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PERTHITE FORMED BY REORGANIZATION OF ALBITE FROM PLAGIOCLASE DURING POTASH FELDSPAR METASOMATISM

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ABSTRACT

Orthoclase microperthite in quartz monzonite and alaskite in the Boulder batholith, Montana, originated by replacement of plagioclase. Orthoclase which crystallized between early-formed crystals of plagioclase late in the magmatic stage is not perthitic. The crystallization sequence leading to perthitic orthoclase was: (1) deuteric alteration of andesine to albite at the contact of invading potash feldspar; (2) replacement of albite by potash feldspar which is perthitic. An intermediate soda-rich potash-bearing feldspar, described as anorthoclase, is locally preserved and formed as an intermediate crystal phase between albite and orthoclase. The textures of the albite blebs in orthoclase resemble replacement perthite, but other evidence of late soda metasomatism is lacking. These perthites are considered to have formed by the reorganization of the albite portion of the original andesine. During potash feldspar metasomatism, albite, which formed at the advancing orthoclase front, was partly taken into solid solution in orthoclase. The remainder was in some instances, left as relic blebs, but in most cases the albite was reoriented into more orderly arranged blebs and patches resembling replacement perthite textures. Perthite of this type, although resembling replacement perthite, does not in itself constitute a criterion of late soda metasomatism.

INTRODUCTION

The perthitic textures commonly found in potash feldspars in granitic rocks have generally been attributed to one of two well established modes of occurrence, namely, exsolution or replacement. The criteria for their recognition are illustrated by Alling (1921). Exsolution perthites occur in potash feldspars which crystallized from a disordered state at elevated temperature and from which albite exsolved on cooling. Replacement perthites are much less well organized than the exsolution types and formed by partial or selective replacement of potash feldspar by albite. Such late soda metasomatism is recognized in many granites, especially those of metasomatic origin.

The perthitic feldspars described in this report are in quartz monzonite and related alaskite of the Boulder batholith in which the perthitic textures appear to have formed as a result of a specific sequence of metasomatic events at the deuteric stage of crystallization and in a chemical environment in which soda metasomatism was lacking. Similar perthites have been recognized at a number of other localities including a granogabbro which is probably related to the Boulder batholith; a granitic differentiate in diabase at Mt. Sheridan in the Wichita mountains, Okla-

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homa; a red granite from the Wichita mountains; and the Silvermine granite in the St. Francois mountains in Southeastern Missouri.

In the rocks of the Boulder batholith, and in those of the other localities mentioned, orthoclase that contains blebs or irregular patches of albite is believed to have replaced plagioclase. The albitic blebs are thought to be residual albite which was originally a part of the plagioclase that could not be taken into solid solution in orthoclase. Perthites formed in this way are neither the product of exsolution nor replacement in the sense of a late stage of soda metasomatism.

PERTHITES IN QUARTZ MONZONITE AND ALASKITE OF BOULDER BATHOLITH

The Boulder batholith, located in southwestern Montana, is generally agreed to be an orthomagmatic igneous intrusive and is comprised principally of quartz monzonite with associated more mafic granodiorite and granogabbro and more felsic alaskite and aplite. In quartz monzonite and the more mafic rocks with hypautomorphic textures, the early sequence of crystallization of minerals followed the classic line. Plagioclase was the first mineral to crystallize in quantity, in part accompanied by minor amounts of pyroxene and followed by hornblende and biotite. Potash feldspar is only a minor constituent in granogabbro, is present in essential amount in granodiorite and is a major constituent in quartz monzonite in which it is nearly as abundant as plagioclase. Quartz crystallized last.

Textures in Quartz Monzonite

Although the essential mineralogy and relative proportions of the minerals are roughly the same in the varieties of quartz monzonite, there is a wide variety of textures ranging from fine grained quartz monzonite porphyry through medium grained holocrystalline rocks to coarse grained rocks which are, in some instances, porphryoblastic. The coarse grained rocks have an average grain size of a little more than 2 mm. This usage follows the practice of the U. S. Geological Survey party that is completing mapping in the batholith (Becraft 1955). The textural varieties are almost entirely due to differences in grain size and habit of potash feldspar and quartz crystals.

In quartz monzonite porphyry, euhedral plagioclase, subhedral hornblende and sometimes biotite crystallized early as phenocrysts. In some cases the groundmass contains subhedral plagioclase and biotite with anhedral potash feldspar and quartz, and in other cases, the groundmass is composed almost entirely of potash feldspar and quartz. Rarely, the groundmass consists of granophyric intergrowths of potash feldspar and quartz.

In medium grained quartz monzonite, the grains of late magmatic potash feldspar and quartz which crystallized between the earlier formed minerals, principally plagioclase, are larger than in quartz monzonite porphyry, so that the porphyritic texture is inconspicuous and both quartz and orthoclase may be recognized with the aid of a hand lens. In some of the medium grained rocks, the potash feldspar crystals which are nearly equal in size to plagioclase occur as anhedral porphyroblasts which formed by recrystallization of much finer grained orthoclase in the groundmass and by the partial replacement of plagioclase.

In coarse grained quartz monzonite, the equigranular texture is due principally to the development of mostly anhedral, but sometimes subhedral, orthoclase porphyroblasts which are about the same size as euhedral to subhedral plagioclase which crystallized early. In rare instances, potash feldspar porphyroblasts are many times larger than the original plagioclase crystals. In these rocks, plagioclase may be partly replaced by orthoclase.

The porphyroblastic growths are found in various stages of development. In quartz monzonite porphyry, the porphyroblasts are inconspicuous and are rarely distinguishable with a hand lens. In the medium and coarse grained rocks, the texture of the rock may be characterized by the size of the potash feldspar porphyroblasts. In these, most of the quartz is fine grained, equal in size to groundmass crystals in quartz monzonite porphyry or to that of some medium grained rocks. Only rarely do euhedral potash feldspar porphyroblasts form to produce a coarse grained porphyroblastic texture.

Texture of Alaskite

The alaskite is believed to be quartz monzonite that suffered extreme deuteric potash metasomatism during which the original texture was all but obliterated. The texture of alaskite is heterogeneous with respect to grain sizes. Potash feldspar and quartz predominate, having replaced large portions of the early minerals. In some instances, the crystal shape of plagioclase is preserved, in other instances, the shape is obliterated.

Mineralogy of Quartz Monzonite

Plagioclase

Plagioclase was clearly the first essential mineral to crystallize in significant amount and occurs in euhedral to subhedral crystals as large as 5 mm. Its composition is more or less uniformly a calcic andesine, about

Ab 55 An 45. It is commonly zoned in the normal habit with more calcic cores, but some rhythmic zoning is recognized. The zoning is conspicuous in sections nearly parallel to 010. Optic angles range from 70° to 75° which are somewhat smaller than the values given for plagioclase of this composition in the standard curves. Crump and Ketner (1953, p. 31) illustrate a wide range of optic angles for plagioclase of this composition, namely from 72° to 88°.

Plagioclase phenocrysts commonly have distinctive internal fractures along which, in many cases, late deuteric solutions reacted with the crystals to produce a much more albitic feldspar, normally albite-oligoclase.

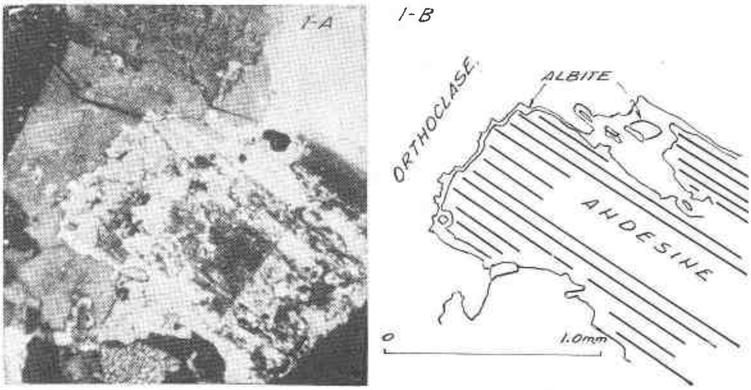


FIG. 1. Andesine plagioclase crystal in contact with and partly replaced by orthoclase. Note particularly the untwinned zone of albite between the two minerals. Figure 1 A is a photomicrograph; 1 B a line diagram which emphasizes the interpreted relationships.

A similar albitic zone is always present at the contact between plagioclase and replacing potash feldspar. Normally, the albitic zone is not twinned, as shown in Fig. 1. Figure 1 A is a photomicrograph which shows an andesine crystal, partly replaced by orthoclase, with an intervening zone of albitic feldspar. The albite twin lamellae in the andesine terminate within the albitic rim. Figure 1 B is a line diagram which emphasizes the distribution and relationships of the feldspars.

Although albitic rims are virtually always untwinned, one rim was observed to be distinctly twinned. The composition, based on its index of refraction and extinction angles, is albite. This twinned rim is on a plagioclase crystal that is partly replaced by potash feldspar and which is next to an incipient vein-like structure. Conceivably, the temperature of formation of the albite was slightly higher than the temperature of formation of most of the albite alteration products. Kohler (1948) and Laves and Chaisson (1950) suggest that such twinned plagioclase formed at a higher temperature than the untwinned product. If there is any thermal significance to the twinned rims, then much of the late potash feldspar metasomatism occurred at a temperature lower than, but only slightly lower than the high-low temperature boundary of the twinned and untwinned albite.

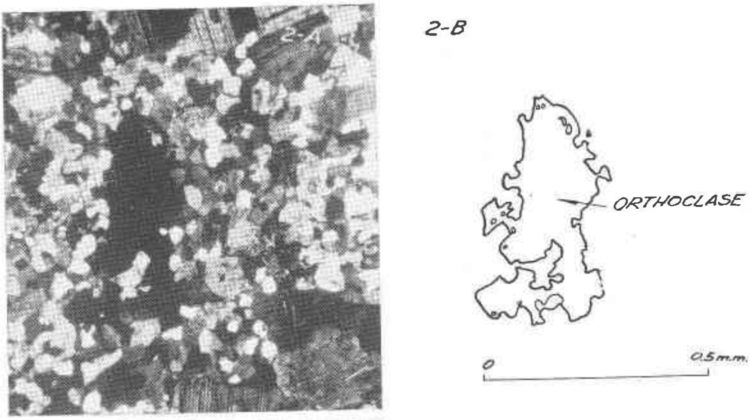
Orthoclase

Orthoclase has several modes of occurrence. That which crystallized with quartz in xenomorphic aggregates and in granophyric intergrowths, is not perthitic. That which is porphyroblastic where plagioclase was incorporated and that which replaced plagioclase, is commonly perthitic. The various modes of occurrence are summarized.

(1) Orthoclase occurs in small xenomorphic crystals in the fine grained groundmass of quartz monzonite porphyry, shown in Fig. 2, and interstitially between plagioclase and other early-formed minerals in some of the coarser grained rocks. It appears to have crystallized from the magma and, together with quartz, occupies the space between earlier formed phenocrysts in the clearly porphyritic rocks and the space between obviously early formed crystals in some of the more nearly equigranular rocks. Orthoclase with these relationships has not been observed to be perthitic.

(2) Orthoclase is present, locally, in micrographic intergrowth where it is dominantly interstitial between early plagioclase phenocrysts. This type of orthoclase is not perthitic.

(3) Orthoclase occurs in a variety of porphyroblastic growths, most conspicuously developed in the coarser grained rocks where xenomorphic orthoclase porphyroblasts are about equal in grain size to plagioclase. Rarely, even larger porphyroblasts, which have good crystal form, are present. The successive stages of porphyroblastic growth are similar to those noted in metamorphic rocks. The first step was the formation of optical continuity over an area of several grains in which quartz may be poikilitically enclosed. Gradual replacement of quartz and "clearing" of the core of the crystal took place, but the margins may remain ragged and poikilitic. Figure 2 illustrates an early stage of porphyroblastic growth. Note the optical continuity, marked by extinction, and the very irregular outline of the grain which is about 0.5 mm. long. Figure 2 A is a photomicrograph. Figure 2 B is a line diagram that indicates the outline of the porphyroblast. Figure 3 shows a more advanced stage with poikilitically enclosed quartz and relics of plagioclase. This crystal, only a part of which is shown, is about 3 mm. long. Orthoclase, which developed in this way, generally encountered and replaced some plagioclase and is commonly partly perthitic. In Fig. 3 A, which is a photomicro-



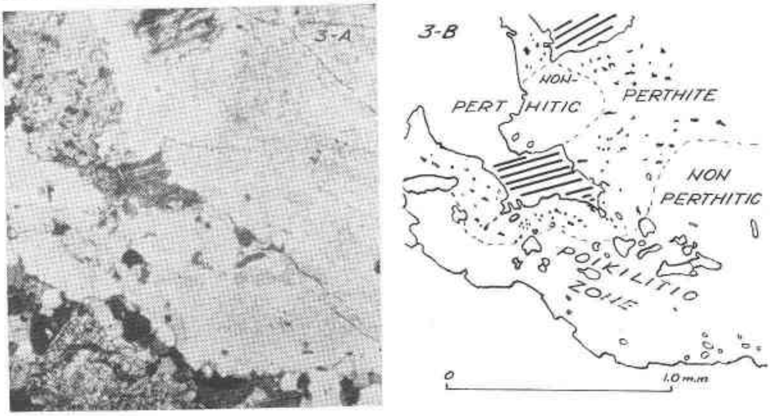


FIG. 2. (Top) Early stage of porphyroblastic orthoclase in fine grained groundmass of quartz monzonite porphyry. The photomicrograph (2 A) illustrates xenomorphic quartz and potash feldspar in the groundmass. Figure 2 B is an interpretation of the area of the porphyroblast, based on the optical continuity, marked by extinction, in 2 A.

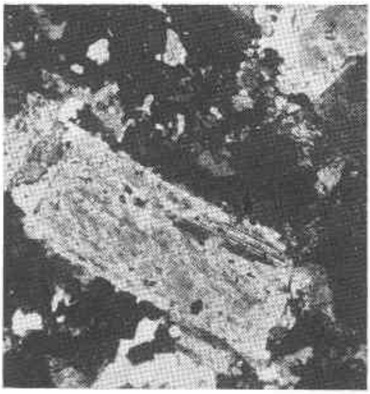
FIG. 3. (Bottom) Advanced stage of porphyroblastic orthoclase in quartz monzonite. The groundmass quartz is only slightly coarser than that shown in Fig. 2 A. Quartz and relics of plagioclase are poikilitically enclosed. In the vicinity of plagioclase which is partly replaced by orthoclase, the orthoclase is perthitic. In the poikilitic zone, the orthoclase is dominantly non-perthitic. Figure 3 A is a photomicrograph; 3 B a line diagram of the interpreted relationships.

graph, the perthitic texture is inconspicuous but present. Figure 3 B is a line diagram showing the outline of the porphyroblast and the poikilitically enclosed minerals. The perthitic areas are indicated in the vicinity of the plagioclase relics.

(4) Orthoclase also occurs in a variety of replacement relations with plagioclase. In some instances, plagioclase crystals are deuterically al-

tered to a more albitic composition and then replaced by potash feldspar in such a way as to preserve the form of the initial plagioclase crystal. Figure 4 is a photomicrograph of such a crystal in which a relic of the original plagioclase is preserved. Figure 6 A is a photomicrograph of a crystal of orthoclase which is perthitic within that part of its area that was formerly occupied by a plagioclase crystal. Where the potash feldspar extends beyond the limits of the original plagioclase it is noticeably less perthitic. Figure 6 B is a line diagram illustrating the relationships more clearly.

In other instances, plagioclase crystals are completely replaced but the space of the original crystal is occupied by two or more grains of potash feldspars with different orientations. Figure 5 is a photomicrograph showing a plagioclase crystal, partly replaced by two grains of orthoclase. Relics of albite or reorganized blebs of albite are in orthoclase within an area formerly occupied by plagioclase. Figures 7 and 8 are photomicrographs of the same field in which a large plagioclase phenocryst was formerly present but is now occupied by three potash feldspar crystals with distinctly different orientations. In Fig. 7, relics of plagioclase throughout the area of the photograph show a common orientation of albite twinning which indicate the position and orientation of the original crystal. Figure 8, rotated about 30° counterclockwise from the position in Fig. 7, shows that the same area is occupied by three potash feldspars. The twinned plagioclase relics are white. The dark gray area represents



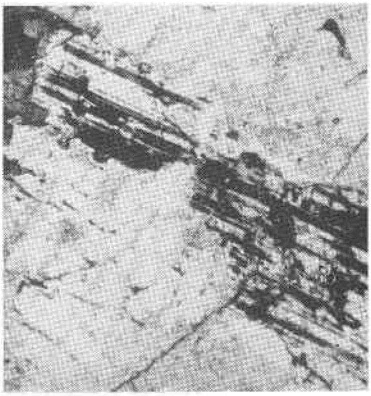


FIG. 4. (Left) A relict of andesine remains in deuterically altered phenocryst. The alteration is partly to albite (white) and a potash-bearing feldspar (light gray). The original shape is preserved. Original crystal about one mm. long.

FIG. 5. (Right) Andesine phenocryst partly replaced from two sides by orthoclase. Note concentration of albite at upper margin of plagioclase and irregular patches of albite in orthoclase within the limits of the original plagioclase crystal. In lower left hand part of photograph, the albite is in irregular strings.

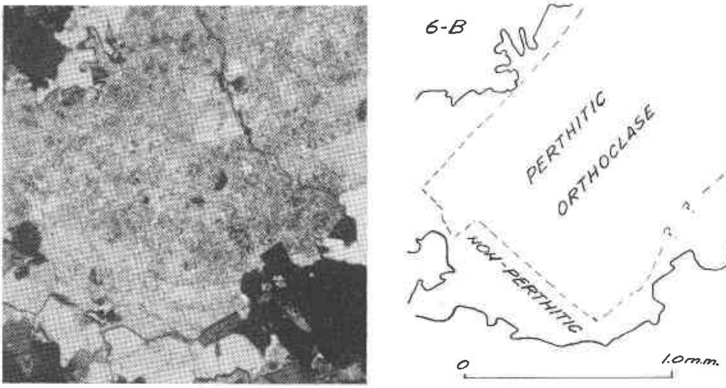
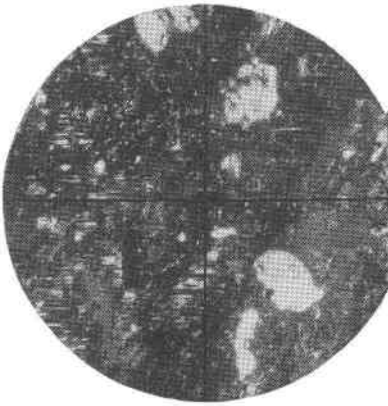


Fig. 6. The photomicrograph (6 A) shows orthoclase microperthite which has the form of a plagioclase phenocryst. The area of the original plagioclase is marked by a sub-graphic perthitic texture. The margin of the crystal, especially in the lower left hand part of the photo, appears to represent orthoclase which grew beyond the limits of the original plagioclase. This portion of the crystal is not perthitic. Figure 6 B is a line diagram of the interpretation of the area of the original plagioclase crystal and the extended, porphyroblastic growth of orthoclase.



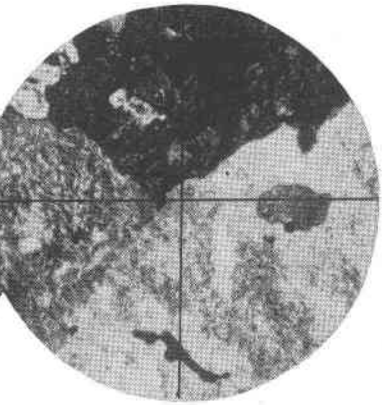


Fig. 7. (Left) Photomicrograph of field of potash feldspars in which relicts of plagioclase (marked by albite twinning) indicate the presence of a plagioclase crystal which nearly filled the field of the photo. Radius of photo about one mm.

Fig. 8 (Right) Photomicrograph of same field as shown in Fig. 7, but rotated about 30° counterclockwise revealing three distinct potash feldspar crystals. The dark gray is anorthoclase, medium gray orthoclase microperthite, light gray probably anorthoclase, white relicts of plagioclase.

anorthoclase with its distinctive inconspicuous grid twinning; the intermediate gray is orthoclase which is conspicuously perthitic; and the light gray is probably ȧnorthoclase. This example is from an alaskite, but similar relations are found in coarser grained quartz monzonite.

Microcline

Microcline occurs in minor amounts in some of the coarser grained rocks only, and is recognized by its clearly defined grid twinning and large optic angle. The bulk of the potash feldspar which shows an indistinct grid twinning is not microcline, and where examined, has a much smaller optic angle. The mineral is anorthoclase or a potash-bearing feldspar similar to anorthoclase.

Anorthoclase

Anorthoclase apparently means different things to different petrologists and it is with some reservation that the term is applied here. There is considerable confusion in the literature about its optical properties and doubt has been cast on the validity of the species (Laves 1952, p. 568). Laves, in his summary of the literature, reports that "Anorthoklas" was first described by Rosenbusch in 1855 but the term has since been applied to a variety of minerals which have slightly different optical properties. He states, "no other mineral of importance appears to play such an ambiguous role in mineralogical and petrographic literature as 'anorthoclase.' Numerous attempts have been made to define and characterize this mineral, and virtually every publication and textbook considers it in a different way" (Laves 1952, p. 567). The principal contributors to the present knowledge of anorthoclase are: Brögger (1890, p. 539, 563; 1897, p. 12–14) who considered anorthoclase a soda-microcline, *Nathronmikroklin;* Forstner (1884) who contributed optical data indicating variable properties; Winchell (1925, 1933, 1951) who assembled and attempted to organize the data; Alling (1926) who considered that anorthoclase may not be homogeneous and may not be triclinic; Spencer (1937, 1938) who studied the stability relations of the mineral; Oftedahl (1948) who considered that the cryptoperthitic nature of anorthoclase is an important characteristic; Laves (1950, 1952) who critically reviewed the literature and whose experiments with melts led him to use the term K-analbite for anorthoclase, indicating that the mineral is disordered and stable at high temperature; Tuttle (1952) who carefully determined the optical and chemical properties of anorthoclases from a suite of volcanic rocks; and MacKenzie and Smith (1955, 1956) who developed *x*-ray techniques for the study of the alkali feldspars, including anorthoclase.

Lacking *x*-ray equipment, the mineral herein called anorthoclase is a potash-bearing, apparently soda-rich feldspar which has the following properties: The optic angle is somewhat variable, even within an individual grain, as also noted by Tuttle (1952, p. 562), but is about 54°; is optically negative; has slightly lower birefringence than orthoclase; commonly exhibits an indistinct grid twinning; gives variable but commonly negative results when stained with sodium cobaltinitrite solution (Gabriel et al. 1929, Chayes 1952b, Rosenblum 1955). Some of the largest crystals in alaskite and in potash-rich selvage zones around segregations of tourmaline and pyrite in quartz monzonite, have an optic angle $2V = 54° \pm 2°$, based on 6 universal stage measurements. One hand picked grain has $n_\beta = 1.529 \pm .001$. From the index of refraction, the composition is estimated to be about Or 20 An 80 (Tuttle 1952, p. 559). Other anorthoclase or anorthoclase-like grains which are slightly stained with sodium cobaltinitrite may contain a larger proportion of potash.

Identification of anorthoclase in thin section is not always certain. The large crystals of orthoclase are commonly perthitic, anorthoclase is not perthitic; anorthoclase commonly exhibits an indistinct grid twinning, similar in some respects to microcline with which it may be confused. The birefringence is somewhat less than orthoclase and the relief difference is insignificant. Anorthoclase commonly lacks uniform appearance throughout the mineral, and has been described in the writer's notes as "messy." The best means of positive identification of the mineral herein called anorthoclase are its twinning and small optic angle. In stained thin sections, the distinction is usually clear. Plagioclase is unstained and twinned according to the Albite law, orthoclase stains uniformly, anorthoclase is normally not stained, but may be stained in patches.

Assuming slowly falling temperatures through the deuteric stage of crystallization, anorthoclase formed at a relatively low temperature—slightly below the albite alteration and somewhat higher than orthoclase which replaced it. In this regard, it more nearly fits the properties and presumed stage of crystallization indicated by Winchell (1951, p. 299) than any other. He does not give any specific temperature of formation, but it is indicated to be at a temperature well below 600° C. The mineral did not crystallize directly from magma and definitely did not form at the elevated temperature of K-analbite of Laves (1952, p. 561).

Other Minerals

Quartz is the last mineral to crystallize, commonly replacing plagioclase and potash feldspars, but in some instances appears to have crystallized simultaneously with orthoclase in granophyric intergrowths.

Other minerals include minor amounts of monoclinic pyroxene, normally augite, which is commonly found in the cores of actinolitic hornblende. Biotite is brown and strongly pleochroic. Magnetite and apatite are the principle minor accessory minerals. Sphene, tourmaline and zircon are present.

MINERALS IN ALASKITE

Plagioclase in alaskite, where preserved as distinct relics of earlier larger crystals, is commonly oligoclase. Albite is abundant in well organized strings and blebs in orthoclase. The potash feldspars are the same as the replacement types in quartz monzonite. Anorthoclase is moderately abundant, and quartz may comprise as much as 20 per cent of the rock, about twice the normal content of quartz monzonite. Some shreds of muscovite represent the position of former biotite crystals. Much of the plagioclase is flecked with sericite and in some instances, individual plagioclase grains are strongly sericitized. Black tourmaline is relatively abundant at some localities.

ORTHOCLASE MICROPERTHITE

Albite, in small, irregular patches, blebs, strings and sub-graphic textures in orthoclase occurs in quartz monzonite as shown in Figs. 8, 2, 10 and 6. Its distribution is frequently erratic and there is no obvious crystallographic control in many instances. In some cases, the albite appears to be small relics. In most quartz monzonite and in alaskite generally, albite occurs in reasonably orderly arranged blebs and strings showing a greater tendency towards crystallographic control, and indicated in Figs. 6, 11 and 12. Figure 11 A is a photomicrograph of a string-type perthite in orthoclase. At the contact with plagioclase, which appears to have been in part replaced by orthoclase, the strings are distinctly broader than in the rest of the orthoclase crystal. Figure 11 B is a line diagram showing the relationship a little more clearly. Figure 12 is a photomicrograph of a typical flame texture in which the albite appears to have become well organized in a specific crystal zone.

The non-uniform distribution of albite in orthoclase and the general absence of obvious crystallographic controls, make an exsolution origin improbable (Alling, 1921, Anderson, 1928). In many of the perthites, and particularly in Figures 11 and 12, the textures clearly resemble replacement textures described by Alling (1921), Anderson (1928) and Faessler and Tremblay (1946). The mobility of soda in the end stage of crystallization in perthites has been brought out by Gates (1953, p. 55) who found the two-fold classification of perthites, replacement and exsolution, unsuitable. Although the textures resemble replacement textures described in the literature, the absence of any other evidence of soda metasomatism, such as late albitization and the occurrence of perthitic textures only in those potash feldspars which replaced plagioclase, leads the writer to question a simple replacement origin.

SODA AND POTASH IN BOULDER BATHOLITHIC ROCKS

Chemical analyses of batholithic rocks reveal a relatively small quantity of soda generally. In the most mafic rocks, the soda content is 4 to 5 per cent; in granodiorite, the amount is somewhat less; in quartz monzonite, about 3 per cent; and in alaskite 2 to 3 per cent. These data plotted on a Larsen variation diagram (1938) yield a straight line whose slope decreases slightly from the mafic to felsic rocks.

Potash, on the other hand, increases from about one per cent in gabbroic rocks to 2 to 3 per cent in granodiorite to 4 to 5 per cent in quartz monzonite to about 6 per cent in alaskite. Similarly plotted, the curve indicates a distinct increase in slope through the range of quartz monzonites and a leveling off in alaskite.

Lime drops from nearly 10 per cent in the most mafic rocks to about 4 per cent in quartz monzonite to less than one per cent in alaskite. The elimination of plagioclase by deuteric potash metasomatism is clearly reflected in the lime and potash curves. Soda remains almost the same but is found in several different minerals at different stages. Larsen diagrams of Boulder batholithic rocks were published by the writer in notes on the chemical petrology of the batholith (Robertson, 1953).

In quartz monzonite, as more and more plagioclase was replaced by orthoclase, the lime was lost, but the soda content remained nearly constant with perhaps a slight tendency towards its reduction. In the nearly complete replacement of plagioclase in alaskite by orthoclase and anorthoclase, the soda content is only slightly lowered and potash increased.

The petrographic evidence of potash metasomatism in striking. The relative abundance of anorthoclase in alaskite suggests that insufficient potash was available to convert all of the anorthoclase to orthoclase. There is no textural evidence for late soda metasomatism in which orthoclase should be replaced by albite. Only the reverse is evident. The available chemical data support the petrographic observations.

PERTHITES FROM OTHER LOCALITIES

Orthoclase microperthites that appear to have been formed in the same manner as those of the Boulder batholith have been noted at several other localities and in a variety of rock types, all considered to be magmatic in origin, and the perthite to have formed by deuteric processes. They have not been investigated in the same detail as those in the Boulder batholith, but they are considered worthy of mention to indicate that this type of perthite may not be rare.

A granogabbro sill, located about 35 miles west of Helena, Montana on U. S. highway 10 N, contains perthitic orthoclase which formed by the replacement of plagioclase by orthoclase. Along small vein-like bodies, anorthoclase-like minerals replace plagioclase, and are in turn replaced by orthoclase, indicating the same late magmatic sequence—late potash metasomatism and absence of soda metasomatism. The amount of orthoclase microperthite is small.

A granitic differentiate formed by deuteric solutions which replaced plagioclase, pyroxene and biotite in a diabase at Mt. Sheridan in the Wichita mountains, Oklahoma, consists of plagioclase, a potash-bearing probably soda-rich feldspar (not anorthoclase), orthoclase and quartz, together with strongly altered mafic minerals (Robertson, 1954). Potash metasomatism is conspicuous in the replacement of plagioclase by orthoclase which is, in part, perthitic. The amount of perthite is small.

Orthoclase microperthite of similar origin occurs in two pre-Cambrian granites, one a red granite in the Wichita mountains, another the Silvermine granite which crops out southwest of Fredericktown, Missouri. In the granite from the Wichita mountains, perthitic orthoclase clearly replaced plagioclase. In the Silvermine granite, a conspicuously perthitic anorthoclase-like mineral is present which appears to represent an intermediate mineral stage in the replacement of plagioclase by orthoclase.

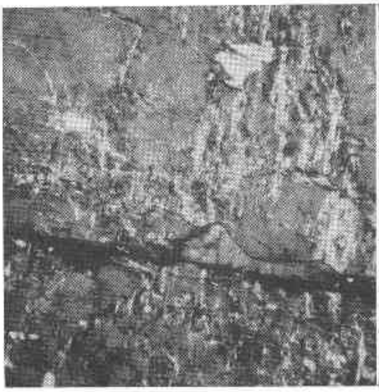
ORIGIN OF THE PERTHITE

Crystallization Sequence

The data accumulated in the study of the perthites in the Boulder batholithic rocks, and probably at the other localities cited, suggest a mode of origin different from either of the classic concepts, viz. exsolution or replacement. Orthoclase which formed by the replacement of plagioclase, and orthoclase which replaced anorthoclase which had previously replaced plagioclase, is perthitic. Gates (1953, p. 65) noted associations of anorthoclase and perthite and reported anorthoclase remnants, usually small, "in crystals which are largely perthitic." He implies that the anorthoclase formed by the alteration of albite blebs after the formation of perthite. In this investigation, anorthoclase appears to have formed at an intermediate stage in the formation of some of the orthoclase microperthite from plagioclase, and that anorthoclase occurs infrequently as relics in perthite, as illustrated in Fig. 9.

Temperature and Environment of Formation

The evidence suggests that the temperature of formation was relatively low, probably below 500° C., and that the perthite formed in essentially a static environment in contrast to a stress environment. The low temperature of formation of the perthites is postulated because of



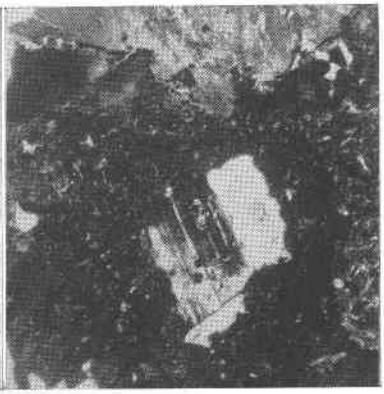


Fig. 9. (Left) Photomicrograph of orthoclase with relict patches of anorthoclase showing the indistinct grid twinning. A relict of plagioclase is shown in the upper part of the photo. The albite twinning in the plagioclase relict is parallel to one of the twin directions in the anorthoclase. The field is about one mm. wide.

Fig. 10. (Right) Photomicrograph of relict of plagioclase in anorthoclase (dark gray) with orthoclase microperthite replacing the anorthoclase. Note the string type albite in orthoclase. Diameter of field about one mm.

the sequence of mineralogical events in the deuteric stage which suggests slowly decreasing temperatures throughout crystallization from normally untwinned albitic alteration of plagioclase, to replacement of albite by anorthoclase (where formed) to replacement of anorthoclase by orthoclase which is perthitic.

Chayes (1952a) and earlier Phemister (1926) pointed out that a stress environment appears to favor the formation of perthite. Mäkinen (1913, p. 35) noted a close relationship between microcline grid twinning and perthite, and considered that the control was one of stress. The presence of granophyric intergrowths in the groundmass and the absence of any obvious directional trends in the rocks tends to favor a more nearly static state than one under stress.

Origin of Albite in Perthite

In the transformation from plagioclase (andesine in the Boulder batholith) to orthoclase microperthite, the chemical and mineralogical sequence appears to be as follows: (1) Plagioclase was altered to albite in a narrow zone between the original plagioclase crystal and the invading potash feldspar. Space was thus made for orthoclase by the expulsion of anorthite and by the greater solubility of orthoclase in albite than in the original plagioclase. (2) Albite was then replaced by orthoclase, or in some instances, anorthoclase. If the replacement proceeded directly to orthoclase, a large part, if not all, of the albite remained essentially in

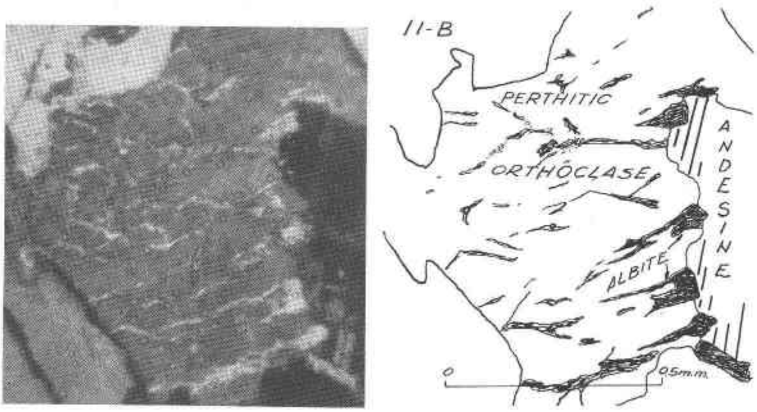


FIG. 11. Photomicrograph (11 A) of string type orthoclase microperthite in contact with plagioclase which has been at least partly replaced by orthoclase. Note that the albite strings terminate against plagioclase in much wider "heads" of albite. Figure 11 B is a line diagram emphasizing the interpreted relationships.

place, evidently within the space occupied by the original plagioclase crystal. Undoubtedly some albite was taken into solid solution in orthoclase. The excess albite which could not be taken into solid solution remained in discrete relics. The final reorganization of albite relics into blebs and strings, commonly with some tendency towards crystallographic control, attests to the mobility of the albite within orthoclase at this late stage. Where anorthoclase formed as an intermediate step, as indicated in alaskite and some quartz monzonite, the anorthoclase was in turn replaced by perthitic orthoclase. The albite originally in anortho-

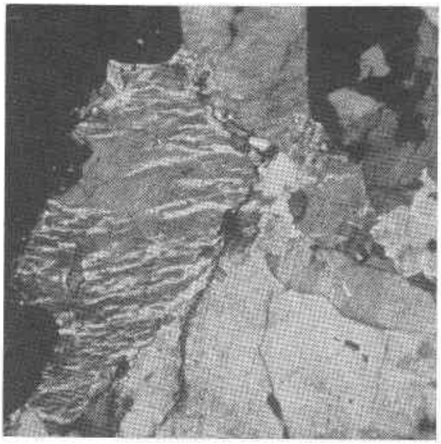


FIG. 12. Photomicrograph of flame-type orthoclase microperthite in alaskite which resembles a replacement type. Width of crystal is about 0.5 mm.

clase was reorganized into blebs in orthoclase. Since anorthoclase is a more potash rich feldspar than albite, it would seem that if anorthoclase did not form generally as a distinct mineral phase, the chemical stage represented by anorthoclase was passed through.

The abundance of anorthoclase in alaskite probably indicates that the replacement process was arrested before completion by the exhaustion of the potash available for replacement of anorthoclase to orthoclase. So far as the writer is aware, perthite which formed in this way, by the reorganization of albite as a consequence of deuteric potash metasomatism, has not been previously described.

Summary of Stages Leading to Formation of Reorganization Perthite

1. Plagioclase (calcic andesine in quartz monzonite) is attacked and altered to albite, commonly in a narrow zone between plagioclase and replacing potash feldspar. The albitic feldspar is normally untwinned, but in one instance, the albite alteration rim is distinctly twinned.
2. Albite was partly replaced by potash feldspar. In some instances there is an intermediate anorthoclase stage with anorthoclase in turn replaced by orthoclase. In orthoclase formed by this sequence of crystallization, albite blebs are found.
3. The albite blebs appear to be small relics in some instances. In most cases the albite appears to have been reorganized into discrete blebs or strings which resemble those found in replacement perthites. Some perthite formed in this way in alaskite and some quartz monzonite indicates further reorganization into crystallographically controlled zones in orthoclase.

In the formation of reorganization perthite, albite, originally in solid solution in plagioclase, remains essentially in the same area, first crystallized to albite, then part of the albite taken into solid solution in orthoclase and the remainder remaining as blebs, patches or strings, reorganized into favorable zones within orthoclase.

Orthoclase microperthite which exhibits textures similar to those found in replacement perthite of the type herein described does not necessarily constitute a criterion of late soda metasomatism.

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