CRYSTALLIZATION OF THE ROCKVILLE GRANITE

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Introduction

The Rockville granite of Minnesota is an unusually coarse-grained rock with abundant microcline phenocrysts and very little secondary alteration. In it late magmatic or deuteric effects are pronounced and, because of the coarse texture, relatively easy to study. The granite has been subjected to no recognized metamorphism beyond such deuteric replacement as occurred in direct continuation of primary crystallization. Therefore the phenomena described here are apparently uncomplicated by forces beyond those within a static body of cooling magma. The granite is an excellent subject for a paragenetic analysis of normal crystallization in a rock of simple history.

The Rockville granite lacks any suggestion of complication by replacement of a sedimentary or metamorphic wall rock. The reactions indicated, however, are so numerous and so complex that in other surroundings they might be interpreted as different from a normal igneous sequence. There is always more or less uncertainty regarding the relative period of formation of any one mineral in any particular rock and it is often difficult or impossible to understand the overlapping of crystallization periods and the formation of the same mineral at more than one stage of the solidification process. However, careful observation of a rock brings out a number of criteria which, though individually of doubtful value, together have cumulative force. Where data are insufficient to draw conclusions, at least they indicate the various possibilities. The complexity of the igneous reaction series was noted by Bowen.[1]

The Rockville granite has been quarried since 1907 in the vicinity of St. Cloud, Minnesota, and it is widely used in Minnesota as architectural stone.

> At the quarry the rock rises in a great dome which is exposed over at least an acre. Open joints are far apart and are somewhat irregular in direction; the most prominent strike S. 70° E. and others N. 45° E., S. 55° E., and N. 10° W. This irregularity, if joints were closely spaced, would result in much waste rock, but here, where they are spaced 20, 40, and even 100 feet apart, the irregularity is of little importance.[2]

[1] Bowen, N. L.: The Evolution of the Igneous Rocks, Chap. V, pp. 54–62, *Princeton University Press*, **1928.**

[2] Thiel, G. A., and Dutton, C. E., The Architectural, Structural, and Monumental Stones of Minnesota: *Minn. Geol. Surv., Bull.* **25,** 66 (1935).

The granite in the quarry ranges from a uniform medium-grained pink rock to an exceptionally coarse-grained rock of large pink microcline phenocrysts with interstitial biotite, hornblende, and quartz. Between these extremes the greater part of the rock is coarse-grained, uniform in composition save for sparse microcline phenocrysts which may be more than an inch in diameter. Many of the phenocrysts are oriented to suggest flow structure. Inclusions of a darker, finer-grained, gray granite a few inches long are also oriented with the flow. Microcline has apparently penetrated these inclusions, forming large phenocrysts within their borders. Several pegmatite veins of pink microcline and quartz are oriented with the inclusions. The pink microcline phenocrysts show notable zones, which are lighter in color towards the outer border. The plagioclase of the rock presents a sharp contrast to the microcline. The grains are pearly white and are crowded with dark inclusions of biotite.

The prevailing uniformity of the rock and the variety in the feldspars are shown clearly by polished surfaces on hand specimens and on Minneapolis buildings. Microcline, besides forming phenocrysts, penetrates every mineral assemblage as veins, stringers, and threads, completely anhedral. The pearly white plagioclase grains are euhedral but are splotched in the centers with abundant biotite inclusions and pink patches of microcline.

CHEMICAL ANALYSIS OF THE ROCKVILLE GRANITE*

SiO_2	69.63	CO_2	0.11
Al_2O_3	14.83	TiO_2	.37
Fe_2O_3	.54	ZrO_2	.05
FeO	3.53	P_2O_5	.28
MgO	.83	S	.07
CaO	2.35	MnO	.23
Na_2O	2.32	BaO	.03
K_2O	4.34	Cl	.05
H_2O^+	.23	Ni, Co	.06
H_2O^-	.10		
		Total	99.95

* F. F. Grout and F. J. Pettijohn, *analysts.*

Measurements of minerals in half a dozen thin sections indicated the following averaged percentages:

Plagioclase	36.0%
Microcline	33.9
Quartz	23.3
Biotite	6.7
Total	99.9

Although the percentage of plagioclase as measured is slightly higher than that of microcline, a hand specimen shows clearly that microcline is actually more abundant. The discrepancy is due to selection among the rock chips used in preparation of the thin sections so that no slide would be entirely microcline. Hornblende occurs in the rock in aggregates of fairly large grains, but it is considerably rarer than biotite and was not encountered in the thin sections measured. The rock is a biotite-quartz monzonite, assigned to the 226 granite subdivision of the Johannsen classification.

Mineral Descriptions

The primary minerals of the Rockville granite crystallized slowly and in the presence of mineralizers as shown by their unusual size, the signs of resorption and recrystallization of the mafic minerals, zoning of the early plagioclase feldspar, and deuteric effects. The mineral suite includes the following, listed in approximate order of abundance:

Primary			Secondary
Essential	Characterizing Accessory	Minor Accessories	
Microcline Andesine and Oligoclase Quartz	Biotite	Albite Hornblende Apatite Allanite Magnetite Zircon Sphene Fluorite	Sericite Chlorite Sphene Epidote Zoisite Calcite Kaolinitic mineral Pyrite

Microcline. The crystals of microcline are commonly as much as 2 centimeters across, equidimensional, and are pale pink in the hand specimen. Zoning is visible to the naked eye as paler and stronger pink bands. Under the microscope it is seen that different perthite patterns characterize successive zones. Perthitic albite is evenly distributed throughout the centers and throughout the individual zones. The outer borders of many of the microcline crystals are comparatively free from albite except for widely spaced veinlets perpendicular to the edge. Between the border and the central part of the crystal is a narrow zone of closely packed albite lamellae (Fig. 6). The megascopically white zones are high in albite content, the pink ones in microcline. Against earlier crystals the outer edges of the microcline are entirely anhedral and exceedingly irregular in detail. Intergranular spaces between the earlier crystals are filled with microcline, or to a lesser extent with quartz. The plagioclase is embayed by microcline and is spotted with microcline inclusions.

Andesine and oligoclase. Plagioclase feldspar occurs in two sharply defined varieties, an early, euhedral andesine-oligoclase, and a late, perthitic or bordering albite, which will be described below. The larger plagioclase crystals examined under the microscope were as much as 3 millimeters across, and hand specimens show considerably larger grains, some more than a centimeter in length. However, these are commonly if not always aggregates. The centers—earliest portions— of the crystals are andesine, grading to oligoclase toward the edges, or even to albite. The edges may be bordered in part by the late albite mentioned above, which is easily distinguished from the early main part of the crystal by the Becke line; zoning in the early crystal is too gradual for a contact line to be perceptible. Smaller crystals of the early plagioclase are of oligoclase. These formed at the time the oligoclase border was growing on the larger, first-formed crystals. The larger crystals contain euhedral inclusions of the accessory minerals as well as introduced microcline and quartz. An even distribution of tiny biotite inclusions of uniform size is characteristic and suggests that the biotite crystals had reached this size at the time the plagioclase crystal started to grow, were caught up and surrounded by plagioclase, and were thus prevented from reaching the larger size of the neighboring biotite grains. Perhaps the force with which plagioclase crystals grow is sufficiently less than that of microcline so that the plagioclase grows around foreign crystals, while the enlarging microcline grains push them aside. Many of the andesine crystals are marked by a pattern of small blocks with edges oriented with and across the albite twinning. The pattern is plainest toward the centers of the crystals. There are three different types: first, in some areas quartz and microcline included in the andesine form the rectangular blocks. Second, in other areas the blocks are of andesine but have a slightly different extinction angle from the surrounding crystal. A faint Becke line shows that these blocks have a slightly lower index than that of the surrounding feldspar, and so are slightly more sodic (Fig. 1). Third, the pattern also results from blocks in which the albite twinning gives way abruptly to pericline twinning at right angles. The alternation of blocks twinned in the two directions produces an effect more truly like a chessboard than the "chessboard albite" pictured by Olaf Andersen[3] or by G. H. Anderson[4] which show interrupted twinning with the

[3] Andersen, Olaf, The genesis of some types of feldspar from granite pegmatites: *Norsk Geologisk Tidsskrift, Bull.* **10,** 116–207, pl. 4, fig. 1 (1928).

twins running in the same direction. In some crystals of the Rockville andesine the block pattern shows up because of interrupted albite twinning, but such interrupted twinning does not seem to be due to enlargement of perthite veins by replacement as postulated by Olaf Andersen[5] for albite. The several types of block pattern may occur individually in any one andesine crystal or collectively.

The plagioclase crystals show rounded edges indicative of corrosion by microcline where the two minerals are in contact, with rims of clear or myrmekitic albite. At intervals microcline has embayed the plagioclase or penetrated it in branching tree-like forms; and it has cut off sections of plagioclase from the main crystal altogether, so that the pieces, corroded and rimmed, form islands optically continuous with the "mainland" crystal. Antiperthitic patches of microcline in the plagioclase are perhaps cross sections cut through embaying arms or stringers of microcline. All degrees of microclinization occur from minute square inclusions widely spaced to large patches of microcline shouldering each other, so crowded that only shreds of plagioclase lie between. Within the larger plagioclase crystals antiperthitic microcline in patches of unusual size has reacted with the surrounding plagioclase, embaying and corroding it in the same fashion that it has attacked plagioclase crystal faces from without.

Quartz. Quartz is of the usual granitic variety showing long rows of pin-point liquid and gas bubbles. Microcline and quartz crystallized contemporaneously, each embaying the other. Although there is much less quartz than microcline in the rock, they replaced plagioclase and hornblende in identical patterns. Both quartz and microcline form bays in the plagioclase; blocks of quartz are included in the interior of corroded andesine crystals as well as blocks of microcline; and one fair-sized corroded plagioclase island was observed in a sea of quartz, paralleling the islands occurring in microcline. Quartz is associated with biotite as inclusions in the interior of the crystals, as blebs intergrown in the corroded fringes at the ends of the biotite grains, and as small crystals intimately intergrown with tiny magnetite grains in corrosion pockets along the edges of the biotite.

Biotite. The grains of biotite are about the same size as hornblende grains—the largest about 2 millimeters long and slightly narrower; pleochroism $Y=Z$ deep brown, X slightly greenish-yellow. Inclusions of zircon, apatite, magnetite, pyrite, and sphene are plentiful. The ends of many biotite crystals are corroded. They may be fringed and chloritized,

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[4] Anderson, G. H., Granitization, albitization and related phenomena in the northern Inyo Range of California-Nevada: *Geol. Soc. America, Bull.* **48,** 1–74, pl. 4, fig. 3 (1937).

[5] Andersen, Olaf, *ibid.*, 170.

with quartz blebs and magnetite intergrown at plagioclase or hornblende contacts; or they may be rounded and edged with magnetite at quartz contacts. Although the chloritized fringes on the biotite occur between biotite and plagioclase, they are best developed against and penetrating hornblende. They are composed of chlorite oriented with the cleavage of residual biotite plates and interspersed with sphene and epidote. At the base of the fringe small quartz blebs and fine-grained magnetite outline the solid biotite core. Several of the biotite grains show signs of corrosion at the sides as well as at the ends. Rounded pockets eaten into the biotite are filled with a more or less regular intergrowth of tiny magnetite and quartz crystals, or with tiny rows of magnetite in a groundmass of plagioclase optically continuous with an adjoining crystal. Distortion of biotite laminae by bending and fracture is common. Small biotite grains may be included in hornblende crystals in parallel intergrowth (Fig. 8). The irregular outline of the biotite and the occurrence of hornblende in the cleavage cracks, as well as the poorly defined character of the hornblende cleavage, suggest the replacement of biotite by hornblende. Such replacement is not uncommon in rocks crystallizing with mineralizers.

Hornblende. Hornblende occurs sparingly in the Rockville granite in crystals of moderate size, about a millimeter across, usually three or four grouped together. The crystals are not sharp and clean-cut but have irregular edges and cleavage, slightly rounded corners, and a cloudy appearance. The pleochroism of most crystals is *Z* deep blue-green, *Y* bright green, *X* greenish-yellow, but the deep blue-green of the *Z* direction is splotched with patchy areas and vein-like traces of greenish blue, suggesting a slightly more sodic composition. Besides the early accessories, biotite, quartz, and microcline form inclusions (Figs. 7, 8). Much of the hornblende immediately surrounding quartz and microcline is blue.

Early accessories. Of the early accessories, apatite and zircon occur included in magnetite; all three minerals are widely distributed in euhedral grains usually 0.01 to 0.1 millimeter across. Apatite, the most abundant, is scattered uniformly throughout the rock, the largest crystals measuring 1.25 by 0.03 millimeter. Zircon and magnetite usually form inclusions in biotite and hornblende. Zircon is plentiful in well-formed prisms surrounded by dark halos in the biotite. Magnetite occurs in two associations, chiefly as an early accessory included in biotite in grains somewhat larger than the zircon prisms, also as fine-grained aggregates marginal to biotite, a by-product of corrosion. Sphene is chiefly secondary, associated with chlorite, but occasional grains of fairly regular outline included in biotite may be primary. Allanite is in euhedral crystals of unusual size—1 or even 2 millimeters long. The crystals are slightly pleochroic, light to orange brown, showing zonal growth and occasional twinning. A trace of purple fluorite is included in one allanite grain; white fluorite in minute crystals occurs scattered through the rock.

Albite. The late plagioclase, albite, is distributed as perthitic intergrowth in microcline and as borders on early plagioclase crystals, especially at microcline or quartz contacts. Three types of perthite as described by Olaf Andersen[6] were recognized, one similar in pattern to his "vein perthite," a second to his "film perthite," the third showing the fine texture of his "string perthite." At intervals narrow albite veins coalesce to form wider ones which might correspond to his "patch perthite," but the appearance is neither common nor marked in character. Little twinning has been observed in any of the perthitic albite. Albite veins are about 0.01 to 0.03 millimeter wide, forming a regular pattern of subparallel streaks 0.1 millimeter apart across microcline. In detail the outline of the streaks is far from regular; alternate thickening and thinning with coalescing and parting of tiny stringers along the sides is the rule. The regular distribution of the veins may be due to replacement of microcline by albite along contraction cracks as suggested by Olaf Andersen.[7] For vein perthite in plutonic rocks Alling[8] accepts Andersen's conclusions, considering the process deuteric—that is, late magmatic. Between the veins tiny lenses of albite forming film perthite are common. Occasionally these tiny lenses occur in patches, the veins giving way to the lenses for a short interval. The outlines of the little lenses are smooth and uniform. In the coarser varieties the lenses may be more than 0.1 millimeter long and perhaps 0.025 millimeter apart, in a patch about a millimeter across, whereas in the finer varieties the lenses can scarcely be distinguished with the 4-millimeter objective, and probably some are submicroscopic. All appearance of grating structure in the microcline is lacking in these areas. The finer lamellae of albite are unquestionably due to exsolution.[9]

Late albite occurs also as rims, chiefly on earlier plagioclase grains, and is most pronounced at microcline or quartz contacts. The earlier plagioclase is corroded and embayed, its corners rounded, then built out again by albite. The albite is very easily distinguished from the andesine or oligoclase because of its lower index and higher birefringence, and because it is much less sericitized (Figs. 3 and 4). Some albite is added

[6] Andersen, Olaf, *ibid.*, 149–150.
[7] Andersen, Olaf, *ibid.*, Chap. II, 121–145.
[8] Alling, H. L., Perthites: *Am. Mineral.*, **17,** 61 (1932).
[9] Alling, H. L., Plutonic perthites: *Jour. Geol.*, **46,** 163 (1938).

to the early plagioclase crystals in continuance of the original twinning pattern but with a slight difference in extinction angle. Around other plagioclase crystals the albite rim is irregular and myrmekitic, and the twinning pattern is absent. Small plagioclase crystals in microcline may have albite rims of varying widths (Figs. 3 and 4). There may be more rim than core, or the core so far corroded and sericitized that it is no longer recognizable as plagioclase. It is not only on early plagioclase that the deuteric albite has crystallized, but rows of tiny albite crystals may be seen along the line of contact between two microcline crystals. These seem to have grown into the microcline from both sides of the contact, spreading in fan-shaped units, a few containing myrmekitic quartz intergrowths.

Many fine examples of myrmekite occur in the albite rims. Commonly myrmekitic albite forms lobes spreading into the microcline with vermicular quartz in a dendritic pattern; or the quartz blebs may lie in a more or less parallel row in a fairly narrow albite rim, branching slightly towards the microcline somewhat like a row of cactus plants; or the quartz blebs may be very short, almost equidimensional, and scattered locally in a broad albite rim with albite twinning passing through the whole area except where interrupted by the quartz.

Secondary minerals. The granite is relatively fresh and unaltered but shows a few signs of hydrothermal action, chiefly on the biotite and calcic plagioclase. Many grains of biotite have been chloritized along the cleavage planes; a few whole crystals, mostly small ones, have been turned to chlorite. The chlorite is accompanied by sphene and some epidote, commonly along cleavage cracks. The chief alteration product of plagioclase is sericite, accompanied by considerable epidote and zoisite. Allanite also contains disintegration products, which may have resulted from hydrothermal alteration. Pyrite occurs associated with magnetite. A kaolinitic mineral in small amounts is widespread.

History of Crystallization

Perhaps the earliest evidence of the behavior of the Rockville magma is shown by scattered xenoliths of a gray rock which were partly digested by the including magma and wholly permeated by alkalic fluids. Crystallization of the magma may have started before the xenoliths were incorporated. The coarse texture of the Rockville granite suggests that its solidification was a slow process with normal crystallization accompanying the falling temperature, although there are evidences of corrosion, resorption, and replacement due to the abundant mineralizers, such as the corrosion of calcic plagioclase, and the slight replacement of biotite by hornblende. The microcline phenocrysts did not result from early crystallization as in an extrusive porphyry but were among the last of the magmatic minerals to form. The sequence of crystallization is on the whole a normal magmatic sequence; the texture of the rock is granitoid; the texture of the individual minerals indicates free crystallization from a liquid for the greater part of them. Observation of paragenetic relationships suggests the following order of crystallization:

PRIMARY.
- *Early magmatic*
  - Zircon and apatite
  - Magnetite
  - Sphene
  - Allanite (and purple fluorite?)
  - Biotite
  - Andesine
  - Oligoclase
- *Late magmatic or deuteric*
  - Magnetite
  - Microcline, albite, and quartz
  - Hornblende
  - White fluorite

SECONDARY (IN MINOR AMOUNTS).
- Sericite and calcite; chlorite and sphene; epidote and zoisite
- Pyrite
- Kaolinite

There is here at least no evidence against the early crystallization of euhedral minor accessories. Zircon and apatite apparently formed at about the same time. Both are included in magnetite. The early magnetite grains are rough in shape, probably corroded by the magma at about the time of growth of the biotite and allanite around them. At this stage some of the sphene of the rock may have formed, for there are a few compact grains included by fresh, unaltered biotite. These, although not definitely euhedral, are yet unlike the straggly anhedral grains associated with secondary products in the rock. Allanite grains both large and small are strictly euhedral.

Biotite was the first of the essential minerals to crystallize. Some of the crystals while still small were surrounded by plagioclase, the next mineral in sequence, forming characteristic minute inclusions. The first plagioclase to crystallize in permanent form was andesine. The large size attained by the crystals is evidence of the great length of time involved in their growth and the presence of the mineralizers. At first they were not abundant. They probably started fairly early, when the biotite crystals were as yet tiny specks in the enveloping magma. As the andesine crystals grew many of the tiny biotite crystals were included as well-distributed, equidimensional grains. As the andesine continued to crystallize, the calcium-sodium ratio in the remaining magma became gradually lower, as shown by the slight but progressive change in the extinction angle of the albite twinning lamellae toward the borders of the crystals, indicative of a correspondingly slight but progressive change in composition to the more sodic plagioclase, oligoclase, or even to albite. As the large plagioclase crystals grew, new centers of plagioclase crystallization were continually forming. From these grew smaller crystals of higher soda content. Therefore, in general the smaller and more sodic plagioclase crystals formed late. Some slight corrosion of biotite crystals took place where plagioclase came in contact with it, for there are pockets of magnetite-plagioclase intergrowth at such contacts.

Late in the primary crystallization sequence the highly alkalic rest-magma became corrosive. Deuteric resorption, recrystallization, and replacement are characteristic of this stage. Microcline and quartz penetrated the crystal boundaries of plagioclase, there solidifying in corrosion channels. Biotite was corroded, and small crystals of residual magnetite became massed along the ends of the grains or in pockets of quartz-magnetite intergrowth in the ends or sides of the grains. A little of the biotite, and some of the microcline which had begun to form, were replaced by hornblende of high soda content, its lime perhaps derived from the corrosion of plagioclase. The plagioclase crystals were corroded from without and were replaced within. Corners were rounded, edges embayed, and whole blocks were separated to form islands later in a microcline sea. Long stringers of microcline worked their way into the interior of plagioclase grains. By this time the magma was sufficiently cool and hydrous so that the calcic centers of plagioclase grains were none too stable. A pattern of small blocks of alternate albite and pericline twinning developed in the interior of many andesine crystals, producing a checkered effect. Other blocks suffered substitution of calcium by sodium so that they are formed of a plagioclase of a distinctly lower index of refraction and slightly different extinction angle. Still other blocks have been dissolved away altogether and microcline, or here and there quartz, substituted. The block pattern is best developed near the centers of the largest plagioclase grains, that is, where the calcic composition makes them least stable. A sequence in the development of the pattern is suggested by its occurrences. Probably the substitution of small amounts of soda was the first alteration. In many of the smaller crystals this is the only alteration. With further attack by rest-magmatic fluids came the crystallographic readjustment marked by the checkerboard twinning. Complete corrosion of the more susceptible cross-twinned or sodic blocks with consequent filling in by microcline or quartz followed. This order was by no means sharply defined. In the same crystal the various steps in the sequence overlapped. In the smaller, more stable crystals blocks of sodic plagioclase, quartz or microcline were slower to develop and less conspicuous finally. Many crystals show only the soda block pattern, others only small and widespread antiperthite blocks. Even in crystals with much reorganization of centers, the more sodic borders are affected little if at all.

The crystals above described formed a very loose mesh, in part were actually suspended in the highly alkalic rest-magma. In this, microcline crystals grew with less abundant quartz. At higher temperatures the microcline crystal lattice may have contained potassium and sodium in equivalent interchangeable positions. Having plenty of time, space, material, and temperature, the microcline grains grew to their observed great size. Upon cooling, the sodium and potassium ions were no longer able to hold identical positions, and the albite unmixed from the solid solution to form strings and films of the characteristic exsolution perthites. Contraction cracks developed on further cooling, making passageways for albitization to form vein perthites. Contraction cracks developed in the simultaneously forming quartz also, and were healed by later quartz, their places marked by rows of microscopic liquid and gas inclusions caught in them.

Among the latest and most widespread of the deuteric phenomena of this last stage in the process of primary crystallization was albitization. The solidification of microcline in the alkalic rest-magma used up the potassium but left a very sodic, mobile solution that before the microcline was completely crystallized was providing molecules of albite which attached themselves most readily to the corroded early plagioclase projecting into the microcline, and which filled contraction cracks in the microcline as fast as they appeared, thus forming vein perthite. Where the microcline was solid against the early plagioclase, albite continued to grow, replacing the microcline bit by bit, penetrating it in fan-shaped projections, including bits of silica here and there which solidified as vermiform streaks in myrmekite. Albite not only attached itself to early plagioclase, but grew along the boundary between adjoining grains of microcline, and, as myrmekite, even developed along the edge of a biotite-magnetite complex. Rare fluorite crystals possibly indicate a final touch of pneumatolysis.

The only metamorphism shown by the Rockville granite is a slight amount of hydrothermal alteration. Hydrothermal solutions may have carried foreign elements into the rock. However, most of the elements involved in the secondary minerals might easily have come from their immediate neighborhood. The formation of chlorite from biotite released potassium to form sericite from andesine. Calcium thereupon released from the andesine was used in the formation of sphene, calcite, and zoisite, and, with iron from biotite, formed epidote. Sphene derived titanium from the biotite upon its change to chlorite. Pyrite is found adjacent to, even included by magnetite, and probably derived its iron thence.

The shreds of kaolinitic mineral were probably the last to form in the Rockville granite, a result of the leaching of alkali during weathering.

Conclusion

Summarizing, the Rockville granite is a magmatic rock the coarse texture of which simplifies the study of its paragenesis. Its crystals formed, in general in the normal order, as follows: (1) minor accessories; (2) biotite and plagioclase; (3) microcline, quartz, hornblende, and albite, with accompanying deuteric phenomena; (4) hydrothermal minerals such as chlorite, sericite, titanite, and epidote.

Acknowledgments

The work was undertaken at the suggestion of Dr. F. F. Grout and chiefly carried out with a microscope kindly loaned by Dr. James Gilluly. Appreciation is here expressed to them and to many others for assistance, advice, and criticism of the manuscript.

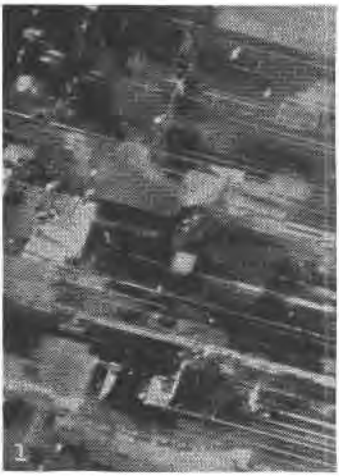
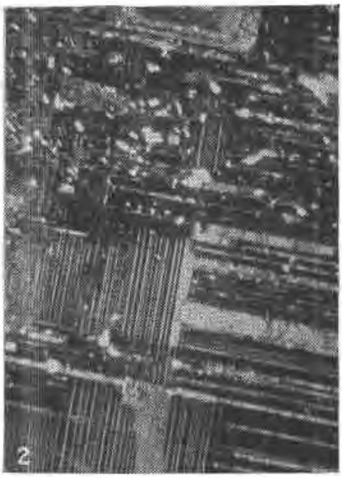
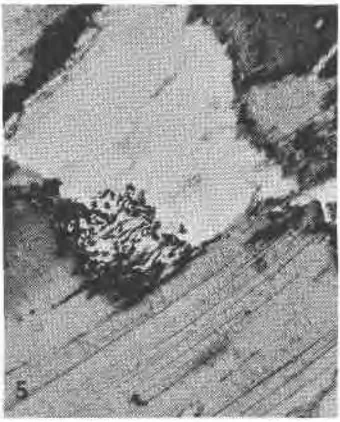



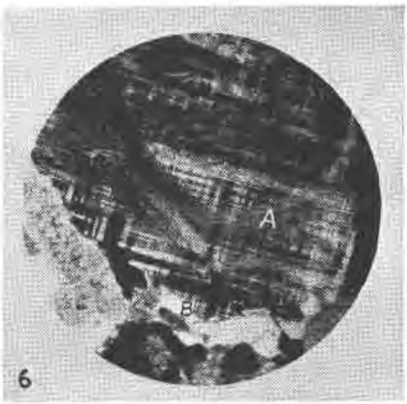
FIG. 1. The center of an andesine crystal contains small rectangular blocks (white in the photograph) of slightly more sodic andesine. The albite twinning passes through them without interruption. Crossed nicols; ×93.

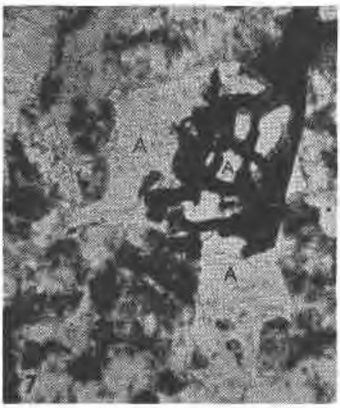
FIG. 2. A small portion of a large andesine crystal here shows blocks of pericline twinning (nearly vertical) interrupting the albite twinning (horizontal). Crossed nicols; ×97.

FIG. 3. Albite borders on minerals in contact with microcline were formed partly by replacement, partly by addition. Here an andesine crystal completely surrounded by microcline shows a white albite border around the sericitized gray core. Crossed nicols; ×87.

FIG. 4. The albite rim (grayish) is wide and twinned in continuation of the albite twinning of the sericitized andesine core. Crossed nicols; ×85.







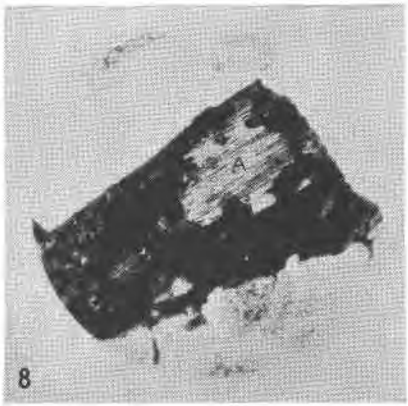


FIG. 5. The rest-magma attacked biotite grains forming pockets of magnetite-quartz intergrowth. Here the intergrowth (center) is lying between biotite (below) and quartz (above). Ordinary light; ×50.

FIG. 6. Microcline crystals grew very large between grains of earlier crystals, perhaps pushing them aside. The end of a large grain is pictured showing a prominent zone at A interrupting the twinning. It is composed of fine albite films barely discernible in the picture, elongated almost horizontally, not parallel to the zone marked A, but rather to the NE-SW twinning direction. B marks the boundary of the microcline crystal against a small plagioclase grain. Following this contact, the irregular, anhedral character of the microcline boundary is observed. Crossed nicols; ×17.

FIG. 7. Microcline (A) is being replaced by hornblende (black). The microcline is optically continuous. Ordinary light; ×49.

FIG. 8. The biotite remnant (A) is enclosed in hornblende which has replaced the greater part of the original biotite crystal. Hornblende occurs along cleavage cracks in the remnant. Ordinary light; ×37.

Photographs 1 and 2 were taken by George Tunell and C. J. Ksanda whose kindness is much appreciated.