, or (001) $\wedge$ (010) which is 90° in the monoclinic system was found to deviate from a right angle anywhere in the range of 0° to 3°. Because of the irrational variation, the angular data are not tabulated, but some general observations can be made.

The value of $\alpha^*$ for microcline is 90°22′, for albite it is 86°25′. On the basis of these values alone, the Leadville crystals with variations from $\alpha^* = 90°$ up to 3° could fit in a triclinic K–Na series, but it turns out that there is no other evidence for this. The value of (100) $\wedge$ (010) $= \gamma^*$ is 92°16′ in microcline and 90°30′ in albite. Although this value cannot be measured directly on these crystals (the (100) face is lacking), it can be determined by measuring (110), $(1\bar{1}0)$, (010), and $(0\bar{1}0)$; in 15 crystals measured deviations of $\gamma^*$ from 90° ranged from 0.1° to 3.5°. The 3.5° deviation is larger than any observed in the feldspars, but it could be accounted for by errors in the angular measurements. Nevertheless, the size and the range of both the $\alpha^*$ and $\gamma^*$ deviations (especially in light of the different values shown by microcline and albite) would indicate that something other than normal crystallographic controls is involved in the morphology of these crystals. Furthermore, some of the crystals show both $\alpha^*$ and $\gamma$ to be $> 90°$ (or both $< 90°$, depending upon the arbitrary orientation with respect to (+) or (−) axial directions), whereas others show $\alpha^*$ to be $> 90°$ and $\gamma < 90°$ (or again, vice versa, depending upon orientation). This is, of course, inconsistent with crystallographic concepts.

Rock deformation is of course an obvious mechanism that could produce the apparent triclinic morphology shown by some of the phenocrysts. Additional insight on the possibility of a deformational process as opposed to normal triclinic growth, aside from the $\alpha^*$ and $\gamma^*$ data, can be obtained by examination of the angle $\beta$. In all of the feldspars, $\beta$ is very close to 116°. In microcline it is 115°56′, in sanidine 116°01′, in albite 116°35′, and in anorthite 115°51′. Thus any significant deviation from 116° must be non-crystallographic in origin. $\beta$ can be measured relatively accurately in these crystals, by placing them alternately on (010) and $(0\bar{1}0)$, and measuring (001) and $(00\bar{1})$ against the edges formed by the combination of the (110) and (010) faces. One obtains a set of 8 measurements one each crystal. A total of 29 crystals were measured in this way, and $\beta$ values ranged from 113.9° to 119.1°. Although it is difficult to set a precise limit of error on any of these measurements, an accuracy within $\pm 1°$ is certainly reasonable, and there is little question that the angular variation exceeds the error of measurement.

There is little doubt that deformation of some sort is responsible for the apparent triclinic geometry. The degree of deformation as expressed in the angle $\beta$ is of the same order of magnitude as that shown by the triclinic angles. Furthermore, of the 29 crystals measured, 9 showed $\beta$ angles between 113.9° and 116.0°, whereas 20 ranged between 116.1° and 119.1°. If one considers the shape of the phenocrysts (or better, the size of the $\beta$ angle), it is immediately apparent that if they were randomly oriented in a rock, and deformed by a unidirectional stress, many more would show an increase in $\beta$ than a decrease. Although this appears to be the case, the data are not considered sufficient to make a statistical analysis.

Portions of several of the crystals that were relatively unaltered were examined optically and by means of single-crystal and powder X-ray diffraction techniques. The microscopic examination did not reveal any deviation from monoclinic symmetry, and the optics were typical of "orthoclase". The X-ray photographs also showed "orthoclase" monoclinic patterns [1]. There is thus no evidence for original triclinic growth in the phenocrysts of the Lincoln porphyry.

## Deformation of the crystals

Our original interest in this problem was related to the crystallography of the feldspars. Once it became obvious that the triclinic geometry was unrelated to crystal structure the problem was not pursued further. Nevertheless, several comments may be in order at this point.

The crystals are undoubtedly true phenocrysts, and therefore grew in a magma that was in large part a liquid. All of the crystals that were examined are well-formed, with plane faces, and none of them show any impressions or evidence of impingement of other solid

[1] Ignoring the detailed fine-structure that may complicate the patterns of optically monoclinic orthoclase (see for example Laves (1950)).

phases. It is unlikely that any deformation took place during the growth of the phenocrysts; it must have occurred either after complete consolidation of the rock, or at a stage when sufficient crystallization had taken place so that the mass would have acquired the mechanical properties of a solid. If the crystals had grown as porphyroblasts in an essentially solid rock, a "deformation" of a sort might well have accompanied growth, or the growth may have proceeded under conditions in which "vicinal development" took place.

On the other hand, there are no other obvious signs of deformation. As indicated, the crystals tend to remain intact, and do not show slips, breaks, cleavages, or irregular and warped surfaces. Of course the deformation was not great, for the angles are generally distorted less than 3°. It is also possible that the deformation took place after the rock was altered. The fine-grained alteration products, including a great deal of calcite, are probably much more susceptible to flow than is the single crystal of K-feldspar itself, and in addition would show less evidence of having suffered movement. As earlier discussed, regional disturbance did follow intrusion of the sills, and the most active faulting also followed the period of ore-deposition, at which time the alteration of the sills may well have taken place. If proper orientation in space of the deformed crystals can be maintained, their study in relation to the structure of the area might prove fruitful.

## REFERENCES

Baskin, Y. (1956): A study of authigenic feldspars. Jour. Geol., vol. 64 (1956) pp. 132.

Böggild, O. B. (1911): Über die crystallform des mikrolins. Zeitschr. Kryst. und Min., vol. 48 (1911) pp. 466.

——— (1953): The mineralogy of Greenland. Meddelser om Grønland; Kommis. Vidensk. Undersøg. Grønland, Bd. 149, Nr. 3, 442 pp.

Emmons, S. F., Irving, J. D., and Laughlin, G. F. (1927): Geology and ore deposits of the Leadville mining district, Colorado. Prof. Paper 148, U.S. Geological Survey, U.S. Govt. Printing Office, 368 pp.

Goldsmith, J. R. and Laves, F. (1954): Potassium feldspars structurally intermediate between microcline and sanidine. Geochim. Cosmochim. Acta, vol. 6 (1954) pp. 100.

——— and Laves, F. (1961): The sodium content of microclines and the microcline-albite series. Instituto Lucas Mallada (Madrid). Cursillos y Conferencias, fasc. 8, pp. 81.

Laves, F. (1950): The lattice and twinning of microcline and other potash feldspars. Jour. Geol., vol. 58 (1950) pp. 548.

——— (1951): Artificial preparation of microcline. Jour. Geol., vol. 59 (1951) pp. 511.