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THE MICROCLINE-ORTHOCLASE TRANSITION WITHIN A CONTACT AUREOLE

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ABSTRACT

Microcline perthites from Precambrian pegmatites in the Front Range, Colorado, have been converted to orthoclase in a zone around a Tertiary intrusive stock. This stock, near the town of Eldor, is 2 miles across and shows fairly well exposed vertical contacts. The microcline-orthoclase transition, the only major manifestation of contact metamorphism, was investigated optically and by X-ray powder diffraction along five traverses. Outside the contact aureole and microcline commonly consists of clear crystals with typical cross-hatched twinning and shows a $2V$ of $80° \pm 5°$ and an obliquity ranging from 0.84 to 0.93. The orthoclase from near the contact is always turbid, untwinned, with axial angles $\perp$ (010) from 50° to 66°. The perthitization and composition ($Or_{77}Ab_{23}$) of the feldspars remain roughly constant across the contact aureole, except within the last few feet from the contact, where an increased albite content or the disappearance of the perthite lamellae may occasionally be observed. Both the nature of the microcline-orthoclase transition and its distance from the contact depend strongly on the configuration of the contact in that particular area. In accordance with the heat flow calculations, the transition is relatively sharp and close (1200 feet or less) to protruding corners of the intrusive, whereas, near re-entrant sections of the intrusive, the transition is gradational and relatively distant (over 2400 feet) from the contact. Heat flow calculations further indicate that the microcline-orthoclase transition may occur at temperatures below 400°C, i.e. more than 50°C lower than was hitherto known from an experimental approach. The order of the transition is not specified by this investigation although the occurrence of some intermediate microcline in the transition zone may be evidence for a continuous type of transformation.

INTRODUCTION

Investigations of potassium feldspars in contact metamorphic zones are of importance since they can provide information which cannot be obtained in well controlled but kinetically unfavorable laboratory experiments. Because of the sluggish reactions involving microcline, the lack of a method for direct synthesis of this phase, and the time restrictions on heating experiments, the stability fields of the K feldspars are still disputed and the transition temperature or range of temperature for the microcline-orthoclase transition has never been firmly established.

In previous studies of mineral age relationships in a contact zone around an intrusive stock (Doe and Hart, 1963; Hart, 1964) it was observed that the microcline of the country rock had been transformed to orthoclase in the vicinity of the contact. This transition was investigated along a single traverse (Eldora traverse) and described in some detail by

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Hart (1964). The present study extends this work with a description of the distribution of orthoclase and microcline along five additional traverses. The data are discussed in terms of the nature of the transition, its temperature range, and the correlation between the geometry of the intrusive and the width of the orthoclase aureole.

In a companion paper, Wright (1966) presents more detailed X-ray and optical data for the orthoclase-microcline relations along the Eldora traverse, reported earlier by Hart (1964). Although some differences exist in the interpretive details of our two papers, the major conclusions are in agreement that the transition temperature is probably less than 400°C and that the thermodynamic order of the transition is not unequivocally specified by the results from this contact zone.

Regional Geology

The area studied lies some 15 miles west of Boulder in the Front Range of Colorado. In this region the Front Range is comprised mainly of the Precambrian Boulder Creek granite and the schists and gneisses of the Idaho Springs Formation. This crystalline core was intruded by several quartz-monzonite stocks during the Laramide revolution. One of these stocks, just west of the town of Eldora (Fig. 1), was chosen for previous studies on the effect of contact heating on the isotopic mineral ages of various minerals (Hart, 1964; Tilton *et al*, 1964) and on lead in potassium feldspars (Doe and Hart, 1963). The Eldora quartz-monzonite stock was selected for this investigation because it shows fairly well exposed, nearly vertical contacts toward the surrounding Idaho Springs Formation. This formation is derived from predominantly sedimentary rocks which were highly and rather uniformly metamorphosed to quartz-biotite-(sillimanite) schists and amphibolites during regional metamorphism. Age determinations on hornblendes and feldspars indicate that the regional metamorphism took place some 1400 m.y. ago. At the same time numerous, usually concordant, pegmatites were formed throughout the Idaho Springs Formation. On approaching the contact of the Laramide Eldora stock, the various mineral ages of the country rock and pegmatites undergo a change from Precambrian to Tertiary. The age of the intrusive, and therefore of the contact metamorphism, was determined to be about 55 m.y.

The contact phenomena at the Eldora stock have been studied by Cree (1948), who has mapped and described the stock in detail. On the eastern side, just west of Eldora, the nearly vertical contact is sharp within an inch or so in many places; in others it is gradational over many feet, and the schists of the Idaho Springs Formation near the contact appear to have lost their foliation. On the western and northwestern contact Cree

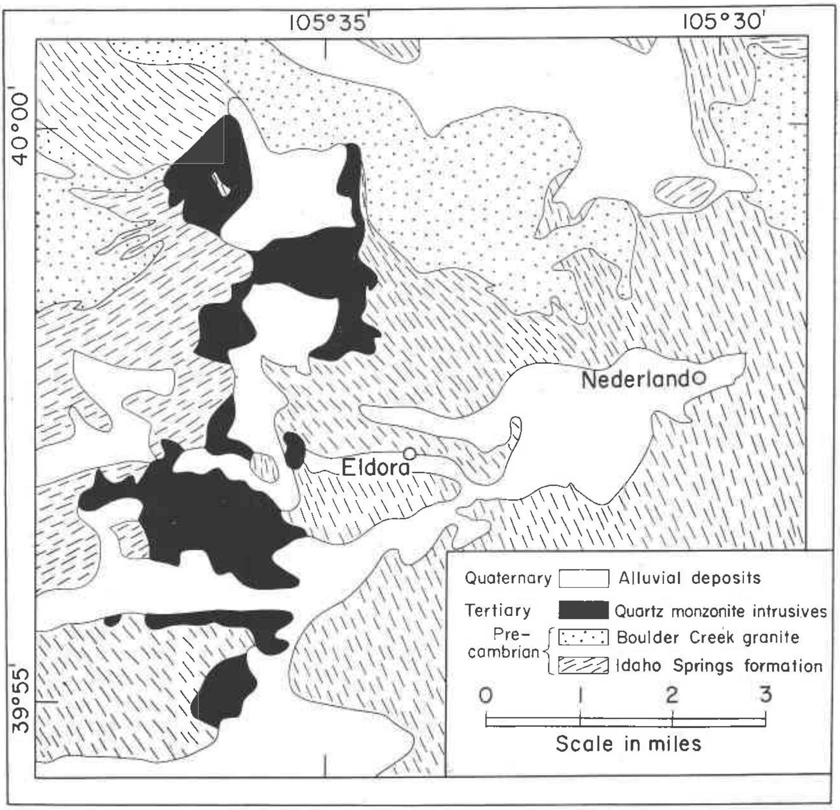

FIG. 1. Tertiary intrusives in the Eldora area. The Eldora contact is based on Cree (1948); other contacts and geology on Lovering and Goddard (1950), with minor modifications by the present authors.

(1948) observed wide exposures of the contact zone showing breccia, schlieren, windows of the stock within the Precambrian rocks, and inclusions of schist and gneiss within the Tertiary stock. He interpreted these to be pendants of the roof of the stock which were being stoped at the time of consolidation. Roof pendants and reentrants were also found in other parts of the intrusive, suggesting that the original roof of the intrusive was not very far above the present level of erosion.

Hart (1964) noted minor contact metamorphic effects in the country rock, such as alteration of hornblende to biotite and untwinned sodic overgrowth over twinned oligoclase within a few feet from the contact. Also, a faint change in the color of the biotites from brown with an orange tinge to brown near the contact was observed. This color change is correlated with the appearance of rutile clusters in the biotites as the contact is approached. The only major mineralogical change found within the contact aureole was the transition of the alkali feldspar from a perthitic microcline of high obliquity in the unaffected country rock to non-perthitic orthoclase near the contact.

Description of Pegmatites

The feldspars collected for the present study are from pegmatites which occur in great number throughout the Idaho Springs Formation. According to Cree (1948) and Lovering and Goddard (1950) these pegmatites vary between rocks essentially composed of feldspars and those which consist essentially of quartz. Many of the pegmatites in the Eldora area contain some biotite but no muscovite. The pegmatites occur along foliation planes in gneisses and schists of the Idaho Springs Formation and also along joints and faults. They range from coarse-grained dikes and sills several feet wide to fine-grained aplitic dikelets less than an inch in width. The pegmatites are often folded and faulted. They appear to be formed during the main metamorphism of the Idaho Springs Formation. This is indicated by the agreement between the K-Ar ages of hornblende from amphibolites and the Rb-Sr ages of the pegmatite feldspars (Hart, 1964). We think that most of the smaller pegmatites from which the feldspars for this study were obtained are not connected with any of the major Precambrian granite intrusions of the region but were formed locally by lateral secretion or partial melting.

Methods of Study

Location of traverses

The feldspars used for the present study were collected from Precambrian pegmatites located in the country rock around the stock.[2] The samples were usually picked up from sites along compass traverses perpendicular to the contact. In each case the contact was located and mapped anew on recent topographic maps of the U. S. Geological Survey (7.5 minute series, scale 1:24,000). The traverses were named after nearby mountains where possible, as shown in Fig. 2. The "Hessie" traverse comprises samples collected along the road connecting the hamlet Hessie and the Fourth-of-July camp. The samples designated "Hessie-Chittenden" (HCh) were obtained on the mountain slopes between the "Hessie" traverse and Chittenden Mountain. Usually the distances from the contact were measured by tape. The sample designations and distances in feet for the five new traverses are listed in the first column of

[2] The choice and direction of the sampling traverses were guided by an attempt to evaluate the assumption made in the heat flow calculations by Hart (1964) of a symmetrical heat flow in E-W direction.

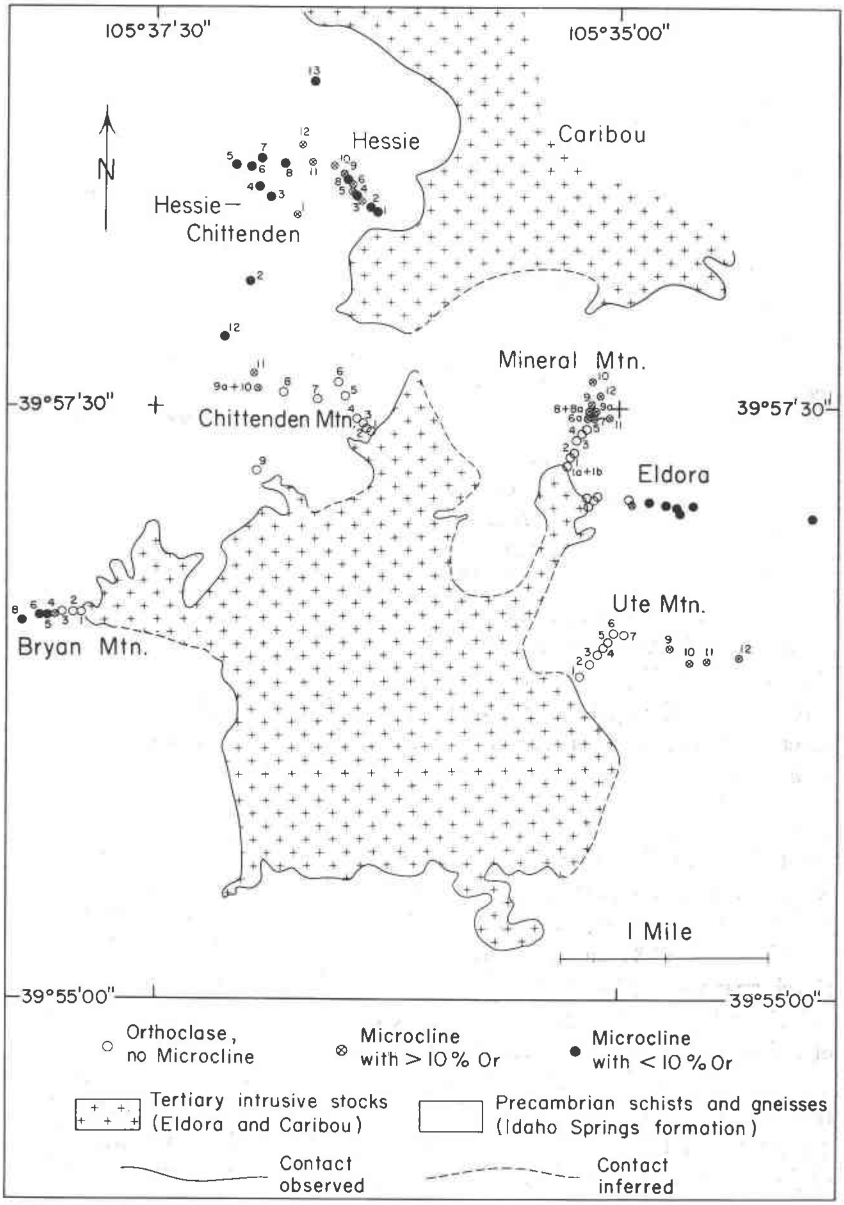

FIG. 2. Eldora and Caribou stocks showing sample locations and the combined results from the optical and X-ray investigation of the K feldspars. The map is based on the work of Cree (1948) and Lovering and Goddard (1950), and the observations of the present authors, redrawn on 7.5 minute series topographic maps of the U. S. Geological Survey (East Portal quadrangle 1958, Nederland quadrangle 1942).

Table 1.[3] For the "Eldora" traverses the original paper by Hart (1964) or the companion paper by Wright (1966) should be consulted.

Optical methods. Initially grain mounts of the alkali feldspars were inspected under oils using a field microscope. The microcline-orthoclase transition is easily recognized by the occurrence or disappearance of the typical crosshatched microcline twinning. Later, the grain mount studies were repeated in the laboratory on the sample powder used for the X-ray investigations. A short description of the optical observations, including those from thin sections, is presented in Table 1.

The optic axial angles were measured from the thin sections by extinction techniques. The difficulties of obtaining these angles are well reflected in the uncertainties assigned to the measurements. The fine-perthitic nature of most feldspars, the twinning of the microclines, alterations, and undulatory extinction usually do not allow reproducibility to better than $\pm 1.5°$–$2.0°$ if both optical axes could be measured or $\pm 3°$–$5°$ if only one axis was observed. Very often multiple measurements were made in the same crystal, some of them in the same position to check the precision. If possible, several different crystals were analyzed from one thin section. More than one thin section was made when the axial angles measured did not agree with the X-ray results. The results of the individual $2V$'s and the observed or estimated errors are listed in Table 1. The plane of the optical axes was found to be perpendicular to (010) in several crystals and this is assumed to be the case for all the monoclinic feldspars.

X-ray methods. X-ray diffraction was used to identify the feldspars, to determine the obliquity of the microclines, and to estimate the proportions of microcline and orthoclase. For identification reflections from $20\bar{1}$ to $13\bar{2}$ were surveyed, then 2θ 29° to 32° was scanned four to six times at 1°/min for the 131 and $1\bar{3}1$ reflections to determine the obliquity of the K feldspars. Standard errors for the mean obliquity range from 0.01 to 0.03. The $\Delta 2\theta$ values were measured between the centers of the main peaks of 131 and $1\bar{3}1$. In many cases these reflections were very sharp, in others there were side peaks (often at lower and/or higher angles), and in some the peaks were rather broad. All these variations are noted in Table 1. They suggest the presence of smaller amounts of microcline with either higher or lower obliquities. No obliquity measurements were possible if

[3] Table 1 has been deposited as Document No. 9180 with the ADI Auxiliary Publications Project, Photoduplication Service, Library of Congress, Washington, D. C. 20540. Copies may be secured by citing the Document number and by remitting in advance, $1.25 for photoprints or for microfilm, payable to Chief, Photoduplication Service, Library of Congress.

the amount of microcline present in the K feldspar was less than about 25 percent.

Proportions of orthoclase and microcline in the K feldspars (Table 1, column 6) were estimated by comparing the diffraction patterns with those of artificial mixtures, as shown in Figure 3. The 131 peak of orthoclase can usually be detected when 5 percent or more is present. For microcline the detection limit is only 20 percent, or higher, depending on the obliquity. Where the microcline content was low, it was estimated optically.

Bulk composition, i.e. orthoclase and albite content, was determined by Orville's (1958) method. Since most of the samples are strongly perthitic, they were homogenized by dry heat treatment. Preliminary experiments had shown that a 16–48 hour heating period at 1050°C was sufficient to homogenize the perthites without necessarily dissolving larger, possibly non-perthitic inclusions of albite. Small fragments (2–3 mm) of the crystals employed for the grain mounts or thin sections were heated in a resistance furnace for 24 hours. Then the samples were ground, mixed thoroughly with $BRrO_3$, and X-rayed. The angle between the 101 reflection of the internal standard and $20\bar{1}$ of the homogenized K feldspar was scanned about ten times. Standard errors for $\Delta 2\theta$ ($20\bar{1}_{\text{K feldspar}}$-$101_{KBrO_3}$) measurements are about 0.004°. Or-Ab content in weight percent (Table 1) was determined applying the curve given by Orville (1958). Allowance was made for the triclinic or monoclinic form of each sample. Orville had shown that for a given $\Delta 2\theta$ value a triclinic phase contains 1.5 weight percent less $KAlSi_3O_8$ than a monoclinic one.

The adopted homogenization procedure was checked for grain size effects and possible influence of calcium on the reaction rate. Three finely ground samples were homogenized hydrothermally to sanidine, in sealed platinum tubes at a temperature of 700°C and a H_2O pressure of 2000 bars for 48 hours. For the two samples which were originally orthoclases, compositions from hydrothermal runs agree within 1 percent of those from the dry heating of crystal fragments for periods from 16 to 48 hours. In one specimen (originally microcline) the hydrothermal procedure indicates an orthoclase content 1–2 percent higher than that obtained by the dry treatment. No change in obliquity was observed in this microcline when heated dry for periods up to 60 hours, although the 131 peak increased in intensity relative to $1\bar{3}1$ and shifted toward the 131 peak of the corresponding sanidine (as established from the hydrothermal run). The probable error in the Or-Ab compositions listed in Table 1 is therefore estimated to be ± 1–2 percent. In isolated cases the error may be larger in the direction of lower Or content, i.e., a higher proportion of albite, owing to dissolved smaller albite inclusions.

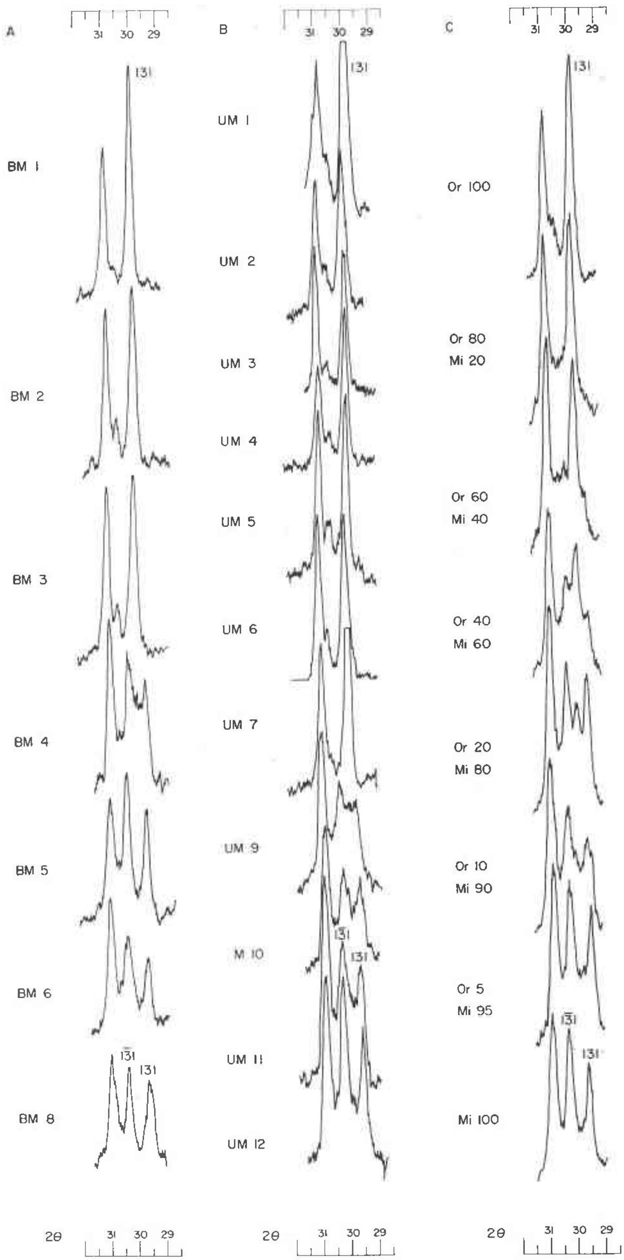

FIG. 3. Diffractometer records (CuK_α radiation) in the region of the 131-1$\bar{3}$1 reflections to show obliquity ($\Delta = 12.5\times[d_{131}-d_{1\bar{3}1}]$) and orthoclase-microcline contents as a function of the distance from the contact. (*A*) Bryan Mountain traverse, (*B*) Ute Mountain traverse, (*C*) artificial mixtures of pure orthoclase (sample UM 6) with increasing amounts of pure microcline (sample 7300, Hart, 1964). These mixtures were used to estimate the orthoclase-microcline content of all samples investigated (see column 6 in Table 1).

Only in rare cases were all observations made on the same single crystal. Usually composite samples were used for investigation.

The results of investigation for the individual traverses are summarized in Table 1 and shown graphically in Figures 4–9, where the different parameters ($2V_\alpha$, obliquity, microcline-orthoclase content) are plotted against distance from the contact.

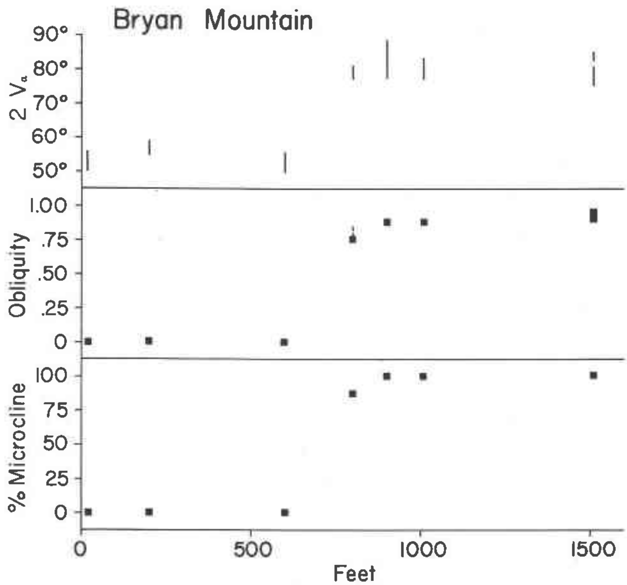

FIG. 4. Bryan Mountain traverse: optic axial angles, obliquity, and microcline-orthoclase content (in percentage of microcline) as a function of the distance from the contact.

Bulk Composition

The bulk composition of the alkali feldspars varies within rather narrow limits (Table 1). Of the 65 samples examined, 60 percent fall within the range $Or_{78}Ab_{22}$-$Or_{82}Ab_{18}$. In microclines from undisturbed areas outside the contact zone a total range in composition of $Or_{71}Ab_{29}$ to $Or_{81}Ab_{19}$ was observed with approximately 60 percent of the samples included in the $Or_{77}Ab_{23}$-$Or_{81}Ab_{19}$ interval. Nearly 65 percent of the orthoclases have a composition between $Or_{78}Ab_{22}$ and $Or_{82}Ab_{18}$, with a total variation of $Or_{92}Ab_8$ to $Or_{70}Ab_{30}$. In three traverses the albite content increases in the samples nearest the contact; in others no such trend can be observed. No obvious difference is found in the albite content of orthoclase and microcline.

The potassium feldspars appear to contain very little anorthite. Wright (1967) determined Ca in the samples of the Eldora traverse and

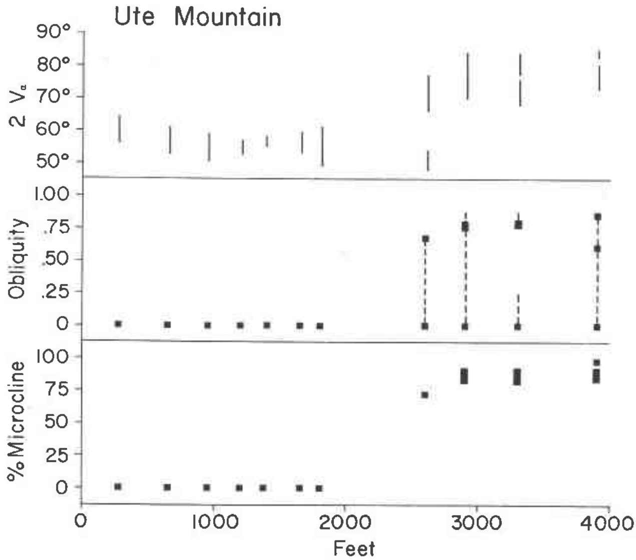

FIG. 5. Ute Mountain traverse: optic axial angles, obliquity, and microcline-orthoclase content (in percentage of microcline) as a function of the distance from the contact.

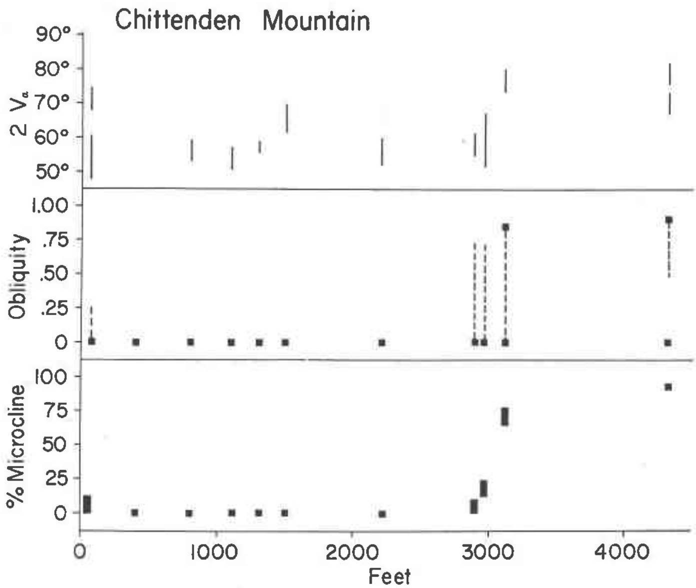

FIG. 6. Chittenden Mountain traverse: optic axial angles, obliquity, and microcline-orthoclase content (in percentage of microcline) as a function of the distance from the contact.

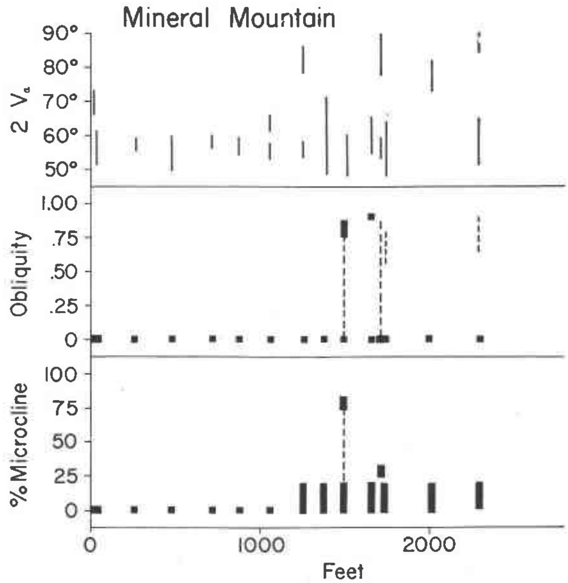

FIG. 7. Mineral Mountain traverse: optic axial angles, obliquity, and microcline-orthoclase content (in percentage of microcline) as a function of the distance from the contact.

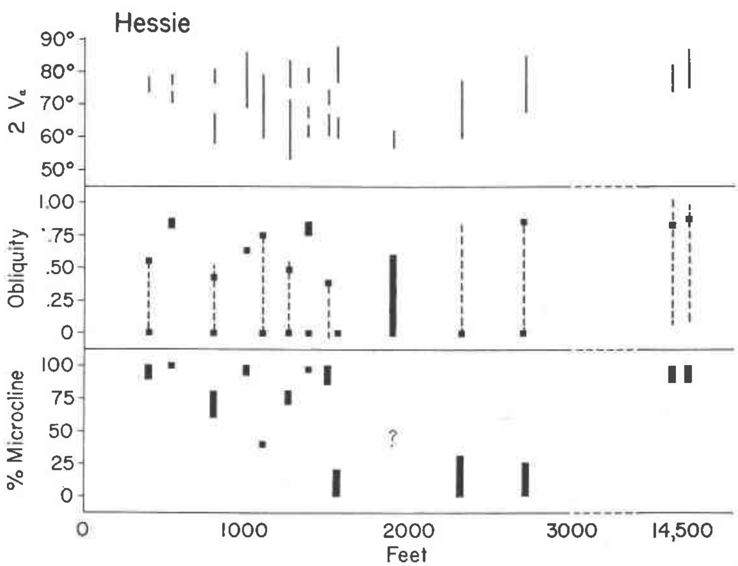

FIG. 8. Hessie traverse: optic axial angles, obliquity, and microcline-orthoclase content (in percentage of microcline) as a function of the distance from the contact.

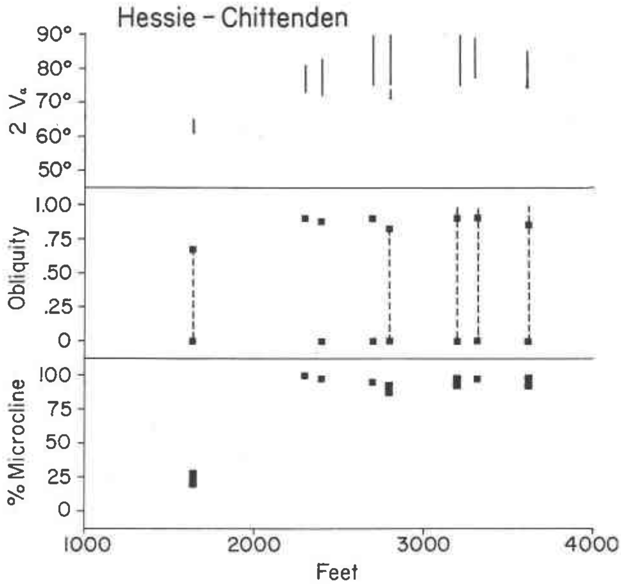

FIG. 9. Hessie-Chittenden traverse: optic axial angles, obliquity, and microcline-orthoclase content (in percentage of microcline) as a function of the distance from the contact.

found that CaO does not exceed 0.5 weight percent and averages about 0.3 weight percent.

The Orthoclase-Microcline Transition

Zone unaffected by contact metamorphism. The K feldspars from areas not affected by contact heating are often relatively clear, transparent crystals. Most of these show sharp and definite crosshatched twinning, indicating that microcline is the dominant phase. Several crystals show both twinned and untwinned areas, suggesting the possible presence of the monoclinic phase. Nearly all samples are perthites. Regular, oriented, and fresh exsolution lamellae range from less than 0.01 to 0.03 mm wide and from 0.1 to more than 0.5 mm long. A distinct silky luster, often combined with undulatory extinction, can be observed in microclines with extremely fine perthitic unmixing.

The measured axial angle ranges from about 70° to 86°; variation of the axial angle in a single crystal may exceed 10°. Typically twinned microclines usually show axial angles of 80° ±5°; some associated untwinned and often diffuse phases have a distinctly lower axial angle of 70° to 72°. No axial angles lower than 70° were found in areas thought to be unaffected by heating. This is interesting with regard to the observations made from the x-ray powder patterns, which suggest minor amounts of orthoclase in most samples.

The obliquity of the unaffected feldspars ranges from 0.84 to 0.93, but only in a few cases (Bryan Mountain traverse, some samples of the Hessie-Chittenden traverse) is it sharply defined. For the majority of the samples smaller amounts of microcline with lower obliquities are indicated. With the notable exception of Bryan Mountain, all microclines appear to contain a small amount of a monoclinic phase. This includes the samples from Arapahoe, which were collected some 15,000 feet from the nearest known contact.

Transition zone. The transition zone is arbitrarily defined as the section of each traverse where the microcline is accompanied by more than 10 percent orthoclase. The width of this zone and its distance from the intrusive contact vary greatly with each traverse. The maximum width of the zone at Bryan Mountain is 300 feet and at Chittenden Mountain some 2000 feet. In the other traverses the transition zone is not so well defined.

Many K feldspars from the transition zone still show perfectly sharp microcline twinning, but the increasing amount of orthoclase is obvious from thin sections and grain mounts. Certain crystals may display both twinned and untwinned areas; others are either twinned or not. Often the typical crosshatched twinning is quite sharp in some parts of the crystal and diffuse in other sections. Most crystals are somewhat altered. They appear to be covered with fine dust, often concentrated in diffuse schlieren. In some places this dust is coarse enough to be identified as sericite. The feldspars usually are perthites. In some cases possibly two generations of perthitic exsolution may be observed. The axial angles measured in the transition zone usually correspond to either microcline ($2V > 70°$) or orthoclase ($2V < 66°$) or both.

In samples Ch 9a and Ch 10 from Chittenden Mountain, perthitic exsolution appears to be restricted to untwinned crystals or sections of crystals. In specimen Ch 11, however, perthitic unmixing was found only in areas with crosshatched twinning. Lamellae of exsolved albite often aggregate to form irregular schlieren. The drop in the axial angles from 74°–78° at 3100 feet down to 53°–64° at 2900 feet clearly expresses the phase change, as does the microcline content, which drops from around 70 to 20 percent within the same interval.

At Mineral Mountain the existence of a transition zone between 1050 feet and 1500–1700 feet from the intrusive contact is suggested, but the microcline content does not increase sufficiently in the outer part or beyond this zone. This may be caused by the effects of contact heating from both ends of the sampling line, i.e. from the Eldora *and* the Caribou stock, some 2 miles NNE of it (see Fig. 2). Within the transition zone perfectly sharp microcline twinning is seldom encountered. A large number of untwinned crystals with diffuse extinction, which in some cases resembles a blurred crosshatched twinning, are always present. Some crystals show distinct microcline twinning in the center but diffuse extinction along the rim. From the axial angles both microcline and orthoclase are inferred in several samples. It was not always possible to measure axial angles corresponding to microcline in the available thin sections, even when microcline was indicated by the twinning pattern. On the other hand, no axial angle greater than 66° was found in samples lacking definite crosshatched twinning. The axial angles of the orthoclase from this traverse range from 50° to 66° and often have a large variation (up to 12°) from crystal to crystal within one sample. The intracrystal variation is 6° at most. The axial angles of the microclines are in the narrow range between 82° and 84°. Sample MM 9 shows axial angles of 55°–57° and 82°–84° within a single crystal.

Along the Hessie traverse a transition zone is thought to exist between 1600 and 3000 feet from the contact. The thin sections and grain mounts indicate definite, sharp microcline twinning in the outer two samples, which also display some silky luster. All specimens contain a fair amount of untwinned material and they are fine-perthitic with a possible second (earlier?) generation of perthitic albite aggregated in irregular schlieren. The axial angles measured increase from about 60° at 1900 feet to 62°–75° at 2300 feet, indicating the presence of both orthoclase and microcline, and to 74°–82° at a distance of 2700 feet from the contact. This is the only instance where such a gradual change in the axial angles was observed.

Microclines from the transition zone are usually characterized by poorly defined obliquity values of the order of 0.55 to 0.85 for the bulk part of the crystals, increasing with increasing distance from the contact. Numerous smaller side peaks in the powder patterns prove the omnipresence of small amounts of microcline with lower (rarely higher) obliquities. Usually the amount of microcline decreases on approaching the contact.

Orthoclase zone. In this zone of variable width, directly adjacent to the intrusive contact, orthoclase is the predominant or exclusive phase of potash feldspar. Most of the orthoclase crystals are more or less turbid. They appear to be dusty, in a state of decomposition, with numerous fine and unidentifiable inclusions. Aggregates of these inclusions may often be explained as alteration products of diffuse former plagioclase inclusions. Larger inclusions of quartz and plagioclase are quite common. Much of the latter is more strongly altered than its host. The quartz often shows strong undulatory extinction. Relatively fresh plagioclase sometimes occurs as a xenoblastic filling (with polysynthetic twinning) between large crystals of K feldspar. Along such mineral boundaries the exsolution of myrmekite may be observed. One altered plagioclase inclusion with a fresh rim had reacted with its K feldspar host. Along cracks the potash feldspars are often filled with fine-grained, sometimes diffuse material, consisting mostly of quartz and plagioclase. Some sections exhibit recrystallized microfractured zones between individual feldspar grains. Neighboring crystals may also be interlocked. In other sections contiguous orthoclase grains show no interaction at all.

With the exception of one sample from very near the contact (BM 1), all K feldspars show some kind of perthitic unmixing. Oriented, fresh, exsolution lamellae are up to 0.03 mm thick and often more than 0.5 mm long. Along three traverses the perthite lamellae thin toward the contact. More conspicuous are exsolved albites which penetrate many orthoclases in all directions as irregular schlieren. Much of this type of unmixed albite is twinned polysynthetically, and altered more than the oriented albite in the same crystal. The orientation of twin planes in these albite schlieren is often identical throughout the host crystal.

Orthoclase from this zone is untwinned, but many crystals display a rather diffuse extinction, which may be mistaken for faint microcline twinning. Diffuse crosshatched patterns result from interference of fine perthite exsolution lamellae with oriented tiny inclusions, or from zoned extinction around such inclusions. An impressive grated extinction pattern in orthoclase is also created by mechanical strain around regular perthite lamellae. In one traverse (MM 1b) an orthoclase sample near the contact shows a small inclusion of microcline with the typical crosshatching.

The optic axial angles are usually less than 66°, indicating orthoclase. The presence of some microcline in two samples nearest the contact (Ch 1 and MM 1a) is also suggested by axial angles from 68° to 71°. Microcline was not seen in these grain mounts and thin sections.

The X-ray powder patterns confirm that very little microcline, if any, is present within the orthoclase zone, with the exception of the Hessie traverse. There about half of the samples between the contact and 1550 feet contain more than 90 percent microcline; only two samples contain less than 50 percent and no pure orthoclase was found. Most microcline had poorly defined obliquity between 0.39 and 0.85. A majority of these samples appear to also include minor amounts of microcline with lower obliquities down to monoclinic. No trend is observed as a function of the distance from the contact.

In thin sections the Hessie feldspars very rarely show a typical crosshatched twinning; in many sections only a diffuse twinning pattern can be recognized. Usually the extinction is very similar to that found in orthoclases from other traverses. Several samples also contain crystals that show no trace of twinning, but a clear, homogeneous extinction.

Many samples are fine-perthitic, displaying a silky luster. Observed interference patterns similar to twin patterns are sometimes caused by mechanical strain around the regular exsolution lamellae. Possibly two different generations of perthitic exsolution are indicated in two samples near the contact. With one exception all specimens give axial angles that clearly correspond to either microcline or distinct microcline *and* orthoclase.

Discussion and Conclusions

Feldspar geothermometry and the interpretation of the perthites. The average composition for the microcline perthites from areas outside the contact aureole is about $Or_{77}Ab_{23}$. Depending on the experimental solvus adopted, the last equilibration or homogenization of these alkali feldspars must have taken place at a temperature above 500° or 550°C. Rb-Sr isochron data on the feldspars from beyond 20 feet on the Eldora traverse (Hart, 1964) prove that the last homogenization or equilibration of strontium occurred some 1400 m.y. ago. The temperature of 500° to 550°C is therefore an indication of the minimum temperature prevailing during the Precambrian regional metamorphism of the Idaho Springs Formation. Such a temperature is consistent with the formation being in the sillimanite-almandine subfacies of the almandine-amphibolite facies.

The solvus between the alkali feldspars has been used by many authors to determine the relative temperatures of formation for rock sequences. Most of the contact aureole feldspars coexist with albite, so in principle the K-feldspar bulk composition might be expected to reflect the strong temperature gradient near the contact, providing the temperatures have been high enough to allow re-equilibration. Only on three traverses does the K-feldspar bulk composition change, and then only in the samples nearest the contact. At Hessie and Chittenden the albite component increases 5–10 percent; at Bryan Mountain it decreases about 10 percent. We believe that the temperature conditions were not sufficient to allow complete re-equilibration of the perthites, except in some of the near-contact samples.

This conclusion by itself does not imply that the perthites in the orthoclase zone could not have homogenized. Here one has to consider the differences in scale involved in homogenization of a microperthite and in true equilibration of two coexisting bulk alkali feldspar phases. Ernst (1960), for example, showed in laboratory experiments that the albite component of a perthite could be dissolved into the host K feldspar fairly rapidly, whereas the solution of albite from a separate albite phase was extremely slow.

There is some evidence that feldspars from the orthoclase zone have been at least partly homogenized. In several traverses, the size of the regular exsolution lamellae appears to decrease on approaching the contact. Since the bulk composition does not change markedly for these, we infer that the part of the albite component which did homogenize is either still in solution or later re-exsolved as a cryptoperthite. In a number of samples we observed two possible generations of albite, one of which may be the re-exsolution of a partially homogenized feldspar.

In some of the orthoclase perthites, albite occurs as fresh interstitial fillings. This albite is apparently related to the contact metamorphism, as it does not appear further out, in the microcline region. It may represent partial re-equilibration of the coexisting alkali feldspars. If the temperatures during the contact heating are lower than those of the Precambrian regional metamorphism the excess albite component in the K feldspar will have a tendency to aggregate externally into separate albite grains. The amount of this albite compared to the quantity of K feldspar is too small to significantly affect the bulk composition of the K feldspar.

We wish to clearly differentiate between the partial homogenization suggested above and the complete homogenization suggested by Wright in the following paper. In our case the temperatures are subsolvus; Wright's infers supra-solvus temperatures. In addition to the textural arguments above, several other arguments favor in complete homogenization. First, practically all the orthoclases are considerably altered, whereas microfractured and recrystallized zones between individual crystals have a fresh appearance. Secondly, the orthoclases are usually idioblastic and some of them contain oriented small inclusions which would have been expelled during a major reprecipitation process. Finally, the feldspars in the orthoclase zone have retained appreciable amounts of their radiogenic argon, the Rb/Sr age of those beyond 20 feet has remained unchanged (Hart, 1964), and the composition of common lead in them changes very little beyond the first several hundred feet from the contact (Doe and Hart, 1963). It is particularly significant in this regard that the only feldspar which has lost all its argon is the 2-foot sample at Eldora, which is now optically homogeneous.

Wright (1967) argues for complete homogenization on the basis of textural evidence and on the basis that the albite in the orthoclase perthites is in an intermediate structural state. We feel that the structural state of the albite may simply be a reflection of the contact heating. The data of MacKenzie (1957) and their kinetic interpretation by McConnell and McKie (1960) clearly show that pure low albite is unstable above 400°–450°C. Consideration of the effect of potassium in the albite further suggests that the formation of natural intermediate albites may take place even below 400°C. In other words, the contact temperatures derived later from heat flow models appear sufficient to account for the formation of the intermediate albites without requiring a derivation by metastable growth during the early stages of exsolution as proposed by Wright (1967).

The width of the orthoclase zone. The combined optical and X-ray investigations clearly demonstrate that the width of the orthoclase zone (compare Fig. 2) around the Eldora and associated stocks shows considerable variation. This zone is 600–800 feet wide at Bryan Mountain, 1050–1250 feet at Mineral Mountain, less than 1650 feet at Hessie-Chittenden, probably 1600–1800 feet at Hessie, and less than 2600 and 2900 feet wide at Ute Mountain and Chittenden, respectively. What is the significance or cause of this variation? Theoretically, many parameters may influence the microcline-orthoclase transition: temperature, time of heating, total hydrostatic pressure, partial pressure of water, state and composition of the original material. For the present work some of these parameters may be estimated from heat flow considerations, others may be assumed from experimental evidence, and some are constants for the samples involved.

As shown earlier, the composition and structural state of the original microcline from areas not affected by the contact heating is fairly constant; therefore, this cannot be a cause of the variation in the width of the orthoclase zone. According to the X-ray powder patterns, most of these specimens appear to contain a few percent orthoclase. The average microcline content is about 95 percent (mean deviation ± 3 percent). Only the samples distant from the contact at Bryan Mountain give no indication of orthoclase. Laves (1950) has demonstrated from single-crystal study that the crosshatched twinning of microclines has to develop while the K feldspar is still monoclinic. Therefore it is assumed that the microcline from the undisturbed areas originally was orthoclase of which traces have persisted in places.

There is evidence that the transition from microcline to orthoclase at the Eldora contact aureole did not take place by solution of microcline and reprecipitation of orthoclase, as discussed by Goldsmith and Laves (1954) as a possible interpretation for the sanidine produced in their hydrothermal experiments. From the observations by Hart (1964) in the Eldora traverse, it appears that hydrothermal or metasomatic activity is restricted to an area within a few feet from the contact. Here alteration of hornblende to biotite and untwinned sodic overgrowths over twinned oligoclase was noted in an amphibolite sample 2 feet from the contact. Systematic observations on the pegmatitic phases from the other traverses indicate that certain contact metamorphic effects such as fresh interstitial plagioclase and myrmekitic reaction zones may have reached farther than previously thought. These effects appear to be of a local secretionary nature rather than of hydrothermal or metasomatic origin. The arguments given here and in the previous section clearly show that the microcline-orthoclase inversion in the Eldora contact aureole took place in the solid state, probably under the catalytic action of water pressure of the type described by Wyart and Sabatier (1961) and Wyart, Curien, and Sabatier (1961).

Little is known of the effect of total pressure or partial pressure of water on the phase transformations in the feldspars. Since feldspars are almost anhydrous phases, the transition temperature should be essentially independent of the partial pressure of water except in so far as the presence of water may influence the rates of transformation through a catalytic effect. Tomisaka (1962) reported a 0.1 percent density difference between microcline and orthoclase and suggested that total pressure may very slightly favor the microcline. He also showed the inversion temperature to be strongly related to water pressure (or total pressure) in the region between 350 and 1500 bars. We do not believe that the ion exchange technique used for his experiments in this pressure range necessarily produces a stable monoclinic phase. A disordered monoclinic framework may be formed at low temperatures by rapid crystallization as in the case of adularia (Laves, 1952). The direct inversion experiments performed by Tomisaka (1962) on the microcline of Takamizu at water vapor pressures of 4000, 2400, and 1500 bars, in which he believes no reprecipitation took place, appear to be more meaningful. They indicate only a minor dependence of the inversion temperature upon the water or total pressure. It seems that this temperature is lowered less than 20°C with water pressure decreasing from 4000 to 1500 bars.

The partial pressure of water in the Eldora contact aureole will lie in the range set by the load pressure as an upper limit and the vapor pressure of the hydrous phases as a lower limit. Since the collection sites between the various traverses do not vary in elevation by more than 2000 feet, the load pressure will not vary by more than 200 bars. It is possible that the amount of water escaping from the intrusive may vary considerably from place to place depending on the local contact configuration and the relative height with respect to the intrusive body. As long as water is actually present, however, it appears that the temperature of the microcline-orthoclase transition will be essentially independent of water pressure and total pressure.

The marked variation in the width of the orthoclase zone therefore seems to be largely a function of the temperature distribution during and after the intrusion of the Eldora stock. The heat flow from the intrusive is determined by the shape of the intrusive body. All geological information obtained at the surface indicates that the intrusive contacts are vertical or nearly vertical. Consequently, the heat flow in a horizontal direction is to a first approximation defined by the shape of the contact as seen on the map (Fig. 2), and the width of the orthoclase zone appears to vary accordingly. The temperature necessary for the complete conversion of microcline to orthoclase was not attained beyond 800 feet at Bryan Mountain and 1250 feet at Mineral Mountain, where the contact is markedly convex in the vicinity of the traverse. At Chittenden and Ute Mountain the transition temperature was reached as far as 2600 and 2900 feet from the contact owing to the slightly re-entrant shape of the contact with respect to the traverse. A similar effect is also observed in the Hessie-Chittenden and Hessie traverses, the latter with some additional complications. Higher temperatures in the vicinity of these concave contacts are also indicated by the somewhat increased albite content of the bulk K feldspars closest to the contact.

In the following paragraph and in the next section we consider several hypothetical heat flow models in order to illustrate the relationship between intrusive geometry and the temperature distribution around the intrusive. The results are discussed only in a qualitative way with respect to our observations at the Eldora stock. In the subsequent section we discuss more realistic heat flow models for the Eldora stock from which meaningful temperature estimates can be made.

For a simple heat flow model where latent heat is neglected, the contact temperature is related to the shape of the contact by the relation

$$T_c = T_i \frac{\alpha}{2\pi}$$

where T_i is the intrusive temperature and α is the interior angle measured between planar contacts (Jaeger, 1964). Thus the contact at a 90° outside corner will reach only 25 percent of the magma temperature, whereas a 90° inside corner will reach 75 percent of the magma temperature. Temperatures in the wall rock have been calculated for these various shapes and are shown in Figure 10. For these calculations a hypothetical intrusive temperature of 1000°C and a diffusivity of 0.01 were assumed. These simple model results clearly show that the temperature distribution around an intrusive depends critically on the shape of the body and that the width of the orthoclase zone may indeed be explained qualitatively in this way. This model is, of course, oversimplified. For example, it would predict such a low contact temperature for an acute angle (such as at Bryan Mountain) that orthoclase would not be expected to form at all. Quantitatively, the situation is improved by adding latent heat into the calculations. In addition, one must consider the shape of the contact in terms of the scale of the sampling; i.e., while the contact at Bryan Mountain is an acute angle when viewed from a distance, very

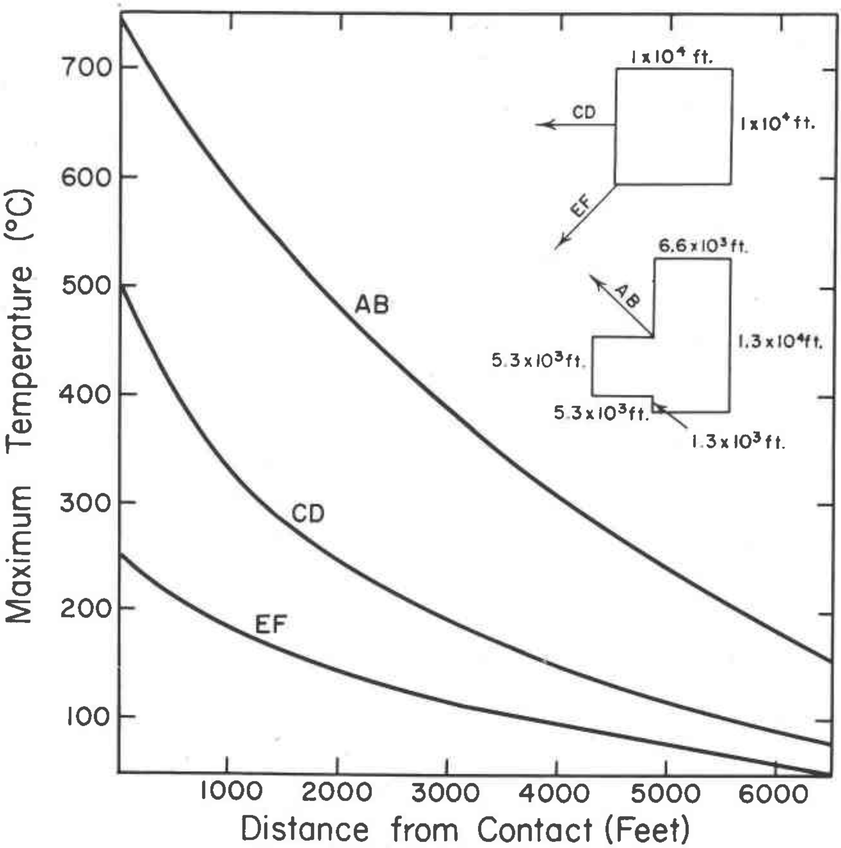

FIG. 10. Maximum temperature *vs* distance along traverses *AB*, *CD*, and *EF* for calculated heat-flow models. The shape and dimensions of the geometric bodies and the locations and orientations of the traverses are given in the insets. Assumptions for the heat-flow calculations: Magma temperature 1000°C, no latent heat, diffusivity 0.01.

near the contact it would, of course, appear semiplanar, and the near-contact temperatures must approach those of the planar case (*CD*).

The nature of the microcline-orthoclase transition. The character of the transition varies from one traverse to another, apparently also in relation to the shape of the intrusive. Near the planar or concave contacts at Hessie, Ute Mountain, and Mineral Mountain, not only is the transition zone further from the contact but the transition zone appears to be wider. In these zones the microcline appears to have intermediate obliquities, at least as low as 0.67. Both twinned and untwinned crystals are present. Sometimes twinned and untwinned areas are observed in the same crystal, with axial angles corresponding to both orthoclase and microcline. Clearly most of the feldspars from this zone did not reach equilibrium.

On the other hand, the Bryan Mountain and Eldora traverses, which are adjacent to convex contacts, show rather narrow transition zones, with no indication of obliquities below 0.7. Furthermore, the obliquities are generally well defined. We believe these differences between the various traverses are related to the shape of the intrusive in the vicinity of the traverse and its influence on the temperature gradient and duration of heating.

To understand the effect of contact shape on the temperature gradient in the feldspar transition zone, we must modify Figure 10 somewhat. Figure 10 shows the temperature distribution adjacent to a right angle corner, but natural contacts are invariably smoothed by the stoping action of the intrusive. On a scale of inches or feet, most natural contacts will appear planar. Therefore, at these distances, the curves *AB* and *EF* of Figure 10 should in fact approach curve *CD*. With increasing distance from the contact the local configuration of the contact becomes less important and the over-all geometry of the intrusive body near the traverse will be the dominant factor. The temperature curves may then join the theoretical curves (*AB* and *EF* in Fig. 10) calculated for an inside and an outside corner. This may lead to an increase in the difference of the thermal gradients for the two cases considered. For example, the Ute Mountain transition (semiplanar, curve *CD*) occurs at 3000 feet where the temperature gradient is rather flat. The Bryan Mountain transition, however, occurs about 700 feet from a convex contact, which would be represented by the curve *EF* modified to approach *CD* near the contact, thus making the temperature gradient quite steep in the region of the transition zone.

The second factor influencing the feldspar transition is time. In Figure 11 the temperatures for the hypothetical models developed in Figure 10 are plotted against time. It can be seen that the time during which a point at a certain distance from the contact will remain above a given temperature depends again on the configuration of the contact. For example, a point at a distance of 1330 feet from a straight contact will remain at a temperature higher than 250°C for some 3×10^4 years, whereas a point at a distance of 4220 feet from a concave contact would remain above that same temperature for 4.5×10^4 years. For a convex contact the time during which the peak temperature will be held at a certain distance from the contact is much shorter than 3×10^4 years. The time of exposure to temperatures which may allow a notable change in

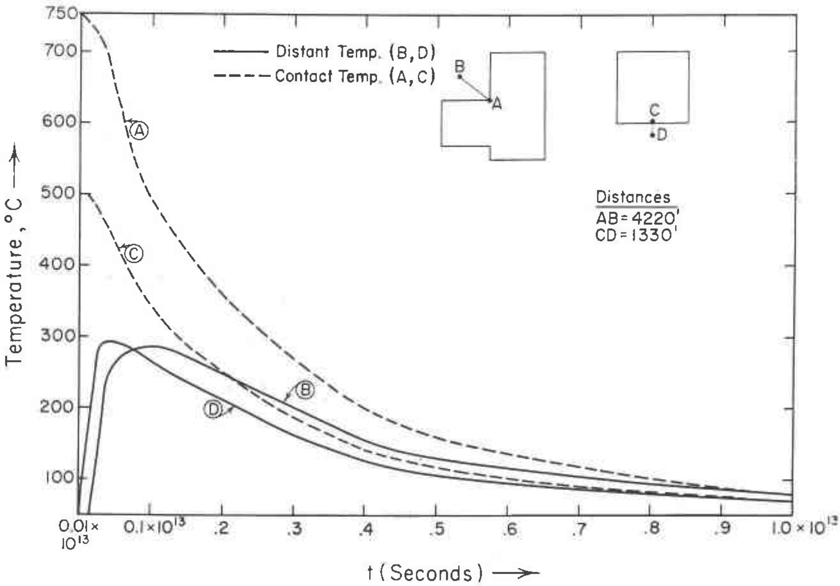

FIG. 11. Maximum temperature *vs* time curves at points A, B, C, and D for calculated heat-flow models. The shape of the geometric bodies and the location of the points are given in the insets. Dimensions and assumptions as in Fig. 10.

Al/Si distribution may therefore vary by a factor of 2 or 3 between traverses adjacent to concave or convex contacts.

It appears that the steep temperature gradient and the relatively short time span during which the feldspars in the narrow transition zones at Bryan Mountain and Eldora were exposed to elevated temperatures prevented the formation of transitional microclines. Along the transition zones of the Hessie, Mineral Mountain, and Ute Mountain traverses, the temperature gradient was less steep, causing a wider transition zone, and the feldspars were subjected to longer heating and cooling times. We believe the variable obliquities in these particular samples and single crystals are a result of these factors.

The scarcity of intermediate microclines in nature was pointed out by Dietrich (1962), who plotted the distribution of obliquity for 500 K-feldspars from a variety of sources. Our observations from the transition zone, which confirm this lack of appreciable amounts of intermediate microclines, may indicate that these transitional types are formed or preserved only under special conditions. Such conditions are thought to have prevailed in the "orthoclase zone" of the Hessie traverse, i.e. the area within some 1700 feet from the contact. Here, instead of a fairly uniform orthoclase as in the other traverses, most of the potassium feldspars consist of more than 50 percent microcline with obliquities varying from 0.39 to 0.85 for the bulk part of the sample. The contact at Hessie is very markedly crescent shaped and concave toward the traverse. This not only increases the heat flow considerably as reflected in the width of the orthoclase zone (probably some 1700 feet), but also affects the temperature distribution with time. The temperature in the vicinity of this contact was brought up faster than in the other traverses and had a much slower cooling rate. We believe that the frequent untwinned microcline in this area results from a retrograde inversion of orthoclase during extended cooling. This interpretation is supported by the fact that several other traverses with "perfect" orthoclase zones show minor amounts of microcline in the samples closest to the contact.

If microcline of intermediate obliquity is indeed stable, our observations imply that it is formed only under relatively rare natural conditions or that the intermediate microcline has a limited stability field, where minor changes of conditions favor the growth either of microclines with high obliquity or of a monoclinic phase. This latter conclusion was also drawn by Heier (1957) and is implied by Laves (1960, fig. 5).

It appears from the heat-flow calculations (Fig. 12) that the change from the highly oblique to the monoclinic phase has occurred in a temperature interval of less than 50°. It is obvious that such a narrow temperature interval would not normally encourage the formation of large amounts of intermediate microcline, especially if the kinetics of the reaction are slow. As discussed above, the Hessie traverse seems to be a favorable exception. The lack of notable amounts of intermediate microclines in the samples from the other transition zones is therefore not necessarily an argument against a gradational transition of the type proposed by Laves (1952, 1960), Goldsmith and Laves (1954).

The temperature of the microcline-orthoclase inversion

(a) Experimental evidence. Goldsmith and Laves (1954) observed that a microcline could be hydrothermally converted to sanidine at 525°C or above. Tomisaka (1962) found that a microcline with an obliquity of 0.945 is stable under a water vapor pressure of 4000 bars at about 470°C and that the same microcline is stable with an obliquity of 0.910 under 1500 bars at about 450°C. In the first case a notable decrease in obliquity with time was observed when the temperature was raised to 485°C; in the second case the obliquity starts to decrease slowly when the temperature is increased to 460°C. In contrast to Goldsmith and Laves, Tomisaka used less than 28 weight percent of water because he believed this would avoid the solution of microcline and reprecipitation of orthoclase (sanidine). His experiments may represent a phase transi-

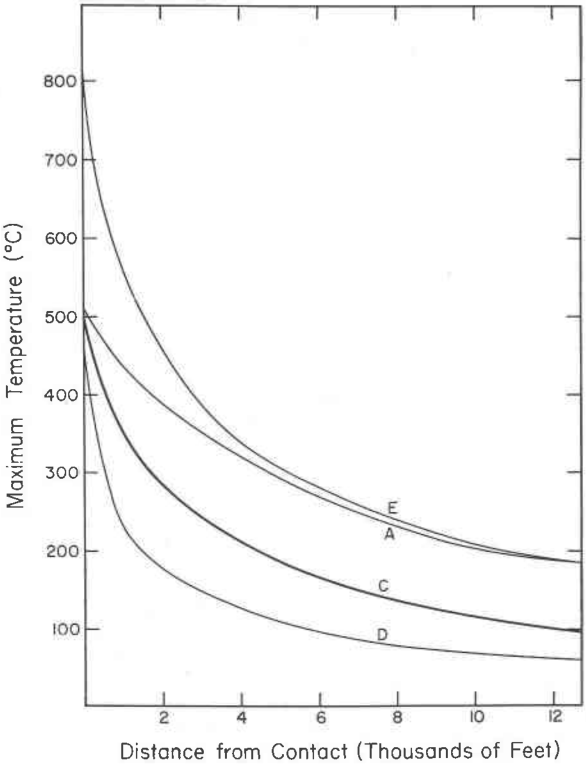

FIG. 12. Eldora stock: Curves of maximum temperature in wall rock *vs* distance from plane contact of three intrusive shapes. Temperatures given along traverses perpendicular to longitudinal axis of the various shapes. (*A*) Indefinite dike, 10,000 feet thick; (*C*) brick, 10,000 feet thick, 26,000 feet long, traverse intersects face 3000 feet below roof and 13,000 feet from edge; (*D*) brick, 10,000 feet thick, 10,000 feet long, traverse intersects face 2000 feet below roof and 1000 feet from edge; (*E*) infinite dike of model A with convection. Other parameters: magma temperature, 780°C; wall rock temperature, 35°C; diffusivity of intrusive and wall rock, 0.009 cm^2/sec. Latent heat of 80 cal/g accounted for by exaggeration of intrusive temperature and size to agree with numerical analysis of Jaeger (1957).

tion in the solid state with catalytic action of water under high pressure. The inconsistent results between the two experimental approaches are not understood. If anything, one would expect a lower transition temperature in Goldsmith and Laves' experiment where reprecipitation presumably took place. By Na-K ion exchange experiments from low-temperature albite, Tomisaka (1962) produced a monoclinic feldspar at temperatures as low as 400°C under a water pressure of 350 bars. As also stated by Wyart and Sabatier (1956), who conducted similar experiments, no definitive conclusions can be drawn from such experiments with regard to the stability fields of the alkali feldspars. Presently available experimental evidence would then only suggest that maximum microcline is not stable at temperatures above 460°C.

(b) Heat-flow considerations. In this section we derive temperature limits for the feldspar transition based on theoretical heat-flow considerations. Hart (1964) described the calculation of maximum temperatures in the Eldora contact aureole for various simplified shapes of the intrusive body assuming a non-convecting magma at 780°C with 80 cal/g heat of fusion and an initial wall rock temperature of 35°C. The curves for these models are shown in Figure 12. The data used in the calculations are tabulated in the figure legend. Model C represents the best approximation to the known geometry of the Eldora intrusive. Model A (infinite dike) is an upper limit to the temperatures which could be derived under the given assumptions. For example, the feldspar transition on the Ute Mountain traverse starts about 3000 feet from the contact where the upper temperature limit according to model A would be 350°C. Since this is more than 100°C below the laboratory transition temperature, it is necessary to examine the assumptions involved in the heat flow theory used to derive this temperature limit.

The most obvious assumption to question initially is that which requires the magma to cool non-convectively. Shaw (1965) studied the convection problem through laboratory determinations of the viscosity of granitic melts and concluded that natural convection was probable in any large (>100 m) plutons.

The heat flow in the contact zone around a convecting magma may be treated as in Jaeger (1964). For a model we use the infinite dike geometry, allowing for 100 cal/g latent heat and a solidification range of 200°C. The temperature throughout the body is assumed to be isothermal during cooling in its solidification range, with convection ceasing after solidification occurs. The maximum temperatures attained for this model are shown by the curve E of Figure 12. There is a very large effect on temperatures near the contact, but beyond one-half intrusive width (5000 feet) temperatures are essentially unaffected, as was pointed out by Jaeger (1964). For the Ute Mountain traverse at 3000 feet, convection would increase the maximum temperature attained by only some 30°C.

In a more drastic convection case discussed by Shaw (1965) a pluton is mechanically connected at depth to a large reservoir, whereby solidification times may be substantially increased. The solidification time for the convection model of Figure 12 is about 5×10^3 years. How long would the convection time have to be increased to raise the temperature at 3000 feet an additional 100°C? Jaeger (1961) showed that a rise of 100° would occur out to distances of about $3(kt/\pi)^{\frac{1}{2}}$. For a diffusivity (k) of 0.008 and a distance of 3000 feet the time required would be about 10^4

years. One cannot rule out convection times of this magnitude a priori. However, the high near-contact temperature produced by such convection would be expected to produce observable petrographic effects. The convection model (E Fig. 12) shows that temperatures are in excess of 700°C for some hundreds of feet from the contact. Temperatures of this magnitude appear to be incompatible with the observed textures and mineral assemblages (Hart, 1964) and with the observations of this paper relating to the perthites, which are homogenized only immediately adjacent to the contact.

A second argument against the convection model is obtained from the results of laboratory measurements on the diffusion of argon from one of the contact hornblendes (Hart, 1961, 1964). At 800°C this hornblende was found to have a diffusion coefficient (D/a^2) for argon of 1×10^{-9} sec^{-1}. A hornblende 11 feet from the contact shows an argon age of 950 m.y., which is about 20 percent lower than its true age. To allow an argon loss of only 20 percent in 5×10^3 years at 800°C (convection model E) would require a D/a^2 value of 2×10^{-14} sec^{-1}. This discrepancy of more than 4 orders of magnitude with the laboratory value demonstrates that near-contact temperatures could not have been as high as those predicted from the convection model. We believe the above mineralogical and diffusion arguments rule out large-scale convection of the kind considered in the above model.

The temperatures in Figure 12 are directly dependent on the assumed ambient or wall rock temperature, and this value should be considered in some detail. The value of 35°C used in calculating Figure 12 was based on a depth of burial of about 1 km with the heat flow of 1.7 $\mu cal/cm^2$-sec measured in the Front Range by Birch (1950). Support for such a shallow depth of burial is given by Lovering and Goddard (1950) in their work on the erosion surfaces of the Front Range. The highest erosion surface, the Flattop, is now at an elevation of 12,000 feet, and Lovering and Goddard (1950) assign an approximate age of early Eocene to this surface. This age is similar to that of the Eldora stock itself. Since the stock is presently exposed at an elevation of 9,000–11,000 feet, a rather shallow depth of burial is indicated.

Greater depths of burial could still be accommodated within the above history by calling for rapid vertical uplift soon after intrusion, before development of the Flattop surface. However, in the depth range 1–3 km the melting temperature of the intrusive (granite minimum) will decrease about 30°C/km as a function of the increasing water pressure (assuming $p_{total} = p_{H_2O}$), and this effect will largely offset the geothermal increase of wall rock temperatures with depth.

The wall rock temperature is most sensitive to the geothermal gradient. If the heat flow during intrusion was twice the present value (3.4

μcal versus 1.7 μcal), the wall rock temperature at a burial depth of 2 km would be about 50°C higher than the value used in calculating the curves of Figure 12. Since present-day tectonic regions seldom have heat flow values greater than 3.5 $\mu cal/cm^2$-sec, we consider this a probable upper limit for the Front Range during intrusion of the Eldora stock. The curves of Figure 12 may be considered therefore to have an uncertainty of less than 50°C in this respect.

The simplified geometries involved in these heat-flow calculations are most nearly realized at the Ute Mountain traverse, which is adjacent to a semi-planar contact. The stability limit for microcline is reached at 3000 feet on this traverse. Even using the extreme values for all parameters, namely a convecting infinite dike in a region with a heat flow of 3.5 $\mu cal/cm^2$-sec, the temperature at 3000 feet would be only 430°C. On consideration of all the arguments we have advanced above, we feel that a temperature of 350°–400°C is the best value for the upper stability limit of microcline in the Eldora aureole.

This value appears to be 50°–100°C lower than the best laboratory measurements. It is tempting to attribute this discrepancy to the fact that the laboratory measurements may be kinetically limited and therefore do not represent true equilibrium. However, we have nowhere considered the effect of sodium on the transition temperature. A large sodium effect is predicted both in the gradational model of MacKenzie and Smith (1961) and the first-order model of Wright (1967)[1] It is therefore difficult to directly compare Tomisaka's (1962) laboratory results with ours, since neither of us gives data on the actual sodium content of the K-feldspar phase involved in the transformation. It is interesting to note that Tomisaka's low-pressure data, which we have questioned above, would suggest a transition temperature of about 350°C for the low water pressure environment of the Eldora aureole.

Summary

The alkali feldspars from Precambrian pegmatites in the Idaho Springs Formation are microcline perthites of high obliquity and rather uniform composition. Within the contact aureole of a Laramide intrusive near Eldora, Colorado, these microcline perthites were converted to the monoclinic phase, orthoclase, stable at higher temperatures. The character of this phase change differs with the location. The microcline-orthoclase transition zone is narrow and relatively close to the intrusive contact when the contact adjacent to our sampling traverse is of convex shape. A wide transition zone, farther away from the contact, is observed where the contact is crescent-shaped and concave with respect to the sampling

[1] Laves (1960) on the other hand, assumes that sodium will have little influence on the *K* feldspar transition.

traverse. From heat-flow calculations we inferred that the temperature, the temperature gradient, and the temperature distribution with time depend largely on the shape of the contact. The sharp transitions close to the contact are readily explained by the relatively low temperatures, steep thermal gradients, and short duration of heating generated from outside corners of the intrusive. Higher temperatures, relatively flat thermal gradients, and prolonged heating in areas near re-entrant contacts produced a more gradual transition further from the intrusive. The same heat-flow calculations also determine an upper limit for the transition temperature. Because large scale convection in the Laramide intrusives can be ruled out by mineralogical and diffusion arguments, the transition from microcline to orthoclase may occur below 400°C, i.e. at least 50°C below the transition temperatures obtained in laboratory experiments. The order of the transition cannot be positively ascertained from the data. Although it appears that most feldspars from the wide transition zones do contain minor amounts of microcline with intermediate obliquities, the obliquity of the bulk part of such samples still remains quite high. On the other hand, since the complete phase change had to take place in a temperature interval of less than 50°C, the reactions are possibly too slow at the lower temperatures where intermediate microclines are to be expected. A non-first order phase change is suggested by the observations from one traverse where, due to slow cooling time, the orthoclase in the vicinity of the contact converted back to an intermediate microcline. If the transition is of a higher order, the samples did not reach complete equilibrium, since orthoclase and microcline coexist over a wide distance.

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