PETROGRAPHY OF THE PIOCHE DISTRICT, LINCOLN COUNTY, NEVADA

By Joseph L. Gillson

LOCATION AND GENERAL GEOLOGY

The geology of a section of the Great Basin in the vicinity of Pioche, Nev., has been studied by members of the United States Geological Survey, and a brief summary of the results, by Westgate and Knopf,[1] has already been published. The writer had the pleasure of serving in the district with Professor Westgate during two field seasons.

The part of the area here described lies in the southern part of the Bristol Range quadrangle and the northern part of the Highland quadrangle. (See fig. 11.) Extending through these quadrangles from north to south is a high range of faulted but gently dipping Cambrian limestone, called in the north the Bristol Range and south of a pass known as Stampede Gap the Highland Range. At the north end of the Bristol Range occurs an overthrust block of Devonian sediments, which is known also in a small range 4 miles to the west, where it overlies Miocene (?) lavas. In the vicinity of Blind Mountain, in the southern part of the Bristol Range quadrangle, and on the western slopes of the Bristol Range, a down-faulted section of this Devonian overthrust mass occurs, there involved with the Miocene (?) lavas and intruded by a quartz monzonite mass, which has caused extensive contact metamorphism not only of the overthrust mass but of the Cambrian rocks adjacent to it.

This quartz monzonite is the only large intrusive mass exposed in the Pioche district, and its outcrops are confined within an area of about 2 square miles, although the desert wash filling the valley west of the Bristol Range probably buries a considerable mass of it. The exposures are considered to represent an upper cupola of a large batholith which underlies the whole Pioche area and from which the ore solutions emanated. The large size of the batholith is indicated by widespread marmarization of certain beds of the limestone and the wide distribution of the ore deposits, of zones of intense contact metamorphism, and of lamprophyre dikes.

The exposed igneous rock has two principal facies, but this study has shown that they are related. Both illustrate the type of differentiation described by Fenner,[2] in which the character of the magma during crystallization was changed because of the upward passage of gases. The already solidified border phase of the rock was intensely endomorphosed by these emanations, and throughout the body of the rock many mineral changes took place after consolidation.

THE QUARTZ MONZONITE

DISTRIBUTION AND GENERAL CHARACTER

As shown on Figure 11, a granitoid quartz monzonite crops out in two belts which are separated by a deep wash-filled valley, here called Kiln Valley. A porphyritic facies, in which the groundmass ranges from fine granitoid to aphanitic, forms two masses on Blind Mountain. Many narrow apophyses also there cut the volcanic rocks and sediments, and a large apophysis extends southeastward for over a mile. The smaller dikes are not shown on Figure 11.

The granitoid rock is light gray to pink, medium grained, and slightly porphyritic, and contains quartz, feldspar, and biotite, with subordinate amounts of other ferromagnesian minerals. The largest crystals in the rock are about 3 millimeters in diameter.

The coarser masses of the porphyritic rock contain white plagioclase phenocrysts as much as 2 millimeters in diameter and less abundant black phenocrysts of like size, set in a groundmass made dark by the abundance of minute grains of the ferromagnesian minerals. Quartz is confined to the groundmass and can be recognized only with difficulty. The finer-grained apophyses differ only in that the phenocrysts are smaller and the groundmass, being more dense, is darker.

At three places the granitoid rock is so intensely endomorphosed and differs so much in appearance from the main body of the rock that it was not correctly identified during the field study. It is a dark-colored medium to fine grained rock containing glistening phenocrysts of plagioclase and in some places of quartz, in a groundmass in which biotite is the only mineral present in crystals large enough to recognize. The identification of the rock in the field was made difficult by its close similarity to metamorphosed lavas and to the cordierite hornfels formed from the metamorphism of the Lower Cambrian shale.

The granitoid facies is cut by aplite dikes and veins and by narrow stringers of pegmatite. The aplite dikes are light-colored fine-grained rocks in which dark silicates are very subordinate. Large masses of

[1] Westgate, L. G., and Knopf, Adolph, Geology of Pioche, Nev., and vicinity: Am. Inst. Min. and Met. Eng., Bull. 1647-I, 21 pp., 1927.

[2] Fenner, C. N., The Katmai magmatic province: Jour. Geology, vol. 34, pp. 743-744, 1926.

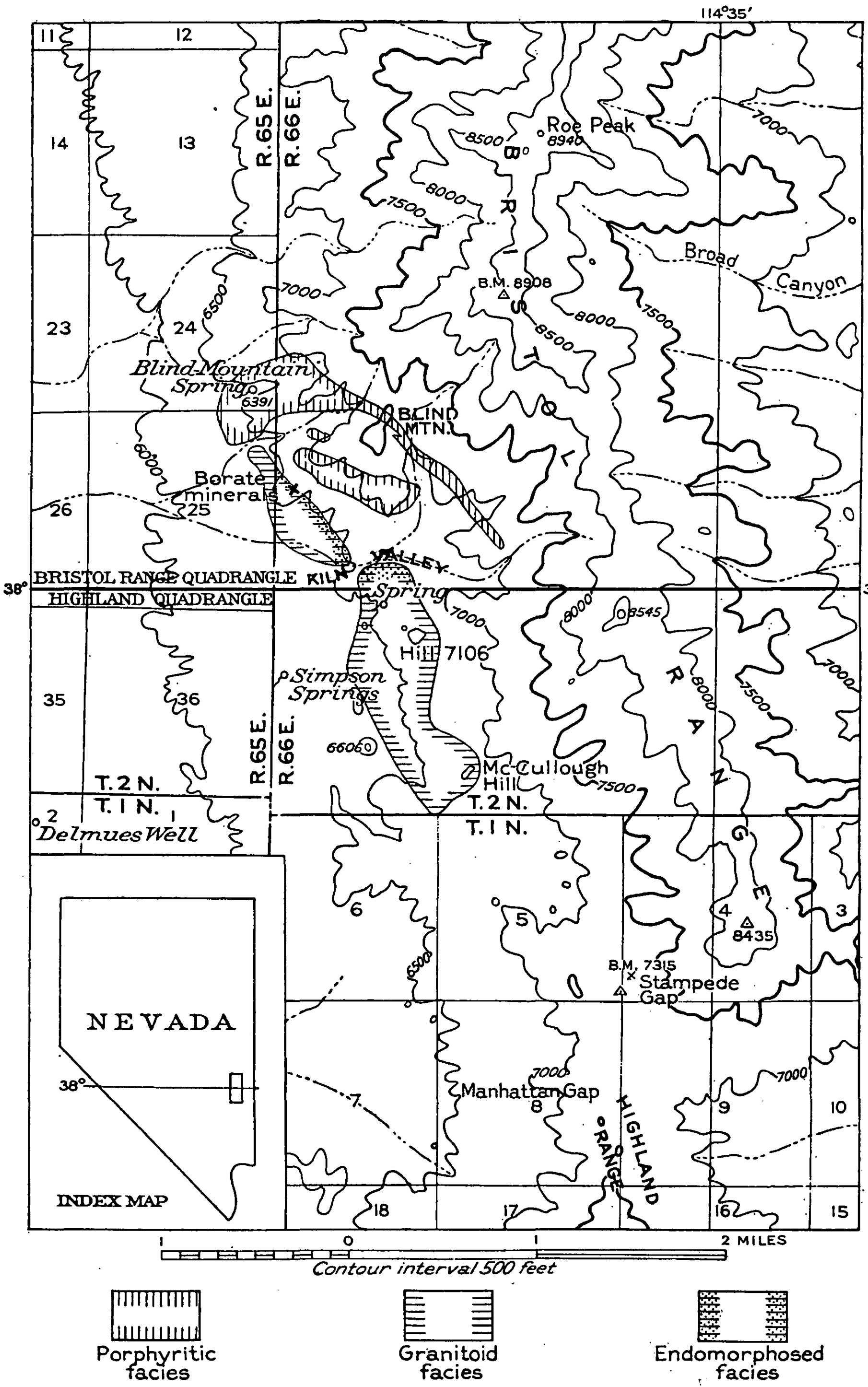


FIGURE 11.—Outline map of the exposures of the quartz monzonite of Blind Mountain, at the west base of the Bristol Range, Pioche district, Nev., showing the distribution of the two facies of the quartz monzonite and the endomorphosed zones

true pegmatite do not occur, but several small miarolitic cavities were found containing attractive crystals of tourmaline, feldspar, and magnetite. In the endomorphosed quartz monzonite narrow pegmatite stringers are abundant, and in several of these large druses occur in which are euhedral crystals of quartz and microcline as large as 2 centimeters in diameter.

PETROGRAPHY

GRANITOID FACIES

The rock away from its margins is subporphyritic and hypidiomorphic in texture and contains the following minerals in about the proportion shown in the table:

Average mineral composition, by weight, of the main mass of the granitoid quartz monzonite

	1	2	3
Quartz	15	16	25
Microcline	25	22	32
Plagioclase	46. 5	49	35
Biotite	9	6	4
Hornblende	2	3	2
Augite	Rare.	2	0
Accessories	2. 5	2	2

1. South slope of McCullough Hill.
2. North slope of hill 7106.
3. 0.2 mile north of latitude 38° and 2.07 miles west of longitude 114° 35′.

The augite occurs as cores of the hornblende grains. The accessories are apatite, magnetite, zircon, allanite, and titanite.

The rock near its border, where almost free from endomorphic effects, is similar to the normal type of the main mass but is richer in dark minerals, especially in pyroxene. The mineral composition of the border rock is as follows:

Average mineral composition, by weight, of the border facies of the granitoid quartz monzonite

	1	2	3
Quartz	15	12	12
Microcline	24	18	24
Plagioclase	40	52	39
Biotite	7	7	9
Hornblende and pyroxene	11	7	13
Olivine	0	Rare.	0
Accessories	3	3	3

1. 1.1 miles south of latitude 38° and 1.32 miles west of longitude 114° 35′.
2. 0.09 mile south of latitude 38° and 1.66 miles west of longitude 114° 35′.
3. 0.42 mile north of latitude 38° and 2.17 miles west of longitude 114° 35′.

The border facies is interpreted as being a chilled margin, representing the composition of the rock magma earlier in the process of differentiation than that shown by the normal type. Hypersthene is almost as abundant as augite in some specimens. As some of the potash feldspar is deuteric, the proportion of it present is not an indication of the composition of the magma during consolidation.

PORPHYRITIC FACIES

The porphyritic facies contains zoned plagioclase phenocrysts, the cores of which are labradorite, set in a groundmass of acidic plagioclase and very interstitial quartz and microcline. Green hornblende and brown biotite occur both as phenocrysts and in the groundmass. Pyroxene is present as cores in a small proportion of the hornblende grains. Biotite is less abundant in the narrow dikes than in the larger masses. The feldspar phenocrysts are all more or less replaced by potash feldspar, by a process here called orthoclasization and described in detail on a later page. Other alteration by emanations after consolidation is conspicuous in most specimens studied.

Two apophyses of the porphyritic facies were found that differ from the more common type. They cut the Devonian sediments on the west spur of Blind Mountain and contain phenocrysts of quartz and potash feldspar. Biotite was the primary ferromagnesian mineral, although deuteric epidote, chlorite, and another finely divided brown but not pleochroic micaceous mineral occur.

CHEMICAL COMPOSITION

Only the granitoid facies of the quartz monzonite has been analyzed. The results are as follows:

Analysis and norm of the granitoid facies of the quartz monzonite of Blind Mountain

[J. G. Fairchild, analyst]

Analysis		Norm	
SiO_2	65. 84	Quartz	20. 64
Al_2O_3	15. 29	Orthoclase	26. 69
Fe_2O_3	2. 48	Albite	29. 34
FeO	2. 26	Anorthite	12. 79
MgO	1. 06	Diopside	1. 33
CaO	3. 05	Hypersthene	2. 60
Na_2O	3. 47	Magnetite	3. 71
K_2O	4. 53	Ilmenite	1. 98
H_2O-	. 01	Apatite	. 34
H_2O+	. 67		
TiO_2	1. 00		
P_2O_5	. 19		
MnO	. 09		
	99. 94		

The norm places the rock in Class II, order 4, rang 2, subrang 3 of the quantitative classification.

DIFFERENTIATION OF THE MAGMA

The border facies of the quartz monzonite, the mineral composition of which has already been given, is inferred to be the quenched product of the magma in a stage of differentiation prior to that from which the main mass finally solidified. Augite and hypersthene are prominent constituents of this facies, and in one specimen crystals of olivine were found. Much of the augite is surrounded by hornblende, indicating that with the progress of crystallization an increase in volatile material took place, making the hydrous mineral the stable form. The amount of potash feldspar present in the border facies is lower than in the normal rock, but in both much of it was formed after consolidation, and hence the quantity is not an indication of the character of the magma.

Both in the border facies and in the main mass an earlier chapter in the differentiation than that revealed by the general composition of the border facies is indicated by corroded cores of labradorite in some of the plagioclase crystals. In many grains scarcely more than a ghost of the corroded core remains. The labradorite is made conspicuous by the presence of tiny black rod-shaped microlites, of general definite arrangement, of the kind that are characteristic of the labradorite of such rocks, for example, as the Duluth gabbro, the Marcy anorthosite of the Adirondacks, the gabbros of the Adirondacks, and the anorthosite of Labrador. These microlites are significant for two reasons. First, the identity of the intensely endomorphosed quartz monzonite was made certain partly by the presence in it of plagioclase crystals containing just such corroded cores of labradorite, with microlites. Second, these microlites are characteristic of the feldspar of basic igneous rocks. An idea of the shape of the corroded cores of labradorite is given by the sketch in Figure 12. These corroded grains are not the normal central cores of zoned plagioclase crystals. The labradorite crystals after a considerable period of growth were so severely attacked by the melt in which they were no longer in equilibrium that many of them entirely and the rest of them largely went back into solution. Then normal zoned plagioclase, the cores of which are andesine, began to crystallize.

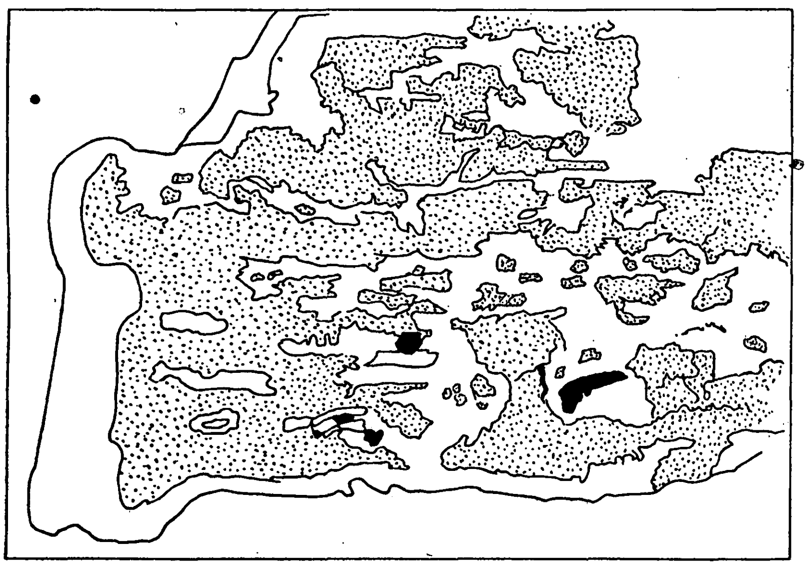


FIGURE 12.—Direct tracing of a photomicrograph of the granitoid facies of the quartz monzonite of the Pioche district, enlarged 32 diameters. Shows the remnants of labradorite, with the black microlites characteristic of it, in an andesine grain. The labradorite was intensely corroded by the magma after differentiation had upset the earlier equilibrium conditions

These labradorite cores and the pyroxene and olivine of the border zone indicate that the rock began to crystallize as a gabbro. Differentiation then took place, these minerals were no longer in equilibrium, and others of more acidic character began to crystallize. The change from augite to hornblende indicates that this differentiation was accompanied or caused by an increase in the volatile materials, and the endomorphism and deuteric mineral formation testify to the abundance of such materials.

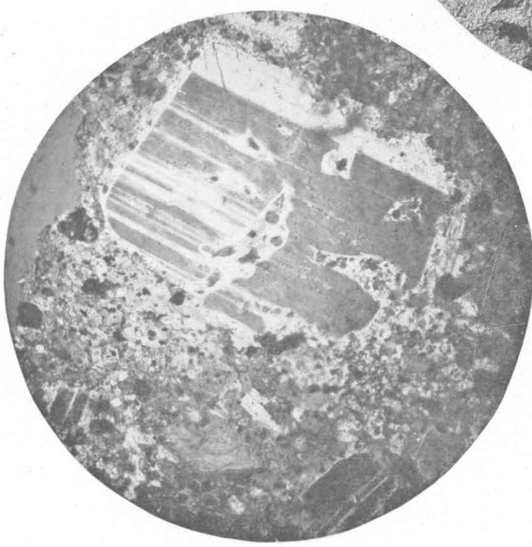
EVIDENCE OF MINERAL FORMATION AFTER CONSOLIDATION

The potash feldspar was not only a late pyrogenetic mineral, but it continued to grow after consolidation and formed by the replacement of quartz and feldspar. Evidence of this growth is seen in every thin section. (See pl. 10, *A*, and fig. 13.) This replacement, which was carried on most intensely in the endomorphosed rock (pl. 10, *C*), is here called orthoclasization and indicates a tremendous introduction of potash from the reservoir below. The introduction must have begun during the crystallization of the magma and must have been one of the factors that upset the equilibrium at the time when labradorite, augite, and hypersthene were the stable minerals. The only way in which potash could have been introduced into the magma, as it was in the solid rock after consolidation, was by means of volatile emanations. The potash feldspar so formed has a small to moderate optic angle, ranging from 20° to 50°, and rarely shows twinning. Much of it is therefore sanidine, but that in other specimens is perthitic and has a larger optic angle and is therefore microcline. Besides the potash feldspar, hornblende and biotite continued their growth into the deuteric stage, as is shown by protuberances on many of the grains, and also deuteric magnetite, apatite, titanite, and probably zircon formed. Their age is shown by the shape of the magnetite and titanite, and also by the apatite, many of the grains of which are long needles, some of which crosscut the boundaries of more than two adjacent grains. The age of zircon is never satisfactorily proved.

The type of alteration which is loosely described as "hydrothermal" but which is considered by the writer to be a late deuteric stage of mineral formation [3] is much more intensely developed in the porphyritic facies than in the granitoid facies. The primary horn-

[3] Gillson, J. L., Granodiorites of the Pend Oreille district of northern Idaho: Jour. Geology, vol. 35, pp. 18–20, 1927.

A



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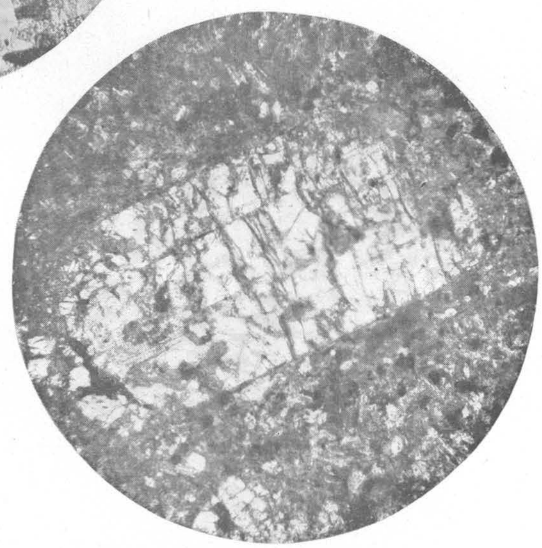

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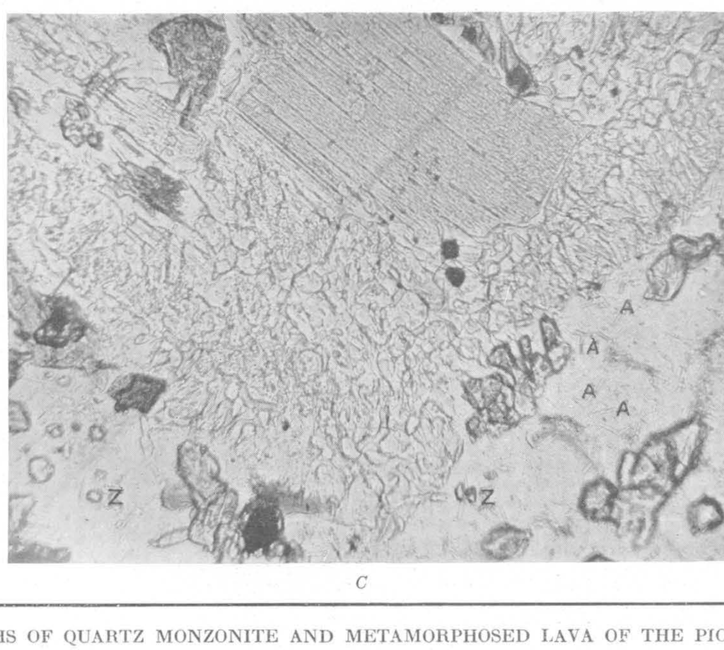

C

PHOTOMICROGRAPHS OF QUARTZ MONZONITE AND METAMORPHOSED LAVA OF THE PIOCHE DISTRICT, NEV.

A, Porphyritic phase of the quartz monzonite, plane polorized light; enlarged about 40 diameters. Shows intense orthoclasization of the plagioclase.

B, Endomorphosed quartz monzonite, enlarged about 40 diameters. An original phenocryst of plagioclase is cut by tongues of andesine and orthoclase, in which there formed also small pyroxene crystals.

C, Endomorphosed quartz monzonite, enlarged about 300 diameters. Shows the graphic intergrowths formed by the replacement of an original plagioclase grain by microcline. Several of the anhedral grains of pyroxene characteristic of the endomorphism are seen, as are also many small needles of apatite (A) and zircon (Z).

D, Metamorphosed Miocene (?) lava, under crossed nicols; enlarged about 40 diameters. Shows the riddling of an old plagioclase phenocryst by veins of potash feldspar.

blende has been replaced by an actinolitic variety, and the chlorite and epidote are so abundant that the rock has a greenish tint. A carbonate was formed in some of the more intensely altered zones, and a zeolite of very low refractive index and strong birefringence was found in many of the altered plagioclase grains.

Alteration of a different type occurred a short distance east of Blind Mountain Spring, where topaz, epidote, and actinolite were abundantly developed along with the intense orthoclasization. The replacement of quartz by orthoclase had proceeded in such a manner that the residuals of quartz have the structure of a graphic intergrowth. Proof that this structure is the result of replacement was afforded by a quartz grain lying between two microcline grains. A graphic intergrowth occurs in the quartz grain on each side, and the quartz component of both intergrowths is in optical continuity with the main part of the grain free from microcline. The microcline component of one is in optical continuity with the nearest microcline grain; that of the other is in optical continuity with the microcline grain adjacent to it.

ENDOMORPHOSED QUARTZ MONZONITE

The endomorphosed quartz monzonite was found at three places. The largest area of its exposures is on the north slope of the spur that extends north from hill 7106 (fig. 11), and the same rock is found on the north side of Kiln Valley and can be traced northwestward along the base of Blind Mountain. A small exposure was also found on the south slope of McCullough Hill, where it seems almost to grade into the hornfels formed by the metamorphism of the Pioche shale. At two points coarsely crystalline aggregates of minerals of unusual variety are interpreted as metamorphosed limestone inclusions in the endomorphosed igneous rock and are described on pages 82–83, under the heading "Metamorphism of mixed rocks."

The identity of the black rock as endomorphosed quartz monzonite was established by microscopic study. It contains plagioclase crystals of the same type, attacked in the same manner (although more intensely) by potash feldspar, and has the corroded labradorite cores in which are the same black microlites as are seen in the quartz monzonite. Furthermore, the border facies of the quartz monzonite contains the first stages of the endomorphism, of which the most characteristic feature is the wide distribution of minute anhedral grains of augite which followed the orthoclasization in a manner so nearly unique that it would probably not be found in different rock types. (See pl. 10, *B*.) The presence of hypersthene in both rocks corroborates the other evidence, as that mineral was not found in any of the other metamorphosed rocks that resemble the endomorphosed quartz monzonite macroscopically.

The character of the rock varies with the degree of metamorphism. The rock has a porphyritic texture and contains plagioclase crystals averaging a millimeter in diameter, set in a groundmass of clear, anhedral, equidimensional grains of potash feldspar, and replacement of the plagioclase by the orthoclase is seen in all stages. Intense orthoclasization of plagioclase produced structures resembling graphic intergrowths, an example of which is illustrated in Plate 10, *C*. Widely scattered through the rock are anhedral augite crystals, many of them subspherical, colorless in section in the less metamorphosed facies,

FIGURE 13.—Direct tracing of a photomicrograph of the granitoid facies of the quartz monzonite of the Pioche district, enlarged 32 diameters. Shows the remnants of two plagioclase grains in orthoclase, the replacement having been a deuteric effect. All outliers marked 1 extinguish together and were originally parts of a single large grain; the same for the outliers marked 2

green in the more metamorphosed. Their size ranges from 0.01 to 0.03 millimeter. Rambling biotite crystals that send out arms or branches inclosing or replacing adjacent minerals are abundant and, being much larger than the other ferromagnesian minerals, can be identified with the naked eye. Biotite is absent, however, from the specimens showing the most intense metamorphism. Widely distributed also are minute grains of magnetite and ilmenite, and large crystals of these minerals of irregular form are found inside of many of the biotite grains. Minute prisms of apatite, seen only with moderately high magnification (pl. 10, *C*) occur by the million in most of the specimens studied. Associated with them are numerous small, generally anhedral crystals of zircon.

When examined closely the plagioclase phenocrysts are seen to have been replaced by potash feldspar only where a previous replacement by glassy andesine had occurred. This replacement was not magmatic corrosion, for where the replacement by orthoclase has gone so far that the pyrogenetic plagioclase crystals are reduced to small residuals of bizarre form, the margin of andesine is invariably found around the edges of the residuals and is also found in the interiors of sections, as spots where the solutions have drilled from above or below.

The small augite crystals never entered the plagioclase phenocrysts except where they had been made over into andesine or potash feldspar. Their formation did not require, however, the presence of the potash feldspar, as they occur in the secondary feldspar of both types.

Quartz is absent from the most intensely endomorphosed varieties, having been replaced by the potash feldspar. In specimens illustrating partial elimination of the quartz, graphic structures showing replacement of the quartz by potash feldspar are very striking.

A small amount of green hornblende of a late generation occurs in some places. Finely divided titanite is abundant locally, and where it is present many of the ilmenite grains are surrounded by a halo of titanite. Very minute prisms, practically opaque although slightly brownish on thin edges, are very abundant, but their identity could not be established..

The most intense endomorphism produced a rock consisting dominantly of potash feldspar in anhedral grains, 0.05 millimeter in diameter, in which are some residuals of plagioclase and abundant anhedral grains of greenish augite and magnetite. Quartz, biotite, and hypersthene are absent, and apatite is not so abundant as in less metamorphosed phases.

At one point, possibly owing partly to the influence on the solutions from passage through limestone blocks near by, the endomorphism went further. Garnet veins cut through the pegmatite stringers, and locally the old igneous rock has been altered to a nearly solid mass of grossularite garnet and two pyroxenes, one having a β refractive index of 1.705 and the other of 1.680. Topaz and calcite also occur in smaller amounts. Thin sections show this stage of metamorphism superimposed on the orthoclasization stage. Residuals of plagioclase remain to prove the genesis of the rock.

In some places nests of epidote occur within the garnet rock.

The paragenesis of mineral formation seems to have been approximately andesine, orthoclase, pyroxene, apatite, zircon, biotite, magnetite, ilmenite, titanite, followed locally by garnet, augite, topaz, and epidote. It is not clear just where in the sequence the pegmatite stringers so commonly found through the rock had formed. They contain principally quartz, potash feldspar, and biotite, with a little andesine.

In some druses found in wider pegmatite veins a few less common minerals occur in small amount. These include small honey-yellow crystals of titanite and a deep-green nonpleochroic pyroxene, the β index of which is 1.725 and the extinction angle $C \wedge Z$ 52°. An unidentified mineral of which a few small grains were found has the following properties: Color black, brittle, β index 1.815, birefringence strong, optically negative, $2V = 15° \pm$, X light brown, Z black.

At one place on the east side of McCullough Hill evidence of endomorphism of a different type was found. In a zone a few feet wide, exactly at the contact with the limestone, the rock is soft and black and consists dominantly of tourmaline, which is pleochroic in shades of pale pink and very deep blue. Quartz, calcite, and small anhedral grains of zircon are disseminated through the tourmaline.

METAMORPHISM OF MIXED ROCKS

On the north slope of the spur extending north from hill 7106 an inquisitive prospector had opened a trench in a 5-foot veinlike mass of green diopside, spinel, and calcite. About 20 feet south of this trench is the normal facies of the granitoid quartz monzonite, and the diopside rock grades sharply on both sides of the vein into recognizable quartz monzonite. Between the vein and the main mass of the intrusive rock no outcrops are found, but the surface is littered with float containing minerals characteristic of the metamorphism of limestone, including vesuvianite and wollastonite. Accordingly, this block of coarsely crystalline minerals grading into the quartz monzonite is considered to be the metamorphosed product of a limestone inclusion in the border phase of the quartz monzonite.

The diopside of the diopside-spinel rock has a β index of 1.692, and the subhedral crystals reach 1 centimeter in diameter and have a grass-green color. The spinel is black, though deep green in color by transmitted light, has a refractive index of 1.740, and gives qualitative tests for magnesium and aluminum and weakly for iron. Most of the grains have curved surfaces but do not appear corroded. A few are octahedrons.

The quartz monzonite on the south side of the "vein" grades sharply within the width of a hand into a nearly white dense rock, consisting of a white pyroxene, the β index of which is 1.690, and an isotropic grossularite garnet. This rock grades into another greenish rock, tinted with red, containing vesuvianite and locally a considerable amount of wollastonite. In several specimens of float there is a second augite, green in section, with a β index of 1.705. Calcite is present in subordinate amount in all specimens.

Another variation, not found in place, is an aggregate of pyroxene, vesuvianite, calcite, and a greenish mica, colorless in section, occurring as pseudohexagonal tabular crystals reaching 1 centimeter in diameter. The indices of refraction of the mica are α 1.555,

β and γ 1.588. The mica is intergrown with or altered to another micaceous mineral, also colorless in section, with indices of 1.530 and 1.555.

Another unusual aggregate of minerals was found at the place marked on Figure 11 "Borate minerals." In a zone 20 feet across, bounded by white marble on one side and by quartz monzonite on the other, occur successively a peculiarly subspherically banded rock, black and white; then a green diopside-spinel aggregate similar to that at the other locality; and then some of the typical endomorphosed quartz monzonite, which gives way to the more normal intrusive rock. The peculiarly banded black and white rock contains the borate minerals ludwigite, szaibelyite, and fluoborite, associated with a great deal of magnetite and serpentine and cut by veins of dolomite and hydromagnesite. This occurrence was described in 1925,[4] but at that time the mineral now considered to be fluoborite was not identified, as the grains were too small and too intimately intergrown for analysis. The optical properties, however, were published, and recently Geijer[5] in studying a similar mineral association identified a new mineral which he called fluoborite, with the composition $3MgO.B_2O_3.3Mg(F,OH)_2$, and which had the same optical properties. Doctor Geijer has suggested that the unknown mineral in the Pioche occurrence is fluoborite.

With the borate minerals occur small amounts of bornite and chalcopyrite, now partly oxidized, and the opening of a prospect on their account has well exposed this interesting occurrence, which otherwise might have passed unnoticed.

At the south contact of the quartz monzonite on McCullough Hill the endomorphosed igneous rock grades sharply but almost imperceptibly into the hornfels that is the product of metamorphism of the Pioche shale. The two rocks appear so similar that the distinction was not recognized in the field.

This grading of endomorphosed igneous rock into exomorphosed sedimentary inclusions or walls indicates that the metamorphism of both followed the intrusion and solidification of the border facies of the quartz monzonite.

CHEMICAL CHANGES DURING ENDOMORPHISM

A composite sample of the endomorphosed quartz monzonite from three places was analyzed. A comparison of this analysis with that of the main mass of the granitoid quartz monzonite suggests the changes in composition caused by the metamorphism, but the comparison is not an exact one because the endomorphosed rock was from the border facies and not the main mass, and border rock free from endomorphism and deuteric potash feldspar could not be found. The endomorphosed rock is low in quartz and rich in feldspar and pyroxene. The analysis suggests an increase in lime, iron, and alumina and a loss in silica and soda. It is probable that if the amount of potash present in the border zone at the time of consolidation could be determined, a notable increase of that oxide would be recorded by the analyses.

Analysis of composite sample of the endomorphosed quartz monzonite of the Pioche district

[Naima Sahlbom, analyst]

SiO_2	57.87
Al_2O_3	18.68
Fe_2O_3	3.13
FeO	3.37
MgO	1.26
CaO	7.38
Na_2O	1.83
K_2O	4.14
H_2O-	.32
H_2O+	.97
TiO_2	.80
P_2O_5	.28
MnO	.07
	99.78

CONCLUSIONS

When the magma stoped its way upward and came to rest, it had the composition of a norite, and augite, hypersthene, labradorite, and olivine were crystallizing from it. Differentiation took place, and the composition of the magma was changed so that the labradorite became unstable and was vigorously attacked by the liquid. The evidence for such vigorous attack indicates that though the change in stability was rather sudden it was not the normal progression of equilibrium following a lowering of temperature. If it had been, the labradorite crystals would exist as uncorroded cores in the plagioclase. A slow lowering of temperature would have completely eliminated the labradorite. Corroded labradorite grains as shown in Figure 12 indicate a more special type of differentiation.

Evidence that this differentiation was the result of the introduction into the magma of new material by gases passing upward from below, as a result of which an original norite magma crystallized into a quartz monzonite rock, is as follows: The change of augite to amphibole, the oscillatory zoning of the plagioclases, and the intense endomorphism and exomorphism testify to the presence of gases in large quantity. The large-scale replacement of plagioclase and quartz by deuteric orthoclase and the orthoclasization in the contact metamorphism indicate that these gases were rich in potash. If these gases were abundantly present during the final period of consolidation, it is reasonable to think that they began to appear earlier and accounted for this rather sudden change in equilibrium conditions above noted.

[4] Gillson, J. L., and Shannon, E. V., Szaibelyite from the Pioche, Nevada, district: Am. Mineralogist, vol. 10, pp. 137-139, 1925.

[5] Geijer, Per, Some mineral associations from the Norberg district: Sveriges geol. Undersökning, ser. C, No. 343, pp. 26-27, 1927.

That crystal settling did not play much part in this differentiation is indicated by the presence of the corroded labradorite crystals in quantity at the roof of the batholith and by the presence of oscillatory zoning in the plagioclase rims around them.

The conclusion is thus drawn that this quartz monzonite illustrates the type of differentiation suggested by Fenner.[6] It shows, also, how different a consolidated rock may be from the magma that made the intrusion.

CONTACT-METAMORPHOSED MIOCENE (?) VOLCANIC ROCKS

The rocks around Blind Mountain are in a downfaulted part of an overthrust block containing Devonian sediments and some of the volcanic rocks. Because of the faulting and the intrusion of many apophyses of a porphyritic facies of the igneous rock, the bedding of the sedimentary and volcanic rocks can not in general be distinguished. Moreover, the close resemblance between the metamorphosed lavas and the fine-grained dikes made mapping difficult in the field.

The volcanic rocks consist dominantly of latite, dacite, and andesite tuffs, breccias, and flows and are in general crumbly and have suffered severely from erosion. Only a few of the more massive flows make bold hills. Blind Mountain, however, one of the sharpest and most conspicuous of the minor summits, consists of tuff and breccia, indurated by the metamorphism into rocks as hard and resistant as quartzite.

A description of the character of the metamorphism which has so profoundly changed these rocks is given below.

GENERAL CHARACTER

The unmetamorphosed flows are black, gray, or reddish fine-grained porphyritic rocks, in many of which flow lines are conspicuous. The breccias are light in color and contain fragments of other volcanic rocks of various size and character. Open cavities are numerous. The tuffs differ from the breccias in the absence of the rock fragments. Most of them contain biotite and feldspar phenocrysts and the microscopic glass fragments described by Pirsson [7] as characteristic of such rocks.

Many of the metamorphosed volcanic rocks have a cream or a brownish-brick color on weathered surfaces and a light greenish color on the fresh fracture. Others are very dark brown or nearly black. Most of them break with a very hackly fracture, and the greater number contain minute feldspar phenocrysts. Many have open cavities containing garnet, epidote, magnetite, and amphibole. Nearly all contain disseminated pyrite and pyrrhotite.

The volcanic breccias can be identified the most easily. They contain angular to rounded fragments of dense dark chocolate-brown rocks embedded in a mottled green matrix. Small subspherical or irregularly shaped green or black masses, with white borders, formed by aggregates of secondary minerals, are widespread and very characteristic of the breccias.

In general, the metamorphism of the volcanic rocks involved the elimination of all the pyrogenetic ferromagnesian minerals and the formation of much potash feldspar and a new generation of ferromagnesian silicates, the latter generally in very finely divided form. To illustrate the process of metamorphism a description will be given of a few flows, tuffs, and breccias.

ILLUSTRATIVE EXAMPLES OF THE METAMORPHISM

East of hill 7106, at the west base of the spur projecting toward the north slope of that hill (see fig. 11), a considerable area is covered with fragments of a nearly black rock, which does not, however, crop out conspicuously. It weathers a light brown and contains scattered plagioclase crystals reaching 1½ millimeters in length. The original character of the rock is shown under the microscope by the old plagioclase phenocrysts, by the quartz and apatite, and by pseudomorphs of the ferromagnesian minerals. An intense orthoclasization of the groundmass and a similar attack on the phenocrysts had nearly eliminated the original minerals. Minute grains of biotite, pyroxene, and magnetite of metamorphic origin give the dark color to the rock. In the groundmass these are so generally distributed as to appear with moderate magnefication as a cloud of minute specks. The plagioclase phenocrysts are zoned and have labradorite cores tinted dark because of submicroscopic inclusions. All the phenocrysts show to a greater or less extent an attack by the orthoclase. This had begun by the formation of narrow irregular veins, in general following cleavage cracks, and from these veins the replacement had extended through the phenocrysts. The minute grains of biotite, pyroxene, and magnetite that are so abundant in the orthoclase of the groundmass are less common in the orthoclase of the phenocrysts, except near the edges. Accumulations of nearly solid masses of the dark silicates and magnetite represent imperfect pseudomorphs of pyrogenetic ferromagnesian minerals, many of which have the form of augite crystals. In addition to the widespread, finely divided magnetite, larger grains of it are fairly abundant. Many have the form of deuteric magnetite found in igneous rocks and are presumably of a late period of formation. A subordinate amount of rutile is also present. In specimens of this rock showing the most intense alteration the plagioclase phenocrysts have been so completely replaced by orthoclase that their pseudomorphs are conspicuous only between crossed nicols, where the outline of orthoclase grains larger than those in the groundmass pre-

[6] Fenner, C. N., The Katmai magmatic province: Jour. Geology, vol. 34, pp. 743–744, 1926.

[7] Pirsson, L. V., The microscopical characters of volcanic tuffs—a study for students: Am. Jour. Sci., 4th ser., vol. 40, pp. 195–197, 1915.

serves the shape of the plagioclase phenocrysts. Through the groundmass irregularly shaped aggregates of pyroxene grains are widespread. The individual grains are about 0.003 millimeter in diameter; the aggregates are as large as 0.25 millimeter. Many aggregates contain cores of magnetite. Aggregates of biotite also occur, and in many of these are single grains of magnetite, larger than those in the pyroxene aggregates. Many of these magnetite grains have projecting fingers penetrating into the biotite, indicating a later formation. They are similar to the late magnetite crystals in the peculiar aggregate structures or "reaction rims" of the Adirondack gabbros.[8] Some grains of ilmenite occur in the groundmass, and these are surrounded by a halo of minute titanite crystals.

Another metamorphosed lava from the summit of Blind Mountain is similar to that just described. Orthoclasization and the formation of very minute silicates and magnetite had been caused by the metamorphism. Besides the finely divided augite, characteristic of most of these rocks, an amphibole of actinolitic habit, epidote, titanite, and a little allanite occur. The rock contains numerous ellipsoids 1 to 5 millimeters in diameter, black but with white rims. The black core in some is augite, in others an amphibole with a β index of refraction of 1.690, weak birefringence, and distinct dispersion, ρ greater than v. With the amphibole is a brown isotropic garnet, index 1.87. The white rim is andesine, partly replaced by orthoclase. The apatite is so abundant in this and in many of the other metamorphosed lavas that it must represent an introduction of phosphate. Long needles of apatite, crosscutting the boundaries of several grains, are certainly of a late period of formation.

A lava flow illustrating the most intense alteration was found on the summit of the spur east of the north end of hill 7106. Along joint seams garnet and rhodonite crystals were found. The phenocrysts in the rock are so completely replaced by orthoclase that the crystal boundaries are distinguishable only between crossed nicols, where the difference in birefringence due to grain size is emphasized. In the pseudomorphs, however, a few remnants of plagioclase occur. The groundmass is made up largely of small equidimensional orthoclase grains in which very minute crystals of high refractive index are abundant. These include apatite, garnet, titanite, and a micaceous mineral similar to biotite in color but nonpleochroic.

In some of the lavas in which considerable quartz was originally present, replacement graphic structures made by the introduction of potash feldspar into the quartz are numerous.

The metamorphosed volcanic breccias represent a similar process of metamorphism but offer wider variations, inasmuch as the original rock was not uniform. The tuffaceous nature of the groundmass is generally readily apparent under the microscope. The irregular streaks and angular fragments of original glass are preserved as pseudomorphs of orthoclase in which there are countless minute grains of dark silicates, the average individual size of which is about 0.001 millimeter. Pseudomorphs of twisted and bent biotite crystals and angular fragments of foreign rocks testify to the original character of the rock. Spots made of spherical aggregates of minerals and partly filled druses are widespread. The plagioclase phenocrysts of the breccias are all more or less replaced by orthoclase. Although several grains of pyrogenetic ferromagnesian minerals were found, their rarity indicates that a complete elimination of such minerals, so common to these rocks, had occurred. One old hornblende crystal was found in one thin section, partly replaced by a carbonate and surrounded by a rim of finely divided pyroxene. In another section a large augite had begun to break down into small crystals of the same mineral. Aggregates of the tiny augite and hornblende crystals of metamorphic origin made crude pseudomorphs of pyrogenetic ferromagnesian minerals.

The rock fragments found in the volcanic breccias show a great variety of mineralogic features. Most of the metamorphosed fragments resemble the metamorphosed lavas and consist of a groundmass of finely divided potash feldspar and larger plagioclase grains, also replaced by orthoclase. Disseminated ferromagnesian grains and magnetite occur in all. Epidote and titanite seem to be more abundant in the rock fragments in the breccias than in the lavas, and biotite, common in the lavas, is absent from most of the metamorphosed volcanic breccias.

Green or black spots or ellipsoids with white rims are characteristic of the metamorphosed volcanic breccias. In a specimen from the summit of Blind Mountain the green cores consist of augite aggregates and of an actinolitic hornblende, the β refractive index of which is 1.650. The white rim is made up of calcite, many of the grains of which are optically biaxial.

Garnet occurs in most of the breccias. Many grains half a centimeter across are readily visible, and under the microscope scattered garnet crystals are found in many thin sections. Their irregular form indicates a late time of crystallization. Where tested the garnet has an index of refraction near 1.690 and a reddish-brown color.

Druses, partly filled with pretty crystals of pyroxene and lined with chlorite and magnetite, were found. In one of them slender needles of a green hornblende are perched on octahedrons of magnetite.

A breccia metamorphosed to a different product than the others was found on the spur east of hill 7106. Although the common process of orthoclasiza-

[8] Gillson, J. L., Callahan, W. H., and Millar, W. B., The age of certain of the Adirondack gabbros and the origin of the reaction rims and peculiar border phases found in them: Jour. Geology, vol. 36, pp. 153-157, 1928.

tion had occurred, most of the rock consists of augite and scapolite, with radiating fibers of chlorite and abundant minute grains of titanite. Large grains of garnet occur haphazardly.

A striking feature in these metamorphosed volcanic rocks is the occurrence on joint surfaces of drusy coatings of crystals. An occurrence of green garnet and red rhodonite, already mentioned, is an example of the beauty of these occurrences. Along another joint seam the zeolite steelerite is associated with an unidentified mineral having the following properties: β 1.615, positive sign, moderate birefringence, $2V = 75°$, hardness 5–6, color white, cleavage none.

CONCLUSIONS

The geologic importance of the contact metamorphism of the Miocene (?) lavas lay principally in the evidence it afforded on the date of the intrusion of the quartz monzonite. Descriptions of contact-metamorphosed volcanic rocks are not numerous, however, and thus the problem deserved study.

When the quartz monzonite was intruded it had the composition of a gabbro (see p. 80), but during its crystallization a rapid differentiation took place because of the upward passage of potash-bearing emanations from below. Because of the chemical changes caused by the reaction between these emanations and the magma the final product of crystallization was a rock of quartz monzonite composition. The border facies, solidified earlier, was intensely endomorphosed by these emanations. Orthoclasization had occurred, and finely divided biotite, augite, apatite, and magnetite formed in the feldspar. In places of intense endomorphism garnet also is found.

The metamorphism of the lavas is in harmony with that of the quartz monzonite. The solutions were rich in potash and iron and carried phosphate and titanium. Whether the magnesium, aluminum, lime, etc., of the metamorphosed rocks are due simply to a recrystallization of material already present or represent some introduction, it is impossible to state.

In the endomorphosed quartz monzonite and in the metamorphosed lavas sericite, chlorite, serpentine, and zeolites, characteristic of late stages of metamorphism such as that in the Pend Oreille district of northern Idaho,[9] are not abundant. The metamorphism was intense but rather short lived and was completed while the temperatures were high, for garnet was one of the late minerals. The heated waters given off in long progression from the cooling solid intrusive and causing "hydrothermal" alteration in other districts were not abundant here or were impotent to make many mineralogic changes.

[9] Gillson, J. L., Contact metamorphism of the rocks in the Pend Oreille district of northern Idaho: U. S. Geol. Survey Prof. Paper 158, pp. 111–120, 1929.